



Recent brackish water Foraminifera and Ostracoda from two estuaries in Ghana, and their potential as (palaeo)environmental indicators

Olga Gildeeva^{a,*}, Lailah Gifty Akita^b, Johannes Biehler^a, Peter Frenzel^a, Mauro Alivernini^a

^a Institute of Geosciences, Friedrich Schiller University Jena, Burgweg 11, 07749, Jena, Germany

^b Department of Marine and Fisheries Sciences, University of Ghana, P. O. Box LG.99, Legon-Accra, Ghana

ARTICLE INFO

Keywords:

Ostracoda
Foraminifera
Brackish water ecology
Water pollution
Western Africa
Keta lagoon and Densu estuary

ABSTRACT

To improve the indicator value of marginal marine Foraminifera and Ostracoda of Ghana, we analysed 22 surface sediment samples for microfauna. They were obtained from the Keta Lagoon and Densu Estuary covering a salinity range from marine waters to 17.5 and one sample within the hyperhaline range (70). Except one, all samples contain Ostracoda and Foraminifera. There are 34 ostracod species belonging to 24 genera. Dominating is *Cyprideis remanei* Klie, 1940, other abundant species are *Pseudoconcha* sp., *Pseudoconcha hartmanni* Omatsola, 1970, *Loxoconcha lacunensis* Omatsola, 1970 and *Chrysocythere foveostriata* Brady, 1870. We found 28 Foraminifera species belonging to 22 genera with the dominant taxa *Ammonia* sp. and *Quinqueloculina* spp. There are five associations, which are mainly driven by the hydrological regime and organic pollution. In contrast to a usual diversity trend reflecting high levels of pollution by lower diversity, our results show higher diversity associated with sites of higher pollution levels. The most tolerant (salinity and pollution) ostracod taxon is *Cyprideis remanei*, which is occurring over the whole salinity range documented as well as in contaminated areas with very high LOI and heavy metal concentrations. In the investigated samples we found many deformed Foraminifera with anomalies like multiple tests, changes in coiling and aberrant shapes of the chambers.

Ongoing investigations in estuaries of Ghana are expanding our data set and will provide a better understanding of species-specific reactions of Ostracoda and Foraminifera to anthropogenic pressure.

1. Introduction

Coastal zones are transitional environments between marine and continental ecosystems and belong to the most densely populated areas of the world with consequently conflicting economical and other interests of use. Ecological risks are increasing in the developing African nations because of the difficult balance between the fast economic and population growth, the limited ecological knowledge and the high cost of continuous coastal zone management. Thus, the agricultural, industrial, and domestic activities are resulting in contaminants flow, directly or via rivers, into estuarine and marine environments. The state of Ghana located in West Africa at the Gulf of Guinea is experiencing an important phase of economic and social changes during the last decades, connected to a strong industrialization, migrations of people from the rural areas to the major cities and the discovery of oil fields along the coast.

These uncontrolled developments are endangering the environment

affecting the lives of millions of people (Appiah-Opoku, 2001; Scheren et al., 2002; Bentum et al., 2011). Moreover, the unregulated recycling of electronic waste as documented by mass media and scientific articles is causing a critical ecological situation in the capital city of Accra (e.g. Feldt et al., 2014) with a consequently high rate of coastal pollution and severe health problems for people living and working in these areas.

Microfossils are widely used as indicators of anthropogenic impact and climate changes for their potential to record variations over time. A very valuable group for this application is Foraminifera, marine protists, which are already widely used as bio-indicators for environmental monitoring in coastal areas (e.g. Watkins, 1961; Nagy and Alve, 1987; Bouchet et al., 2007; Alve et al., 2009; Jorissen et al., 2009; Schönfeld et al., 2012). Their shells (tests) are easily preserved as fossils and carry signatures of environments, thus enabling evaluation and reconstruction of present and past conditions. Ostracoda are small crustaceans with bivalved shells living in all types of waters. They are well known as a very sensitive group in terms of environmental changes (e.g. Anadon

* Corresponding author.

E-mail addresses: olga.gildeeva@uni-jena.de (O. Gildeeva), lailah.lailah@gmail.com (L.G. Akita), joe.b@posteo.de (J. Biehler), peter.frenzel@uni-jena.de (P. Frenzel), mauro.alivernini@uni-jena.de (M. Alivernini).

<https://doi.org/10.1016/j.ecss.2021.107270>

Received 3 July 2020; Received in revised form 27 January 2021; Accepted 10 February 2021

Available online 20 February 2021

0272-7714/© 2021 Elsevier Ltd. All rights reserved.

