

Palynology and micropalaeontology of the Pliocene - Pleistocene transition in outcrop from the western Caspian Sea, Azerbaijan: Potential links with the Mediterranean, Black Sea and the Arctic Ocean?

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ABSTRACT

New palynological, ostracod and foraminiferal data are presented from a long outcrop section in the Jeirankechmez river valley, Azerbaijan, near the western coast of the Caspian Sea. The interval studied includes the upper part of the Pliocene Productive Series and overlying Plio-Pleistocene Akchagylian (Akchagyli) and Apsheeronian (Apsheeron) regional stages. Productive Series sediments were deposited in a closed fluvio-lacustrine basin, isolated from any marine influence. The onset of Akchagyli deposition is marked by a lithological change associated with a significant flooding event that, at its maximum extent, reached the Sea of Azov and into present-day Iran, Kazakhstan, Turkmenistan and Russia. At the Jeirankechmez locality, the lowermost beds of the Akchagyli contain predominantly freshwater assemblages with very minimal marine or brackish content showing that the onset of Akchagyli deposition was not a marine induced event. Reworked Mesozoic palynomorphs occur frequently in this lowermost interval, including the reworked pollen taxa *Aquilapollenites-Triprojectus* that were eroded from the north or north-east.

Significant marine influence is evident ca. 30 m above the base of the Akchagyli in the studied outcrop, marked by the 'Cassidulina Beds' which contain a distinct but low diversity assemblage of foraminifera that occurs widely and can be correlated in many parts of the greater Caspian region. Dinoflagellate cysts (dinocysts) in the marine interval include frequent specimens very similar to *Algidasphaeridium capillatum* (Matsuoka and Bujak), a species only previously recorded from the northern Bering Sea. The combined evidence from these dinocysts and foraminifera suggests that a marine (i.e. seaway) connection existed briefly between the Arctic Ocean and the Caspian Sea at the very end of the Pliocene.

Re-examination of core material from the Adriatic Sea shows that *Cassidulina reniforme* (Nørvang) was present in the Mediterranean during and shortly after the Last Glacial Maximum. The possibility that the end Pliocene marine incursion came from the Mediterranean via the Black Sea region to the Caspian Sea cannot be entirely ruled out but is considered unlikely. Biometric analyses are applied to obtain a better understanding of the palaeoenvironmental significance of the assemblages dominated by cassidulinids.

An interval > 300 m thick is assigned to the Apsheeron regional stage on the basis of predominantly brackish ostracod and dinocyst associations. The dinocysts are of 'Peri-Paratethyan' affinity and closely resemble species first described from Miocene and Pliocene sediments in the Pannonian and Dacic basins of Eastern Europe. Many similarities exist in the microplankton records (dinocysts and acritarchs) between the Caspian Sea, the Black Sea and Central Paratethys.

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1. Introduction

The Caspian Sea is the largest lake in the world by volume and surface area (Dumont, 1998). It is in a constant state of flux, with fluctuations in water level in the order of 100 s of metres occurring throughout the Pleistocene (Svitoch, 2014; Yanina, 2013). Because of the relatively flat topography in the northern Caspian region, water level highstands are associated with enormous expansions of the sea-surface area. The largest sea-surface area of the Caspian Sea in the Pliocene was achieved during the Akchagyl regional stage (Molostovsky and Guzhikov, 1999; Nevesskaya et al., 2003), beginning around three million years ago in the latest Pliocene and continuing into the early Pleistocene. This transgression was particularly significant in that it occurred following a period, lasting more than two million years, when the Caspian Basin was isolated from the world's oceans and non-marine, fluvio-lacustrine deposition of the Productive Series occurred, predominantly in the deeper South Caspian Basin (Forte et al., 2015; Hinds et al., 2004; Reynolds et al., 1998). Later expansions during the Apsheon and younger Pleistocene regional stages never stretched as far inland as during the maximum Akchagyl transgression (Svitoch, 2014).

Akchagyl sediments are generally described as marine and in most accounts (e.g. Jones and Simmons, 1996; Svitoch, 2014) are presumed to have originated following a rise in global sea levels during the late Pliocene that raised the level of the Mediterranean Sea, that subsequently flooded the Black Sea and then over-spilled into the Caspian Sea to the north of the Caucasus. An opposite view is held by Zubakov (1992) who considers that Caspian transgressions, including the Akchagyl, result from increased river runoff, particularly from the Volga, with subsequent over-spill from the Caspian Sea to adjacent basins, including the Black Sea. Irrespective of the origin of the initial rise in Caspian waters, there is undoubtedly some direct marine influence in the Lower to Middle Akchagyl, and this is most evident in the so-called 'Cassidulina Beds' that have been documented in previous biostratigraphic studies from Azerbaijan and elsewhere. These beds are described (e.g. Agalarova et al., 1940; Jones and Simmons, 1996; Mandelstam et al., 1962; Yassini, 1986) as containing an influx of calcareous benthonic foraminifera, most often including species of *Cassidulina* and *Cibicides*, including *C. lobatulus* (Walker and Jacob). Previous palynological studies of the late Pliocene to early/middle Pleistocene of the Caspian Sea region (e.g. Filippova, 1997; Naidina, 1999; Naidina and Richards, 2016; Yakhimovich et al., 2000) are essentially pollen and spore based. These, therefore, give limited interpretations in that inferred environmental or climatic changes are based only on terrestrial vegetation.

The sediments overlying the Akchagyl are most often referred to as the Apsheon regional stage and these are widely deposited across Azerbaijan (Aliyeva and Kengerli, 2014) and the wider Caspian region (Abdullayev et al., 2012). Deposition of the Apsheon occurred during the early Pleistocene in a closed brackish water basin resembling the modern Caspian Sea according to Svitoch (2014). Here we study the Akchagyl and Apsheon fossil faunas (ostracods and foraminifera) and floras (dinoflagellate cysts, pollen and other palynomorphs) in a long and continuously exposed outcrop record in the Jeirankechmez River Valley, Gobustan region of Azerbaijan (Fig. 1). The aim of the study is to document the faunal and floral changes that occurred in response to variations in palaeoenvironmental conditions associated with the Akchagyl transgression of the Caspian Sea and subsequent Apsheon deposition. These events occurred during the latest Pliocene to early Pleistocene, at the time of the onset of northern hemisphere glaciations. Biostratigraphic methods are used to differentiate the Akchagyl and Apsheon intervals due to the lack of mollusc fauna and absence of a clearly defined lithological boundary. Comparisons of microfaunal data

are made with published records from the Arctic Ocean and with newly obtained foraminiferal data from a core of late Pleistocene age from the Adriatic Sea.

2. Regional stage nomenclature and previous micropalaeontological studies

A long research history of micropalaeontological and stratigraphic studies of the Akchagyl and Apsheon stages exists, dating back to the 19th century. The name 'Akchagyl' is derived from the name of a locality in the coastal region of Turkmenistan (Jones and Simmons, 1996). Sediments attributed to the Akchagyl regional stage in Azerbaijan were first described by Andrusov (1902) and since then have been the subject of much study and debate (see Alizadeh et al., 2016; Jones and Simmons, 1996 for further details). Akchagyl sediments are widespread throughout most of the Caspian region and extend beyond the present-day Caspian Sea area eastwards into Kazakhstan and Turkmenistan (Alizadeh, 1961; Danukalova, 1996; Trubikhin, 1977), westwards into Azerbaijan and Georgia (Agalarova et al., 1961; Shatilova et al., 2009), to the north into Russia (Svitoch, 2014; Yakhimovich et al., 2000) and to the south into Iran (Yassini, 1986). Not surprisingly, the faunal content varies significantly across the region, leading to problems in correlation of microfaunal assemblages and chronostratigraphic calibrations. Additional complications have arisen by using the original biostratigraphically defined Akchagyl stage as a lithostratigraphic unit. As such, a large number of different definitions of boundaries and sub-divisions have been proposed over time. It is clear from the overlapping and variable nature of these assemblages that the true relationship relative to lithostratigraphic units, and also time, remains open to question. According to the Russian chronostratigraphic schemes, Akchagyl sediments are not older than ca. 3.60 Ma and not younger than ca. 1.80 Ma (Trubikhin, 1977) and therefore fall within the late Pliocene (Piacenzian) to early Pleistocene (Gelasian) and the Gauss and Matuyama magnetic chrons (see Alizadeh et al., 2016; Van Baak et al., 2013 for further details).

Akchagyl sediments typically comprise grey, dark-grey and grey-blue sandy clays, and fine to medium-grained sands, sandstones and shell beds (Alizadeh et al., 2016). Interbeds of volcanic ash and breccia also occur. According to Aliyeva and Kengerli (2014), the mud-prone Lower Akchagyl typically contains freshwater ostracods, with *Cyprideis torosa* (Jones), a brackish form, predominant in the more-sandy Middle Akchagyl. The Upper Akchagyl characteristically comprises alternating grey and brown sandy shales with interbeds of sandstone and volcanic ash, and contains mainly brackish water ostracods. The lower boundary of the Akchagyl is defined by the appearance of 'poor marine fauna' (Alizadeh et al., 2016; Danukalova, 1996; Molostovsky, 1997) which includes the foraminifera *Cibicides* and *Cassidulina*, and molluscs *Avimactra subcaspia* (Andrusov), *Cardium (Cerastoderma) dombra* (Andrusov), *Cerastoderma glaucum* (Bruguière) and *Potamides (Prenella)*. Detailed descriptions of the mollusc faunas are presented by Nevesskaya et al. (1987) and Nevesskaya et al. (2001) among others.

A three-fold sub-division for the Akchagyl in the northern Caspian region is often used (e.g. Naidina and Richards, 2016) but is not accurately time-constrained. Typical microfaunal associations are described by Svitoch (2014), referring to earlier work by Karmishina (1964) and others. Following the scheme of Svitoch (2014), the lowermost Akchagyl (Ak₁) contains foraminifera such as *Bolivina*, *Cassidulina* and *Elphidium* as well as the ostracod genera *Leptocythere*, *Loxoconcha*, *Limnocythere* and *Candona*. The Middle Akchagyl (Ak₂) contains the richest microfaunal assemblages with increased numbers of foraminifera and ostracods observed. Marine fauna become diminished once again in the Upper Akchagyl (Ak₃) where ostracods predominate, including *Cyprideis littoralis* (Brady) (= *C. torosa* according to

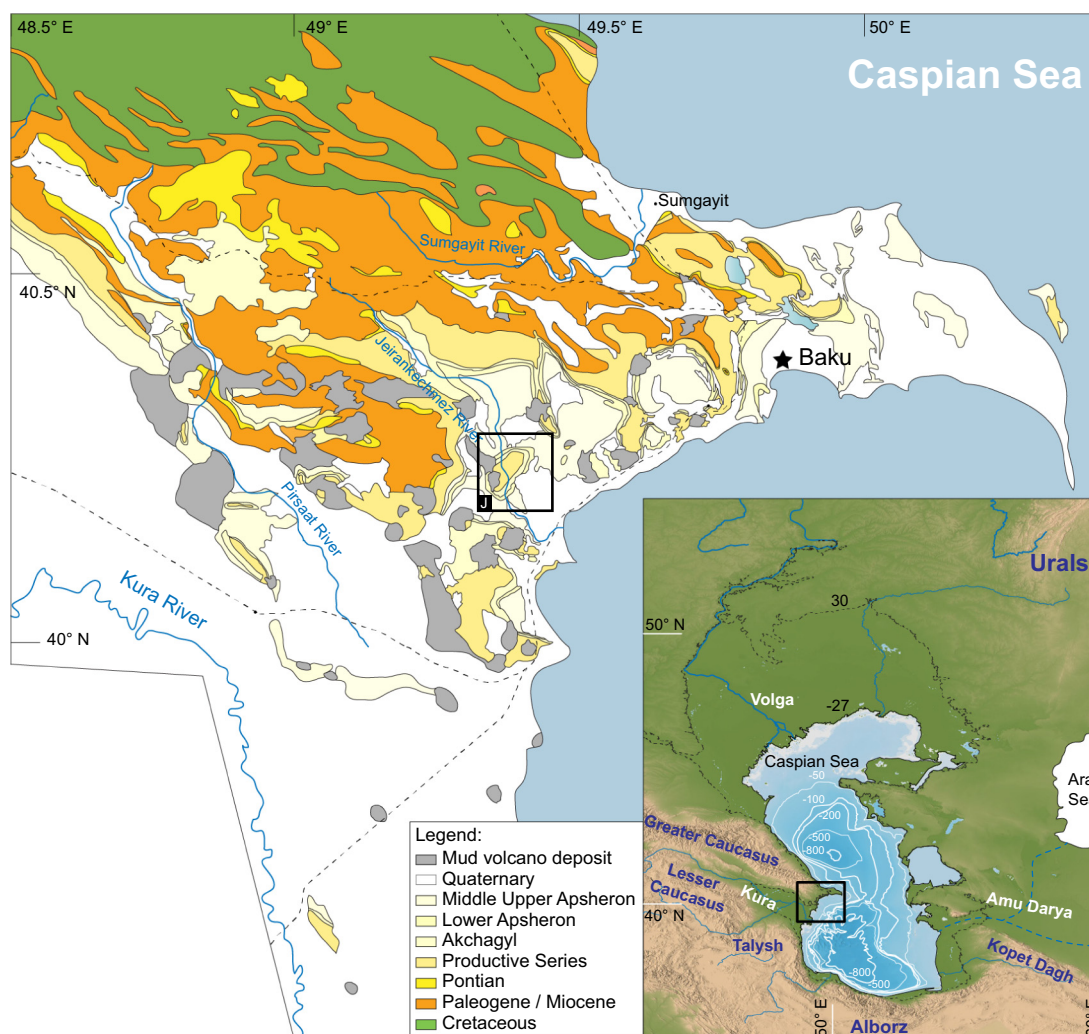


Fig. 1. Simplified geological and location map showing the Jeirankechmez locality and study area to the west of the Apsheron Peninsula, Azerbaijan, near the western coast of the Caspian Sea.

Kempf, 2017), *Limnocythere pliocenica* (Suzin), *L. tenuireticulata* (Suzin) and *Eucythere naphtatscholana* (Livental), interpreted as a response to reduced salinity. Svitoch (2014) assigns the Plio-Pleistocene (2.58 Ma Gauss-Matuyama) boundary within the Middle Akchagyl (Ak₂).

In the central and southern regions of the Caspian region, Rozyeva (1966), referring to Alizadeh (1961), also indicated that a three-fold sub-division of the Akchagyl Formation was possible on the basis of ostracods in Turkmenistan. Numerous species of *Candona* and *Limnocythere* were recorded from the lower sub-division. In addition, the foraminifera *Cassidulina* and *Cibicides lobatulus* were recorded. These foraminifera were first recorded in the Lower Akchagyl by Agalarova et al. (1940) and have subsequently been found in many localities in the greater Caspian region (e.g. Alizadeh et al., 2016; Yassini, 1986). Rozyeva (1966) describes the middle sub-division of the Akchagyl in Turkmenistan as being thin and poorly fossiliferous, and the upper sub-division as being characterised by numerous species recorded as *Leptocythere* (which do not occur below) and by *Loxococoncha eichwaldii* (Livental), *Cytherissa* (= *Eucythere*) *naphtatscholana* as well as undifferentiated species of *Limnocythere* and *Candona*. For Azerbaijan, Mandelstam et al. (1962) presented a similar sub-division based on ostracods. These authors formalised the sub-divisions into a lower *Eucypris puriformis* zone, a middle unnamed interval and an upper *Leptocythere* zone. It is also interesting to note that a comparable *Loxococoncha-Leptocythere-Cytherissa-Limnocythere* assemblage is described by Svitoch (2014) but attributed to the Apsheron rather than Akchagyl. The

Apsheron regional stage is typically recognised biostratigraphically by the incoming of a 'Ponto-Caspian' endemic mollusc fauna, which includes the genera *Apsheronia*, *Dreissena*, *Hyrkania*, *Monodacna*, *Parapsheronia* and *Pseudocatlillus*, among others (Molostovsky, 1997; Svitoch, 2014).

3. Section description

The data used in this study are derived from a continuous outcrop of ca. 1600 m in thickness exposed along the Jeirankechmez River, in the Gobustan region of Azerbaijan, around 50 km to the south-west of Baku. The base of the section is located at grid point 40.237771° N, 49.365299° E. The lowermost part of the studied section consists of > 750 m of fluvio-deltaic sandstones and brown, silty clays of the Pliocene Productive Series. This is overlain by an interval of > 800 m of light-grey and yellow-brown marls that, based on field characteristics, are attributed to the Akchagyl and Apsheron regional stages. There is, however, no obvious stratigraphic break visible within the outcrop that can be used to assign the Akchagyl-Apsheron boundary. Organic-rich (sapropel) layers of up to 1 m thick occur at three levels; 897 m, 940 m and 990 m (Fig. 2). Initial field observations indicated that the study outcrop contained very few fossil molluscs. Palynology and micropalaeontology were therefore chosen as the preferred methods of biostratigraphic study.

