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Stratigraphic signatures of climatic change during the Holocene evolution of the Tigris–Euphrates delta, lower Mesopotamia

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Abstract

Fluctuations in climate, sea level and sedimentation rates, in addition to the neotectonic activity, during the geological evolution of the Tigris–Euphrates delta (in the last 10,000 years) had resulted in the deposition of various sedimentary units. Previously, five main stratigraphic units, with other sub-units, have been identified by the author during the study of the Holocene deltaic successions of Lower Mesopotamia and as based upon the results of petrological, geochemical, palaeontological and radiometric analyses of his PhD dissertation. Each unit has been produced through various depositional and diagenetic processes in addition to the dominant climate. Such processes together have been clearly recorded in the forms of either the authigenic minerals occurring in each sequence, particularly the Ca–Mg carbonates, evaporites and clay minerals, the biological activities represented by shell remains of molluscs, foraminifers and ostracods, or the preservation of organic matters within organic-rich layers. This review discusses the impact climatic changes had on the accumulated sedimentary facies during the Holocene evolution of the Tigris–Euphrates delta.

Arid climate dominated the study area in the early Holocene after a long period of the wetter conditions of Pleistocene. Such a climatic change has resulted in the formation of gypcretes rich in palygorskite and dolomite occurring within the calcareous fluvial-plain muds, similar to the modern fluvial plain deposits. However, the sediments were highly admixed with coarser sandy deposits of playa and aeolian sources in the western desertic margins, and with older reworked sands of Zagros foothills to the Northeast of Lower Mesopotamia.

During the mid-Holocene marine invasion, when the climate became wetter as well, brackish-water/marine sedimentary sub-units were deposited, overlying the previous fluvial plain deposits. The deposition started with a transitional sub-unit flourishing over the older early Holocene gypcrete deposits signaling the marine transgression. The best preservation of organic matters occurred beneath this sub-unit. This sub-unit, which is also characterised by microcrystalline mixing zone dolomite, was followed by the deposition of another sub-unit rich in molluscs and foraminifera that collected during the transgressive period.

After about 2000 years of maximum flooding (i.e. high stand period), a regressive tidal flat unit was deposited ending the marine/brackish-water deposition and signaling another climatic change towards a more arid setting around 4000 years ago. These climatic conditions are still continuous in the area and reflect the petrology of the modern salt-covered fluvial plain

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deposits of these rivers. However, marsh/lacustrine deposits and environments remained, covering some vast lowland parts of the fluvial plains, but further inland to the north of the present-day northern Gulf coasts. Complex implications of neotectonic activities, sea-level fluctuations and differential sedimentation rates in addition to the climatic changes during Holocene have resulted in the formation and preservation of these unique marshlands, which are still covering most parts of the ancient Tigris–Euphrates–Karun delta.

Keywords: climatic changes; Tigris–Euphrates delta; sea-level fluctuations; stratigraphic sequences; dolomite/palygorskite; organic matter preservation

1. Introduction

One of the main factors controlling the facies distribution in any basin is climate. Climate, in addition to sea-level changes, sedimentation rates and tectonism, is considered as an essential element in sequence stratigraphy (e.g. Vail et al., 1977; Van Wagoner et al., 1990; Loucks and Sarg, 1993). As a result of any abrupt changes in climate, the sediments deposited in a basin will undergo different depositional and diagenetic processes, particularly in basins dominated by the deposition of clastic sediments. The Holocene deposits of the lower reaches of the Tigris–Euphrates rivers are presented in this study as a recent small-scale model for such climatic changes, which occurred in general during the Holocene sedimentation in Lower Mesopotamia. In addition to representing an important delta where some well-known ancient civilisations were raised, geologically, there were some clear implications between sea-level fluctuations, sedimentation rates, neotectonic activities and climatic changes during the short Holocene depositional history of this delta (e.g. Aqrawi, 1993a). As a result, this region might be considered as a unique recent lacustrine deltaic case study.

Some climatic changes have been highlighted as the result of archaeological expeditions. Only a few articles have mentioned the impact of such changes have on human habitation, particularly regarding the agricultural activities (e.g. Jacobson and Adams, 1958). Previously, few workers had recognised one significant climatic change at about 4000 before present (BP), which is represented on a more regional scale, covering the whole Gulf region (e.g. Evans et al., 1969; Larsen and Evans, 1978; Baltzer and Purser, 1990, Aqrawi, 1993a). Later studies of the sedimentation patterns of this deltaic complex have led to the identification of changes in sea level, climate and sedimentation rate within the Holocene stratigraphic sequences, in addition to the effects of some neotectonic activity (for details see Al-Zamel, 1983; Al-Azzawi, 1986; Aqrawi, 1993a,b,c, 1994, 1995a,b, 1997; Aqrawi and Evans, 1994).

The current paper reviews the Holocene stratigraphy and evolution of the Tigris–Euphrates delta, based on the previous studies and some additional geochemical evidence, within a specific timeframe. It is recording the influence of climatic change by highlighting the petrological, biological and geochemical criteria, and interpreting the mechanism of organic matter preservation within the recognised sedimentary units of the delta.

2. Area of study

The complex delta of the Tigris–Euphrates–Karun rivers occupies the lower reaches of the Mesopotamian plains (Fig. 1). It is bordered by the Zagros foothills to the east, the Iraqi Western Desert and Wadi Al-Batin fan to the west and southwest, respectively, and the northern Gulf shorelines to the south. These southern plains are covered by shallow fresh- and brackish-water lakes of < 3 m depth, surrounded by extensive reed marshes of *Phragmites* sp and *Typha* sp. The lakes and their surrounding reed marshes are locally called “Ahwar”.

Many parts of these lacustrine-marsh regions (i.e. Ahwar) have been subjected to drainage modifications during the 1970s, responding to global warming and some petroleum industrial activities, such as