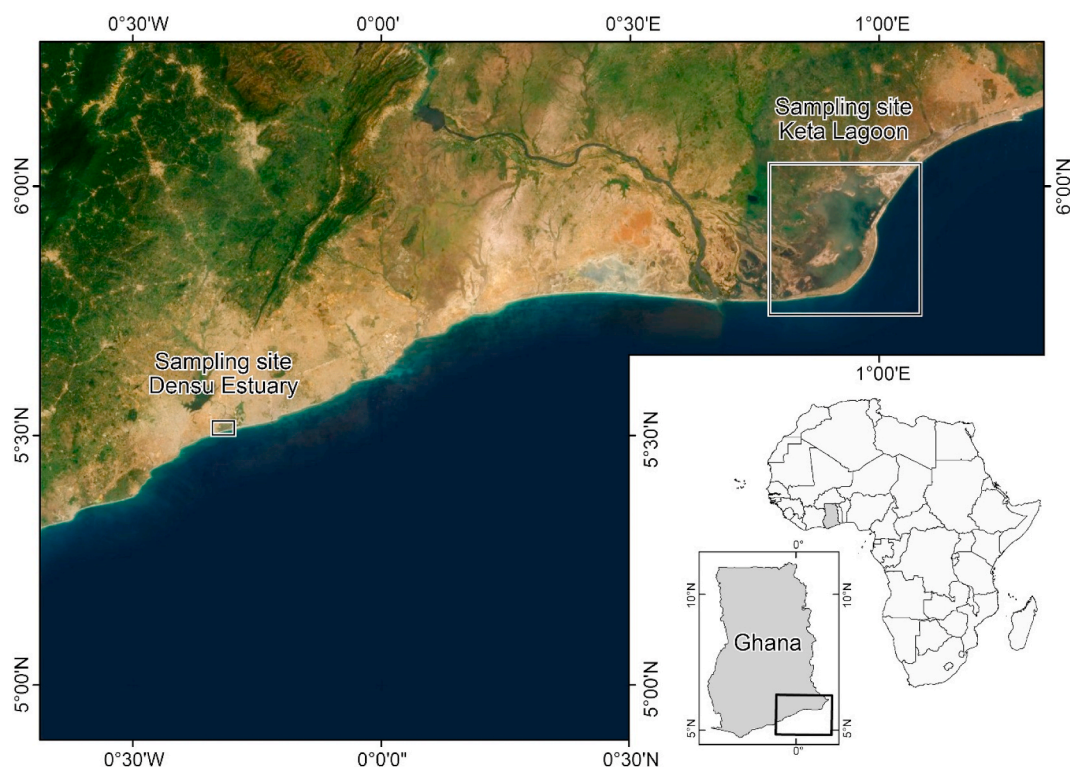


Fig. 1. Location of Ghana and satellite image of the studied coastal stripe with indication of the two study areas.

et al., 1994; Alvarez-Zarikian et al., 2005; Mischke et al., 2008; Frenzel et al., 2010; Schornikov, 2011; Schornikov and Zenina, 2014). Individual species of Ostracoda can have relatively narrow ecological preferences reflecting water temperature, salinity, water depth, grain size, man-made impacts etc. (e.g. Rosenfeld and Ortal, 1983; Havel and Talbot, 1995; Griffiths and Holmes, 2000; Altınsoçlu and Griffiths, 2001; Ruiz et al., 2005). If Foraminifera is known for decades as bio-indicator for environmental monitoring in coastal areas, then Ostracoda was not well implicated yet, with only several studies showing its potential in environmental monitoring (e.g. De Deckker and Forester, 1988; Curry, 1999; Ruiz et al., 2005; Schornikov and Zenina, 2014).

Until now Ostracoda and Foraminifera have been poorly investigated in West Africa, and more specifically in Ghana. There are only a very few papers covering marginal marine Ostracoda and Foraminifera from the Gulf of Guinea, like the description of 27 foraminiferal taxa by Fajemila and Langer (2017), the impact of oil spills by Denoyelle et al. (2010) and a series of taxonomic ostracod studies from Nigeria by Omatsola (1970a–c, 1972). The lack of data in Western Africa requires taxonomic and ecological investigations. In preparing a project on the use of Foraminifera and Ostracoda as bioindicators of anthropogenic impacts in estuarine systems of Ghana first sampling was done in two selected sites, Densu Estuary (Greater Accra Region) and Keta Lagoon (Volta Region) (Fig. 1). The aims of this study are: i) to improve the faunistic and ecological knowledge on the local ostracod and foraminiferal assemblages, and ii) to assess their use as potential environmental and water quality indicators.

2. Material and methods

2.1. Study area

Keta Lagoon is located on the eastern coast of Ghana in the western part of a vast fault-controlled sedimentary basin extending from Ghana to Nigeria. The lagoon is strongly influenced by the Volta river estuary

flowing into the Gulf of Guinea (Fig. 2).