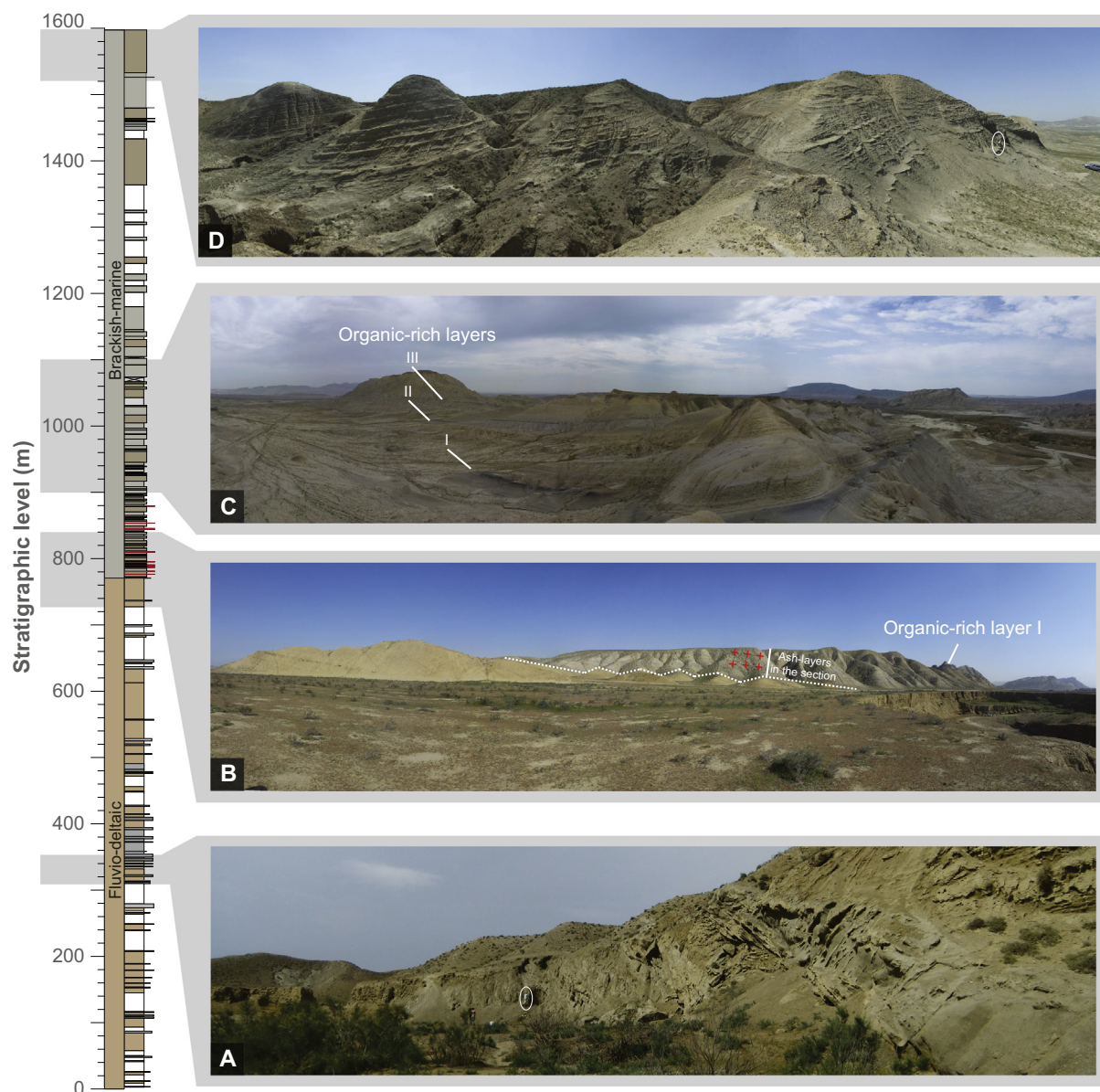


Fig. 2. Field photographs and lithostratigraphic summary of the Jeirankechmez locality: A) fluvio-deltaic sediments of the Pliocene Productive Series (see person for scale); B) overview of the outcrop section, the dashed line showing the lithological change from the olive-brown Pliocene Productive Series to the mainly grey silty clays with ash layers of the Akchagyl and Apsheron (latest Pliocene to early Pleistocene); C) freshwater, brackish (oligohaline/mesohaline) Apsheron sediments (early Pleistocene) showing black, organic-rich layers (samples BL1, BL2 and BL3); D) overview of the uppermost (presumed Apsheron) section of the Jeirankechmez outcrop (not included in the present study) (see person for scale). Outcrop photographs by Chris van Baak.

4. Materials and methods

Sixty four samples were analysed for microfossils (primarily ostracods and foraminifera) and palynology from the Akchagyl (including the boundary with the underlying Productive Series) and presumed Apsheron intervals of the outcrop section at Jeirankechmez. Samples described in this study are from an interval around 375 m thick. Average spacing of samples over the entire interval is approximately one sample per six metres. In general, studied samples are more closely spaced in the lower (Akchagyl) interval and more widely spaced in the upper (Apsheron) interval. After initial results were obtained, additional infill samples were analysed over specific intervals of interest. Samples referred to in the text are indicated by their relative stratigraphic position (i.e. elevation in metres) within the outcrop, followed by the sample reference (e.g. 1140.98 m, JE146). An additional sample LOK2 was studied from the Lokbatan locality, situated ca. 20 km to the

north-east, near Baku, on the Apsheron peninsula. Foraminiferal results are compared with previously unpublished data from gravity core JM10-03-GC, taken at Wijdefjorden, northern Svalbard and from core IN68-21 collected in the Adriatic Sea.

For microfossils, each sample was washed through a 125 μm sieve and the residue dried at 100 $^{\circ}\text{C}$ with quantitative counts then made of each species. Identifications and environmental interpretations for ostracods are based on numerous sources including Agalarova et al. (1961), Athersuch et al. (1989), Boomer et al. (2005); Boomer et al. (2010), Mandelstam et al. (1962), Meisch (2000), Van Baak et al. (2013), Stoica et al. (2016) and Daniel (2013).

Samples for palynology were processed without oxidation using cold HCl (20%) and cold HF (40%) with residues sieved using 10 μm mesh sieve cloth. Counts were made of all palynomorphs i.e. pollen grains, spores, algae, non-pollen palynomorphs (NPP) and dinocysts, including reworked taxa. A minimum sum of 200 palynomorphs was

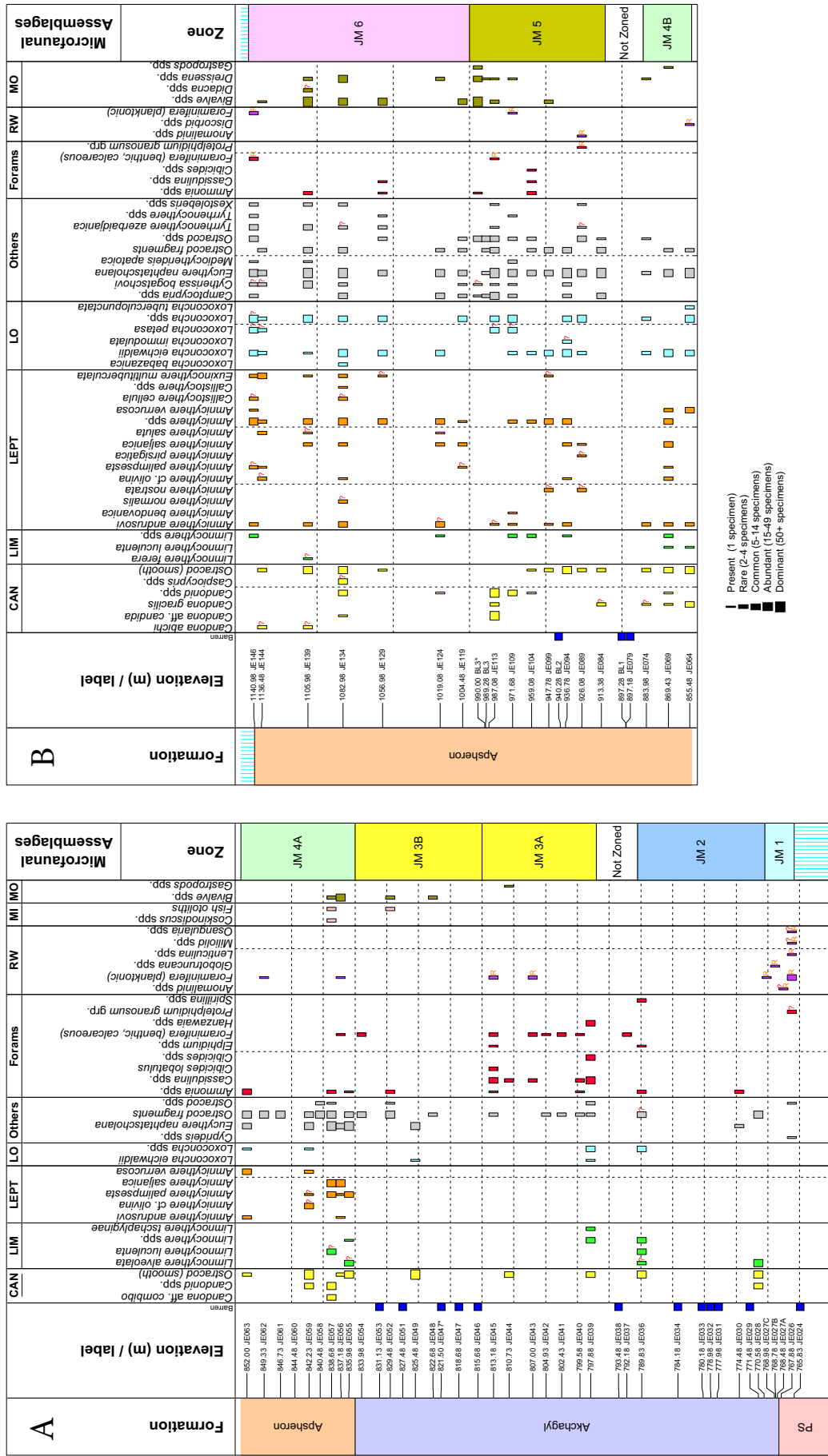


Fig. 3. Semi-quantitative display of microfaunal data from the Jeirankhezmez outcrop showing ostracods and other microfossils recorded. 3A = Akchagyl and lowermost Apshehon interval; 3B = Apshehon interval (part). CAN = candonids, LIM = Limnocythere, LEP = leptocytherids, LO = Loxocoelha, RW = reworked, MI = miscellaneous microfossils, MO = molluscs.

obtained in most cases, except where palynomorph recovery was much reduced in sandy or otherwise less-fossiliferous lithologies. Pollen identifications were made primarily with reference to north-west European and Russian pollen floras (e.g. Bobrov et al., 1983; Kuprianova and Alyoshina, 1972; Kuprianova and Alyoshina, 1978). Dinocysts and NPP were identified from numerous sources including Bakrač et al. (2012), Baltes (1971), Evitt et al. (1985), Marret et al.

(2004), Mudie et al. (2011), Mudie et al. (2017); Mudie et al. (2018), Richards et al. (2014); Richards et al. (2017), Soliman and Riding (2017), Sütő-Szentai (1982); Sütő-Szentai (2010); Sütő-Szentai (2011) and Wall et al. (1973).

Biostratigraphic zonations are, in most instances, supported by CONISS cluster analysis (Grimm, 1987) using StrataBugs® v.2.1. Due to problems inherent from some samples being barren of microfauna or

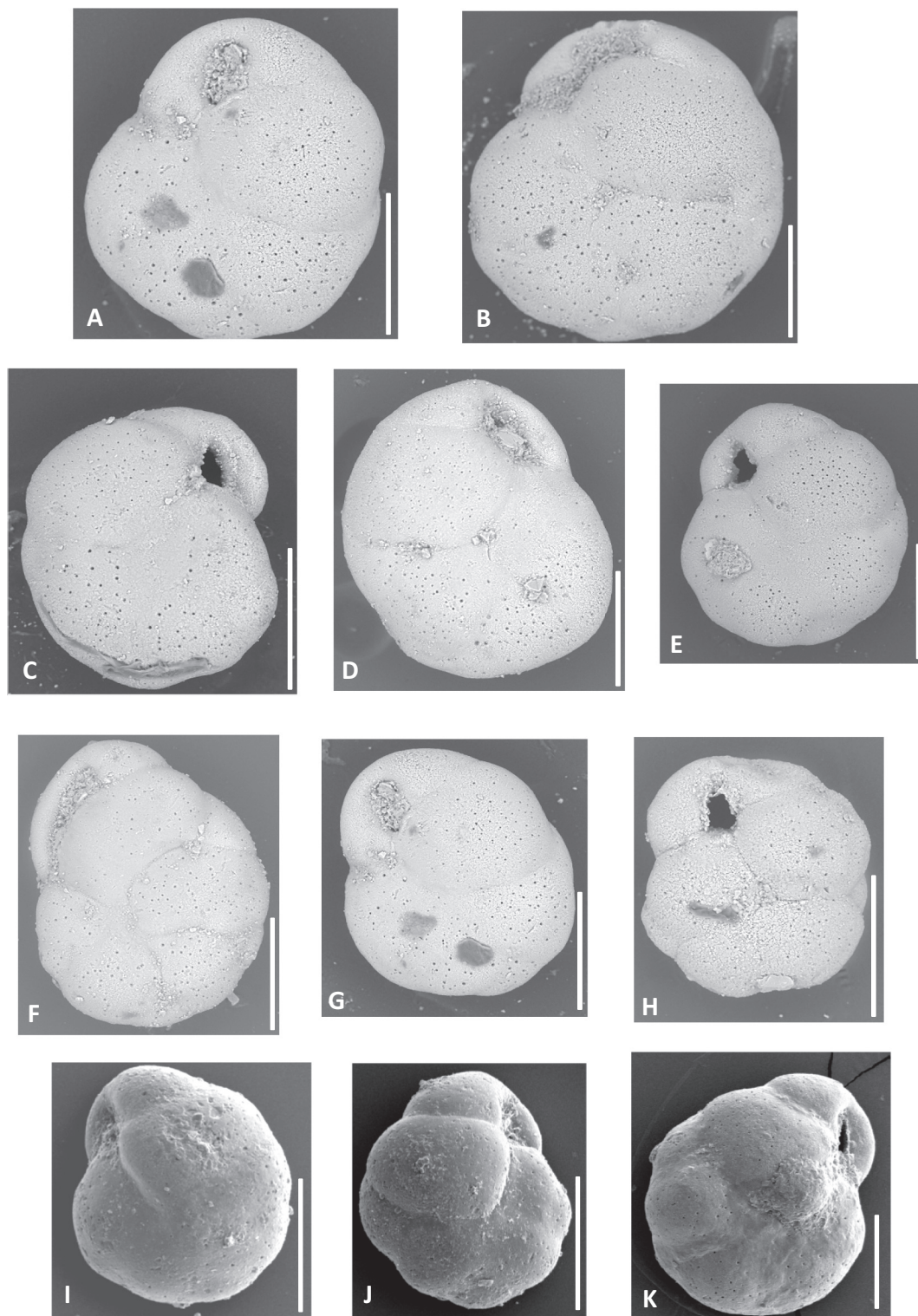


Fig. 4. Scanning electron microscope images of fossil cassidulinid foraminifera from the Akchagyl regional stage, Azerbaijan, Caspian Sea: A-H specimens from sample JE039-1 (Jeirankechmez); I-J specimens from sample JE039 (Jeirankechmez); K specimen from sample LOK2 (Lokbatan). The scale bar is 100 μ m.

containing very impoverished assemblages, zones are assigned by a combination of observed distributions and reference to their assigned clusters. The CONISS cluster analyses were carried out on the entire micropalaeontological (i.e. ostracods and foraminifera combined) and palynological data sets. Clustering was stratigraphically constrained in order to determine, as far as possible, events of biostratigraphic value. Barren or very poorly fossiliferous samples are excluded from the cluster analysis of microfaunal data and from zone assignments.

For the SEM palynological preparations, approximately 0.5 ml of residue was mixed with distilled water in a plastic Petri dish. Specimens were isolated with a glass micropipette using an inverted microscope and washed in distilled water. Clean specimens were then mounted on a Cambridge aluminium stub and sputter coated with gold/palladium (Polaron E5100). Specimens of ostracods and foraminifera selected for SEM preparations were hand-picked from dried processed residues.

