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Title

Ostracods from a Marmara Sea lagoon (Turkey) as tsunami indicators

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Marmara Sea; Gulf of İzmit; Ostracoda; lagoon; brackish water; tsunami

Abstract

A 352 cm long sediment core from Hersek Lagoon (Gulf of İzmit) was investigated for its ostracod species composition in order to evaluate the potential of ostracods to detect tsunami deposits in coastal environments. The Gulf of İzmit is the eastern bay of the Marmara Sea which is tectonically controlled by the North Anatolian Fault. Ostracod shells are rare in the lower third of the core, which probably represents a coastal wetland environment. According to radiocarbon dating of terrestrial plant remains, this unit was deposited between AD 500 and AD 800. Above, ostracod shells are abundant and dominantly monospecific, composed almost exclusively of the widespread brackish water ostracod *Cyprideis torosa*. This almost monospecific occurrence indicates the establishment and maintenance of the Hersek Lagoon after AD 800. Three distinct layers of mollusc shells and fragments contain ostracod shells of marine and to a lesser extent non-marine origin in addition to those of *Cyprideis torosa*. The shell layers are further characterized by significant maxima in total ostracod shell numbers. The high concentration of ostracod shells, the higher species numbers and the mixture of marine, lagoonal and non-marine ostracod shells shows that shell layers were formed as high-energy deposits resulting from tsunamis or large storms in the Marmara Sea. The partial occurrence of non-marine ostracod shells in the shell layers possibly indicates that tsunamis with extensive run-ups and significant backwash flows caused the high-energy deposits rather than large storms. The investigated sediments show that lagoonal ostracods can serve as good proxies for tsunamis or large storms through significant variations in total shell numbers, species numbers and the mixing of shells of different origin.

1. Introduction

Tsunamis and large storms are significant threats to coastal population and infrastructure. Precautionary/mitigation measures were intensively discussed following the devastating tsunami in the Indian Ocean on 26 December 2004, and hurricane Katrina that destroyed large parts of New Orleans in August 2005. The risk assessment of specific coastal regions often relies on systematic records of tides and meteorological data although the observational data do not necessarily cover periods of tsunami occurrence. Less systematic records such as historical documents and, eventually, geological evidence is required to obtain longer records for long-term assessment of catastrophic risks by tsunamis and storms (i.e. Leroy et al., 2010).

Consequently, several examples of tsunami or storm reconstructions based on geological evidence were presented in recent years (e.g., Leroy et al., 2002; Maramai et al., 2005; Dominey-Howes, 2007; Fujino et al., 2009). Sedimentological features such as erosional contacts, normally graded beds, rip-up clasts or boulders and organism remains were used for the reconstruction of catastrophic flooding as a result of tsunamis or large storms in coastal regions (Dawson and Smith, 2000; Dawson and Stewart, 2007; Morton et al., 2007; Dahanayake and Kulasena, 2008, Donato et al., 2008). Foraminifera and diatom tests are thought to be the most significant biotic indicators for the identification of tsunami and storm deposits (Clague et al., 1999; Dawson and Smith, 2000; Dawson, 2007; Kortekaas and Dawson, 2007; Dahanayake and Kulasena, 2008). In contrast, ostracods, which represent one of the most widespread organism groups that produces readily fossilized remains, have only rarely been used for the recognition of tsunami and storm deposits (Fujiwara et al., 2000; Ruiz et al., 2005, 2010; Boomer et al., 2007; Alvarez-Zarikian et al., 2008). Ostracods may however provide more information than foraminifers in coastal water bodies with low salinity or freshwater inflow. In comparison to diatoms, ostracods may be more efficiently **used** since sample processing is usually less laborious. In addition, the possibility to perform stable isotope and trace element analyses on the calcitic ostracod shells may represent a significant advantage over diatoms and some groups of foraminifers (Frenzel and Boomer, 2005). Therefore, we examined the potential of ostracods as indicators of tsunamis and large storms using a sediment core from Hersek Lagoon at the southeastern Marmara Sea shore

(Gulf of İzmit, Turkey). Additional results and those of other cores from the lagoon are presented in a separate paper by Bertrand et al. (submitted).

