Geological Quarterly, 2023, 67: 13
DOI: http://dx.doi.org/10.7306/gq.1683

First record of tempestites from Quaternary lacustrine deposits in the Ağrı Basin (Eastern Anatolia, Türkiye): palaeoclimatological and palaeogeographic implications

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Üner, S., 2023. First record of tempestites from Quaternary lacustrine deposits in the Ağrı Basin (Eastern Anatolia, Türkiye): palaeoclimatological and palaeogeographic implications. Geological Quarterly, 2023, 67: 13, doi: 10.7306/gq.1683

Associate Editor: Anna Wysocka

Several event layers have been identified in lacustrine deposits in the Ağrı Basin of Anatolia (E Türkiye). Sedimentological and palaeontological data newly indicate a storm-induced origin for some of them. The sedimentary structures in three sections, a few tens of metres apart from each other laterally, such as hummocky cross-stratification, wave-generated cross-bedding, parallel bedding, erosional surfaces, and graded bedding, which are considered characteristic of tempestites, are clearly present. Additionally, fining-upwards units and biogenic escape structures located at different levels of these sections indicate a similar origin. The vertical variations in layer thickness, grain size, and sedimentary structures in these sedimentary sections indicate fluctuating hydrodynamic conditions during deposition, while lateral decrease in the size and wavelength of the structures reflects deepening. This interpretation of storm-induced deposition is compatible with regional palaeoclimatological and palaeogeographical data, and is supported by evidence of Quaternary storm-induced sedimentation in adjacent lacustrine basins in the region.

Key words: tempestite, hummocky cross-stratification, Quaternary, eastern Anatolia.

INTRODUCTION

The shape of coastal systems can change either rapidly or slowly as a result of erosion or deposition (Boyd et al., 1992; Bird, 1994). Storm events represent processes that can shape coasts very quickly. Ancient storm deposits, known as tempestites, constitute important palaeoclimatic data, but they are much less commonly reported than deposits of other processes in subaqueous environments, such as those generated by waves, tides, and currents. Most tempestites have been reported from marine (Ball, 1971; Kelling and Mullin, 1975; Aigner and Reineck, 1982; Jeffery and Aigner, 1982; Johnson, 1989; Monaco, 1992; Baarli, 1998; Ito et al., 2001; Bussert and Aberhan, 2004) and transitional settings (Kahn and Roberts, 1982; Liu and Fearn, 1993; Roman et al., 1997; Collins et al., 1999; Morton, 2002; Donnelly, 2005; Wang et al., 2006; Sabatier et al., 2008, 2010, 2012; Woodruff et al., 2009; Dezileau et al., 2011; Phantuwongraj et al., 2013).

Although heavy storms most commonly occur in oceanic equatorial regions, they also may affect continental areas, and consequently also lacustrine basins. Lacustrine tempestites are rare in the geological record, due to the rapid erosion that is a logical consequence of the nature of the storm process itself (Van Djik et al., 1978; Allen, 1981; Li et al., 2007; Myrow et al., 2008; Kempf et al., 2009; Page et al., 2010; Orpin et al., 2010; Liu et al., 2012; Wang et al., 2015; Üner, 2018; Zhang et al., 2018; Üner et al., 2019). Previous interpretations of ancient lacustrine tempestites have mostly been based on the recognition of hummocky cross-stratification (Greenwood and Sherman, 1986; Hamblin, 1992; Liu et al., 2012; Zhang et al., 2018). However, storm deposits may also show erosive surfaces, graded bedding, parallel bedding, wave-generated cross-bedding, shell beds and biogenic escape structures (Harms et al., 1975; Hamblin and Walker, 1979; Allen, 1982; Dott and Bourgeois, 1982; Walker et al., 1983; Myrow and Southard, 1996; Myrow, 2005; Morsilli and Pomar, 2012; Alván and Von Eynatten, 2014; Li et al., 2016; Puga-Bernabéu and Aguirre, 2017; Üner, 2018).

The Ağrı Basin is located on the Eastern Anatolian Plateau that was formed as a result of the collision between the Arabian and Eurasian plates (Fig. 1A). The basin developed marine to terrestrial environments as a result of this collision during the Early to Mid-Miocene (Okay et al., 2010). The Quaternary succession in the basin is represented by lacustrine and fluvial deposits (Demirkaya et al., 2017; Fig. 1B), their spatial distribution of indicates that the lake in the Ağrı Basin covered an area of ~1200 km^2 during the Quaternary. However, it no longer exists because of climate changes and structural developments (Demirkaya et al., 2017).