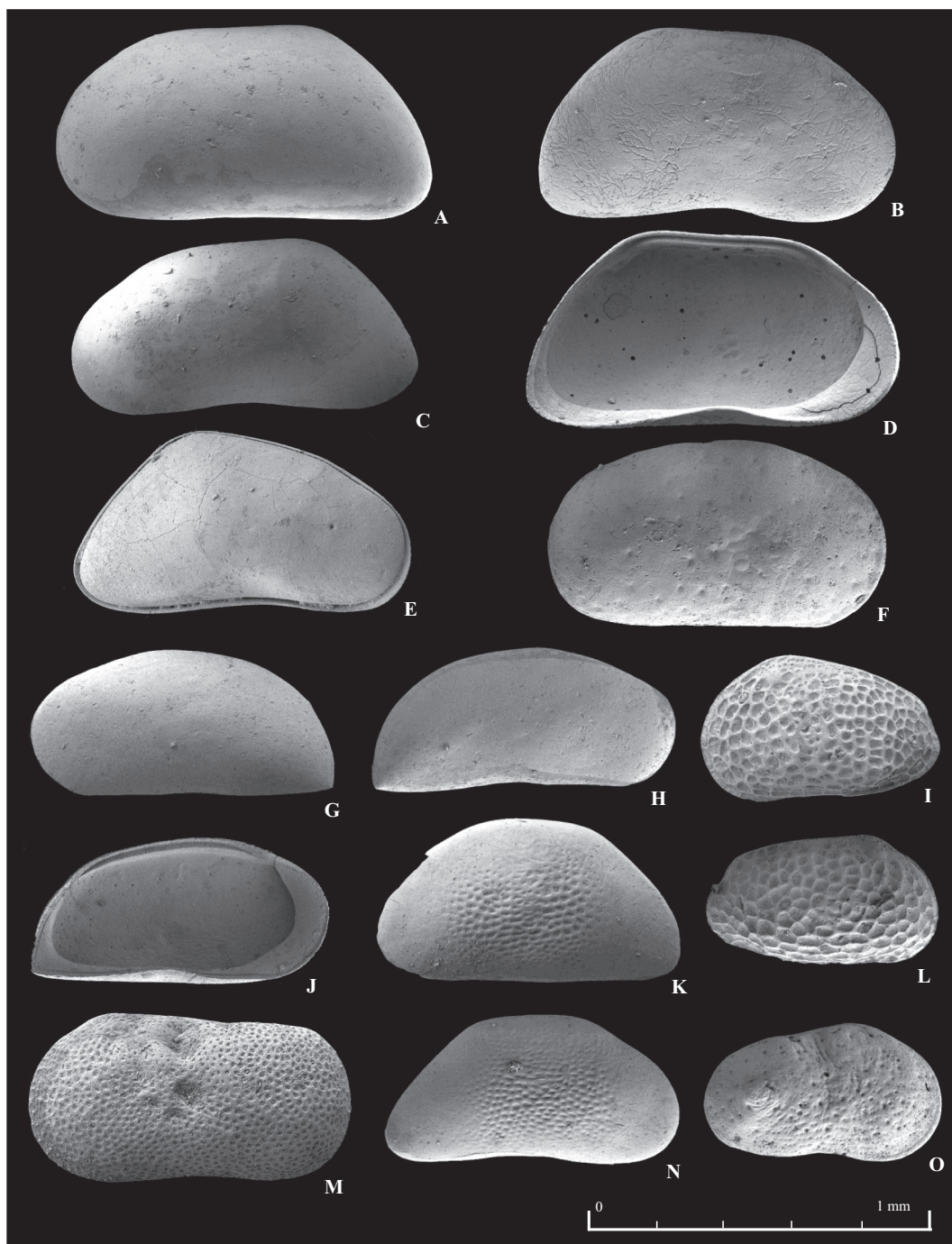


Fig. 5. Scanning electron photomicrographs of Akchagylian and Apsheronian ostracods from Jeirankechmez section, Azerbaijan (LV-left valve, RV-right valve). A, B, D. *Candona (Caspiocypris) candida* (Livental): A. LV, external view, JE100; B. RV, external view, JE100; D. LV, internal view. C, E. *Candona aff. combibo* Livental: C. LV, external view, JE057; E. carapace, view of RV, JE057; F. *Cyprideis torosa* (Jones); RV, external view, JE091. G, H, J. *Camptocypris acronasuta* (Livental): G. LV, external view, JE080; H. RV, external view, JE112; J. LV, internal view, JE112. I, L. *Tyrrhenocythere azerbaijanica* (Livental): I. LV, external view, JE111; L. RV, external view, JE129. K, N. *Candona (Typhlocypris) gracilis* Livental: K. LV, external view, JE103; N. RV, external view, JE118. M. *Ilyocypris bradyi* Sars, LV, external view, JE112. O. *Cytherissa bogatschovi* (Livental), RV, external view, JE95.

5. Micropalaeontology results

Six distinct intervals can be recognised in the studied section based on microfauna (ostracods and foraminifera) (Fig. 3). These are assigned as Zones JM (JM = Jeirankechmez Microfauna) 1 to 6, which coincide

with CONISS clusters in almost all cases. Samples studied from the Productive Series (assigned as Zone JM-1) were mostly poorly fossiliferous and of little interpretive value, except for the presence of a single specimen of the ostracod *Cyprideis torosa* and a sparse, reworked foraminiferal assemblage. Zones JM 2 to 6 occur within the Akchagyl to

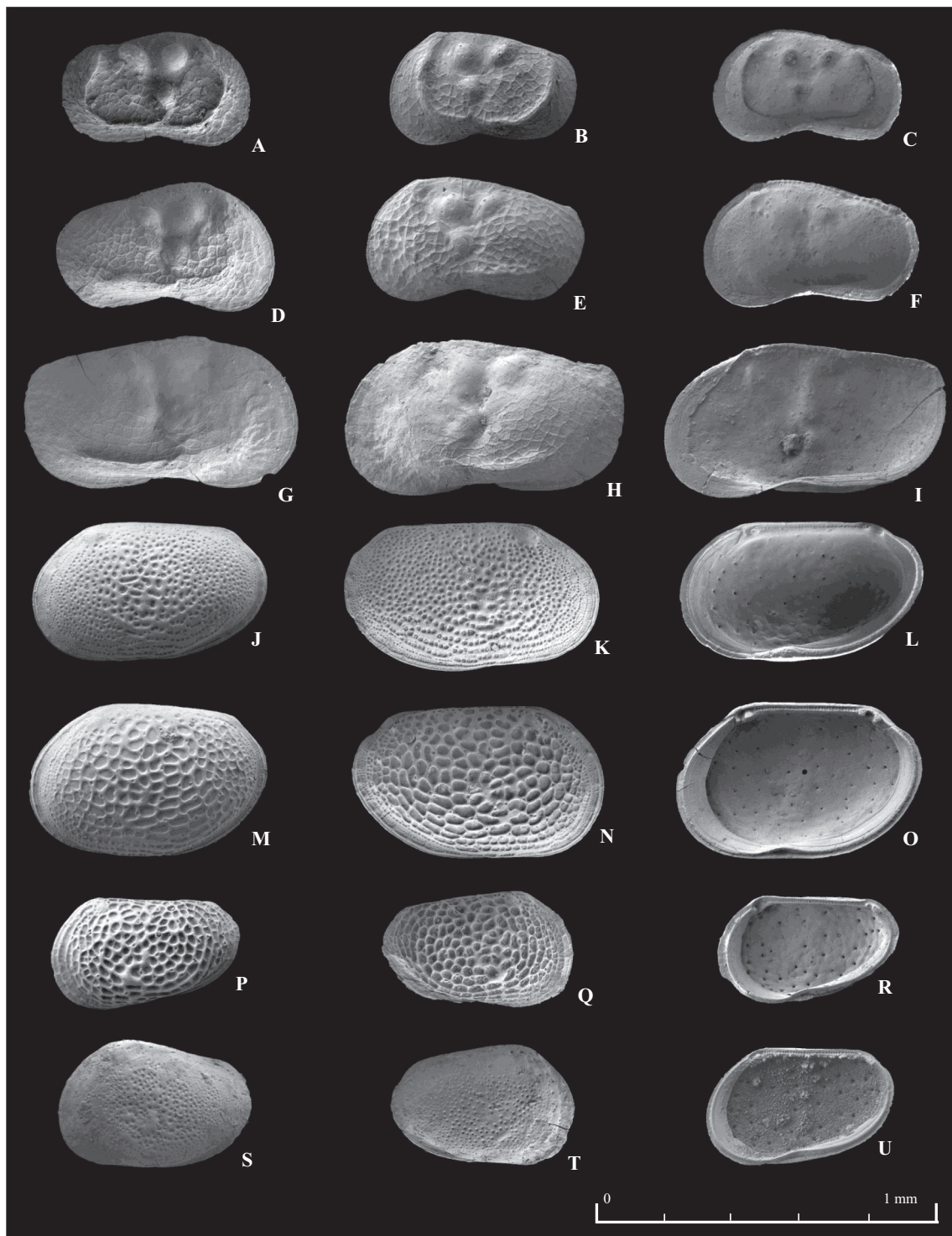


Fig. 6. Scanning electron photomicrographs of Akchagyl and Apsheronian ostracods from Jeirankechmez section, Azerbaijan (LV-left valve, RV-right valve). A–C. *Limnocythere tschaplignyae* Suzin: A. RV, external view, JE041; B. LV, external view, JE039; C. RV, internal view, JE041. D–F. *Limnocythere alveolata* Suzin: D. RV, external view, JE036; E. LV, external view, JE036; F. RV, internal view, JE036. G–I. *Limnocythere luculenta* Livental: G. RV, external view, JE039; H. LV, external view, JE041; I. RV, internal view, JE041. J–L. *Loxoconcha eichwaldii* Livental: J. LV, external view, JE058; K. RV, external view, JE057; L. RV, internal view, JE075. M–O. *Loxoconcha petasa* Livental: M. LV, external view, JE109; N. RV, external view, JE108; O. RV, internal view, JE109. P–R. *Loxoconcha babazanica* Livental: P. LV, external view, JE055; Q. RV, external view, JE097; R. RV, internal view, JE094. S–U. *Loxoconcha assimulata* Livental: S. LV, external view, JE039; T. RV, external view, JE039; U. RV, internal view, JE52.

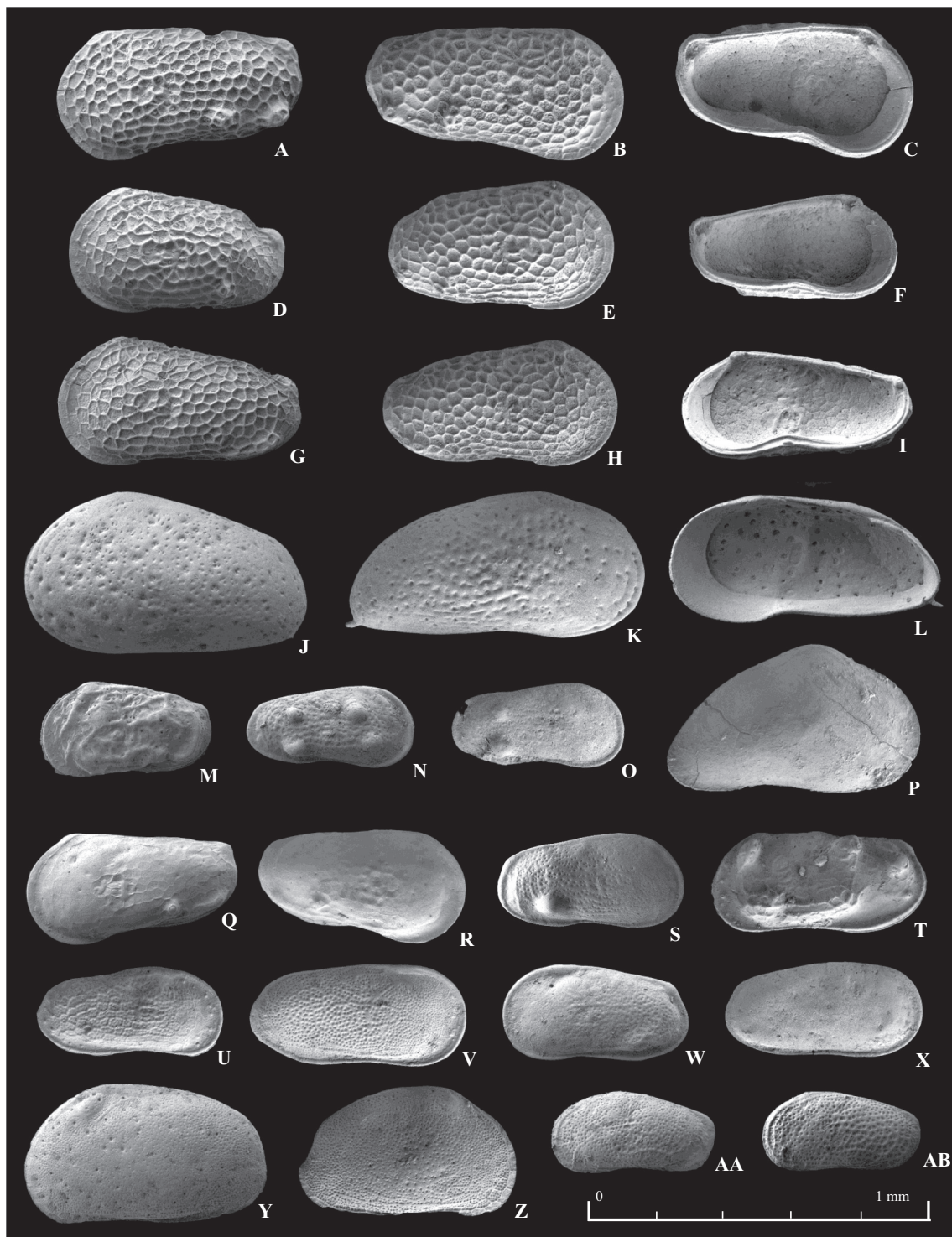


Fig. 7. Scanning electron photomicrographs of Akchagylian and Apsheronian ostracods from Jeirankechmez section, Azerbaijan (LV-left valve, RV-right valve). A–C. *Amnicythere* aff. *andrusovi* (Livental): A. LV, external view, JE068; B. RV, external view, JE068; C. LV, internal view, JE075. D–F. *Amnicythere* aff. *saljanica* (Livental): D. LV, external view, JE057; E. RV, external view, JE057; F. LV, internal view, JE057. G–I. *Amnicythere* aff. *palimpsesta* (Livental): G. LV, external view, JE064; H. RV, external view, JE057; I. RV, internal view, JE057. J–L. *Eucythere naphatscholana* (Livental): J. LV, external view, JE095; K. RV, external view, JE095; L. RV, internal view, JE060. M. *Euxinocythere (Maotocythere) aff. bosqueti* (Livental) or *Callistocythere cellula* (Livental), LV, external view, JE102. N. *Amnicythere quadrituberculata* (Livental), RV, external view, JE111. O. *Amnicythere bicornis* (Livental), RV, external view, JE071. P. *Eucypris* sp., RV, external view, juvenile, JE029. Q–R. *Amnicythere* aff. *normalis* (Livental): Q. LV, external view, JE071; R. RV, external view, JE071. S, W. *Amnicythere ?bona* Stepanaitis: S. RV, external view, JE060; W. LV, external view, JE103. T. *Amnicythere quinquetuberculata* (Schweyer), LV, external view, JE118. U. *Amnicythere* aff. *saluta* (Livental), RV, external view, JE091. V. *Amnicythere* aff. *nata* (Markova), RV, external view, JE103. X. *Amnicythere propinqua* (Livental) or *A. cymbula* (Livental), RV, external view, JE112. Y–Z. *Tyrrhenocythere* sp.: Y. LV, external view, JE129. Z. RV, external view, JE091. AA–AB. *Leptocythere ?gubkini* Livental: AA. LV, external view, JE038; AB. LV, external view, JE041.

Apscheron intervals and are described below. A distribution chart showing all microfauna recorded is provided as supplementary information (Appendix 1). Representative SEM photomicrographs of microfauna are shown in Fig. 4 (foraminifera) and Figs. 5, 6, and 7 (ostracods). The illustrations of ostracods are of specimens from a duplicate set of samples and therefore contain some species which were not identified in the principal section analysed. Nannofossil analysis of sample JE039 (797.88 m) yielded an entirely reworked nannoplankton assemblage lacking in a clear biostratigraphic signal (Table 1).

5.1. Zone JM-2: 770.58 m (JE028)–789.83 m (JE036)

Ostracod assemblages are characterised by the presence of *Limnocythere*, including *L. alveolata* (Suzin) and *L. luculenta* (Livental). A few juvenile specimens of *Eucythere naphhtatscholana* were recovered from one sample only (774.48 m, JE030). Otherwise, the assemblages contain undifferentiated species of *Loxococoncha*, candonids and various smooth ostracods. Rare calcareous benthonic foraminifera were recorded including *Ammonia* (774.48 m, JE030; 789.83 m, JE036), *Elphidium* and *Spirillina* (both at 789.83 m, JE036). Five of the studied samples contained no microfauna.