2. Study area

Hersek Lagoon is located on a northward-prograding delta (Hersek Delta or Hersek Peninsula) in the Gulf of İzmit of the eastern Marmara Sea (Turkey, Fig. 1). The area of the lagoon is 1.4 km² and the water depth ranges between 0.3 and 0.7 m. The salinity is 28-30 P.S.U. in most parts of the lagoon, and 38-40 P.S.U. at its northwestern margin. The lagoon is separated from the sea by a narrow sand ridge reinforced by a concrete dike in the last century. The topography in the vicinity of the lagoon is flat (2-3 m above sea level [asl]) except for a prominent hill of uplifted Pleistocene marine sediments at the northern tip of the peninsula (Fig. 1). The climate is characterized by dry summers and mild and rainy winters.

The Gulf of İzmit is the eastern extension of the Marmara Sea, which connects the Mediterranean Sea in the south to the Black Sea in the north. The water in the Marmara Sea is permanently stratified, with a halocline at 20-25 m depth. Less saline (salinity: 18) surface water of the Black Sea flows to the Aegean Sea and saline bottom water (38) flows in the opposite direction (Ünlüatu et al., 1990). Water depth in the western and central Gulf of İzmit basins near the Hersek Peninsula reaches ca 200 m but does not exceed 50 m in the close vicinity of the delta (Dolu et al., 2007; Fig. 1).

The tectonic setting in the Marmara Sea region is mainly controlled by the North Anatolian Fault Zone (NAFZ), which is one of the longest and most active strike-slip faults in the world (Fig. 1). The NAFZ runs roughly parallel to the Black Sea coast of Anatolia and splits into two strands in its western part (Fig. 1). The northern strand passes through the Gulf of İzmit and Hersek Lagoon (Yalova fault segment) and runs further through the Marmara Sea, representing the source of numerous large historical earthquakes (Dolu et al., 2007; Fig. 1). The most recent major earthquake of the NAFZ (17 August 1999) triggered surface ruptures including vertical displacements, submarine slumps and eventually a devastating tsunami in the Gulf of İzmit (Tinti et al., 2006).

3. Materials and methods

Ten cores were obtained with a Livingstone piston corer from an anchored raft in Hersek Lagoon. Core HK04LV5 (40.724°N, 29.519°E, 0.47 m water depth), which is one of the longest cores collected and the only one from a position north of the Yalova segment of the North Anatolian Fault, was selected for ostracod analysis.

Samples of about 65 g were collected continuously from 5 cm segments of a core half for ostracod analysis and sieved with 500, 250 and 63 µm meshes. Absolute ostracod shell abundances and the presence of mollusc shells and fragments, and charred and non-charred plant remains were determined with a low-power binocular microscope. Up to 300 ostracod shells were counted and picked from the sieve residues of the >250 µm fraction. For samples containing more than 300 shells, randomly selected subsamples of the remaining sieve residue material were used for further counting and total shell abundances were then calculated by extrapolation. Identification of ostracod species mainly followed Athersuch et al. (1989). Shells of the less frequent species were only identified with reservation due to their low numbers and occurrence at juvenile stages.

Grain size was estimated by measuring the volume of sediment in the fractions obtained after sieving at 500, 250 and 63 µm.

Radiocarbon dating was performed on terrestrial plant remains from four stratigraphic levels (334-329 cm, 215-210 cm, 102.5-97.5 cm, 45-40 cm; Fig. 2). Samples were analyzed at the Poznan Radiocarbon Laboratory, Poland, and the radiocarbon ages were calibrated with OxCal 4.0 using the IntCal04 calibration curve (Reimer et al., 2004).