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Received: January 16, 2023; accepted: March 8, 2023; first published online: May 12, 2023

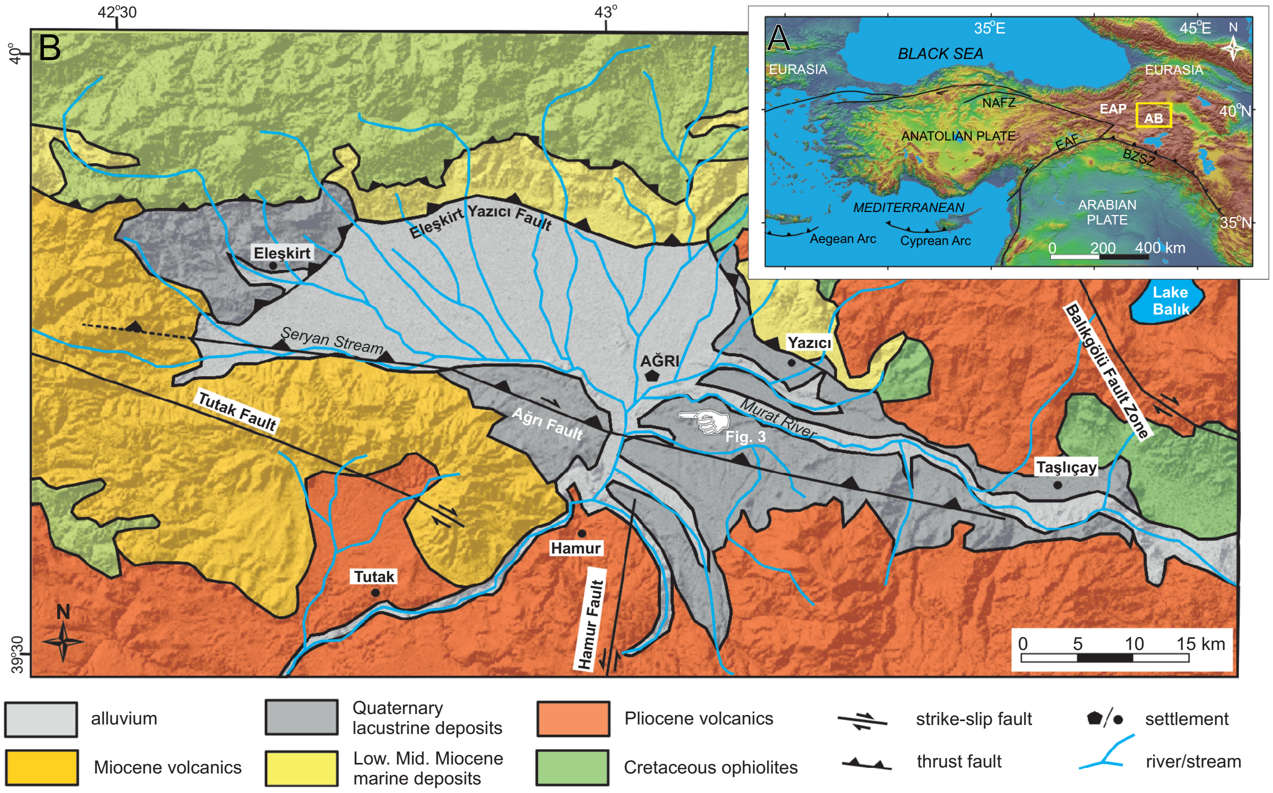

Fig. 1. Location maps showing: A – major neotectonic features of the Eastern Anatolia Plateau and adjacent areas; B – geological features of the Ağrı Basin (modified from Keskin and Dönmez, 2013)

EAP – Eastern Anatolian Plateau, AB – Ağrı Basin, NAFZ – North Anatolian Fault Zone, EAFZ – East Anatolian Fault Zone

Eastern Anatolia has both a mid-latitude temperate and a subtropical climate. The high topography has a significant effect on the atmospheric circulation. Location and topography jointly control present and past climatic features (Stockhecke et al., 2012; Meydan et al., 2022). The present contribution describes the first sedimentological and palaeontological evidence of storm-event beds in the Quaternary lacustrine deposits of the Ağrı Basin, and reconstructs the related palaeoenvironmental conditions.

REGIONAL GEOLOGY

The East Anatolian Plateau emerged from the collision between the Eurasian and Arabian Plates (Şengör and Yılmaz, 1981). Numerous basins were formed by this compressional tectonism, including the Pasinler, Muş, Lake Van, and Ağrı basins (Şaroğlu and Güner, 1981). The fan-shaped Ağrı Basin trends E–W, with an average elevation of 1700 m. It is a piggy-back basin formed on basement rocks of Cretaceous ophiolites, Lower to Middle Miocene marine deposits, and Miocene to Pliocene volcanic rocks (Keskin and Dönmez, 2013). It is bordered by the Eleşkirt-Yazıcı Thrust Fault to the north and the Ağrı Thrust Fault to the south (Fig. 1B).