5.2. Zone JM-3

5.2.1. Sub-zone JM-3A: 797.88 m (JE039)–813.18 m (JE045)

Limnocythere, including the supposedly Akchagyl restricted *L. tschapyginae* (Suzin) and *Loxococoncha* (including rare *L. eichwaldii*) are present at the base of the interval. Undifferentiated smooth ostracods and fragments of valves also occur. The main feature of this interval is the significantly increased presence of benthic foraminifera particularly species of *Cassidulina* in association with *Cibicides* (including several morphotypes/sub-species) and *Hanzawaia*. This assemblage is present in most samples studied between 797.88 m (JE039) and 813.18 m (JE045). Other benthic foraminifera occurring sporadically include specimens of *Ammonia* and *Elphidium* and several undifferentiated calcareous forms.

5.2.2. Sub-zone JM-3B: 815.68 m (JE046)–833.98 m (JE054)

This interval is characterised by reduced microfaunal recovery in most samples. Sample 825.48 m (JE049) is an exception and contains abundant smooth ostracods (probably cyprids), common *Eucythere naphhtatscholana* and a single *Loxococoncha eichwaldii*. Undifferentiated bivalves also occur rarely. Foraminifera are absent except for several specimens of *Ammonia* (829.48 m, JE052) and undifferentiated calcareous benthonic taxa (833.98 m, JE054).

5.3. Zone JM-4

5.3.1. Sub-zone JM-4A: 835.98 m (JE055)–852.00 m (JE063)

Numerous species of *Amnicythere* including many tuberculate/noded forms referable to *A. andrusovi* (Livental), *A. palimpsesta* (Livental) and *A. saljanica* (Livental) were recorded, although these may be morphological variants of the same species. *Amnicythere verrucosa* (Suzin) occurs at and above 842.23 m (JE059) and *Eucythere naphhtatscholana* is common or abundant in most samples. Fewer foraminifera occur relative to the underlying section, limited to several specimens of *Ammonia* (recorded at 835.98 m, JE055; 838.68 m, JE057 and 852.00 m, JE063); other sporadic occurrences (including rare planktonics) are considered as most probably reworked.

5.3.2. Sub-zone JM-4B: 855.48 m (JE064)–883.98 m (JE074)

Ostracod assemblages are similar to the interval below except that *Loxococoncha eichwaldii* increases in numbers. Foraminifera are absent.

5.4. Zone JM-5: 913.38 m (JE084)–989.28 m (BL3)

This zone is characterised by a continuation of common or abundant *Eucythere naphhtatscholana* and *Loxococoncha eichwaldii*. *Caspiolla* spp. (= *Camptocypria*; see Spadi et al., 2018) and *Cytherissa bogatschovi* occur at and above 913.38 m (JE084) and 936.78 m (JE094) respectively. The latter species (which is easily identified and therefore not in doubt) is recorded as an Apscheron or younger species by Agalarova et al. (1940), Agalarova et al. (1961) and Mandelstam et al. (1962). Undifferentiated *Limnocythere* occur sporadically throughout. A black shale sample from 940.28 m (BL2) was devoid of microfauna whereas a similar sample from higher in the section (989.28 m, BL3) yielded a poor ostracod fauna and rare bivalves (*Dreissena*). Foraminifera including rare *Ammonia* and single specimens of *Cassidulina* and *Cibicides* were recorded at 959.08 m (JE104) but may be reworked.

5.5. Zone JM-6: 1004.48 m (JE119)–1140.98 m (JE146)

Maximum abundances of leptocytherids occur, with species of *Loxococoncha* and undifferentiated smooth ostracods also common or abundant. *Cytherissa bogatschovi* (Livental) and *Xestoleberis* spp. are consistently present (and sometimes common) higher up the section (above 1082.98 m, JE134). Peak abundances of *Eucythere naphhtatscholana* occur between 1082.98 m (JE134) and 1105.98 m (JE139). Isolated specimens of *Mediocytherideis apatoica* (Schweyer) are also present. *Tyrrhenocythere azerbaidjanica* (Livental) makes its first consistent appearance up-section at 1056.98 m (JE129) and *Euxinocythere* (*Leptocythere*) *multituberculata* (Livental) at 1082.98 m (JE134): both of these are characteristic of the Lower Apscheron according to Aliyeva and Kengerli (2014). Foraminifera include rare specimens of *Ammonia* (1056.98 m, JE129 and 1105.98 m, JE139) and *Cassidulina* (1056.98 m, JE129) which may be reworked. Undifferentiated bivalves are periodically common to abundant.

Table 1

Calcareous nannofossils recorded in the Akchagyl at the Jeirankechmez locality (sample JE039, 797.88 m) and their respective ages.

Early Cretaceous	<i>Cruciellipsis cuvillieri</i> (Manivit) <i>Diazomatolithus lehmanii</i> (Noël) <i>Rhagodiscus asper</i> (Stradner)
Late Cretaceous	<i>Arkhangelskiella mastrichtiensis</i> (Burnett) <i>Broinsonia parca constricta</i> (Hattner) <i>Broinsonia parca parca</i> (Stradner) <i>Eiffellithus eximius</i> (Stover) <i>Eprolithus eptapetalus</i> (Varol) <i>Helicolithus trabaculatus</i> (Görka) <i>Lithastrinus grillii</i> (Stradner) <i>Quadrum eptabrachium</i> (Varol) <i>Reinhardtites levis</i> (Prins and Sissingh) <i>Chiasmolithus danicus</i> (Brotzen)
Paleocene	<i>Cruciaplacolithus frequens</i> (Perch-Nielsen) <i>Fasciculithus</i> spp. <i>Prinsius</i> spp.
Early to Middle Eocene	<i>Discoaster lodoensis</i> (Bramlette and Riedel) <i>Lanternithus</i> spp. <i>Micrantholithus breviradiatus</i> (Bown) <i>Reticulofenestra wadeae</i> (Bown)
Late Eocene - Oligocene	<i>Isthmolithus recurvus</i> (Deflandre) <i>Reticulofenestra bisecta</i> (Hay, Mohler and Wade) <i>Reticulofenestra daviesii</i> (Haq) <i>Reticulofenestra reticulata</i> (Gartner and Smith) <i>Reticulofenestra stavensis</i> (Levin and Joerger) <i>Reticulofenestra umbilicus</i> (Levin)
Neogene ^a	<i>Calcidiscus leptoporus</i> (Murray and Blackman) <i>Calcidiscus tropicus</i> (Kamptner) <i>Coccolithus pelagicus</i> (Wallich) <i>Helicosphaera ampliaptera</i> (Bramlette and Wilcoxon) <i>Helicosphaera carteri</i> (Wallich) <i>Umbilicosphaera jafari</i> (Muller)

^a All Neogene nannofossil taxa interpreted as reworked.

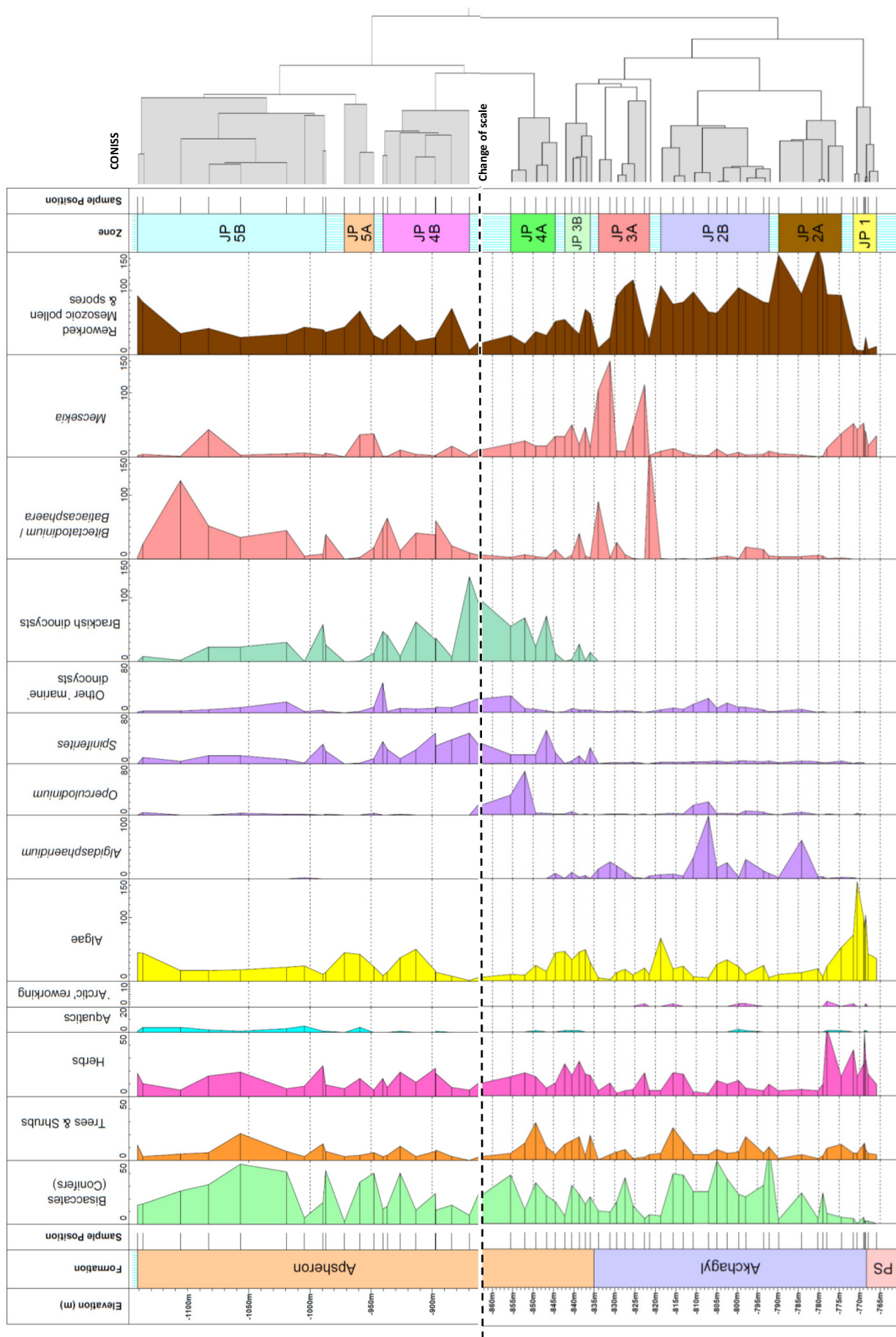
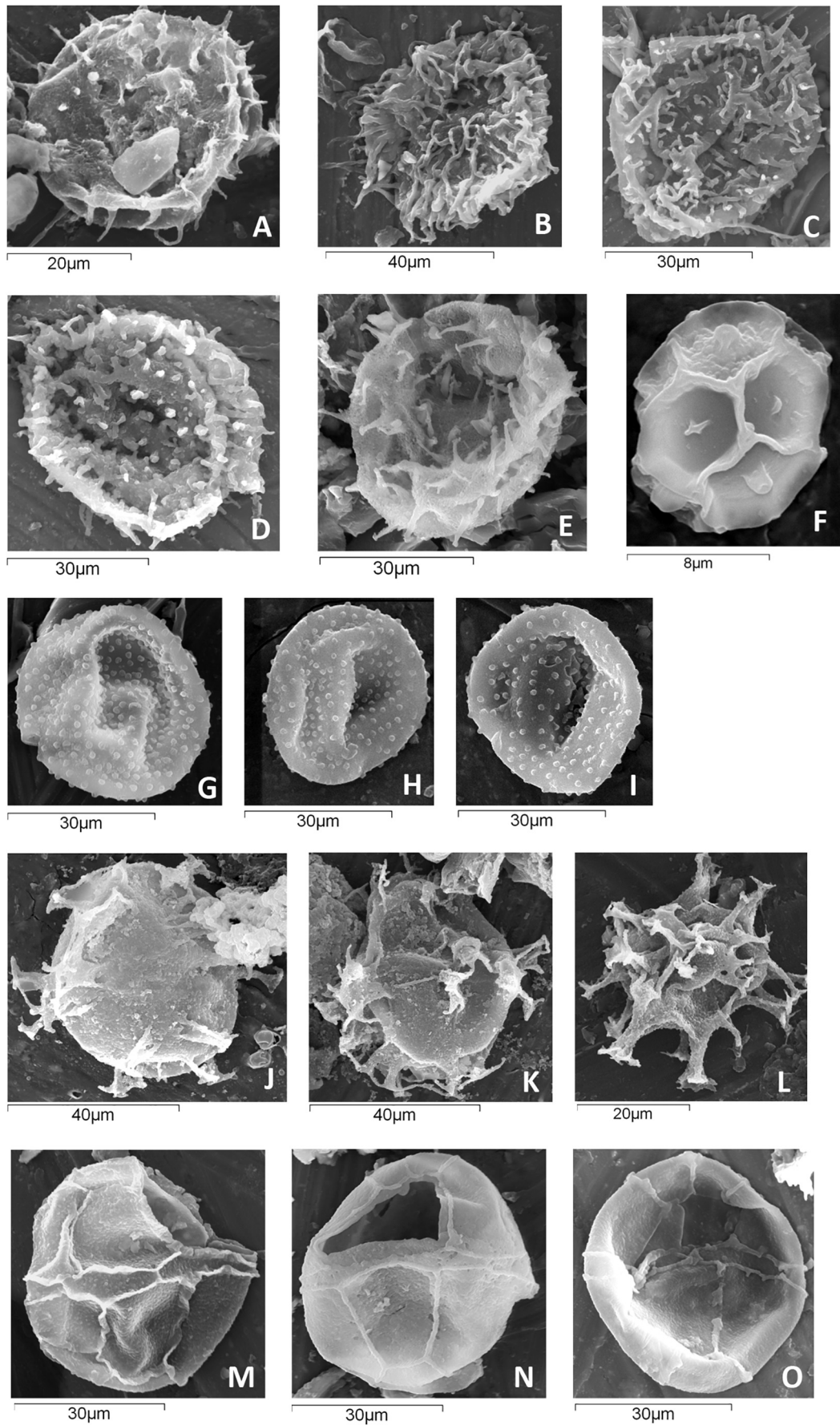


Fig. 8. Summary of palynology data from the Jeirankhechmez locality with zones constrained by CONISS clustering. The filled clusters (grey shading) represent statistically valid clusters accounting for 50% or more of the total dispersion. Abundances shown are recorded counts. Not all taxa are included.



(caption on next page)

Fig. 9. Scanning electron photomicrographs of dinocysts and acritarchs. A–D. *Algidasphaeridium cf. capillatum* with mainly distally closed, occasionally slightly bifid or capitate processes: A. JE043, Akchagyl; B–D. JE053, Akchagyl. E. *Operculodinium centrocarpum* sensu Wall and Dale 1966: JE043, Akchagyl. F. *Cymatiosphaera* sp.: JE053, Akchagyl. G–I. *Mecsekia 'orientalis'* Sütő-Szentai (unpublished form): JE053, Akchagyl. J–K. *Spiniferites* spp.: JE061, Apsheron; these are similar to *S. tihanyensis* Sütő-Szentai (2000) and also to *S. pannonicus* (Soliman and Riding, 2017). L. *Spiniferites* sp.: JE069, Apsheron. M–O. *Impagidinium* spp.: M–N, JE069, Apsheron; O, BL2, Apsheron. These cysts are very variable but are most similar to the *I. spongianum/I. globosum* lineage of Sütő-Szentai (1982), Sütő-Szentai (1985), Sütő-Szentai (2011). For size, see individual scale bars. Photos by Carmel Pinnington.

6. Palynology results

Palynological associations occurring in the Upper Productive Series, Akchagyl and Apsheron intervals are assigned to Zones JP-1 to JP-5 (JP = Jeirankechmez Palynology). All of the JP zones and sub-zones match CONISS clusters (Fig. 8). Assemblages are composed of pollen and spores, freshwater or brackish green and prasinophycean algae, dinocysts and various reworked components; the latter are predominantly of Mesozoic origin, with Cenozoic (mainly Paleogene) and Paleozoic forms also present rarely. The most frequent taxa include dinocysts, acritarchs and green algae. Microforaminiferal test linings occur but account for 1% or less of the total palynological assemblage. Taxonomic notes for some of these taxa are given in Section 8.4. Several of the dinocysts recorded have affinity with taxa originally described from Mio-Pliocene sediments in Central Paratethys, particularly the Pannonian and Dacic basins. These dinocysts are referred to in this text as of 'Peri-Paratethyan' affinity using the palaeobiogeographic entities documented by Neubauer et al. (2015). Recovery of contemporary pollen is quite low, with counts of > 100 obtained in most samples, not sufficient for reliable interpretations of palaeo-vegetation. A summary of palynological data is shown in Fig. 8. SEM and LM (Light Microscope) photomicrographs of key taxa are shown in Fig. 9 and Fig. 10. Quantitative distributions are provided as supplementary information (Appendix 2 and 3).