4. Results

Radiocarbon dating yielded the following ages: 1590 ± 80 ^{14}C a BP at 334-329 cm, 1230 ± 60 ^{14}C a BP at 215-210 cm, 1190 ± 30 ^{14}C a BP at 102.5-97.5 cm and 1235 ± 35 ^{14}C a BP at 45-40 cm. The corresponding weighted averages of calibrated ages are AD 511, 792, 834 and 777, respectively.

Recovered sediments mainly comprise homogenous mud (Fig. 2). Laminations, organic-rich sediments, and four distinct sand layers occur in the lower third of the core. Three layers of brackish-marine mollusc shells and fragments were recorded in the upper half of the core. The grain size fraction <63 µm predominates with a mean proportion of 77 %. The fractions 63-250 µm, 250-500 µm, and >500 µm have mean proportions of 10 %, 4 % and 9 %. The finest (<63 µm) and coarsest (>500 µm) fractions have a relatively large variability compared to the intermediate fractions (Fig. 2). Grain size changes are only shown for the > 500 µm fraction since the 63-250 µm and 250-500 µm fractions are relatively stable, and the <63 µm fraction shows an opposite but otherwise similar trend (Fig. 2).

Ostracod shells are almost absent from the lower part of the core but abundant in its upper half (Fig. 2). Shells of *Cyprideis torosa* clearly predominate whereas those of *Loxoconcha elliptica*, *L*. cf. *rhomboidea* and *Heterocypris salina* are restricted to a number of stratigraphic levels (Fig. 2, Plate 1). All shells of *Cyprideis torosa* belong to the smooth form *Cyprideis torosa* forma *littoralis* apart from a single noded shell (*Cyprideis torosa* forma *torosa*) recorded at 40-35 cm depth (Fig. 2, Plate 1). Those of *Pontocythere* sp., *Aurila* cf. *arborescens*, *Eucyprinotus* cf. *rostratus* display a more erratic occurrence. Total numbers of ostracod taxa and total shell concentrations peak at three levels in the core: 153-142 cm, 98-87 cm and 38-27 cm (Fig. 2).

Mollusc shells and fragments occur in all samples above 213 cm, charred plant remains occur between 294 and 242 cm, and non-charred plant remains were observed between 243 and 172 cm (Fig. 2). Charophyte gyrogonites were recorded at 97 and 47 cm core depth, and in two adjoining samples at 32 and 27 cm (Fig. 2).

5. Discussion and conclusion

Calibrated ages of the four samples analyzed for radiocarbon indicate that the sediment was deposited between ca AD 500 and 800. The upper three samples yielded virtually identical ages, most likely reflecting particularly high accumulation rates in at least the upper 215 cm of the core. Alternatively, the incorporation, transportation and accumulation of aged terrestrial organic matter of similar source over a longer period of time could have caused the similar age results for the upper three ^{14}C samples.

The most striking feature of the core from Hersek Lagoon is the predominance of ostracod shells of *Cyprideis torosa* in its upper 185 cm. *Cyprideis torosa* is a widespread inhabitant of brackish coastal waters of the northern hemisphere with a salinity tolerance ranging from almost pure freshwater to hyperhaline conditions (Meisch, 2000). *Cyprideis torosa* is the most abundant species in the Baltic Sea (Frenzel and Boomer, 2005) and it often inhabits lagoons and estuaries of the Mediterranean Sea alone and at high concentrations (Meisch, 2000; Ruiz et al., 2000). It was the only species recorded in all of the eight lagoons of Turkey examined by Altinsaçli (2004) including two lagoons of the Marmara Sea coast. Furthermore, it frequently occurs in brackish continental waters in northern Africa, the Near East and Central Asia (Meisch, 2000; Mischke et al., 2010). Although commonly occurring in the present Marmara Sea and the Gulf of İzmit, *Cyprideis torosa* seldom predominates (Kubanç et al., 1999; Kubanç, 2005). Its dominance in the recovered sediments is evidence that Hersek lagoon was separated from the Marmara Sea during the period represented by the middle and upper part of the core.