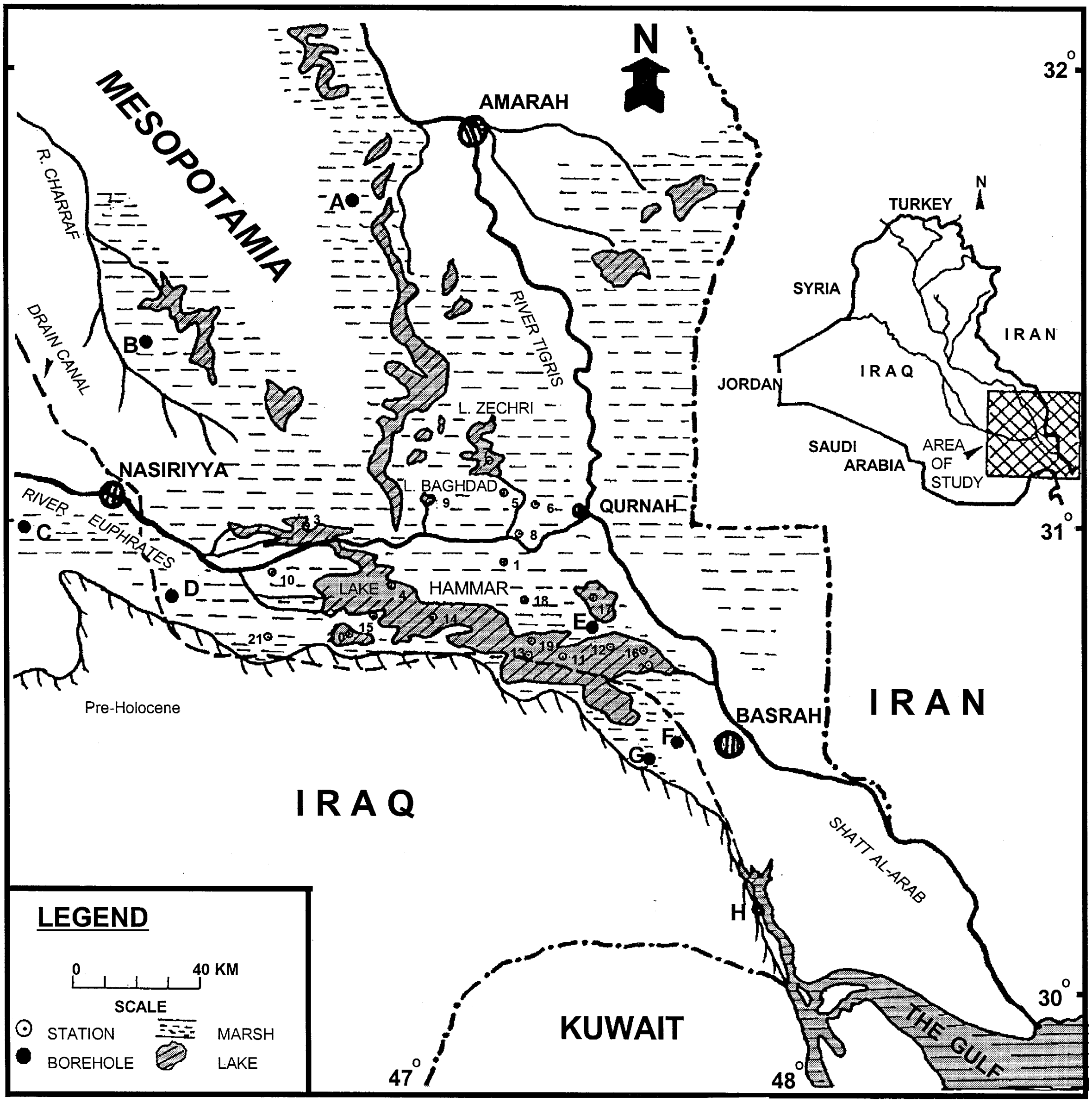


Fig. 1. A map showing the location of sampling stations of short cores (30–80 cm long) and boreholes (down to 15–20 m depth) in southern Mesopotamia (modified after Aqrawi, 1997).

oilfield development. In addition, there are low river discharges reaching southern Mesopotamia at present, which are mostly contaminated with various salt ions, reflecting the intensive irrigational systems and dam construction on the Tigris and Euphrates rivers and their tributaries throughout their courses in Turkey, Syria and Iraq. As a result, various sub-environments could be recognised in southern Mesopotamia such as salt-covered plains, river levee and dried marsh/lake, in addition to the predominant lakes and marshes (Fig. 1). The latter have consequently in many parts become brackish and saline,

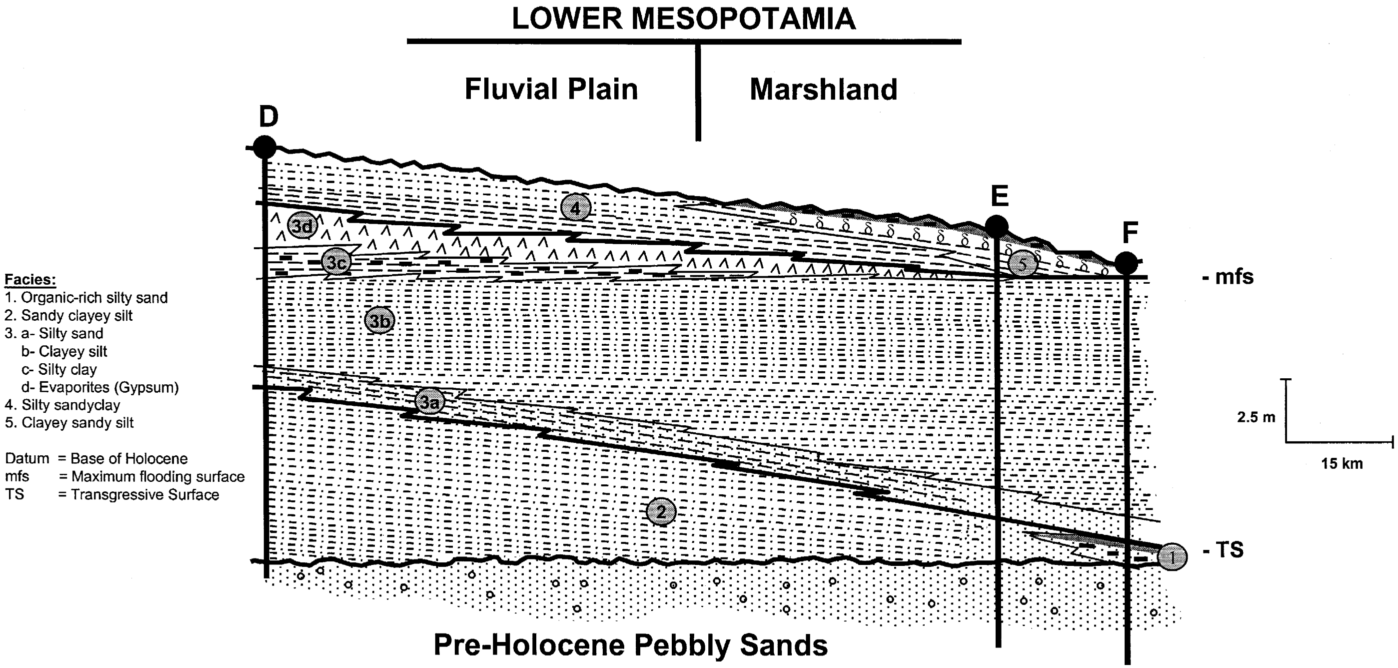


Fig. 2. The West–East correlation of the Holocene major sedimentary units identified in shallow boreholes D, E and F of southern Mesopotamia.

particularly during summer when the river discharge reaches its lowest levels. As a result, seasonal fluctuations (i.e. winter and summer) in salinity (< 1‰ to > 15‰) and water temperature (about 10°C to $>$ 30°C) were clearly detected during the field investigation in various seasons (Aqrawi and Evans, 1994). These are mainly related to seasonal variations in the Tigris and Euphrates rivers discharge, air temperature, and rainfall and evaporation rates (Aqrawi, 1993a).

The highest river discharge is restricted to spring season, particularly in April. Later the discharge drops down and reaches its lowest by the end of summer. Sediments are potentially supplied to the area of study by both fluvial discharge and aeolian transport. The latter is mostly in the form of dust fall-out starting from early spring (usually in March) until the end of autumn (i.e. November). However, the highest aeolian contribution is normally restricted to summer (i.e. May–August).

3. Database, material and methodology

This review is mostly based on the data published previously by the author on the delta (such as Aqrawi, 1993b,c, 1994, 1995a,b, 1997; Aqrawi and Evans, 1994), and partly on some additional data carried out during his PhD studentship at Imperial College, University of London (1990–1993).

The most commonly collected materials were surface cores some 30–80 cm long from Stations 1–16 of the modern lakes and marshes (i.e. Ahwar) of Lower Mesopotamia (Fig. 1). Other sediment samples were collected from recently dug drainage channels and pits in Stations 17–21. In addition, about 150 core samples were taken from cores (down to about 20 m depth) of selected shallow boreholes (A–H in Fig. 1) drilled during 1979–1980 by the Geological Survey of Iraq. The boreholes are regionally distributed in southern Mesopotamia covering the areas from Amarah-Nasiriyya to the north down to Basrah-Fao to the south.