Densu Estuary is one of the most important coastal drainage basins in Ghana. The city of Accra covers a large part of the catchment containing floodplains and river channels. The catchment has been dramatically altered by human activities, like salt mining, fishing, irrigation and so on. It covers an area of 2488.41 km² with a length of 225.6 km (Kusimi, 2008).

2.2. Fieldwork

Field samplings were carried out during two campaigns in 2017. Sediment samples were obtained from Densu Estuary (eleven samples) and the eastern part of Keta Lagoon (four samples) in March and in the southern part of Keta Lagoon (seven samples) in September 2017, respectively. A total of 22 surface samples from these two water bodies is the base of the present study (Fig. 2). The sediment samples were collected with a box corer with dimensions of 20 cm × 20 cm and a height (maximum penetration depth) of 35 cm. The uppermost centimetre of the sediment was taken for analysis.

The maximum water depth sampled was 4.5 m. Geographical coordinates within the WGS84 system were registered using a hand-held GPS device with a horizontal error of 3–6 m. Water quality parameters such as salinity via specific conductivity, oxygen content, pH and water temperature were recorded at the sampling sites using a multiple parameter Horiba Probe. Habitats were described including substrate and thickness of the oxygenized surface sediment layer.

To better characterize possible human impact, visible anthropogenic activities were documented. Samples were preferentially taken from sectors close and distant to villages for comparison, and from the deepest points of the water bodies to collect relatively undisturbed sediment. After taking the surface samples, they were mixed with Rose Bengal dissolved in ethanol for later distinction between living and dead Foraminifera at the time of sampling.

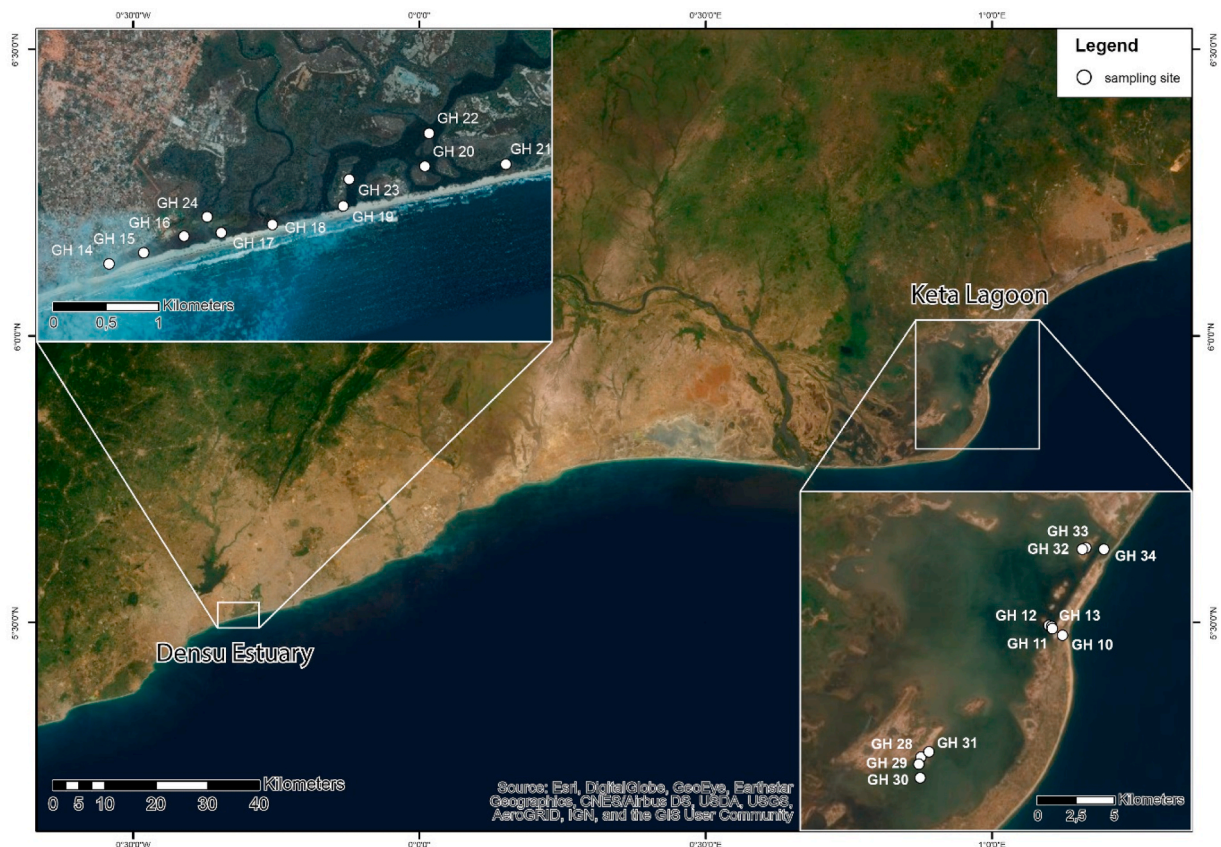


Fig. 2. Location of sampling points within Densu Estuary and Keta Lagoon, Ghana.