In contrast, the lowermost part of the core (352-223 cm) is characterized by only sporadic occurrences of ostracod and mollusc shells in low numbers, and more silty and organic-rich sediments with charred plant remains probably representing a coastal wetland environment. Sediment samples between 223 and 172 cm all contain shells of *Cyprideis torosa* although in low numbers, mollusc shells and fragments, and non-charred instead of charred plant remains, probably representing the establishment of a lagoon with a high sediment influx during its initial stage. This interpretation is supported by geochemical data from the core (Bertrand et al., submitted).

Three distinct layers of brackish-marine mollusc shells and fragments occur at ca 150, 90 and 30 cm core depth, within the homogenous mud that composes the upper part of the core (Fig. 2). All three shell layers contain shells of *Loxoconcha elliptica* and *Loxoconcha* cf. *rhomboidea* beyond those of *Cyprideis torosa*. In addition, a few more erratically occurring ostracod species are apparently confined to these shell layers (Fig. 2, Plate 1). The ostracod shell concentration reaches three pronounced maxima corresponding to increases in the number of ostracod taxa in the shell layers. *Loxoconcha elliptica* is a typical brackish water species inhabiting estuaries, lagoons and pools, commonly associated with algae and mud (Athersuch et al., 1989). *Loxoconcha rhomboidea* is a predominant species in the near-shore waters of the southern Marmara Sea and other species of *Loxoconcha*, *Aurila* and *Xestoleberis* occur in this region too (Kubanc, 2005). Furthermore, *Loxoconcha rhomboidea* and other species of *Loxoconcha*, *Xestoleberis* sp., *Pontocythere* sp. and *P. elongata*, and *Aurila* sp. were recovered from Pleistocene marine sediments in the Gulf of İzmit in the north of Hersek Peninsula. Thus, shells of *Loxoconcha rhomboidea*, *Xestoleberis*, *Pontocythere* and *Aurila* in the Hersek Lagoon sediments probably originate from the Gulf of İzmit section of the Marmara Sea.

In contrast, *Heterocypris salina* and *Eucyprinotus* cf. *rostratus* are typical non-marine ostracod species (Fig. 2, Plate 1). *Heterocypris salina* is an abundant inhabitant of small slightly brackish coastal water bodies of the Baltic and North Sea and small inland water bodies, and it generally occurs where salinity is <10 (Meisch, 2000). Accordingly, the specific conductivity tolerance of *Heterocypris salina* ranges between 2.8 and 8.2 mS cm^{-1} and 0.7 and 5.9 mS cm^{-1}, as determined from the occurrence of this species in 37 water bodies in Israel and at 43 sites in Spain, respectively (Mezquita et al., 2005; Mischke et al., 2010). *Eucyprinotus rostratus* was recorded from few freshwater sites in Europe, Turkey and the Near East (Martens et al., 1992, 2002; Martens and Ortal, 1999; Eitam et al., 2004; Tunoğlu and Ertekin, 2008; Mischke et al., 2010). We assume that the few shells of *Heterocypris salina* and *Eucyprinotus* cf. *rostratus* originated from small fresh to slightly brackish water bodies on **the** Hersek Peninsula. Three out of four samples containing charophyte gyrogonites correspond to the upper two shell layers (Fig. 2). Although charophytes may occur at relatively high salinities too, the coinciding occurrence of the non-marine ostracods and the charophyte remains suggests that the gyrogonites were probably transported from more marginal, less brackish positions in the lagoon or from small fresh to slightly brackish water bodies on the peninsula.