6.1. Zone JP-1: 765.83 m (JE024) – 771.48 m (JE029)

The main feature is the common or abundant presence of freshwater green algae (mainly *Pediastrum* and *Botryococcus*) and brackish tolerant prasinophycean algae including *Tasmanites* and *PterospERMella*. Acritarchs occur commonly, with high numbers of *Mecsekia 'orientalis'* (sensu Sütő-Szentai) (see Section 8.4.3 and Fig. 9G–I), consistent *Mecsekia incrassata* (Sütő-Szentai) and *Cymatiosphaera* (Fig. 9F) recorded. Algal frequencies are highest in sample JE28 (770.58 m) which is composed of laminated mudstone sediments and contains abundant *Botryococcus* and *Pediastrum*. Pollen elements are made up mainly of non-arboreal pollen (NAP) such as Asteraceae and Poaceae, with *Alnus* the most common of the arboreal pollen (AP) component. Marine dinocysts include mainly single occurrences of *Islandinium minutum* (Harland and Reid), *Operculodinium centrocarpum* sensu Wall and Dale, 1966 and *Lingulodinium machaerophorum* (Deflandre and Cookson). A key feature is the low proportion of reworked forms although two specimens of *Aquilapollenites-Triprojectus* pollen (age range Late Cretaceous to Paleogene) were recorded.

6.2. Zone JP-2

6.2.1. Sub-zone JP-2A: 774.48 m (JE030)–789.83 m (JE036)

A significant increase in reworked taxa is evident above 774.48 m (JE030). The most frequent of the reworked forms is *Classopollis*, a Mesozoic gymnosperm pollen type (range Triassic to Mid-Cretaceous) which co-occurs with many other typical Mesozoic pollen, spores and dinocysts. Reworked specimens of *Aquilapollenites-Triprojectus* occur rarely. Contemporary pollen and spores are not common but include moderate numbers of *Pinus* and mainly single occurrences of other AP taxa including *Alnus*, *Betula*, *Carpinus*, *Quercus* and *Tsuga*. NAP includes pollen of Poaceae and Asteraceae, with *Artemisia* and *Amaranthaceae* pollen notably increased at 777.98 m (JE031). Freshwater green algae

are reduced relative to the interval below, whereas numbers of dinocysts are increased, including a peak occurrence of *Algidasphaeridium cf. capillatum* (see Section 8.4.2) at 784.18 m (JE034).

6.2.2. Sub-zone JP-2B: 792.18 m (JE037)–818.68 m (JE047)

This interval contains a low-diversity dinocyst assemblage, characterised by common and locally abundant *Algidasphaeridium cf. capillatum* (Fig. 9A–D) with an abundance peak recorded at 807.00 m (JE043). An increased presence of *Operculodinium centrocarpum* sensu Wall and Dale, 1966 (Fig. 9E) occurs at and above 793.48 m (JE037) which coincides with the presence of foraminiferal test linings and cysts of *Pentapharsodinium dalei* (Indelicato and Loeblich). Other dinocysts present in low numbers include *Lingulodinium machaerophorum*, *Islandinium minutum* together with undifferentiated species of *Spiniferites* and *Impagidinium*. Green algae (e.g. *Pediastrum* and *Botryococcus*) are less frequent than in the interval below. A peak in *PterospERMella* occurs at 818.68 m (JE047). Pollen records show an increase in AP, mainly from conifers such as *Pinus*, *Picea*, *Abies* and *Tsuga*. Broad-leaved taxa represented include *Alnus*, *Ulmus* and *Carya*. Taxodiaceae pollen is present in low numbers and is likely to be reworked. Unquestionably reworked forms occur frequently, making up almost 50% of the total palynoflora in some samples. The most prevalent of the reworked pollen is *Classopollis* with specimens of Mesozoic restricted spores (e.g. *Callialasporites dampieri*) and dinocysts also present. Pollen reworked from high latitude Late Cretaceous to Paleogene sediments, includes single specimens of *Wodehousia* at 799.58 m (JE040) and 815.68 m (JE046).

6.3. Zone JP-3

6.3.1. Sub-zone JP-3A: 821.50 m (JE047*)–833.98 m (JE054)

Large increases in the dinocysts *Bitectatodinium/Batiacasphaera* (above 821.50 m, JE047*) (see Section 8.4.4, Fig. 10D–E, Fig. 10J) and the acritarch *Mecsekia 'orientalis'* (sensu Sütő-Szentai) (above 822.68 m, JE048) are noted. Other taxa include *Algidasphaeridium cf. capillatum* and reworked components continue to be common.

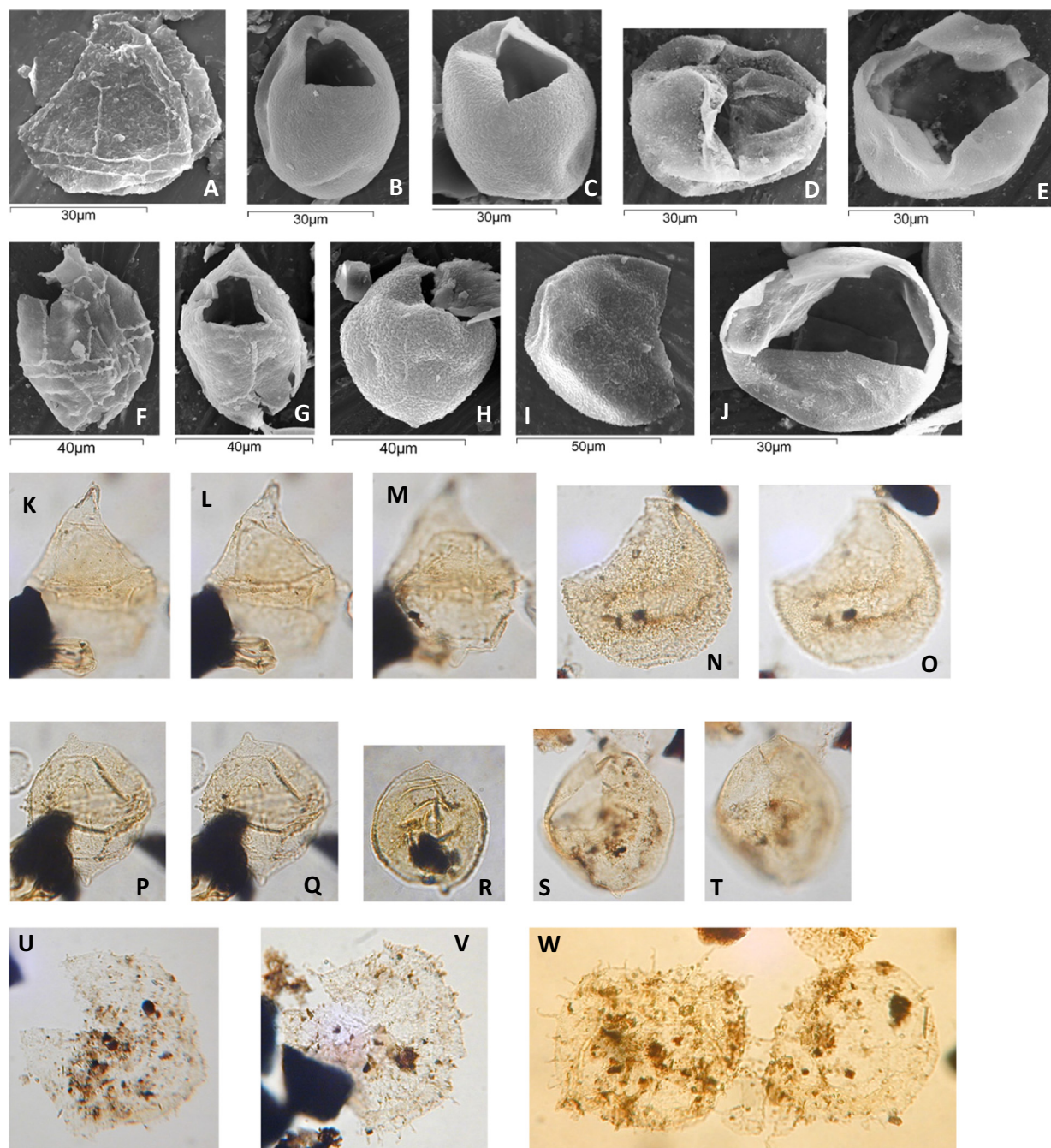
6.3.2. Sub-zone JP-3B: 835.98 m (JE055)–842.23 m (JE059)

Pollen recovery is increased with *Pinus*, *Ulmus* and Asteraceae well-represented. Algal numbers are also increased with *Pediastrum* and *Botryococcus* recorded, whereas numbers of reworked palynomorphs are reduced. Dinocyst associations show an increased presence of species of *Spiniferites* and small increase in species of *Impagidinium*. The sub-zone contains records of several 'Peri-Paratethyan' dinocysts including *Spiniferites 'pannonicus - tihanyensis'*, (Fig. 9J–K), *Seriliodinium explicatum* (Eaton) and a single occurrence of *Galeacysta etrusca* (Corradini and Biffi).

6.4. Zone JP-4

6.4.1. Sub-zone JP-4A: 844.48 m (JE060)–855.48 m (JE064)

Spiniferites 'pannonicus/tihanyensis' increases in numbers, co-occurring with *Impagidinium ?obesum* (Sütő-Szentai) (Fig. 10H), *Impagidinium ?pecsvaradense* (Sütő-Szentai) (Fig. 10F–G), *I. globosum/spongianum* (Sütő-Szentai) (Fig. 9M–O) and *Chytroisphaeridia hungarica/tuberosa* (Sütő-Szentai) (Fig. 10I, Fig. 10N–O). These taxa are known from the Miocene of the Pannonian Basin (e.g. Bakrač et al., 2012; Soliman and Riding, 2017; Sütő-Szentai, 1982; Sütő-Szentai, 2000; Sütő-Szentai,



— scale bar = 30 µm (K-T), 20 µm (U-W)

Fig. 10. Scanning electron and light photomicrographs of dinocysts. A. *Caspidium rugosum* Marret: BL2, Apsheron. B–C *Pyxidinospis psilata* Wall: JE069, Apsheron. D. *Bitectatodinium/Batiacasphaera* (archaeoeyle configuration unclear): JE047*, Apsheron. E. *Bitectatodinium* sp.: JE047*, Apsheron. F–G. *Impagidinium ?pecsvaradense* (= *Pontiadinium pecsvaradense* Sütő-Szentai, 1982): JE069, Apsheron. H. *Impagidinium ?obesum* (= *Pontiadinium obesum* Sütő-Szentai, 1982): JE069, Apsheron. I. *Chytroisphaeridia hungarica* Sütő-Szentai (1990); Sütő-Szentai (2011): JE063, Apsheron. J. *Bitectatodinium* sp.: JE047*, Apsheron. K–M. *Impagidinium ?pecsvaradense* (= *Pontiadinium pecsvaradense* Sütő-Szentai (1982): JE063, Apsheron. N–O. *Chytroisphaeridia tuberosa* Sütő-Szentai (1982): JE063, Apsheron. P–Q. *Impagidinium ?obesum* (= *Pontiadinium obesum* Sütő-Szentai (1982)): JE094, Apsheron. R–T. *Impagidinium ?obesum* and/or *Komewuia?* of Soliman and Riding (2017): JE094, Apsheron. U–W *Algidasphaeridium* cf. *capillatum*: JE043, Akchagy; U and V show chasmic (slit-like) archaeoeyle. See individual scale bars for SEM photos (A–J). For LM photos, scale bar is 30 µm (K–T) or 20 µm (U–W). SEM Photos by Carmel Pinnington, LM photos by Keith Richards.

2010; Sütő-Szentai, 2011) and similar forms occur in Pliocene sediments in the Dacic Basin and adjacent localities of Romania (Baltes, 1971). Several of these dinocysts have prominent apical and/or antapical nodes (Fig. 10R–T), and are related to the *Pontiadinium* complex (sensu Sütő-Szentai) and possibly *Komewuia?* (sensu Soliman and

Riding, 2017). These co-occur with cysts of *Pentapharsodinium dalei* (marine to brackish). Other dinocysts present commonly include *Operculodinium centrocarpum* sensu Wall and Dale 1966 and undifferentiated species of *Spiniferites*, *Impagidinium* and *Bitectatodinium/Batiacasphaera*. The acritarch *Mecsekia 'orientalis'* (sensu Sütő-Szentai) is

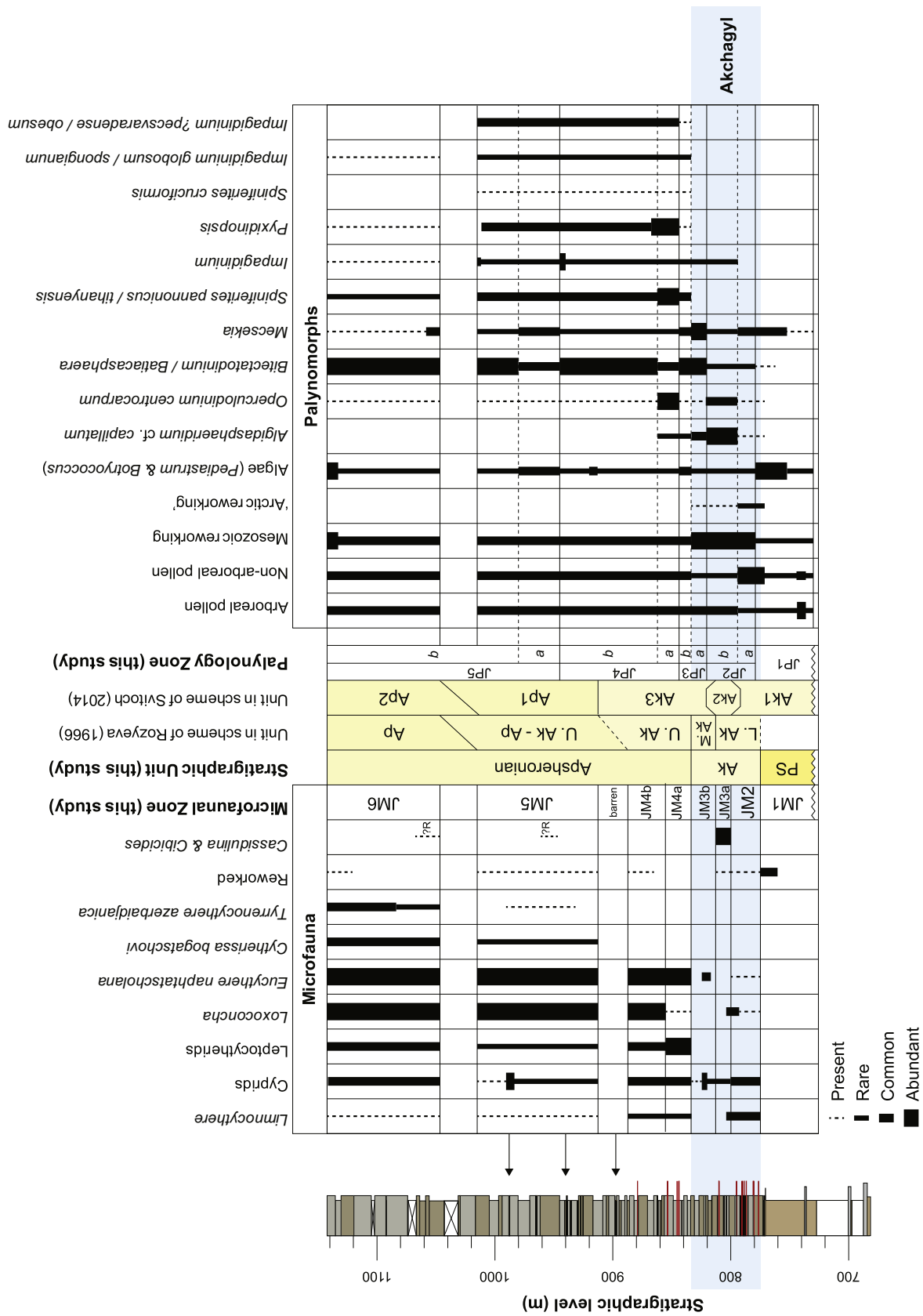


Fig. 11. Summary of lithostratigraphic and biostratigraphic data in the Jeirankechmez study, showing simplified distributions and relative abundance changes observed for the principal ostracod, foraminiferal and palynomorph taxa.

less frequent than in the interval below, whereas *Mecsekia incrassata* is present in increased numbers. Algae have a varied presence with low numbers of *Botryococcus* present and *Pediastrum* common at 844.48 m (JE060). Pollen components include mixed populations of AP (e.g. *Pinus*, *Betula*, *Carpinus* and *Ulmus*) and NAP (e.g. *Amaranthaceae*, *Asteraceae* and *Poaceae*). Reworked Mesozoic pollen, spores and dinocysts typically account for ca. 25% or less of the total palynofloras.