For the technical details of the fieldwork and its methodology, and the analytical techniques employed in the laboratories, the reader is referred to the technical details published by the author, particularly Aqrawi (1993b,c, 1994, 1995a,b, 1997) and Aqrawi and Evans (1994). Such details include the core description and radiography, petrography, palaeontology, radiometry, inorganic geochemistry and clay mineralogy, in addition to the geochemical examination of organic matter.

4. Holocene stratigraphy and the evolution of the Tigris–Euphrates delta

Holocene sediments have not been distinguished properly from the underlying Pleistocene deposits, particularly in the eastern and central parts of the Mesopotamian Plains (e.g. Tyracek, 1980). In most of the western parts, the sediments overlying the older pebbly sandstones of the Pliocene Dibddiba Formation are usually younger than 10,000 years, and are considered of Holocene age. However, some of the underlying pebbly sands could be reworked Pliocene Dibddiba deposits that collected during the Pleistocene (Ya'acoub et al., 1981).

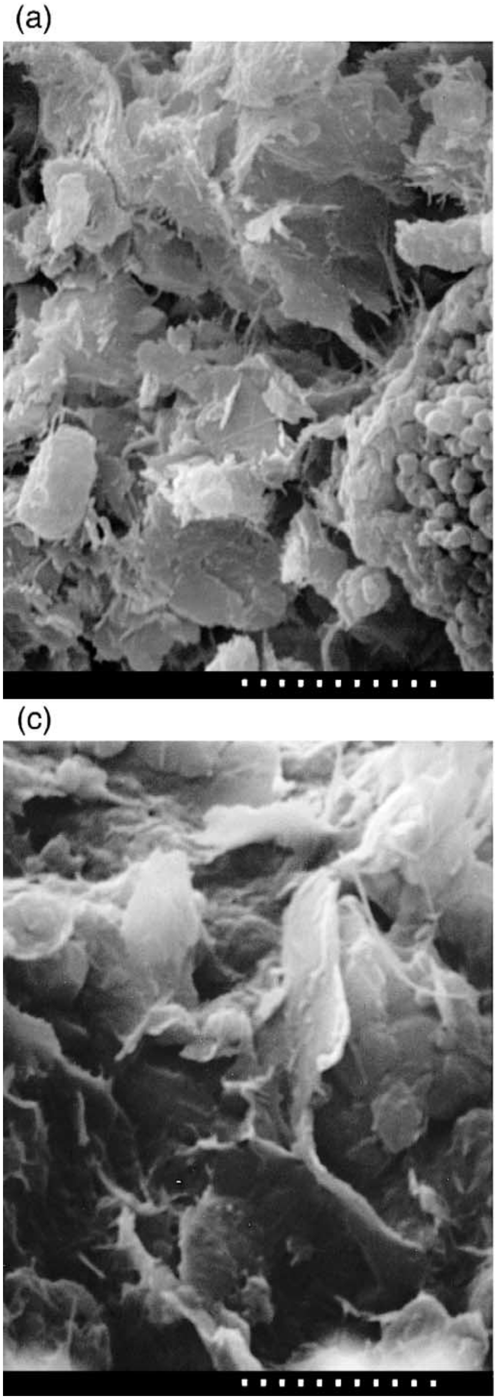
In several successions of the studied shallow boreholes down to 15–20 m depth (i.e. boreholes A–H in Fig. 1), five main lithological units of the Holocene deposits could be recognised and correlated regionally (e.g. Fig. 2) throughout southern Mesopotamia (see Aqrawi, 1995b for more details). During Holocene, various depositional and diagenetic processes together with climatic changes have resulted in the deposition of these sedimentary units as follows.

4.1. Early Holocene sedimentation

One of the main units corresponding to the early Holocene is the ancient marsh/lacustrine silty sand,

Plate 1. Scanning electron micrographs showing in (a) the fibrous authigenic palygorskite, and in (b) the authigenic micro-rhombs of dolomite covered by palygorskite. Both are indicating to be formed within an alkaline/arid environment. (c) Shows that the expandable clay mineral flakes, mostly smectite, dominate the clay particles of the modern sediments of the study area. (d) Shows the occurrence of cubic/framboidal pyrite within the ancient organic-rich sediments as an indication of the domination of anoxic conditions resulted from the marine influence during Mid-Holocene sea-level rising. (The scale is in microns and represented by the white dashed line in the lower right corner of each micrograph. It is equal to 6 in a, 7 in b, 10 in c and 1 in d.)

which is rich in organic matter, and is dominant along the depositional axis of the Mesopotamian basin. This unit (Unit 1) usually merges laterally into thicker ancient fluvial-plain deposits, rich in