The palaeogeographical evolution of the Ağrı Basin has been significantly affected by tectonism. The resulting evolution can be subdivided into four stages:

- a pre-Late Miocene stage with basin formation and a transition from marine to terrestrial conditions because of collision and regional uplift (Şaroğlu and Güner, 1981; Şengör et al., 2008);
- a Late Miocene-Pliocene stage with collision-related volcanic activity (Karaoğlu et al., 2005; Özdemir et al., 2011; Açlan et al., 2020) and lake formation (Fig. 2A);
- a Pliocene-Late Quaternary stage with draining of the lake due to tectonic activity;
- a Late Quaternary-recent stage with fluvial activity (Demirkaya et al., 2017).

Quaternary sedimentary successions in the southern part of the Ağrı Basin clearly show the sedimentological characteristics of shallow- and deep-lacustrine deposits (Fig. 2A, B) with a coastal facies including flattened and rounded pebbles (Fig. 2C). Fluvial channels that eroded these lacustrine deposits represent the transition from the lacustrine to a fluvial environment (Fig. 2D). These lacustrine successions also contain storm event deposits.

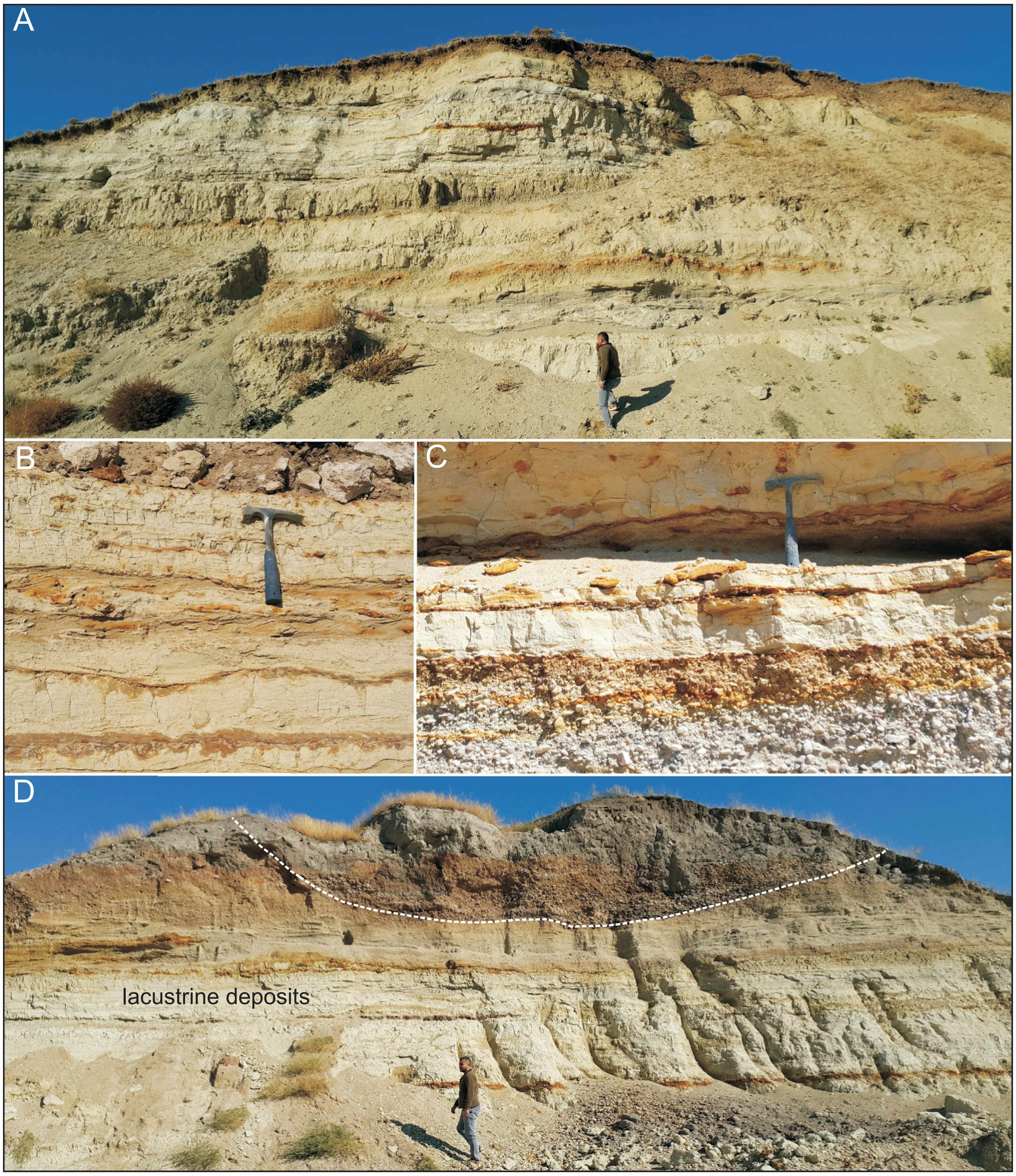

Fig. 2. The lacustrine deposits of the Ağrı Basin

A – general view of the lacustrine succession, **B** – deep lacustrine silty and clayey horizontal laminae alternating with planar cross-bedded sands, **C** – gravelly marginal deposits and overlying sandy shallow-lacustrine deposits, **D** – lacustrine succession eroded by a fluvial channel