6.4.2. Sub-zone JP-4B: 869.43 m (JE069)–940.28 m (BL2)

Pollen and spore floras are largely unchanged, except for a minor increase in fern spores. Algal associations show periodically increased *Pediastrum* (913.38 m, JE084) and *Tasmanites/Pterospermella* (926.08 m (JE089)). Significantly increased numbers of dinocysts are evident, particularly of *Chytroisphaeridia hungarica/tuberosa* and *Pyxidiniopsis psilata* (Wall and Dale). ‘Noded cysts’ of the *Impagidinium ?pecsvaradense* and *I. ?obesum* lineage are present consistently together with rare *Spiniferites cruciformis* (Wall and Dale). Undifferentiated species of *Spiniferites*, *Impagidinium* (Fig. 9M–O) and *Bitectatodinium/Batiacasphaera* are also present frequently, including in the ‘black shale’ samples from 897.28 m (BL1) and 940.28 (BL2).

6.5. Zone JP-5

6.5.1. Sub-zone JP-5A: 947.78 m (JE099)–971.68 m (JE109)

Reduced numbers of dinocysts occur. *Mecsekia ‘orientalis’* (sensu Sütő-Szentai) shows renewed increases, in association with various algal bodies including *Botryococcus*.

6.5.2. Sub-zone JP-5B: 987.08 m (JE113)–1140.98 m (JE146)

Diminishing numbers of the ‘Peri-Paratethyan’ dinocysts are noted, although several (e.g. *Spiniferites ‘pannonicus/tihanyensis’* and *Pyxidiniopsis psilata*) are present throughout. Two specimens of *Caspidium rugosum* (Marret) occur at 1082.98 m (JE134) and a single *Spiniferites cruciformis* at 987.08 m (JE113). The most frequent taxa are *Mecsekia ‘orientalis’* (sensu Sütő-Szentai) (common at 1082.98 m, JE134) and *Bitectatodinium/Batiacasphaera* (very abundant at 1105.98 m, JE139). Other dinocysts include low numbers of *Lingulodinium machaerophorum* and species of *Spiniferites* and *Impagidinium*. Increased numbers of *Botryococcus*, *Pediastrum* and *Tasmanites* were found in the uppermost portion (at and above 1136.48 m, JE144). In situ pollen includes moderate numbers of *Pinus*, *Betula*, *Ulmus* and NAP. Reworked elements account for around 20% to 45% of the total palynoflora. ‘Black shale’ sample 989.28 m (BL3) contains mainly brackish and/or marine forms.

7. Biostratigraphic interpretation

A summary of the main biostratigraphic indicators and lithostratigraphic units is presented in Fig. 11.

7.1. Uppermost Productive Series - Akchagyl: ca. 766 m–ca. 834 m

Samples studied for microfauna from the uppermost Productive Series are either barren or contain foraminifera of reworked origin (Zone JM-1). Palynological assemblages over the Productive Series to Akchagyl lithological transition show no significant change, with predominantly freshwater palynofloras present for a few metres either side of the boundary. This observation requires further investigation as there appears to be a discrepancy between the lithostratigraphic boundary and biostratigraphic signature at the Productive Series to Akchagyl transition.

An interval of ca. 65 m in thickness between 768.80 m and 833.98 m is confidently assigned to the Akchagyl based on lithology and microfauna (Zones JM-2 and JM-3A/3B). The ostracod assemblage contains a mixture of fresh or brackish water, oligohaline (e.g. *Limnocythere*, cyprids) and mesohaline taxa (e.g. *Loxococoncha*, *Eucythere*, leptocytherids).

Marine foraminifera (*Cassidulina*, *Cibicides*, *Hanzawaia*) also occur. The assemblage is a good match for the Lower Akchagyl as described by Agalarova et al. (1940), Mandelstam et al. (1962) and Rozyeva (1966). Palynological assemblages show strong freshwater influence with minimal marine influence in the interval below ca. 771 m (Zone JP-1) indicated by the presence of frequent *Pediastrum* and *Botryococcus*. Reworking in the interval 774.48 m to 789.83 m is frequent (Sub-zone JP-2A), with the age range of many of the identified species (e.g. *Classopollis*) indicative of a sediment provenance from the Caucasus and/or the Russian Platform.

Marine foraminifera, especially *Cassidulina* and *Cibicides* present commonly between 797.88 m (JE039) and 813.18 m (JE045), suggest a tie with the Middle Akchagyl (Ak₂) in the scheme of Svitoch (2014). Dinocyst assemblages also indicate marine influences within the same interval, based on the common presence of *Algidasphaeridium cf. capillatum*. This event occurs at Jeirankchmez (Zone JP-2B), and also in outcrops at Babazanan and Lokbatan, Azerbaijan, where this taxon accounts for up to 75% of the total palynoflora and up to 96% of the dinocyst assemblage (K. Richards, unpublished data). One of these samples is LOK2, which also contains the *Cassidulina* and *Cibicides* foraminiferal association (see Section 8.3). The specimens of *Algidasphaeridium cf. capillatum* are, on the whole, very poorly preserved, a possible indication of fairly high energy deposition. The presence of *Islandinium minutum* and cysts of *Pentapharsodinium dalei* is also noted. These taxa frequently occur in the northern oceans (Head et al., 2001; Radi et al., 2013; Zonneveld et al., 2013) but both are also known to occur in the Black Sea, and *P. dalei* cysts are known from the present-day Caspian Sea (Mudie et al., 2017).

The Middle Akchagyl sensu Rozyeva (1966) is not clearly evident from the ostracod record but may be represented in the interval above ca. 815 m (JM-3B) where microfaunal recovery is diminished and locally barren (see Fig. 11). The interval with abundant *Mecsekia ‘orientalis’* (sensu Sütő-Szentai) and *Bitectatodinium/Batiacasphaera* (Zone JP-3A) is consistent with a brackish depositional setting, without necessarily requiring a connection to open marine waters.

7.2. Apsheron: ca. 836 m–ca. 1141 m

A major shift in faunal assemblages occurs at around 836 m in the section. Increased numbers of ostracods above 835.98 m (Zone JM-4A) including *Eucythere naphtatscholana*, *Loxococoncha eichwaldii* and *Leptocythere verrucosa* is consistent with that described by Rozyeva (1966) as characteristic of the Upper Akchagyl but is also comparable with the Apsheron association described by Svitoch (2014). Higher in the section, the presence of consistent *Camptocypria* (Zone JM-5, at and above 913.38 m, JE084) and *Cytherissa bogatschovi* (at and above 936.78 m, JE094) again suggests probable affinity with the Apsheron. Further increased numbers of *C. bogatschovi*, in association with *Tyrhenocythere azerbaijanica* and *Xestoleberis* spp. in Zone JM-6 (above 1056.98 m, JE129), suggests that this uppermost studied interval does correspond to the Apsheron. The overall impression is of a brackish, mesohaline environment with occasional freshening episodes, indicated by the presence of *Limnocythere*. Short-lived marine influences could be indicated by rare occurrences of *Cassidulina*, *Cibicides* and *Ammonia* if those are in situ.

The co-occurrence of freshwater to brackish (oligohaline/mesohaline) ostracods, rare foraminifera and low salinity dinocysts is good evidence that this interval was not subject to fully open marine influences. All of the dinocysts found in significant numbers in this interval, such as *Spiniferites ‘pannonicus/tihanyensis’*, the ‘noded cysts’ of the *Impagidinium ?obesum/?pecsvaradense* lineage (*Pontiadinium* sensu Sütő-Szentai), *Seriliodinium explicatum* and species of *Spiniferites* and *Impagidinium* occur within typical low salinity-tolerant ‘Peri-Paratethyan’ assemblages. Salinities are unlikely to have regularly exceeded ~19‰ which is the maximum salinity tolerated by most of the ‘Peri-Paratethyan’ dinocysts (Mudie et al., 2017). Other dinocysts such

as *Operculodinium centrocarpum* sensu Wall and Dale 1966 indicate potentially higher salinities, and point to localised increases in marine influence for example at ca. 852 m to 855 m (JE063 and JE064). These and similar dinocysts occur at the present time in the Black Sea where the salinity is typically between 17 and 19‰ (Mudie et al., 2017) maintained by the connection to the Mediterranean Sea. Svitoch (2014) estimates that, based on molluscs, maximum salinity during Akchagyl deposition was within the range of 18 to ~20‰ and therefore comparable with the present-day Black Sea. Ostracod faunas suggest brackish, mesohaline conditions above ca. 1057 m. This is in agreement with the reduced numbers of ‘Peri-Paratethyan’ dinocysts, frequent *Bitectatodinium/Batiacasphaera* (e.g. at 1105.98 m, JE139) and *Mecsekia* (1082.98 m, JE134).

8. Discussion

8.1. Ostracod nomenclature

Micropalaeontological differentiation of lithostratigraphic units within the Plio-Pleistocene interval of the Caspian region relies on the correct identification of numerous ostracod species. However, published accounts of this largely endemic microfauna often present poorly illustrated ‘species’ which makes reliable identification difficult. The situation has not been helped by the fact that the two seminal works on Caspian ostracods (by Agalarova et al., 1961; Mandelstam et al., 1962) were published independently with ensuing taxonomic confusion. Furthermore, as Schornikov (2011) has commented, the names of Mediterranean species have often been incorrectly applied to Caspian taxa, and Holocene species have on occasions been confused with those from older horizons. Moreover, morphological variants and juveniles (particularly among leptocytherids), and sexual dimorphs (for example of *Loxococoncha*) have sometimes been given different names. The identification of smooth-shelled forms is even more difficult as they have been mainly described purely on shell outline. Unfortunately, the taxonomic type collections on which many of the species concepts are based have been lost. Only recently have some authors re-examined type specimens where they exist (Gliozzi et al., 2013) or illustrated their own material using modern imaging techniques (Boomer et al., 2005; Chekhovskaya et al., 2014; Spadi et al., 2018; Van Baak et al., 2013; Van Baak et al., 2016). As a consequence, stratigraphic ranges given to many forms are unreliable. The poor state of their taxonomy is also a limiting factor in determining the ecological preferences and tolerances of Caspian ostracods and makes detailed environmental interpretation extremely difficult. However, there are some species whose identity is not in dispute. Such species, together with supra-generic groupings, have been used in this study as the principal stratigraphic indices.

8.2. Calcareous nannofossils

Previous reports of calcareous nannofossils in the Akchagyl of the Caspian Sea (e.g. Jones and Simmons, 1996; Zubakov and Borzenkhova, 1990) include records of *Discoaster brouweri* (Tan) (range NN9–NN18, Tortonian–Gelasian) and *Discoaster pentaradiatus* (Tan) (range NN10–NN17, Tortonian–Gelasian) that have been used to infer marine influence in the early Pleistocene, Gelasian. Although this is possible, a reworked origin for these marker nannofossils cannot be excluded in view of their extended stratigraphic ranges. Similarly, the reported presence of *Reticulofenestra pseudoumbilicus* (Gartner) (range NN4–NN15, Burdigalian–Zanclean) in the Yasamal Valley, Azerbaijan was used by Zubakov and Borzenkhova (1990) to imply a marine connection to the Caspian Sea during the early Pliocene, Zanclean, prior to 3.5 Ma. Again, the likelihood of reworking should be considered as *R. pseudoumbilicus* is a long-ranging Neogene taxon and the Caspian Sea was isolated from the world’s oceans at that time. Svitoch (2014) also notes the presence of *Coccolithus pelagicus* (Wallich) (range NP2 to present) and *C. cf.*

doronicoides (Black and Barnes) (= *Gephyrocapsa oceanica* Kamptner) (range NN19–Recent, Gelasian–Recent) within the Akchagyl of the Caspian region. The former is likely to be reworked whereas the latter is likely to be an in situ occurrence based on its inferred stratigraphic range. New analyses from the marine interval in the present study (three samples from around 797.88 m, JE039) provided no evidence of in situ nannoflora, with reworked taxa present abundantly (Table 1). Only three potentially in situ nannofossils were recorded: *Calcidiscus tropicus* (Kamptner), *C. leptoporus* (Murray and Blackman) and *Umbilicosphaera jafari* (Muller). These, however, range throughout the whole of the Neogene and are likely to be reworked. Low numbers of *Coccolithus pelagicus* were also recorded. This taxon does range to the present day but the relatively low numbers present are undoubtedly a result of reworking from the Paleogene where *C. pelagicus* typically occurs in very high abundances (Simon Cole, personal communication, March 7th 2017). More detailed nannofossil studies are required but the absence of good in situ assemblages means that the studied sediments are, in general, not of open marine (i.e. oceanic) origin. Similarly, the presence of frequent reworked taxa makes age inferences from nannofossils very speculative.

8.3. Palaeoenvironmental significance of the *Cassidulina* / *Cibicides* foraminiferal assemblage

As described in Section 5.2.1, an interval containing frequent calcareous benthonic foraminifera occurs within the studied outcrop section at Jeirankechmez. An identical microfaunal assemblage also occurs at the Lokbatan locality (sample LOK2). A large number of specimens of the genus *Cassidulina* dominate these assemblages, and the intervals can be confidently assigned to the ‘*Cassidulina* Beds’, as described in previous publications. These *Cassidulina* specimens from the Akchagyl of the Caspian Sea have been previously determined as *C. aff. crassa* (Agalarova et al., 1940) or *C. ex gr. crassa* (Agalarova et al., 1961). The assemblage recorded in the present study also contains numerous specimens of the foraminifera *Cibicides* (including *C. lobatulus*) and *Hanzawaia*. Neither *Cassidulina* or *Cibicides lobatulus* are known to occur in the Caspian Sea at present time, and have not been recorded there in the more recent Pleistocene (Yanko-Hombach, 2014), i.e. within the last ~1.8 Myr.

Preliminary observations of the Caspian specimens in our study indicate a close similarity with *Cassidulina reniforme*, although they are not identical, most notably by having a poorly developed toothplate. According to Sejrup and Guilbault (1980), *C. reniforme* prefers cold, arctic waters (with a mean July temperature of 10 °C or less) or occurs in strata deposited under arctic conditions. The species occurs most frequently in cold arctic and cool temperate water biomes, as defined by Dinter (2001). It may also be a dominant faunal component in fjord environments proximal to glaciers (Korsun et al., 1995). The Caspian specimens differ from *Cassidulina crassa* (d’Orbigny) by being less inflated and with sutures almost flush with the surface. Potential similarities are also noted with *Globocassidulina subglobosa* (Brady). The possibility that the Caspian specimens may represent a previously undescribed endemic species is the subject of ongoing study.

Korsun et al. (1995) performed a size analysis of *C. reniforme* and showed that its average maximum diameter (AMD) was significantly higher in open marine sediments from the western Barents Sea (194–207 µm) than in glaciomarine fjord sediments from Spitsbergen (148 µm) and Novaya Zemlya, offshore northern Russia (169 µm). Therefore, in order to obtain more insight into the palaeoenvironmental significance of the Caspian cassidulinid assemblages, we have performed comparative morphometric analyses using material from the Jeirankechmez and Lokbatan study sites in the Caspian Sea and in a gravity core JM10-03-GC, taken at 72 m water depth at the southern end of Wijdefjorden, northern Svalbard, in the Arctic Ocean. Samples are from core depth 90–91 cm in an undated interval but presumed to be post-glacial. For further comparison, we have also included size data

for specimens of *C. reniforme* newly reported from the Adriatic Sea in core IN68–21, where the present-day water depth is 252 m (Jorissen et al., 1993). These foraminifera occur in core IN68–21 in a late Pleistocene interval dated between ca. 19,840 to 14,010 cal yr. BP (2σ calibrated range using marine 13.14c calibration curve of Reimer et al. (2013).

Results, as one might expect with a rather conservative form of a bi-serially enrolled benthic foraminifer *Cassidulina*, show a fairly constant ratio between maximum and minimal test diameter, but clearly show size differences within the investigated species and assemblages (Fig. 12A, B). We note that the size distribution of the contemporary arctic material (Wijdefjorden, AMD = 227 μm) is consistent with the description of Sejrup and Guilbault (1980) from St Lawrence Valley, Canada (225 μm) and with the open marine material from the Barents Sea (194–207 μm) described by Korsun et al. (1995). However, the material from the Caspian study sites is typically smaller (AMD = 204 μm at Lokbatan, 162 μm at Jeirankechmez), as is the late Pleistocene Adriatic Sea material (AMD = 181 μm). These values are comparable with those reported by Korsun et al. (2005) for specimens in proximal glaciomarine sediments from Spitzbergen (148 μm) and Novaya Zemlya (169 μm). The tendency for smaller size could be due to reduced growth in sub-optimal conditions. Haynes (1973) found very

small specimens of *C. reniforme* (maximum diameter 130 μm) in Cardigan Bay, Wales, where the species is clearly outside its preferred range due to low salinity and relatively high temperature. It appears probable that the relatively small size of specimens obtained from the Jeirankechmez and Lokbatan outcrops shows that they have survived in sub-optimum conditions.