The simultaneous occurrence of ostracods of different origin (lagoonal: *C*. *torosa* and *Loxoconcha elliptica*; shallow marine: *L*. *rhomboidea*, *Xestoleberis* sp., *Pontocythere* sp. and *Aurila* cf. *arborescens*; and inland waters: *H*. *salina* and *E*. cf. *rostratus*) within beds of brackish-marine mollusc shells and fragments indicates that the shell layers were deposited under high-energy environmental conditions (Ruiz et al., 2010). In the case of Lake Manyas (140 km west of Hersek Lagoon), ostracods of different origins also are interpreted as reflecting an event of large amplitude (seiche) leading to a spatially averaged snapshot of regional assemblages (Leroy et al., 2002).

The shell layers are separated by homogenous mud of ca 40 cm thickness suggesting three distinct events. Tsunamis or large storms are the two main processes which may have turned the sheltered setting of Hersek lagoon into a high-energy depositional environment. The occurrence of shells of two species from only slightly brackish or even freshwater habitats implies that there was not only a landward transport of marine ostracod shells but also a seaward transport of non-marine shells. Since tsunamis have generally a larger inland extent than storms (Dawson and Stewart, 2007; Kortekaas and Dawson, 2007), we assume that the shallow marine ostracod shells were transported to Hersek Lagoon during the run-up phase and the non-marine ostracod shells during the backwash phase of tsunamis although this differentiation between tsunamis and large storms as the triggering processes for the high-energy deposits in Hersek Lagoon remains speculative.

Alternatively, the occurrence of ostracod shells from inland waters in Hersek lagoon could be explained by transport and deposition from the **Yalak** River (Fig. 1). There are however four arguments against this assumption: (1) the present disconnection between the **Yalak** River and Hersek Lagoon existed apparently during the entire period covered by the investigated core and additional cores from **the** Hersek Lagoon as revealed from clay mineral analysis by Bertrand et al. (submitted), (2) there is no evidence for the delivery of terrestrial plant matter occurring as charred or non-charred plant remains within the three shell beds, (3) the > 500 µm grain size fraction shows rapid changes associated with the shells beds rather than gradual changes expected for the accumulation of more proximal or distal delta sediments in a lagoon, and (4) the occurrence of especially *Heterocypris salina* in somewhat higher abundances apparently coincides systematically with the occurrence of the shallow marine ostracods in the core. Thus, delivery of the non-marine ostracod shells by the **Yalakdere** to the core site is unlikely.

In addition, transport to the core site of non-marine ostracod shells originating from the erosion of Quaternary sediments of Hersek Peninsula is regarded as an unlikely process due to the intense weathering of the exposed Quaternary sediments and to the expected poor preservation or destruction of the fragile calcitic ostracods shells. The recorded non-marine ostracod shells do not display a difference in shell preservation in comparison to the shells with lagoonal and shallow marine origins. Although the incorporation of non-marine ostracod shells from eroded Quaternary sediments cannot completely be ruled out based on the available data, we do not consider this scenario as a realistic option.

The inferred shift from a coastal wetland to a lagoon in ca AD 800 probably resulted from coseismic subsidence of part of the Hersek Peninsula, which was most likely triggered by the historically documented AD 740 earthquake with a magnitude of 7.1 in the Marmara Sea region (Ambraseys, 2002). This inference and results from additional cores in Hersek lagoon are presented in Bertrand et al. (submitted). Three further earthquakes with magnitudes ≥6.8 were documented in AD 823, 860 and 869 (Ambraseys, 2002). However, the lack of historical records for earthquake-induced tsunamis and the insufficient precision of our age-depth model does not allow an unequivocal assignment of the three shell beds to these earthquakes.

To conclude, our study of Hersek Lagoon sediments exemplified the great potential of ostracods as indicators of tsunamis or large storms through several lines of evidence: (1) the large number of ostracod shells accumulated during the high-energy events, (2) the higher number of taxa which is not typical for an undisturbed lagoon setting, and (3) the mixture of ostracod shells with clear marine, lagoonal and non-marine origins, i.e. spatial average. This last criterion might help to differentiate between tsunami and storm deposits in appropriate coastal settings with near-shore water bodies.