METHODS

The Quaternary lacustrine deposits of the Ağrı Basin were investigated in the field. The sedimentary structures were examined in detail. Their size and shape, and the palaeoenvironmental setting under which the structures originated, were interpreted for each of the three sections investigated and the hydrodynamic processes that formed these structures were reconstructed on the basis of their characteristics. All sedimentary characteristics were compared with storm deposits (tempestites) described in previous studies (Aigner, 1982; Dott and Bourgeois, 1982; Walker et al., 1983; Duke et al., 1991; Weidong et al., 1997). A palaeoenvironmental depositional model was finally prepared by combining all data from the three sections investigated (Fig. 3).

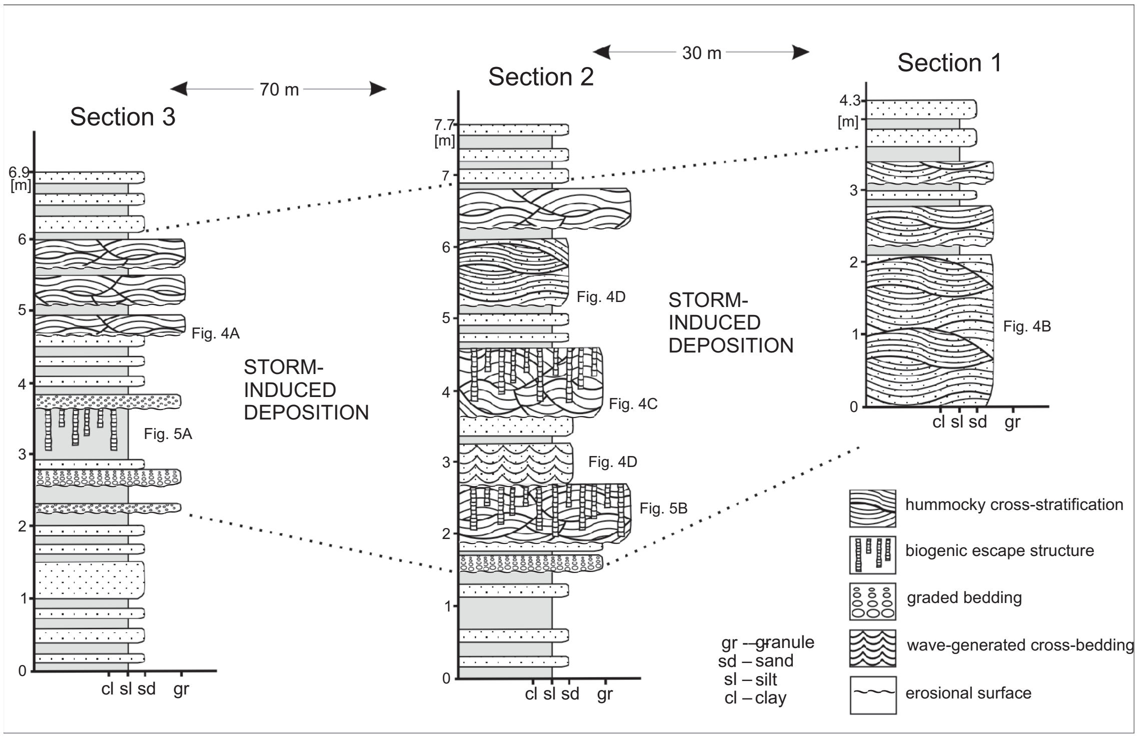

Fig. 3. The three sections investigated (see Fig. 1B for locations) with the level affected by heavy storm action

DESCRIPTION AND INTERPRETATION OF THE SEDIMENTARY STRUCTURES

The Quaternary fill of the Ağrı Basin consists mostly of lacustrine successions composed of alternating semi-consolidated, fine- to medium-bedded sands, silts, and clays (Demirkaya et al., 2017). Gravelly shore deposits with a delta and beach facies were deposited coevally with these fine-grained lacustrine deposits. The most important sedimentary structures are erosional structures, graded bedding, parallel bedding, hummocky cross-stratification, wave-generated cross-bedding and biogenic escape structures.