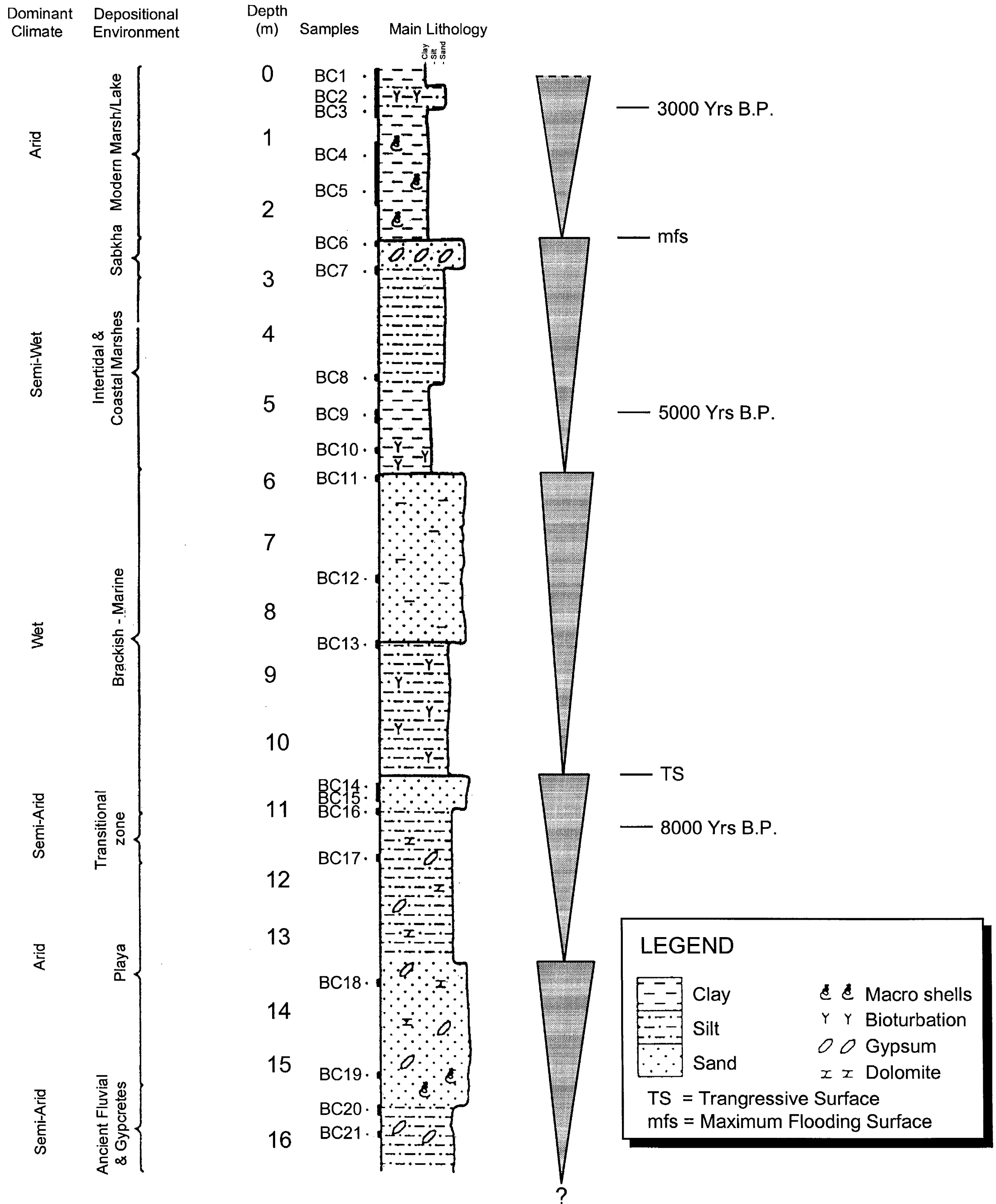


Fig. 3. The sequences and sedimentary units of borehole C together with their depositional environments and the dominant climatic conditions within a dated timeframe (modified after Aqrawi, 1995b).

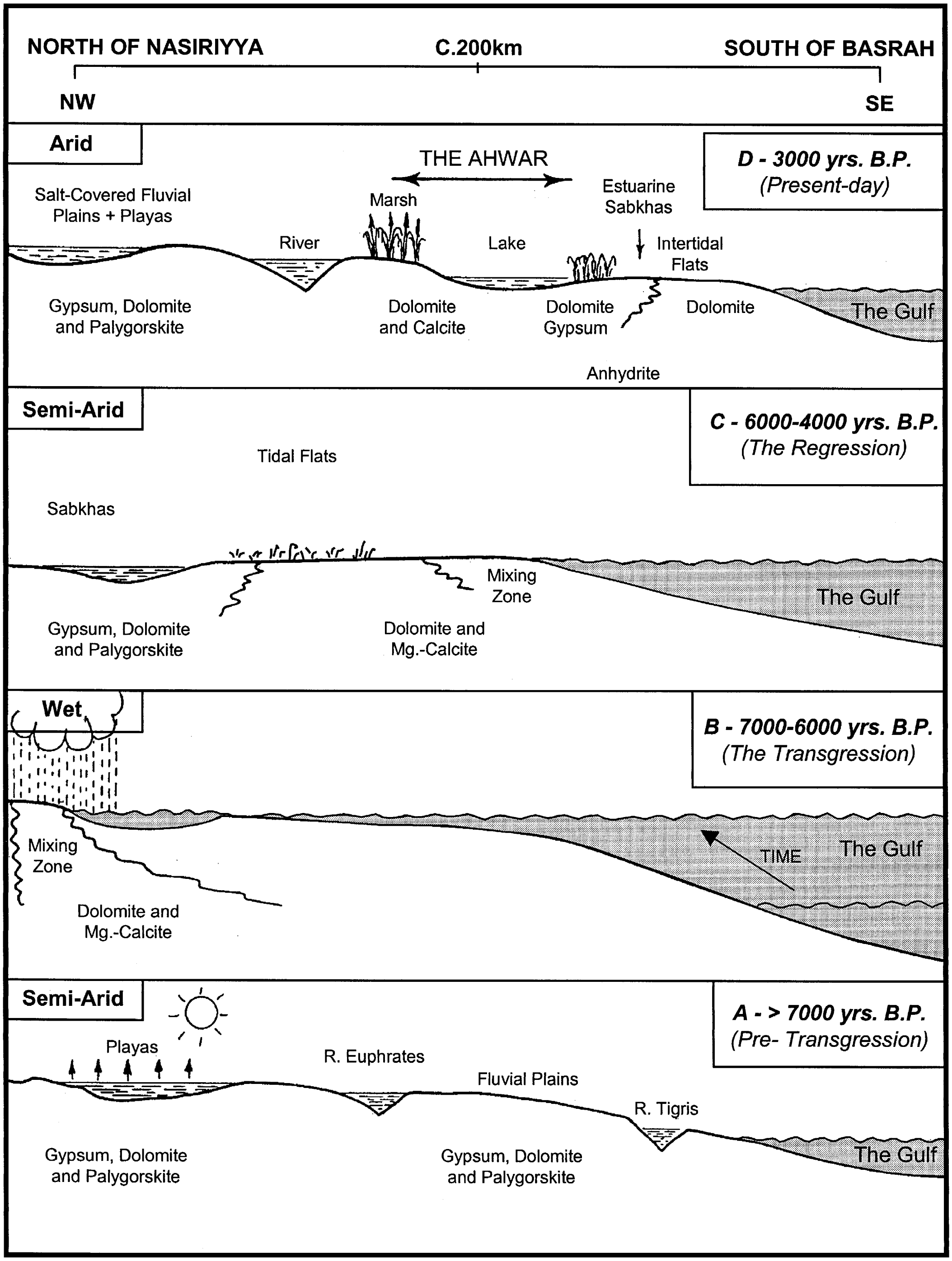


Fig. 4. Schematic cross-sections showing various periods of the Holocene evolution of the Tigris–Euphrates delta when various climatic conditions were dominant (modified after Aqrawi, 1995a).

gypcretes, particularly towards the eastern sides of the basin, and/or into playa evaporitic clayey sandy silt, particularly towards the western desertic margins. Both of the latter units are representing the earliest Holocene deposits of the study area recognised (Unit 2) during this study. The sediments of Unit 2 are characterised by higher gypsum contents in addition to the occurrence of authigenic dolomite and palygorskite (Plate 1a) indicating the domination of arid climate (Aqrawi, 1993c, 1995a). The deeper continuation of such a unit should lead into the Pleistocene deposits in many parts of the basin even beneath Unit 1, because the total Quaternary succession recorded within the Mesopotamian plains was more than 150 m thick (Tyracek, 1980).

These early Holocene deposits (Fig. 3) represent low stand sea level sequences. However, two coarsening-up cycles could be recognised within these deposits, particularly in the western boreholes where the aeolian contribution was at the highest level (Fig. 4).

The most commonly distinguished feature of the ancient marsh/lacustrine (Unit 1) is the occurrence of high organic matter contents (> 5% and up to about 15% TOC) (Table 1). The latter are believed to have been preserved when higher sedimentation rates dominated (Aqrawi, 1997) during the deposition of the overlying unit (i.e. the brackish-water/marine Unit 3). However, the domination of wetter climate at early middle Holocene (COHMAP members, 1988) might have also been in favour of such preservation (Fig. 4). The change of climatic conditions to more arid had resulted in the deposition of fluvial-plain and then playa deposits in eastern and western sides of the basin, respectively.

4.2. Middle Holocene brackish-water / marine deposits

These deposits are represented by one major sedimentary unit (Unit 3), which can be subdivided into four sub-units, each of which has distinctive features, although they are all genetically related to the same two coarsening-up sequences (Figs. 2 and 3). The whole unit has been deposited when marine influence was dominating the study area (Fig. 4). The unit has been detected in every studied borehole, covering areas from the present-day northern Gulf shorelines (i.e. Fao and Abadan Cities) to the vicinities of Nasiriyya and Amarah Cities northwards (Fig. 1), but during various Holocene time intervals (Fig. 5). The deposition of this unit took place during the mid-Holocene transgression. Such a transgression resulted in the domination of brackish-marine conditions. This started at about 9000 years BP in the vicinity of Fao-Abadan cities and prograded northwards to the Basrah vicinity at about 8000 years BP, and then further north reaching Nasiriyya–Amarah arc at about 6000 years BP (for more details see Aqrawi, 1993b, 1995a,b).