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Figure and plate captions

Fig. 1

Location of the coring site in Hersek Lagoon (arrow) at the northeastern side of Hersek Delta/Peninsula. The study area is part of the Marmara Sea (inset), which is crossed by the northern strand of the North Anatolian Fault (red lines).Geological units are represented according to Witter et al. (2000) and Kozaci (2002), bathymetrical information according to Lettis et al. (2002), and fault locations according to Kuşçu et al. (2002) and Özaksoy et al. (2010). Figure modified from Bertrand et al (submitted).

Fig. 2

Ostracod abundance data, number of taxa and total number of shells per gram for the investigated sediments from Hersek Lagoon (core HK04LV5). Hollow bars for *Cyprideis torosa* represent ten times exaggerated results. Triangle next to the *Cyprideis torosa* column indicates the position of the sole specimen of the noded form of the species *Cyprideis torosa* forma *torosa* and the stars mark the samples for which the 250-500 µm sieve fractions were not available. Core lithology, volumetric portions of particles >0.5 mm, and occurrence of mollusc and plant remains are also indicated. Grey horizontal bars indicate high-energy layers. ^{14}C marks the location of samples used for radiocarbon dating.

Plate 1

Ostracod shells from Hersek Lagoon, core HK04LV5. 1-3 *Cyprideis torosa*, 1 female carapace (Cp); 2 male Cp; 3 noded female Cp; 4 *Eucyprinotus* cf. *rostratus*, right valve (RV), external view (ev); 5-6 *Loxoconcha* cf. *rhomboidea*, 5 juvenile (juv.) female left valve (LV), internal view (iv); 6 juv. male RV, ev; 7 *Aurila* cf. *arborescens*, juv. RV, ev; 8-9 *Loxoconcha elliptica*, 8 juv. female RV, ev, 9 juv. male LV, ev; 10 *Xestoleberis* sp., Cp; 11 *Heterocypris salina*, LV, ev; 12 *Pontocythere* sp., juv. LV, iv. Specimens housed in the Institute of Geological Sciences, Freie Universität Berlin, Germany.