EROSIONAL STRUCTURES

Erosional structures in the study area are present as irregularly undulose surfaces (Fig. 4A). Depressions are maximally 50 cm long and 30 cm deep, and are filled by wave-generated cross-beds and graded deposits. Erosional structures are frequently observed at different levels of the lacustrine successions studied.

These types of sedimentary structures have commonly been interpreted as having formed at the base of storm-induced sedimentary units due to the action of strong waves and currents (Harms et al., 1975; Allen, 1982; Walker et al., 1983; Liu et al., 2012; Morsilli and Pomar, 2012; Li et al., 2014).

GRADED BEDDING

Upwards-fining graded beds consisting of small pebbles and finer sediments are only rarely present. They were observed in the depressions of the erosional surfaces and are overlain by undulose sandy and silty parallel beds. The thickness of the graded beds varies between 10 and 30 cm.

The grading is ascribed to turbulent flow related to rapid fluctuations in hydraulic energy associated with wave action (Allen, 1982; Obi, 1998; Liu et al., 2012; Li et al., 2014).

PARALLEL BEDDING

Parallel bedding consists of alternating semi-consolidated sandy and silty deposits. Undulose and laterally continuous parallel beds 2–10 cm thick are present among the graded beds and hummocky cross-strata.

Although parallel bedding may form in oscillatory flow conditions, its coexistence with graded bedding and hummocky cross-stratification indicates that it formed by strong unidirectional flows (Myrow and Southard, 1991; Li et al., 2014; Zhang et al., 2018).

HUMMOCKY CROSS-STRATIFICATION

Hummocky cross-stratification is present above the horizontal parallel bedding. According to their wavelengths and amplitudes, they can be divided into metre- and centimetre-scale sets. The metre-scale structures have a wavelength of 3–5 m and an amplitude of 50–90 cm (Fig. 4B) whereas the centimetre-scale sets have a wavelength of 30–80 cm and an amplitude of 5–25 cm (Fig. 4C). Both groups consist of sediments of granule size and coarse to fine sand size and have limited lateral continuity. The orientation of the long axes of the grains is variable.

This structure, which is the combined result of multidirectional flows and intense oscillation of gravitational waves (Hays, 1967), is considered as the key criterion for the recognition of storm events (Harms et al., 1975; Barron, 1989).