A transitional sub-unit (3a) can be distinguished at the base of this main sedimentary Unit 3 (Fig. 2). It is characterised by a transgressive surface rich in

Table 1
TOC contents of the studied sediments according to their sedimentary environment

Main sedimentary environment	TOC (%)	Number of samples	Station/borehole
Modern levee and crevasse splay of Euphrates River	2.1 (1.04–3.60)	10	8, 10
Modern freshwater lakes	5.1 (0.66–18.06)	13	7, 9
Modern freshwater marshes	6.9 (0.38–22.43)	18	3, 5, 6
Modern brackish-water lakes	1.7 (0.22–6.12)	24	4, 12, 13, 14, 16, 17, 19
Modern brackish-water marshes	2.7 (0.22–6.34)	8	1, 18
Modern saline lakes	0.47 (0.42–0.51)	2	20
Modern saline marshes	0.89 (0.30–0.1.90)	10	15, 21
Ancient marshes/lakes	6.2 (2.32–14.55)	4	B, G
Ancient coastal marshes	1.4 (1.35–1.54)	2	C
Ancient brackish/marine	1.1 (0.80–1.31)	4	C, D, E
Ancient playa/fluvial plains	0.3 (0.27–0.35)	5	A, C, D

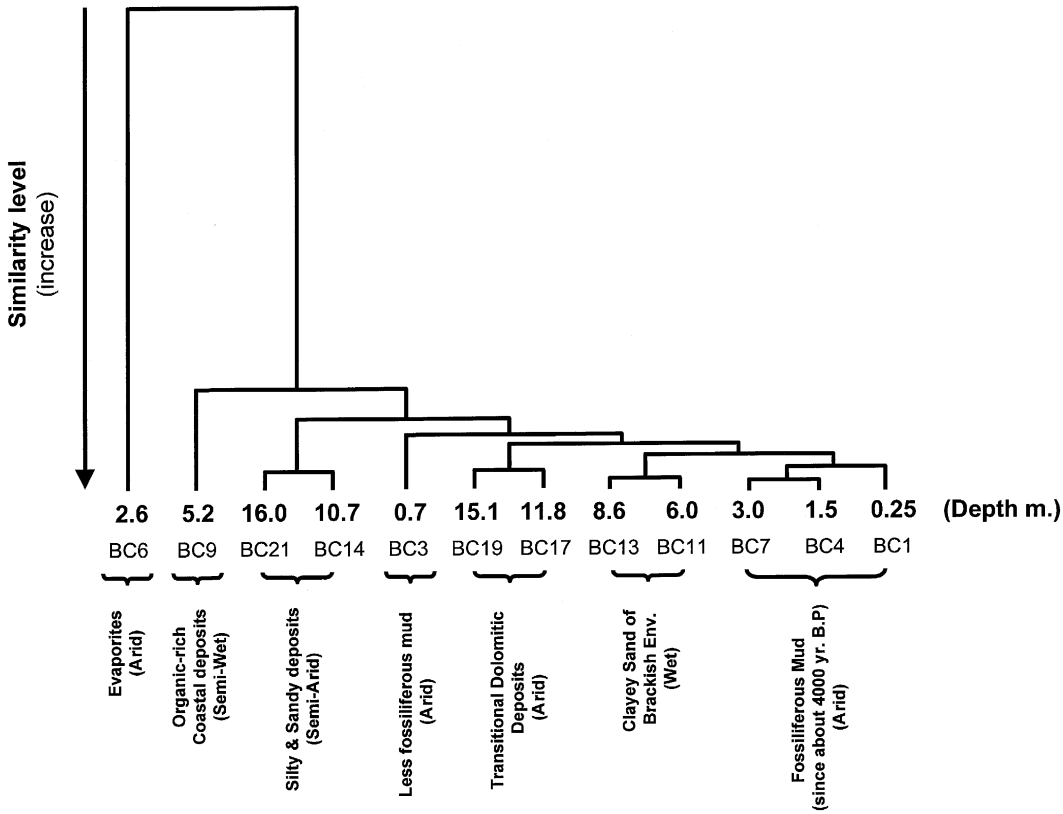


Fig. 5. Cluster analysis dendrograms of the grouped samples (represented by depths) of borehole C, based on their geochemical associations of elements (Table 3).

shelly deposits and by authigenic brackish-water dolomite. This dolomite type was quite recognisable via oxygen and carbon isotopic signatures (e.g. sample BC17 in Table 2) and its calcian nature, which was examined using backscattered SEM and XRD techniques (Aqrawi, 1995a). This sub-unit is covered by a thicker sub-unit (3b) of grey marine clayey silts rich in foraminifera, particularly *Ammonia beccarri*, and ostracods, and particularly *Cypridis torosa* (Aqrawi, 1993a). The latter sub-unit (3b) may either grade up directly into Unit 5 (i.e. modern lake/marsh deposits) within the late Holocene lake/marsh (Ahwar) complex, or into a coastal marsh/intertidal sub-unit (3c) and then a sabkha sub-unit (3d), particularly in the western margins of the study area. The latter two sub-units (i.e. 3c and 3d) are clear indications of the marine regression (Figs. 2, 3, 4 and 5). At about 5000 years BP, brackish-water conditions were prevailing for these western coastal parts, and a semi-arid climate prevailed during the formation of supratidal flats (i.e. sabkhas) rich in gypsum, evaporitic dolomite and palygorskite (Plate 1b). The sub-unit 3d is also characterised by dolomites depleted in higher carbon and oxygen isotopes (e.g. sample BC6 in Table 2), which formed in a hypersaline setting and associated with the clay mineral palygorskite (Aqrawi, 1993c, 1995a). After the deposition of this sub-unit, the marine/brackish conditions terminated, beginning in the northern parts of the study area, and the development of a new hydro-/geo-morphology began.

4.3. Late Holocene continental sediments

During the late Holocene (from about 3000 years BP and later), the deposition of fluvial-plain muds

Table 2
Oxygen and carbon isotope contents of selected dolomitic samples, according to their sedimentary environment, showing that all the analysed samples are carbon-depleted and most of them are oxygen-depleted

Station/ borehole	Sample	Depth	δ^{13}C PDB	δ^{18}O PDB	Main sedimentary environment
1	1B4	38–42 cm	−3.553	−5.109	Modern brackish marsh hammar
2	2C2	16–18 cm	−3.201	−5.516	Modern brackish-water lake hammar
7	7B7	52–58 cm	−2.918	−4.214	Modern freshwater Lake Zechri
8	8A4	29–31 cm	−3.412	−6.040	Modern Euphrates levee within a marsh
9	9A7	43–45 cm	−2.275	−8.133	Modern fresh water lake Baghdad
21	21P4	25–50 cm	−2.240	−3.371	Modern saline dried lake, Kuraiz Al-Meleh
C	BC6	2.5–2.6 m	−5.022	+4.347	Ancient sabkha
C	BC14	10.6–10.7 m	−0.731	−0.638	Ancient brackish/marine (embayment ?)
C	BC17	11.7–11.8 m	−17.693	+0.603	Ancient brackish (transitional such as intertidal?)
C	BC19	15.0–15.1 m	−4.038	+4.158	Ancient playa rich in gypcretes
D	BD21	14.7–15.5 m	−2.853	+3.218	Ancient playa rich in gypcretes
D	BD27	19.6–19.9 m	−4.281	+4.452	Ancient fluvial plain rich in gypcretes