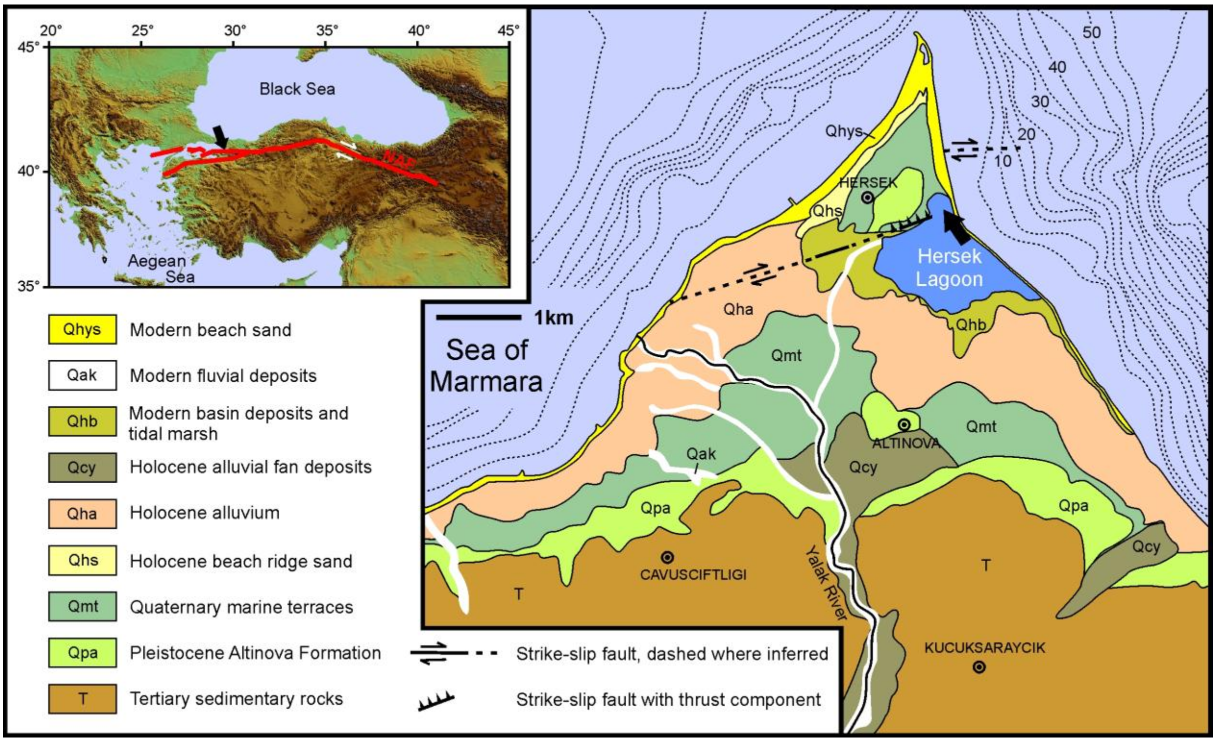

Figure 1

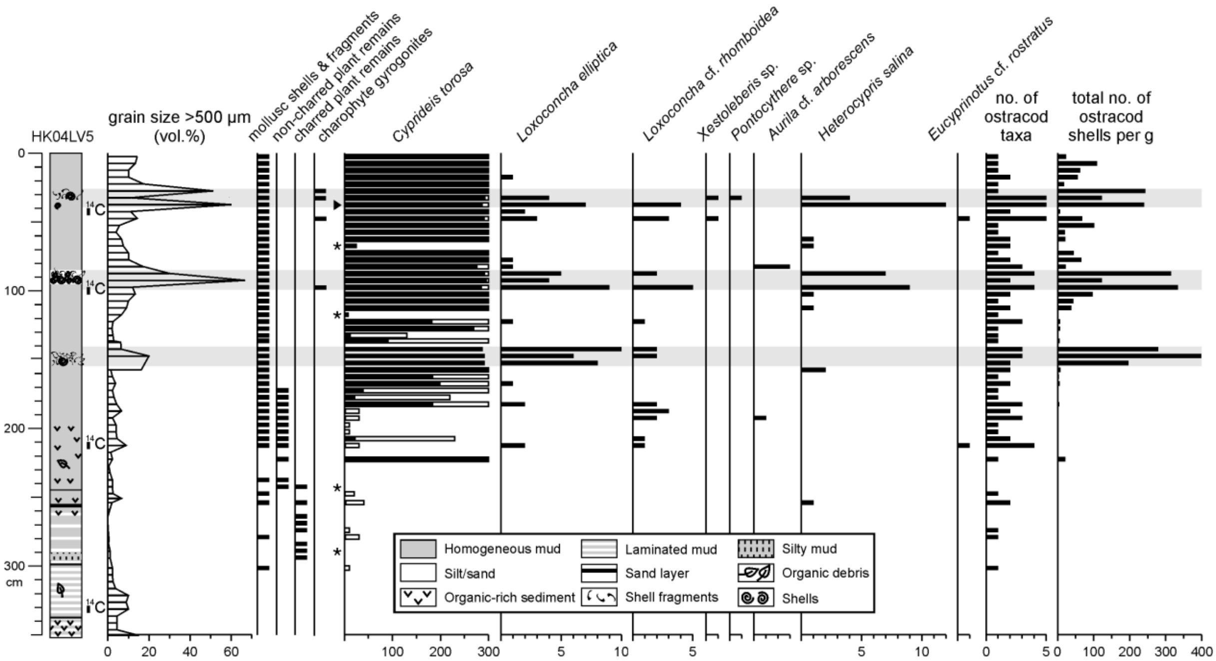