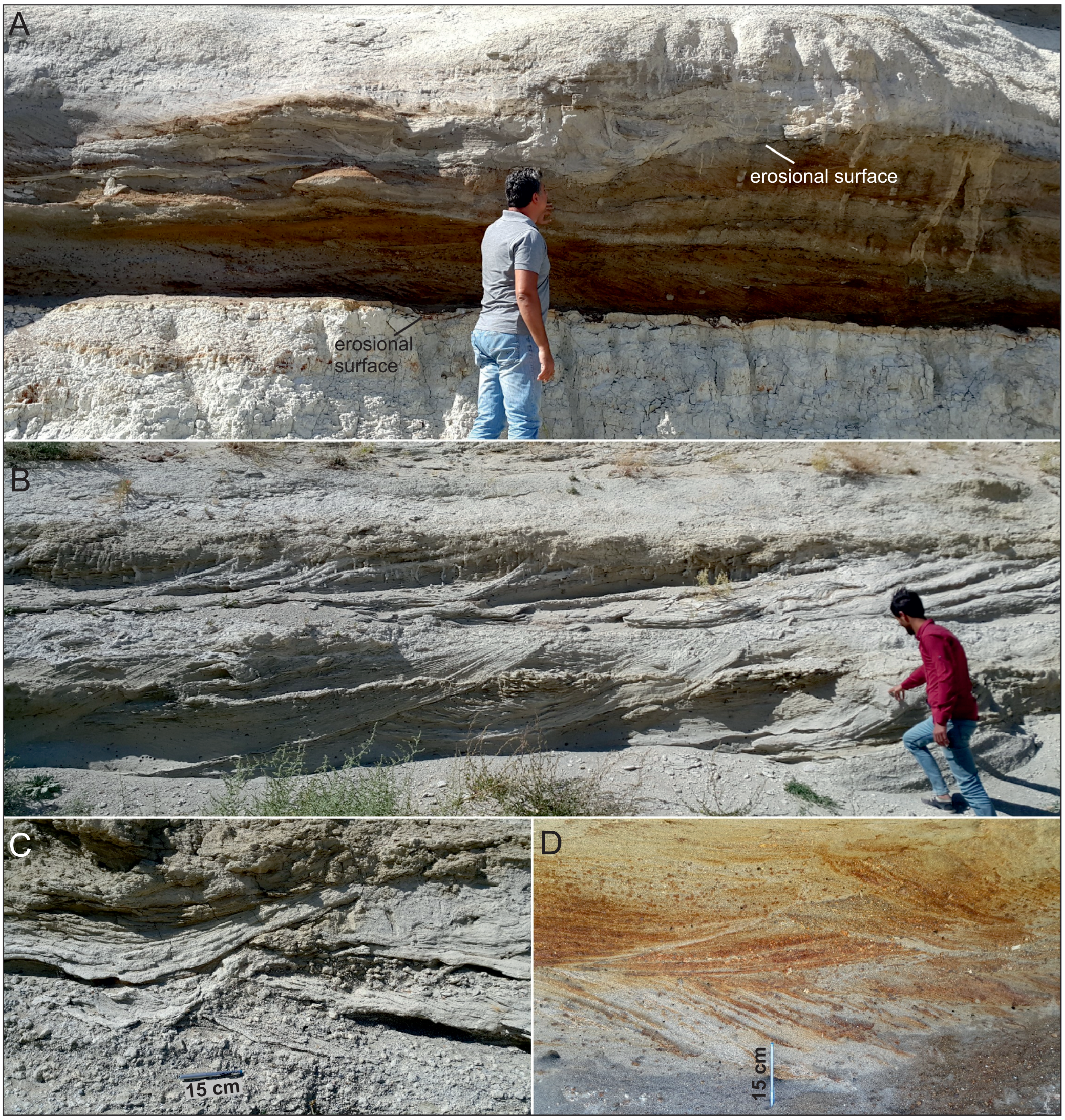

Fig. 4. Sedimentary structures those together are characteristic of tempestites

A – irregular strongly and slightly eroded surfaces showing erosion of the fine-grained shallow-lacustrine deposits; Section 2 (see Fig. 3); **B** – metre-scale hummocky cross-stratification; Section 1; **C** – centimetre-scale hummocky cross-stratification; Section 2; **D** – wave-generated cross-beds; Section 2

WAVE-GENERATED CROSS-BEDDING

The wave-generated cross-bedding occurs between sediments with hummocky cross-stratification and parallel beds. It consists of granules and coarse sand. These structures, having a wavelength of 30–70 cm and an amplitude of 5–30 cm, consist of laminae with opposing inclinations that override each other. Their angles of inclination decrease upwards (Fig. 4D).

These wave-generated cross-beds have been indicated in previous studies (Allen, 1982; Morton et al., 2007; Komatsubara et al., 2008; Phantuwongraj et al., 2013; Üner, 2018) as a criterion for the recognition of past storm events.

BIOGENIC ESCAPE STRUCTURES

Two types of burrows are present at different levels of the lacustrine deposits of the study area. Narrow burrows (0.5–1 cm in diameter) in silts and fine sands have vertical orientations (Fig. 5A), while larger ones (2–4 cm in diameter and length maximally 60 cm) that occur in fine to coarse sandy and gravelly deposits are also vertical, but occasionally are connected to each other by horizontal pathways (Fig. 5B).

These large tube-like structures were created by organisms that tried to reach the sediment/water contact when suddenly buried, so as to reach again an oxygen-rich environment (Bhattacharya et al., 2004; Magyar et al., 2006; Liu et al., 2012).