(mostly clayey silt and silty clay) occurred throughout southern Mesopotamia (reaching no more than 2.5 m in thickness) (Unit 4). However, the thickness was restricted to less than 1 m within the Ahwar (marsh/lake) areas, where the sediments are represented by Unit 5 (mainly lacustrine and marsh deposits studied by examining the surface cores and samples only). Unit 5 starts with clayey brackish/marine deposits, coarsening-up into lacustrine shelly deposits, which are usually covered by 5–10 cm of organic-rich silty sand and silt. The repetition of these three layers is obvious in all modern lake types (i.e. of fresh, brackish and saline water) and their surrounding marshes. The total organic matter content (TOC) of the upper-most organic-rich layer is controlled by salinity (Table 1). It increases whenever the salinity of the lake or marsh decreases (Aqrawi and Evans, 1994) and may reach up to 22% TOC, even in the dried or reclaimed parts of the Ahwar, but it drops to <1% TOC in saline parts of the Ahwar. Expandable clay minerals such as authigenic smectite and mixed layers of illite–smectite are dominant in both Units 4 and 5 (Plate 1c) in addition to some palygorskite, and less detrital illite and kaolinite.

5. Stratigraphic signatures of the climatic changes: a discussion

Traditionally, wetter-climatic conditions are interpreted to be responsible for the preservation of organic matter in arid settings. Limited organic matter has been preserved within the Tigris–Euphrates deltaic deposits (Ya'acoub et al., 1981; Al-Azzawi, 1986; Baltzer and Purser, 1990; Aqrawi, 1997). This occurs particularly as organic-rich layers rather than pure peat (Aqrawi, 1993a). Such a preservation is diachronous in age, and the main layers are usually covered by the brackish/marine sedimentary Unit 3 and its sub-units (Aqrawi, 1997). Although the domination of favourable sedimentological and geochemical conditions (such as previous hiatus, organic matter accumulation, followed by higher sedimentation rates in addition to anoxia) was the main factor, the preservation would also have been affected partly by the wetter climatic conditions. In particular, the early Holocene organic-rich deposits reported by Godwin et al. (1958) near Fao, which were ascribed to an age of more than 9000 years BP, and some others within the Basrah vicinity (Aqrawi, 1995b) and in Bubiyan Island (Al-Zamel, 1983), which have almost an equivalent age. Such wetter climatic conditions have been reported to have dominated the Middle East and North Africa in the early Holocene (COHMAP members, 1988). Peat layers of similar ages in the Sahara Africa have been reported by Chateauneuf et al. (1991). However, such preservation in the study area was enhanced by the domination of the anoxic conditions. This is associated with the marine invasion at the start of the Holocene transgressive phase, when the deltas of the Tigris and Euphrates rivers retreated towards the hinterland of Lower Mesopo-

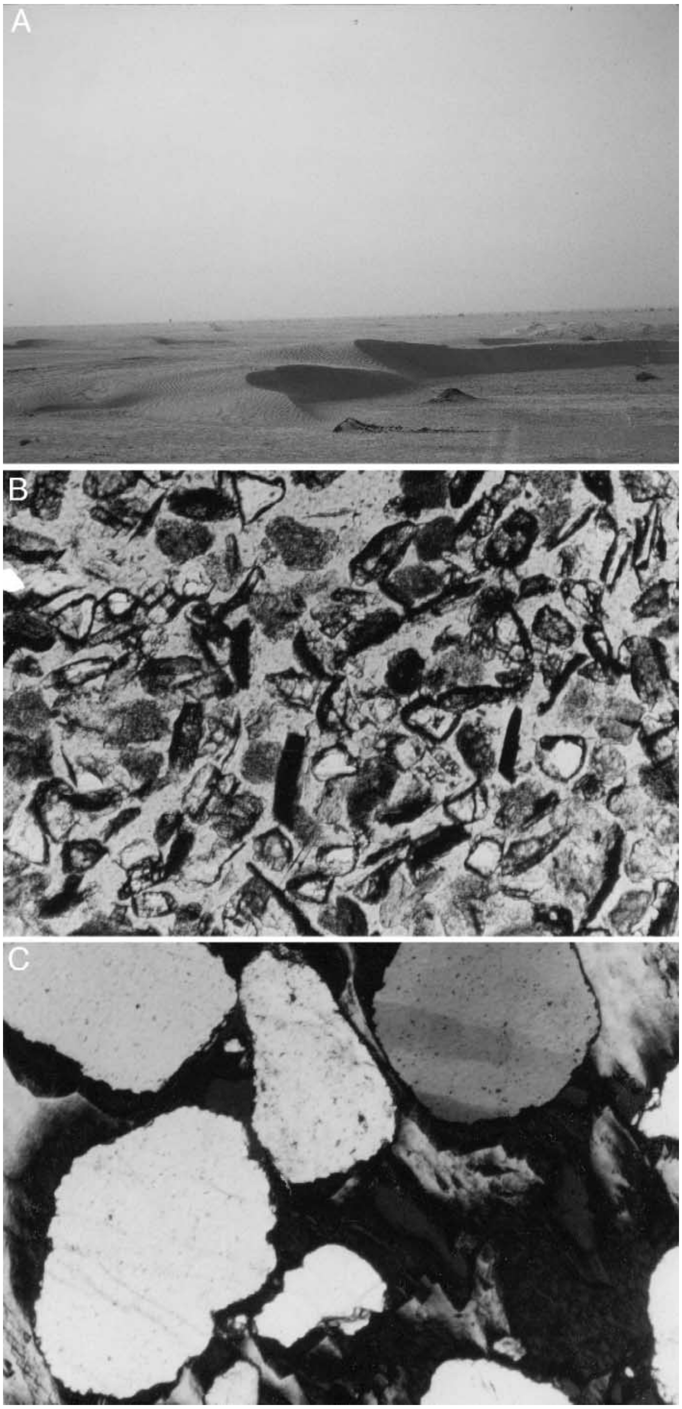


Plate 2. As a result of the present-day domination of arid climate, (A) sand dunes from western and southwestern deserts advance towards the fertilised Mesopotamian plain, and (B) dust fall-out of silt and clay size particles dominates the long summer season. (C) Similar sever arid conditions were started dominating the area around 5000 years ago, and dune-sand layers (of 0.5 m thick) preserved within the western Holocene marginal sequences such as in boreholes C and D of Fig. 2. (Scale: The photo width is equal to almost 200 m in A, 0.5 mm in B and 2.5 mm in C.)

tamia. The concentration of authigenic pyrite within the sediments associated with this organic matter may support the presence of such anoxic conditions (Plate 1d).

This preservation was concentrated along the depositional axis of the basin, where extensive marshes are reported to have been grown historically during the development of the ancient civilisations of Sumer and Babylon (e.g. Oates, 1969). The organic-rich layers might be considered as good lithological markers for the stratigraphic correlation; however, they do not represent specific times within the sequence of stratigraphic framework. This is because they are diachronous in age, and become older and deeper southwards. During most of the Holocene, the climate in the study area was semi-arid to arid, excluding few early and middle Holocene short wetter periods. However, the depositional and diagenetic patterns associated with the sediments were changed during these short wetter climatic periods.