In previous studies (e.g. Nees and Struck, 1999), *Cassidulina* species have been considered as opportunistic. Kaminski et al. (2002) describe *C. carinata* (Silvestri) as a ‘pioneering species’ which can initially colonise a barren substrate in large numbers. For example, *C. carinata* appeared to have an opportunistic response to phytodetritus deposits at a 550 m deep site in the Bay of Biscay (Fontanier et al., 2003), whereas small specimens of this species strongly dominated benthic foraminiferal faunas in a 640 m deep submarine canyon site (Hess et al., 2005). *C. carinata* also strongly dominated (≥50%) the faunas in several Late Glacial samples from core IN68-16 in the Adriatic Sea (present water depth 194 m, see Jorissen et al. (1993), confirming its opportunistic tendency in coastal cold water environments with substantial freshwater input, possibly in combination with a high organic matter input. *C. reniforme* also appears to thrive under similar conditions.

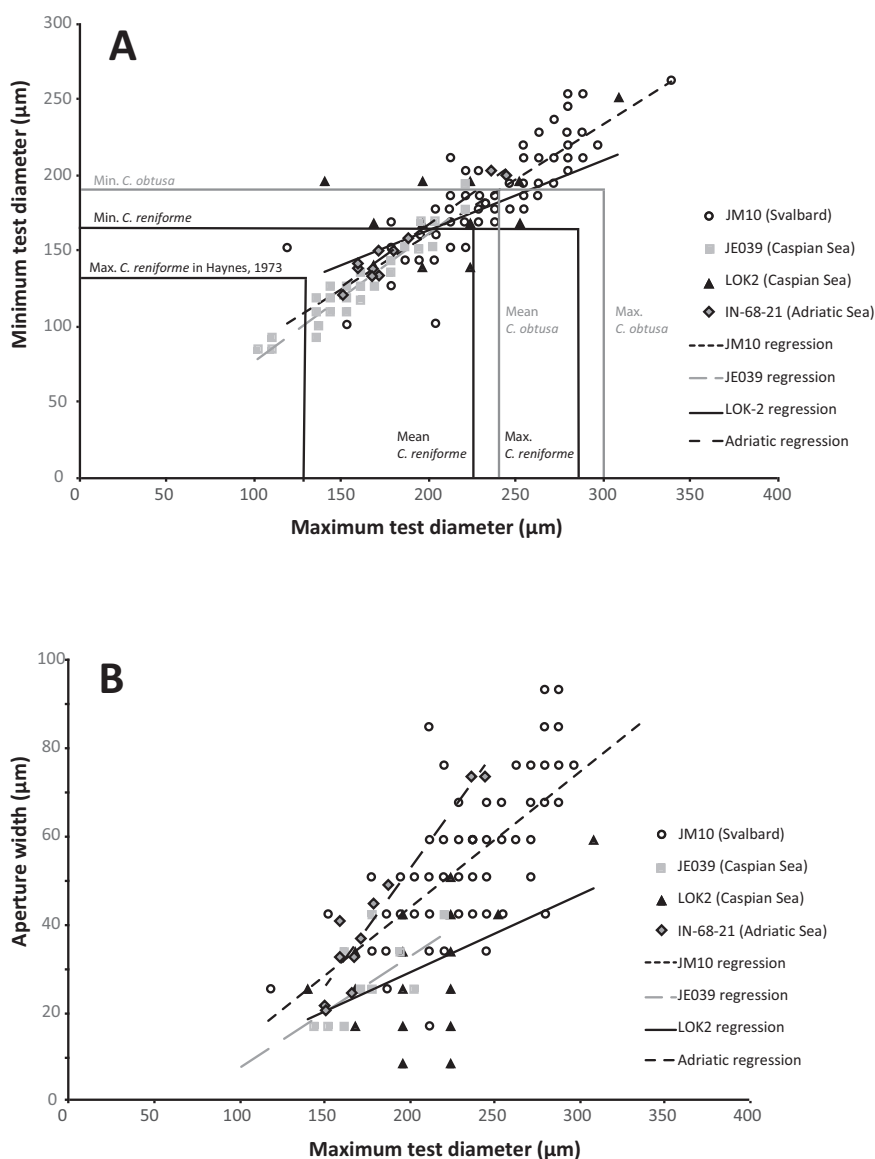


Fig. 12. A) Comparative morphometric analyses of maximum and minimum test diameters (including Pearson's correlation coefficient, r) of: i) fossil *Cassidulina* specimens from Caspian Sea sites Jeirankechmez (sample JE039, grey squares, dashed grey regression line of $R^2 = 0.915$; $r = +0.956$, $p(a) < 0.01$, $n = 34$) and Lokbatan (Sample LOK2, black filled triangles, solid black regression line, $R^2 = 0.292$; $r = +0.541$, $p(a) < 0.01$, $n = 86$); ii) arctic sub-fossil *Cassidulina reniforme* specimens from the site JM10-03-GC from Wijdefjorden, Svalbard (black circles, short-dashed black regression line, $R^2 = 0.724$; $r = +0.851$, $p(a) < 0.01$, $n = 112$); iii) sub-fossil *Cassidulina reniforme* specimens from core IN68-21 taken in the Adriatic Sea (diamonds, long-dashed black regression line, $R^2 = 0.948$; $r = +0.974$, $p(a) < 0.01$, $n = 11$). Minimum, mean and maximum diameters shown are according to data from Sejrup and Guilbault (1980).

B) Comparative morphometric analyses of maximum test diameters and aperture lengths (including Pearson's correlation coefficient, r) of: i) fossil *Cassidulina* specimens from sites JE039 (grey squares, dashed grey regression line of $R^2 = 0.465$; $r = +0.682$, $p(a) < 0.05$, $n = 13$) and LOK2 (black filled triangles, solid black regression line, $R^2 = 0.218$; $r = +0.467$, $p(a) < 0.01$, $n = 55$); ii) arctic sub-fossil *Cassidulina reniforme* specimens from the site JM10-03-GC from Wijdefjorden, Svalbard (black circles, dashed black regression line, $R^2 = 0.476$; $r = +0.690$, $p(a) < 0.01$, $n = 103$); iii) sub-fossil *Cassidulina reniforme* specimens from core IN68-21 taken in the Adriatic Sea (diamonds, long-dashed black regression line, $R^2 = 0.905$; $r = +0.951$, $p(a) < 0.01$, $n = 11$).

8.4. Palynology: nomenclature, origins and palaeoenvironmental affinities

8.4.1. *Aquilapollenites-Triprojectus* and *Wodehousia*

Several specimens of *Aquilapollenites-Triprojectus* and *Wodehousia* pollen were recorded in the Akchagyl interval. These are un-mistakable pollen types, and in this case are reworked from sediments of Late Cretaceous to Paleogene age. The *Aquilapollenites* palynofloral province was located mostly to the north of 60° N palaeolatitude (Batten, 1984; Hengreen et al., 1996; Sweet and Braham, 2001), although more southerly extensions are known (e.g. Vajda and Bercovici, 2014). *Aquilapollenites*, *Triprojectus* and *Wodehousia* were common components in the latest Cretaceous palynoflora of the western Siberian lowlands (Hengreen et al., 1996). These pollen types have not been recorded from the Caucasus or further westwards from the Black Sea region, except as rare, presumed reworked occurrences. Their presence in the Jeirankechmez record confirms a high latitude provenance for at least part of the studied sediments. In other Caspian sediment records, these taxa only occur very rarely in the Pliocene Productive Series, but are consistently present in some Khazarian (middle Pleistocene) sections (K. Richards, unpublished data).

8.4.2. *Algidasphaeridium*

The Akchagyl interval at Jeirankechmez contains frequent specimens of *Algidasphaeridium* cf. *capillatum* (Fig. 9A–D). This is a correlatable event that occurs in several other Akchagyl sections, for example in outcrop at Babazanan and Lokbatan, Azerbaijan, as well as in subsurface intervals in the offshore Caspian Sea (K. Richards, unpublished data). *Algidasphaeridium capillatum*, the only currently valid species of the genus *Algidasphaeridium* (Matsuoka and Bujak), was first described from an interval of late Miocene age in a well section in the Navarin Basin of the Bering Sea (Matsuoka and Bujak, 1988). *Algidasphaeridium capillatum* is a colourless cyst with numerous hair-like spines that are blunt or minutely distally capitate, with a chasmic archaeopyle, consisting of a straight or curved slit (Head et al., 1993). Confirmed occurrences of *A. capillatum* other than the first records from the Bering Sea are hitherto known. SEM examination of the Caspian specimens suggests close affinity to *A. capillatum*, although the spines on the Caspian specimens appear to be slightly more robust. For this reason they are assigned as *Algidasphaeridium* cf. *capillatum*. Further work is ongoing to try to determine if the Caspian forms are new species of *Algidasphaeridium* or a sub-species of *A. capillatum*. In almost all cases the Caspian cysts are very poorly preserved, a possible indication of transportation and/or fairly high energy deposition. They are believed to be in situ as the cysts occur in very high numbers, their presence is noted in several localities and nothing resembling it is known from the older Cenozoic of this region (K. Richards, personal observation).

8.4.3. *Mecsekia*

Mecsekia is an acritarch genus, with several species (*M. spinosa*, *M. spinulosa* and *M. heteropunctata*) first described by Hajós (1966) from the Miocene of the Mecsek Mountains in southern Hungary. *Mecsekia ultima* was subsequently described, originally as *Pleurozonaria ultima*, also from Hungary by Sütő-Szentai (1982), followed by *Mecsekia incrassata* (Sütő-Szentai, 1986). The form occurring abundantly in the Jeirankechmez sequence differs from all previously published species of *Mecsekia*, and is referred to as *Mecsekia 'orientalis'* (sensu Sütő-Szentai), an assignment made after consultation with Maria Sütő-Szentai. This form was found in abundance in sediments of lower Meotian (late Miocene) age in the Galidzga region of western Georgia (Maria Sütő-Szentai, personal communication, February 28th 2017) but has not been published as a formal species of *Mecsekia*. In the Galidzga sections, *M. 'orientalis'* is dominant, co-occurring with several other species of *Mecsekia* (including *M. incrassata*) and rare dinocysts of restricted marine aspect (Sütő-Szentai, unpublished data). Blooms of *Mecsekia* (various species) are known to occur throughout the Neogene in the Pannonian Basin (e.g. Magyar and Geary, 2012; Zoltáné and Éva,

2008), for example in the middle Miocene (Sarmatian sensu stricto) where they are associated with restricted lagoons and shallow water carbonates (Bakrač et al., 2012). It is possible that they have been found previously in the Black Sea (e.g. Popov et al., 2016) but assigned as *Micrhystridium* rather than *Mecsekia*.

8.4.4. *Bitectatodinium/Batiacasphaera*

Dinocysts referable to *Bitectatodinium* and *Batiacasphaera* are present commonly in the upper part of the Akchagyl and Apsheron intervals in this study. The two taxa are not differentiated in the counts as they are often poorly preserved making the archaeopyle configuration sometimes difficult to ascertain. Most specimens appear to have a pre-cingular archaeopyle with loss of 2 plates (Fig. 10J) and are therefore most similar to *Bitectatodinium*. The wall structure is smooth to vermiculate and the closest affinity is *B. tepikiense* (Wilson). This species has a bipolar to temperate distribution (Zonneveld et al., 2013) and is known to occur in the Marmara Sea and south-eastern Black Sea (Mudie et al., 2017). *Batiacasphaera* is a genus of marine and brackish dinocysts with many species, and large numbers of some species have been recorded at various times in Black Sea Neogene sediments (e.g. Filippova, 2002). It is described as 'neritic and nearshore-lagoonal' by Popov et al. (2016), sometimes associated with high nutrient levels and algal blooms. One species (*B. hirsuta*) is locally abundant in the Dacian and Pannonian basins, described as 'coastal and lagoonal' and 'recorded in Paratethyan embayments' by Harzhauser et al. (2008).

8.4.5. *Spiniferites* and *Seriliodinium*

Spiniferites is a distinct but hugely varied genus with > 100 valid species (Williams et al., 2017). In the present study, specimens of *Spiniferites* frequently occur but cannot always be reliably attributed to species level. One morphotype observed is an elongate form of *Spiniferites* with an asymmetric process arrangement that is most similar to *Spiniferites tihanyensis* (Sütő-Szentai, 2000). A broadly similar cyst, but with an elongated apical node, was first described as *Spiniferites bentorii* subsp. *pannonicus* by Sütő-Szentai (1986) that has been re-assigned as *Spiniferites pannonicus* by Soliman and Riding (2017). The similar forms recorded in the present study are referred to as *Spiniferites 'pannonicus/tihanyensis'* to illustrate an affinity with these cysts, although further work is required to determine an exact species assignment.

Several dinocyst specimens within the basal interval of the Apsheron are assigned as *Seriliodinium explicatum* (Eaton), the only valid species of this genus. The attribution of the Caspian specimens to *Seriliodinium* is made on the basis that the cysts are ovoidal or sub-cruciform and have a complete trabeculum. They differ from *Galeacysta etrusca* in that the trabeculum is ribbon-like or membranous rather than 'galeate' (helmeted), and from *Seriliodinium? imperfecta* (Soliman and Riding) in that the trabeculum is complete, rather than discontinuous.

8.4.6. 'Pannonian' taxa

Several of the dinocysts present in the Apsheron interval show strong similarity to taxa first described (and subsequently commonly recorded) from Central Paratethys, in sediments of Miocene age in the Pannonian Basin (Sütő-Szentai, 1982) and of Pliocene age in the Dacic Basin and adjacent areas of Romania (Baltes, 1971). Most of these are described in various publications from Hungary by Maria Sütő-Szentai. Although this taxonomic data trail is not without its problems, many of the forms observed in the present study can be related to, or at least closely compared with, these 'Pannonian' taxa. Important examples include *Impagidinium ?obesum* (Fig. 10H, P, Q) and *Impagidinium ?pecsvaradense* (Fig. 10, F, G, K–M), that were originally (and validly) published as *Pontiadinium obesum* and *Pontiadinium pecsvaradense* by Sütő-Szentai (1982) and are currently re-assigned as questionable species of *Impagidinium* by Williams et al. (2017). Similarly, *Impagidinium spongianum* and *Impagidinium globosum* were first illustrated by Sütő-Szentai (1982) but not published as valid taxa until a few years later (Sütő-Szentai, 1985). *Chytroisphaeridia tuberosa* was also validly

published by Sütő-Szentai (1982) whereas *Chytroeisphaeridia hungarica* (Sütő-Szentai, 1990) is morphologically distinct but, strictly speaking, remains invalid (Williams et al., 2017). In view of these taxonomic uncertainties, specimens recorded in the present study are assigned as *Impagidinium globosum/spongianum* and *Chytroeisphaeridia hungarica/tuberosa*.

It is important to distinguish the dinocyst taxa that are of ‘Pannonian’ affinity as opposed to those which are of Black Sea, ‘Neoeuxinian’ affinity. The former are, for the most part, dinocysts described from Hungary (e.g. Sütő-Szentai, 1982), whereas the latter are mainly those first described from the late Quaternary to early Holocene (‘Neoeuxinian’) of the Black Sea (e.g. Wall et al., 1973). These two groups of cysts are quite different in terms of species composition, although overlaps do occur, the differences most probably being due to variations in salinity. In broad terms, the ‘Neoeuxinian’ group includes *Spiniferites cruciformis*, *Caspidium rugosum*, *Pyxidropsis psilata* and *Galeacysta etrusca* which were common in the Black Sea prior to ca. 7500 BP (Marret et al., 2009; Mudie et al., 2001; Mudie et al., 2004), with the addition of *Impagidinium caspiense*, which occurs in the Caspian Sea at the present time (Marret et al., 2004). Known salinity tolerances of taxa such as *Spiniferites cruciformis* show that the ‘Neoeuxinian’ group consists of essentially low salinity indicators ($\leq 13\%$). The ‘Pannonian’ group includes the ‘Pontiadinium’ complex of (Sütő-Szentai, 1982) and Baltes (1971), in particular *Impagidinium ?obesum* and *Impagidinium ?pecsvaradense* along with *Impagidinium globosum/spongianum*, *Chytroeisphaeridia hungarica/tuberosa* and *Spiniferites ‘pannonicus/tihanyensis’*. Other taxa include forms recently described by Soliman and Riding (2017) such as the ‘noded’ *Komewuia?* species A and B. Less is known about the tolerances of the ‘Pannonian’ group, but the presence of many species of *Impagidinium* suggests it (as a group) has a higher salinity tolerance than the ‘Neoeuxinian’ group.