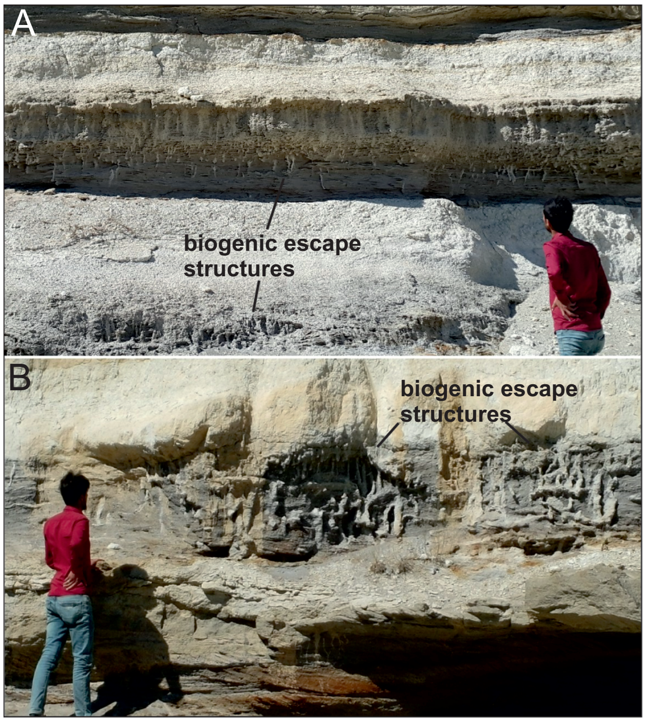

Fig. 5. Biogenic escape structures

A – narrow burrows; Section 3 (see Fig. 3); **B** – wide burrows; Section 2

ANALYSIS OF THE HYDRODYNAMIC PROCESSES

The variations in layer thickness, grain size, and sedimentary structures in the sections investigated indicate variable hydrodynamic conditions during deposition. For instance, erosional structures (erosional scours) at different levels of the lacustrine succession occur mostly above fine-grained, horizontal beds that represent the fair-weather conditions at the end of a depositional event and indicate the beginning of a new depositional episode. Erosional structures formed by strong waves and currents are the most common structures at the base of storm sediments and are considered direct evidence, when co-existing with other storm-induced structures such as hummocky cross-stratification, wave-generated cross-bedding etc., for a storm event (Harms et al., 1975; Allen, 1982; Walker et al., 1983; Liu et al., 2012; Morsilli and Pomar, 2012; Li et al., 2014). The erosion surfaces were at different levels, indicating that the wave energy fluctuated during the storm and resulted in both erosion and deposition.

The depressions caused by these erosional surfaces were filled by normally graded sediments and subsequently by sandy and silty horizontally-bedded sediments. This vertical arrangement indicates changes in the flow regime. The upwards fining results from the size/weight dependent settling velocity related to instability in the prevailing hydraulic energy connected with wave activity (Allen, 1982; Obi, 1998; Liu et al., 2012; Li et al., 2014). The overlying sediment with parallel bedding reflects the upper flow regime and developed under strong unidirectional flow conditions (Myrow and Southard, 1991; Li et al., 2014; Zhang et al., 2018).

The metre-scale hummocky cross-stratification in coarse sand and granule-sized sediments indicating strong storm activity overlies parallel beds. The formation of this metre-scale hummocky cross-stratification is related to oscillatory combined flows (Dott and Bourgeois, 1982; Arnott and Southard, 1990; Southard et al., 1990; Cheel, 1991; Cheel and Leckie, 1993; Midtgaard, 1996). The centimetre-scale smaller hummocky cross-stratified units, which have limited lateral continuity, are located in the top parts of storm-induced depositional units throughout the stratigraphic sections. Decrease in the size of structures represents a relative reduction in storm impact (Li et al., 2014).

Deposits with wave-generated cross-beds overlie gravelly and sandy deposits with metre-scale hummocky cross-stratification. These wave-generated cross-beds were produced by oscillatory combined flows (Yokokawa et al., 1995; Yamaguchi and Sekiguchi, 2010; Perillo et al., 2014; Zhang et al., 2018). The upwards diminishing size and depositional angle of the wave-generated cross-beds indicate a decrease in current energy during deposition. The upwards succession of parallel bedding, hummocky cross-stratification and wave-generated cross-stratification is characteristic of lower-shoreface deposits influenced by storm waves (McCubbin, 1982; Greenwood, 2006).

Tube-like vertical biogenic structures are frequent in lacustrine deposits. These structures are created by organisms to avoid becoming buried and so are also considered as an indicator of storm-induced rapid deposition (Pemberton et al., 2001; Bhattacharya et al., 2004; Magyar et al., 2006; Liu et al., 2012; Scott et al., 2012). The vertical attitude and the abundance of these structures are attributed to the increase in energy level due to the storm effect (Howard 1971a, b, 1975; Pemberton et al., 2001). These vertical escape traces with occasionally roughly horizontal interconnections are characteristic of the most common trace fossil in high-energy lacustrine environments, *Skolithos* (Bromley and Asgaard, 1979; Mángano et al., 1994; Melchor et al., 2003; Buatois and Mángano, 2004; Nehyba and Roetzel, 2022). The presence of such trace fossils burrowing through hummocky cross-stratified deposits indicates energy fluctuations (Buatois and Mángano, 2009).