On the other hand, the high contribution of aeolian deposits within the Holocene deltaic successions, particularly to the western parts (Aqrawi, 1993c) occurred during the high aridity periods, which is still continuous (Plate 2A and B). This contribution increased to form up to one third of the sediments accumulated in the region after the domination of more severe dry conditions and an arid climate from about 5000–4000 years BP (e.g. Jacobson and Adams, 1958; Aqrawi, 1995b).

This dramatic change in the climate, which is the result of a decline in the rain precipitation, has resulted in the reduction in sediment load and the discharge of the Tigris and Euphrates rivers. Consequently, this has reduced the sedimentation rates in the study area to less than 0.5 m/1000 years (Aqrawi, 1995b) during the last 3000 years BP. As a result, most of the sediments reaching the northern parts of the Gulf since then are believed to be transported by the Karun River (Aqrawi, 1994) rather than the Shatt

Table 3
Elemental contents (in ppm) of selected samples from borehole C

Sample	Depth (m)	Ca	Mg	Sr	Na	K	Ba	Al	Ti
BC1	0–0.25	87,000	38,220	417.4	15,820	12,720	260.9	52,100	3466
BC3	0.5–0.7	613,000	41,800	354.2	13,710	13,690	293.4	56,900	3798
BC4	1.0–1.5	112,900	32,340	478.1	10,390	11,300	227.3	48,230	3234
BC6	2.5–2.6	88,100	5910	164.0	2040	2590	69.3	6680	339
BC7	2.9–3.0	102,600	31,420	351.9	13,780	10,460	226.5	49,420	3657
BC9	5.5–5.7	16,040	29,110	192.4	21,170	15,380	320.3	67,200	4893
BC11	6.0–6.1	87,300	13,790	335.7	22,990	10,340	317.7	50,900	2341
BC13	8.5–8.6	93,100	17,970	366.1	18,180	9850	277.2	49,920	2568
BC14	10.6–10.7	14,820	21,210	302.2	19,050	8330	339.6	36,800	2249
BC17	11.7–11.8	85,000	57,700	435.2	17,170	10,850	148.6	42,400	2450
BC19	15.0–15.1	85,600	50,500	211.2	17,560	10,120	237.1	39,640	2501
BC21	15.6–16.0	14,910	20,980	301.8	19,060	8320	338.7	36,790	2245

Sample	Depth (m)	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	P
BC1	0–0.25	99.3	13.0	722.0	36,940	22.5	188.0	37.3	62.0	654
BC3	0.5–0.7	109.8	199.5	736.0	43,690	27.5	227.0	49.5	76.5	728
BC4	1.0–1.5	89.0	195.5	681.0	33,910	21.0	176.0	34.3	54.5	496
BC6	2.5–2.6	10.5	6.0	75.8	3150	2.5	15.5	3.5	8.0	114
BC7	2.9–3.0	98.0	224.0	797.0	34,260	21.5	180.5	30.0	51.0	492
BC9	5.5–5.7	218.8	268.5	426.0	43,410	25.0	216.5	39.3	76.5	578
BC11	6.0–6.1	58.5	244.5	418.5	14,770	8.0	53.0	22.8	27.0	244
BC13	8.5–8.6	67.8	298.5	533.0	20,060	12.0	80.5	23.0	24.0	298
BC14	10.6–10.7	60.8	211.5	424.5	15,250	10.0	82.0	13.0	25.5	274
BC17	11.7–11.8	83.5	120.5	614.0	33,030	16.0	148.5	24.3	46.0	332
BC19	15.0–15.1	57.5	375.0	534.0	18,010	10.0	67.0	13.3	23.5	344
BC21	15.6–16.0	49.0	174.0	301.5	15,510	10.0	70.0	8.5	21.5	266

Al-Arab (i.e. Tigris and Euphrates). The Shatt Al-Arab was developed in very late Holocene, most probably during the Abbasid Era (Aqrawi, 1993b), and followed the ancient channel of the Tigris River, at the confluence with the Euphrates River at the Qurnah Town.

It is worth mentioning that the highest aeolian contribution occurred through the advance of sand dunes and storms (Aqrawi, 1995a,b). Almost pure aeolian, very well-sorted and rounded sands dominate a 0.5-m bed in western shallow boreholes such as in boreholes C (Fig. 3 and Plate 2C) and D (Fig. 2), which referenced to about 5000–5500 years BP. However, just beneath this layer, a coastal marsh/intertidal sedimentary bed rich in organic matter was deposited (Table 1), which might be considered together with the underlying brackish/marine deposits as a breakdown (i.e. semi-wet to wet conditions) within the dominant Holocene arid climate of the delta.

Changes in climate and facies could also be detected when the inorganic geochemical results of 17 major and trace elements in several selected sediment samples of borehole C (Table 3) were subjected to cluster analysis (Fig. 5). One of the advantages of utilising this technique is that samples accumulated in similar environments of deposition can be categorised into one dendrogram representing a distinctive depositional facies according to their elemental concentrations (e.g. Aqrawi and Darmoian, 1988; Aqrawi and Evans, 1994). The resultant dendrograms of Fig. 6 were interpreted on the basis of the similarity level between the analysed samples. Each facies (represented by one or more samples) was produced during a different climate, when specific depositional and diagenetic patterns dominated the study area.

Previously, during the middle of this century, the Holocene evolution of the Tigris–Euphrates delta was mainly ascribed to the tectonic subsidence of the Mesopotamian foreland basin (e.g. Lees and Falcon, 1952). Later research in the last two decades reported the marine influence in southern Mesopotamia (e.g. Ya'acoub et al., 1981; Al-Azzawi, 1986; Al-

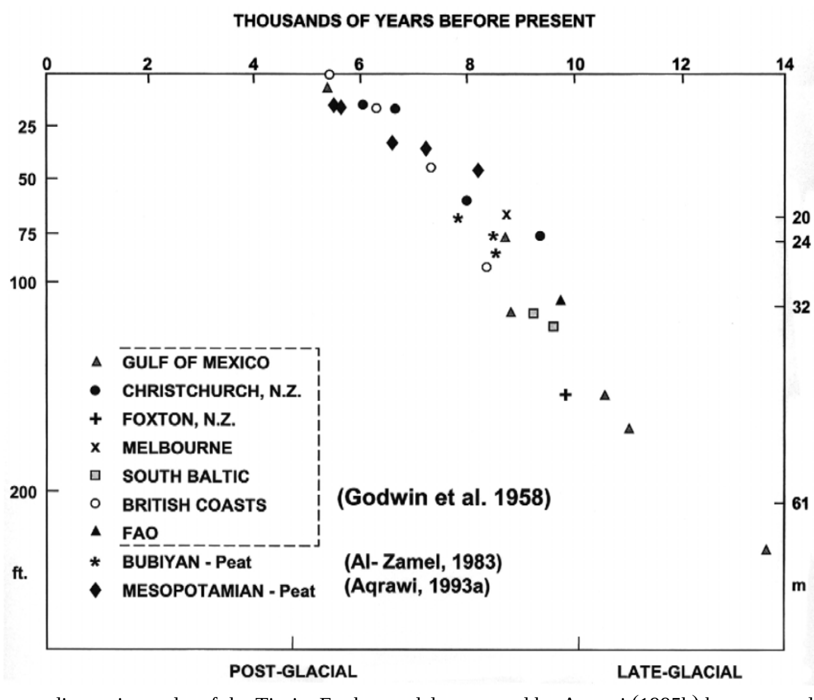


Fig. 6. The plotted carbon-radiometric results of the Tigris–Euphrates delta reported by Aqrawi (1995b) have generally confirmed the global trend developed due to the sea-level changes in the Late Pleistocene and Holocene, when correlated to some international results reported by Godwin et al. (1958) and other regional results reported and plotted by Al-Zamel (1983).