Figure 2

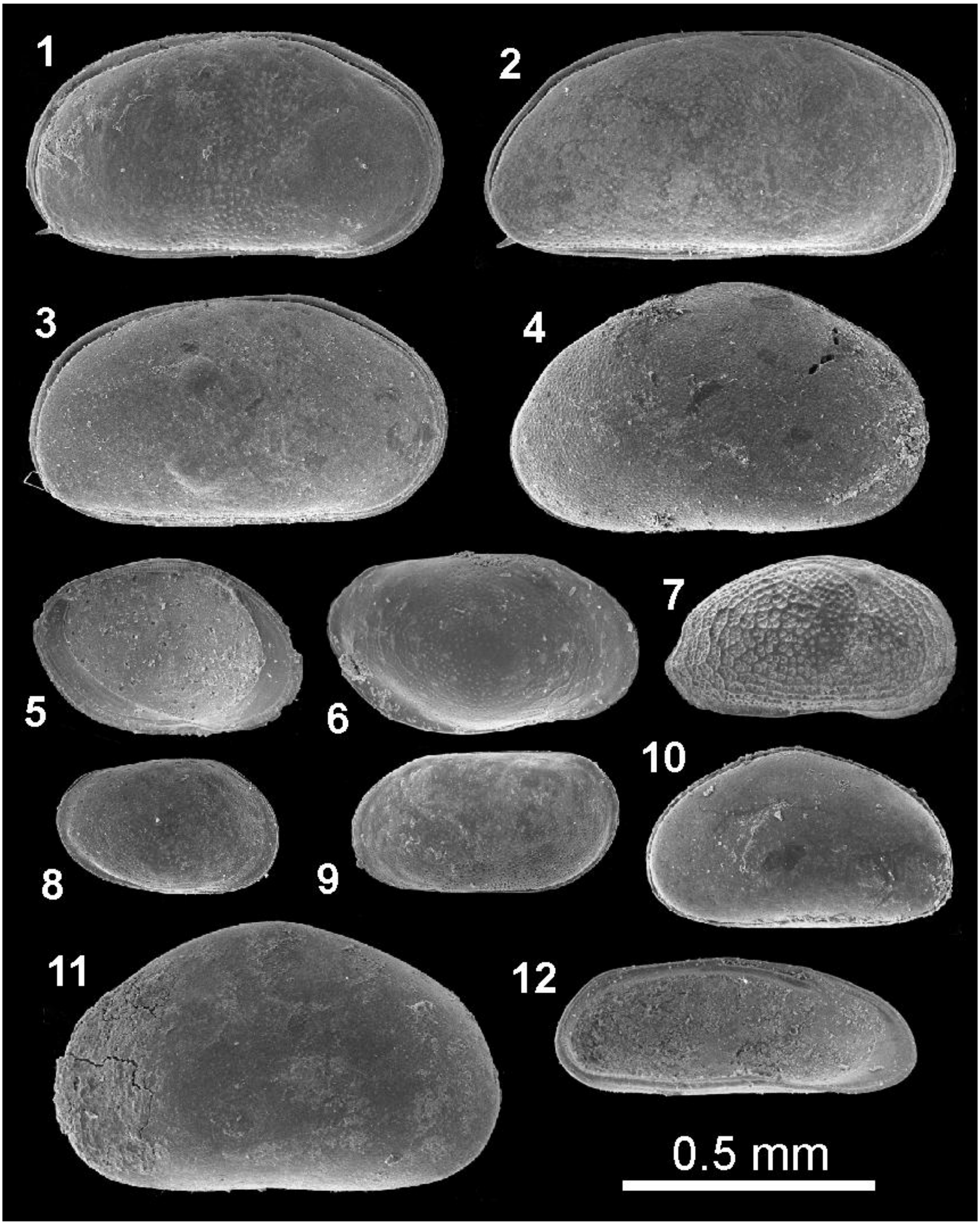

Plate 1. HK 05