DISCUSSION

SEDIMENTARY MODEL

All the sedimentary structures that occur in the successions under study have frequently been mentioned in previous studies of storm-induced deposits (Schwartz, 1975; Aigner, 1982; Dott and Bourgeois, 1982; Walker et al., 1983; Duke et al., 1991; Myrow and Southard., 1996; Weidong et al., 1997; Tuttle et al., 2004; Komatsubara et al., 2008; Liu et al., 2012; Wang et al., 2015). These studies have in common that they deduce that an ideal tempestite shows sedimentary structures such as irregular erosional surfaces, graded bedding and/or parallel bedding, hummocky cross-stratification, wave-generated cross-beds, and silty or sandy deposits with biogenic escape structures. However, the order and size of these features can vary due to fluctuations in environmental conditions such as wind speed, wavelength and water depth (Liu et al., 2012; Li et al., 2014). Similar storm-induced depositional records have been reported from Quaternary lacustrine deposits in different lakes in the region such as Lake Van (Türkiye) (Üner, 2018; Üner et al., 2019), Lake Hamoun (Iran) (Hamzeh et al., 2016), and the Caspian Sea (Kazancı et al., 2004).

Three sedimentary sections, only a few tens of metres apart from each other laterally (Fig. 3), which contain the studied part of the lacustrine deposits of Ağrı Basin, have been investigated in detail. They all contain the hummocky cross-stratification, which is diagnostic of storm-induced sediments; moreover, this structure indicates the shoreface-to-offshore transition zone (Hays, 1967).

Section 1 is 4.3 m high and includes metre-scale hummocky cross-stratification (Fig. 3). Sections 2 and 3 show such structures at a centimetre-scale. The size difference of the hummocky cross-stratification indicates that the storm effect on deposition decreased, which might be ascribed to deepening (Fig. 6). In addition, the presence of several erosional structures, hummocky cross-stratification, and silty parallel beds in vertical order in all three sections supports interpretation of fluctuations in the energy of a single storm during formation of these tempestites.

Vertical biogenic structures are commonly considered as evidence of rapid deposition due to storms (Savrda and Nanson, 2003; Bhattacharya et al., 2004; Magyar et al., 2006; Buatois and Mángano, 2009; Liu et al., 2012; Üner, 2018; Schwarz et al., 2021). Fairly rare narrow and short escape structures occur in the sandy and silty deposits (section 3), whereas relatively closely-spaced, thick and long structures occur in the coarse-grained deposits (section 2). This may be related with the higher sedimentation rate near the shore than in the deeper water during the storm (Fig. 6).

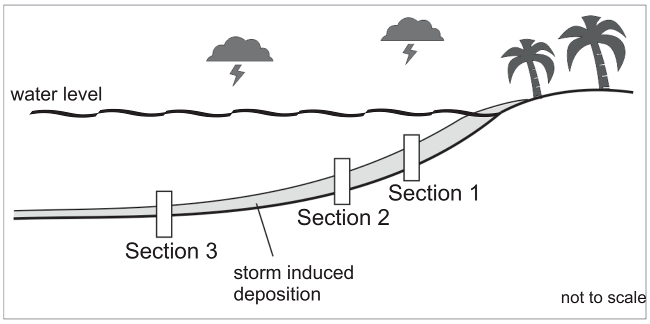

Fig. 6. Schematic depositional model of the lacustrine setting in which the tempestites accumulated

CONCLUSIONS

Lacustrine environments are very sensitive to climate-related changes and effectively store the sedimentological records of these changes. However, storm-induced deposits are not commonly found in such records due to rapid erosion during the storm. Storm activity is recorded in the present study by the presence of hummocky cross-stratification, erosional surfaces, graded and parallel bedding, wave-generated cross-beds, and biogenic escape structures in the Late Quaternary lacustrine deposits of the Ağrı Basin.

Hummocky cross-stratification is present in different levels of the sections investigated. These structures, which result from oscillatory combined flows, are present in all three sections followed by horizontal silt layers, deposited under relatively quiet conditions. Repetition of this combination of features indicates a powerful storm and fluctuations in the storm energy. The hummocky cross-stratification also indicates that deposition occurred in a shoreface-to-offshore transitional zone, and the laterally decrease in the size of these structures suggests deepening of the water in this direction.

The various findings about the Quaternary palaeogeographic and palaeoclimatic approach to lacustrine deposits of the Ağrı Basin provide a new perspective in further study about the basin evolution.

Acknowledgements. I am grateful to A.F. Meydan, D.F. Demirkaya, N. Aksoy and A.V. Yılmaz for their help and suggestions. I also thank the anonymous reviewers for their constructive comments on the manuscript.

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