9. Where did the Akchagylian marine microfauna and microflora come from?

9.1. From the Mediterranean via the Black Sea?

9.1.1. Evidence from microfauna

There are no known contemporary records of *Cassidulina* or closely related taxa in the Black Sea (WoRMS Editorial Board, 2017; Yanko, 1990). The Mediterranean and adjacent seas have documented occurrences of *Cassidulina crassa* (Jorissen, 1987; Jorissen, 1988) and related taxa such as *Globocassidulina subglobosa* (WoRMS Editorial Board, 2017). Several species of *Cassidulina* occur at the present time in the Marmara Sea, namely *C. carinata*, *C. crassa* and *C. laevigata* (d’Orbigny), recorded by Kaminski et al. (2002). Further records of *C. carinata*, *C. crassa*, *C. minuta* (Cushman) and *C. obtusa* (Williamson) in the Marmara Sea are reported by Kirci-Elmas and Meriç (2016). *Cassidulina carinata* was found in the Marmara Sea and Bosphorus, but not in the Black Sea, in study of Turkish coastal waters by Meriç et al. (2014). The same study documented *Globocassidulina subglobosa* as present in the Aegean Sea and Marmara Sea, but not in the Black Sea. The precise taxonomic affinity of the Caspian cassidulinids remains unclear and is the subject of ongoing investigations, although an exact match with the species known from the Mediterranean and Marmara Sea is so far not proven. Such is the complexity of foraminiferal taxonomy, which is further highlighted by DNA studies at generic/species level (e.g. Darling et al., 2016), that a firm answer to true origins of the cassidulinid foraminifera in the Caspian Sea may not be achievable without significant further study.

9.1.2. Evidence from palynology

The dinocyst assemblages in the Jeirankechmez outcrop within the lower part of the Akchagyl unit are, as previously noted, dominated by *Algidasphaeridium cf. capillatum*, of which there are no confirmed records from either the Black Sea or the Mediterranean Sea. Associated

forms such as *Islandinium minutum*, *Lingulodinium machaerophorum* and cysts of *Pentapharsodinium dalei* occur in low numbers, and all of these are known from, but by no means restricted to, the Black Sea and Mediterranean Sea (Zonneveld et al., 2013). Minor increases in *Operculodinium centrocarpum* sensu Wall and Dale (1966) also occur within the studied section. This taxon occurs in the Black Sea region at the present time but it is not especially common. It has a worldwide occurrence but is most frequent in the North Atlantic where sea surface temperatures are $< 0^\circ\text{C}$ (Mudie et al., 2017; Zonneveld et al., 2013). It is suggested here that if the Akchagylian transgression did originate in the Mediterranean and/or Black Sea, it more than likely would have been characterised by dinocysts of ‘Peri-Paratethyan’ (e.g. *Galeacysta etrusca*) or Mediterranean affinity (e.g. *Operculodinium israelianum*), which is not the case in our studied section. Furthermore, high proportions of non-arboreal pollen in the Black Sea record from DSDP 380A at the end of the Pliocene (Popescu et al., 2010), closely match those typically present in the late Pleistocene to early Holocene ‘Neoeuxinian’ (e.g. Filipova-Marinova et al., 2013) that are linked with a significant lowstand of the Black Sea (Aksu et al., 2002; Yanko-Hombach, 2007).

9.1.3. Mechanism?

A transgression of great magnitude would be required if the Caspian cassidulinid foraminifera were dispersed from the Mediterranean and/or Black Sea. The newly confirmed presence of *Cassidulina reniforme* in the Adriatic Sea during the late Pleistocene, however, occurred after the Last Glacial Maximum when global sea levels were as much as 134 m lower than at the present time (Lambeck et al., 2014), and the level of the Black Sea was lowered by ca. 120 m (Lericolais et al., 2011). Despite a lack of firm evidence, water levels in the Black Sea at the end of the Pliocene were likely to have been relatively low, indicated by the brackish Kuyalnikian mollusc and ostracod faunas (Nevesskaya et al., 1986; Popov et al., 2006). These are overlain by Akchagylian mollusc faunas characterised by *Cardium dombra* and *Avimactra subcaspia* in the Kuban-Terek Strait, at the southern end of the present-day Sea of Azov, which Zubakov (1992) interprets as outflow from the Caspian Sea, rather than a transgression from the Mediterranean or Black Sea region. Popov et al. (2006) suggest that a connection from the Mediterranean via the Black Sea could not have occurred at this time as the Black Sea was effectively ‘closed’, indicated by the brackish water faunas. Furthermore, Popov et al. (2006) postulate that there may have been a direct connection from the Mediterranean to the Caspian Sea. As noted above, the dinocyst records suggest that this scenario would have been extremely unlikely.

9.2. From the Arctic Ocean?

9.2.1. Evidence from microfauna

According to Alizadeh and Aliyeva (2016), an Arctic Ocean to Caspian Sea connection has been ‘well substantiated’ in Russian literature for many years. Studies by Kovalevsky (1933), Kovalevsky (1951) and Muratov (1951) refer to ‘the problem of the Akchagyl’, proposing a northern origin for Akchagylian microfaunas. This was based on observed similarities between the Caspian Akchagylian marine faunas and foraminifera (including cassidulinids) present in Pliocene-aged sediments in the Northern Dvina region (reported in Afanasyev and Belkin (1963)). Alizadeh (1954), reported in Alizadeh and Aliyeva (2016), used the measured hypsometric height of Akchagylian sediments (~250 m above global sea level) to infer a narrow seaway connection between the North Dvina-Pechora and Volga-Kama catchments, which enabled euryhaline and eurythermal species to progress southwards to the Caspian Sea. Data from the lower Volga region include records in late Pliocene (Piacenzian) sediments of boreal foraminifera *Criboelphidium heterocameratum* (Voloshinova) and *Criboelphidium subarcticum* (Cushman) that could have come ‘only from the north’ according to Zubakov and Borzenkhova (1990).

The present study has determined that the species of *Cassidulina* present in the Caspian Sea closely resembles, but is not identical to, *Cassidulina reniforme*, which is predominantly an arctic or cold water species (Sejrup and Guilbault, 1980). This potential arctic affinity is reinforced by the co-occurrence in the Caspian assemblages (at more than one locality) of common *Cibicides* spp., including *C. lobatulus*. A foraminiferal assemblage characterised by common *Cassidulina reniforme* with *Cibicides lobatulus* is well-known in the northern oceans, including the Norwegian Sea (Hald and Vorren, 1987) and Barents Sea (Korsun et al., 1995). Moreover, *Cassidulina* (and related genera) are deep water foraminifera typically occurring at water depths in excess of 200 m at low latitudes (e.g. Jorissen, 1987; Van Marle, 1991) but at high latitudes they occur in much shallower water, sometimes of < 10 m (Sejrup and Guilbault, 1980). Temperature appears to be the main controlling factor in their depth distribution. In view of > 2 million years of environment and evolutionary pressure, there is a very real possibility that these cassidulinids in the Caspian Sea arrived via a seaway connection from the Arctic Ocean within the recent geological past.

9.2.2. Evidence from palynology

The presence of frequent *Algidasphaeridium* cf. *capillatum* also requires explanation as the only prior records of *A. capillatum* are from the Navarin Basin of the northern Bering Sea, just to the north of latitude 60° N (Matsuoka and Bujak, 1988). As previously noted, these records were from sediments of late Miocene age and occur within an interval deposited at middle neritic water depths (~20 to 100 m) that also contains species of *Cassidulina* and *Islandiella*, among other foraminifera (Turner, 1984). At that time the Bering Strait was closed, subsequently opening between ca. 5.5 and 5.4 Ma (Gladenkov et al., 2002). Initially the water flow was from north to south, with mollusc evidence indicating a switch to a south-north water flow after 3.6 Ma (Matthiessen et al., 2009). It is possible that *Algidasphaeridium capillatum* may have extended its range into the Arctic Ocean at (or before?) that time. The Caspian specimens of *Algidasphaeridium* are therefore potentially derived from the Bering Sea via the Arctic Ocean, subsequently reaching

the Caspian Sea as a distinct species or sub-species, but clearly closely related to *A. capillatum*. The presence of reworked specimens of *Aquilapollenites-Triprojectus* and *Wodehousia* pollen in the present study also indicates a likely northern provenance within the lowermost Akchagyl.

Recent molecular studies by Mertens et al. (2017) show that the dinocyst *Impagidinium caspiense* (Marret), which occurs frequently in the Caspian Sea at the present time, is closely related to the motile stage species *Gonyaulax baltica* (Ellegaard). *G. baltica* was first described from the western coast of Sweden at latitude just above 58° N (Ellegaard et al., 2002) and co-occurs with cysts similar to *Impagidinium caspiense* in northern Denmark (Ellegaard, 2000; Mertens et al., 2017). These studies reinforce the likelihood of one or more seaway connections existing between the northern oceans and the Caspian Sea during the Pleistocene.

9.2.3. Mechanism?

We consider that the marine foraminiferal and dinocyst associations in our Caspian record were most probably derived from the Arctic Ocean at the very end of the Pliocene, and therefore a mechanism for dispersal from the north is required. Cassidulinids are bottom dwellers, preferring deep, cold waters at low latitudes but occurring at much shallower waters at high latitudes. This is significant as only a relatively small rise (i.e. of several metres) in global ocean level would be needed to enable dispersal from high latitudes. It is probable that sea water reached the Caspian Sea from the north via the palaeo-Volga canyon, which extended northwards to at least to the latitude of Moscow (55° N). The canyon was incised into sub-strata of Paleozoic, Mesozoic and Paleogene age to a recorded depth of 550 m below the present-day land surface, > 400 m below global sea level (Kroonenberg et al., 2005; Sidnev, 1985). The canyon formed at the time of the latest Miocene to Pliocene Caspian Sea lowstand and contains mostly Pleistocene sedimentary fill (Kroonenberg et al., 2005); it is likely to have remained a topographic depression for much of the Pleistocene. Possible seaway routes from the north include via the Northern Dvina (currently +113 m above global sea level) and/or via the River Ob, to the east of the Ural Mountains (currently +55 m above global sea level) (Fig. 13).

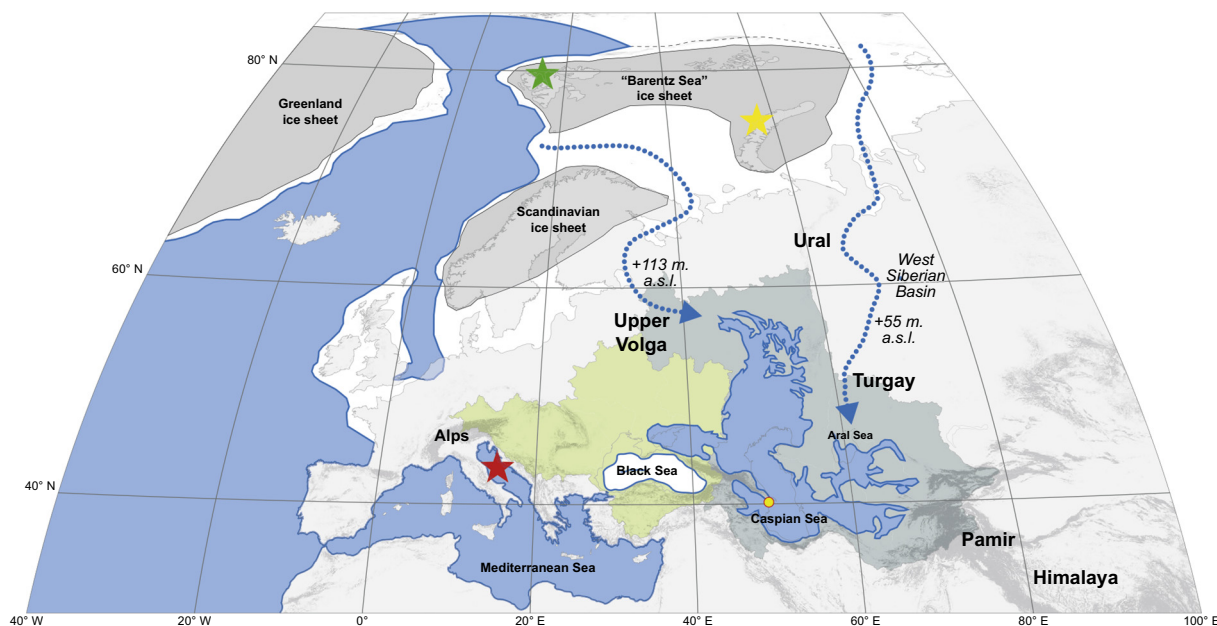


Fig. 13. Map showing the principal catchment areas of the Black Sea (light green) and Caspian Sea (grey-blue) drainage basins interpreted for the latest Pliocene to earliest Pleistocene. The yellow dot is the approximate position of the Jeirankechmez study site, the green star shows the position of the JM10-03-GC gravity core site at Wijdefjorden, northern Svalbard, the yellow star is the Novaya Zemlya locality, northern Russia and the red star is the position of the IN68-21 core, Adriatic Sea. Areas in bright blue show the approximate maximum extent of the Akchagylian transgression (and open marine water in the Mediterranean and Atlantic Ocean) at around the time of the Plio-Pleistocene boundary. The dotted blue lines show possible pathways for a connection from the Arctic Ocean to the Caspian Sea, indicating the present-day minimum elevation needed for marine water to enter the Caspian drainage basin.

The latter is situated along the route of the former ‘Turgay Seaway’ that connected the Arctic and Tethyan Oceans during the Paleogene (Akhetiev et al., 2012; Naidina and Richards, 2016) and formed part of a route from the north towards the Aral Sea in the late Pleistocene (Mangerud et al., 2004). No firm evidence, however, is currently known from the literature that pinpoints a precise location for an arctic to Caspian gateway, despite a long research history on this subject, especially in Russia. The matter is further complicated by the fact that erosion during successive glacial and interglacial cycles is likely to have removed large parts of the Pleistocene sedimentary records in the region.

9.3. Maybe there was no marine connection?

Although bottom currents may have accounted for the migration of cassidulinids to the Caspian region, it is not clear if the foraminifera would have required successive suitable marine environments for colonisation, including feeding and reproducing, every step of the way towards the Caspian Sea. A more incidental migration, perhaps in wet sediment carried by floating vegetation or ice is possible, as is the possibility of migration by attachment to the feet of migrating birds or in the guts of aquatic fauna (e.g. Sen Gupta, 1999). *Cibicides lobatulus* has varied water depth tolerances but is typically an epiphytic species and therefore is likely to be found within the photic zone and/or in high energy environments, and may have travelled on floating vegetation such as *Azolla*, seaweed or perhaps attached to ice-rafted debris. In general, it must be borne in mind that faunal migrations, even if improbable, only need to be successful once, provided that a suitable environment is found upon arrival. The very low diversity of the cassidulinids and associated microfauna suggests strong selection during the migration path and probably even serendipitous survival before their short-lived colonisation of the circum-Caspian region. Whilst incidental migration and colonisation is theoretically possible, it is unlikely to have accounted for the more or less simultaneous arrival of cassidulinids, *Cibicides* and *Algidasphaeridium* in more than one locality in the Caspian Sea in the latest Pliocene.

10. Conclusions

A major transgression of the Caspian Sea occurred in the Plio-Pleistocene and resulted in the deposition of sediments of the Akchagyl and Apsheron regional stages, which are widely known from around the Caspian Sea region. In the absence of a clear lithostratigraphic boundary, biostratigraphic records are used in this study to assign the Akchagyl stage in an interval ca. 67 m in thickness that contains the most marine influence.

Frequent freshwater algae and ostracods in the latest Pliocene interval suggest that the Akchagyl flood at the Jeirankechmez locality began as a freshwater event with minimal marine influence. Marine conditions were then briefly established, indicated by the presence of a low diversity assemblage of calcareous benthonic foraminifera, including species of *Cassidulina* (or closely related taxa) and *Cibicides*, and dinocysts (*Algidasphaeridium* cf. *capillatum*).

We consider that the Caspian cassidulinids and associated microfauna and microflora were most probably derived from the Arctic Ocean, and entered the Caspian Sea via a seaway connection as a result of rising global sea levels during the latest Pliocene. Faunal migration from the Mediterranean via the Black Sea is not substantiated. Recruitment and dispersal via ice-rafted debris or vegetation, or transportation by birds or aquatic fauna, are possible but are also considered unlikely.

We have documented the presence of *Cassidulina reniforme* in the Mediterranean (Adriatic) Sea for the first time in sediments deposited just after the Last Glacial Maximum.

An overlying interval of > 300 m in thickness contains mainly brackish microfaunas and microfloras and is assigned to the Apsheron

regional stage. Rich ostracod faunas are present throughout most of the studied interval and indicate a mesohaline environment in the Apsheron interval that is predominantly brackish with periodic freshening episodes. The Apsheron interval contains a distinct palynoflora of ‘Peri-Paratethyan’ endemic dinocysts, with most forms being of ‘Pannonian’ affinity.

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Appendices. Supplementary data

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