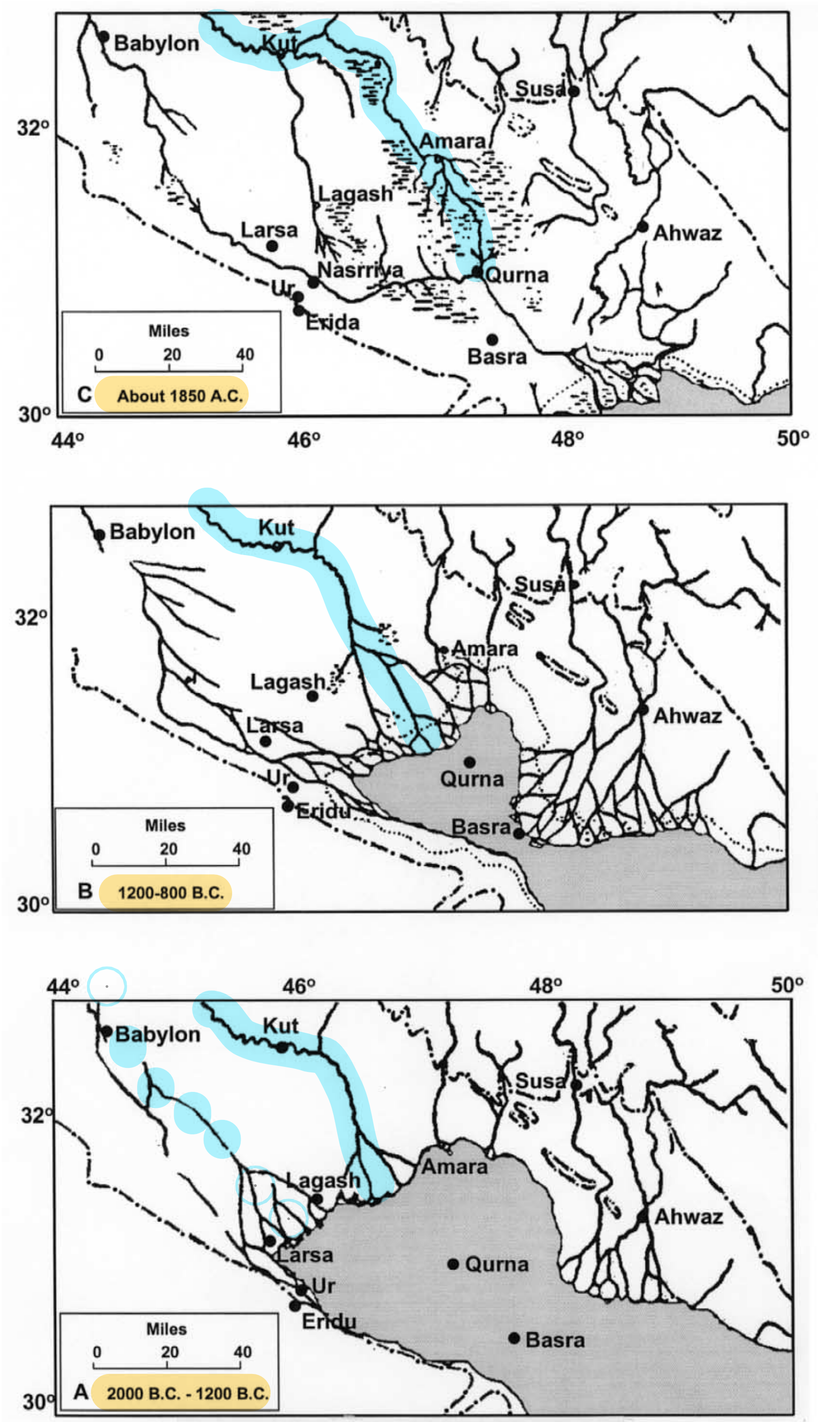


Fig. 7. Selected archaeological maps of southern Mesopotamia (adapted from Geographical Handbook of Iraq and Persian Gulf, 1944) showing the historical changes in the northern shorelines of the Gulf.

Zamel, 1983; Aqrawi, 1993a). The radiometric dating results of Lower Mesopotamia by Aqrawi (1993a, 1995b) are plotted together with those of Al-Zamel (1983) for the Bubiyan Island and others by Godwin et al. (1958). No significant anomalies are tied to the numerous tectonic subsidence events observed within the deltaic region (Fig. 6). When compared with other international dating results, the distribution trend of the plotted deltaic samples (i.e. those from Fao, Bubiyan Island and Mesopotamia in Fig. 6) may confirm the global Holocene sea-level change, rather than the regional tectonic subsidence formerly claimed by some workers such as Lees and Falcon (1952).

Such a Holocene marine invasion was originally reported by the earlier archaeologists working in Iraq during the early part of this century. Some of their results were published in the Geographical Handbook of Iraq and Persian Gulf (1944). Later, Rzoska (1980) has re-published six maps from this book showing the historical locations of the northern shorelines of the Gulf and various river deltas mapped on the basis of the archaeological findings (Fig. 7). In the last two decades, the geological evidence has supported these views. However, a new tectonic input would not be excluded (e.g. Aqrawi, 1993b) in either the regional and/or local scale, because Lower Mesopotamia represents a part of an active foreland basin. Locally, the continuous uplifting of subsurface oilfield domes and anticlines, which caused the diversion of various river channels in southern Iraq (e.g. Al-Sakini, 1986; Aqrawi, 1993b), supports this criteria. As a result, this Holocene deltaic sequences can be seen to be affected by climatic and sea-level changes, together with differential sedimentation rates and neotectonic activities, which have resulted in the evolution of this unique lacustrine delta, and its associated inland lakes and marshes (Ahwar) in southern Mesopotamia.

6. Conclusions

(1) Responding to fluctuations in climate, sea level and sedimentation rates, in addition to the neotectonic activities, several sedimentary units have been deposited during the Holocene evolution of the Tigris–Euphrates deltaic complex.

(2) Each unit has been subjected to various depositional and diagenetic processes, responding particularly to the dominant climate, which had a significant influence. These signatures have been recorded clearly within the recognised sedimentary units in the form of petrological products and biological remains.

(3) After a long period of wetter conditions during the previous glacial age, semiarid and arid climate has dominated the study area in early Holocene. Such a climatic change has resulted in the formation of gypcretes rich in palygorskite and dolomite minerals within the calcareous fluvial-plain muds, similar to the modern salt-covered fluvial-plain deposits and continental playas of southern Mesopotamia.

(4) Brackish-water/marine sedimentary units, rich in foraminifers and mixing zone dolomite, were deposited overlying the previous fluvial plain deposits during the mid-Holocene marine invasion, when the climate became wetter as well.

(5) Gradual climatic changes toward greater aridity started around 5000 years ago, so highly salinized Mesopotamian soils were developed around 4000 years BP. These arid climatic conditions still prevail in the present-day setting of the study area.

(6) Changes in sedimentary facies contents clearly reflect the changes in climatic conditions, based on both petrological/biological contents and geochemical association of major/trace elements, particularly when the latter are treated statistically.

(7) The complex implications of sea-level fluctuation, neotectonic activity, and differential sedimentation rates, which reached the lowest levels during the last 3000 years, have resulted in the formation and preservation of some unique marshlands (Ahwar) covering the lowland parts of the ancient Tigris–Euphrates delta at the present time.

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