2.3. Micropalaeontological analysis and visualisation

Before sieving, the volume of each sediment sample was measured as reference for abundance calculation. In total, 22 samples were analysed, of which eleven samples are from Densu Estuary and eleven from Keta Lagoon. The samples were sieved with tap water through a 63 μm sieve and dried at room temperature in the lab of the Institute of Aquatic Sciences and Fisheries, University of Ghana, in Accra. For quantitative foraminiferal and ostracod analysis at the Institute of Geosciences, University of Jena, the dry samples were sieved for the $>200 \mu\text{m}$ and 125–200 μm size fraction and were split into sub-samples using a micro splitter. Valves and tests from subsequent splits were counted until 300 of both, Foraminifera and Ostracoda, for the $>200 \mu\text{m}$ fraction and >200 foraminifer tests for the $>125 \mu\text{m}$ fraction were reached. Ostracod carapaces were counted as two valves. The species proportions and the total abundance were calculated from these two counts. For the identification of living ostracods, the closed double valved individuals were opened and checked for the remaining soft parts inside. Living foraminifers were recognized by the occurrence of stained tests with remaining stained or pale to greenish germplasm in some chambers (Lutze and Altenbach, 1991; Murray and Bowser, 2000). Malformed foraminifera were counted to calculate the Foraminiferal Abnormality Index (FAI; Frontalini and Coccioni, 2008). Reworked individuals of both Foraminifera and Ostracoda were counted separately, e.g. with abraded ornamentation or sediment inside the chambers. To assess water turbulence and to check for the possible removal of thinner juvenile valves by dissolution, the adult/juvenile ratio was determined following Boomer et al. (2003). Identification relies mainly on Omatsola (1970a, b, 1972) and Witte (1993) for Ostracoda and on Schmidt-Sinns (2008), Fajemila and Langer (2017), Fürstenberg et al. (2017) and the World Register of Marine Species (<http://www.marinespecies.org/>) for Foraminifera. Identification was performed primarily with a low-power

binocular microscope and was occasionally supported by a Scanning Electron Microscope (SEM) and a Keyence Digital Microscope.

A Hierarchical Cluster Analysis (WARD method, Euclidian distance) of the relative ostracod and foraminifera abundance of all samples with at least 50 specimens was applied to reveal similarities between associations as a proxy for habitat similarity. The species diversity was evaluated using the Shannon's diversity (H') index (Shannon, 1948).

Distribution maps were created and shaped with ESRI ArcMap 10.5 and the Spline with Barriers (SWB) tool was configured with a cell size 15 and 0 as a smooth factor. The interpolation shows the spatial distribution of the most influential environmental factors and spatial distribution of foraminifer and ostracod associations.

2.4. Sediment analyses

The LOI (loss on ignition) was determined with a muffle furnace (L9/11) of Nabertherm and with a laboratory balance Sartorius "Quintix 6102-1x" with an accuracy of 0.001 g. An agate mortar was used to prepare a sediment powder (approx. 1.5 g per sample). The sediment powder was dried in crucibles in the muffle furnace at 105° C until the mass was constant. After cooling in a desiccator, they were weighed into porcelain crucibles. Subsequently, the loss on ignition was determined in accordance with DIN 18128, whereby the total organic carbon is represented by LOI. LOI was determined after annealing at 550° C and calculated from the weight difference.

For elemental analysis, unprocessed sediment samples (all grain size fractions) were ground with an agate mortar. The element contents were determined by ICP-MS (XSeries II, Thermo Fisher Scientific) or ICP-OES (725 ES, Agilent). For the measurements of both instruments, the mean value and the simple absolute standard deviation of three individual measurements were calculated.

Because of the loss of some sub-samples during transport LOI and

heavy metal data could not be measured for all sites.

3. Systematic part

In total, 34 ostracod species belonging to 24 genera were found. Foraminifera were present with 28 species belonging to 22 genera. They

are documented with the following taxonomic reference list and on Fig. 3 and Fig. 4. Systematics are based on the World Register of Marine Species (<http://www.marinespecies.org/>). Taxa found with living individuals are marked with * in the following lists.

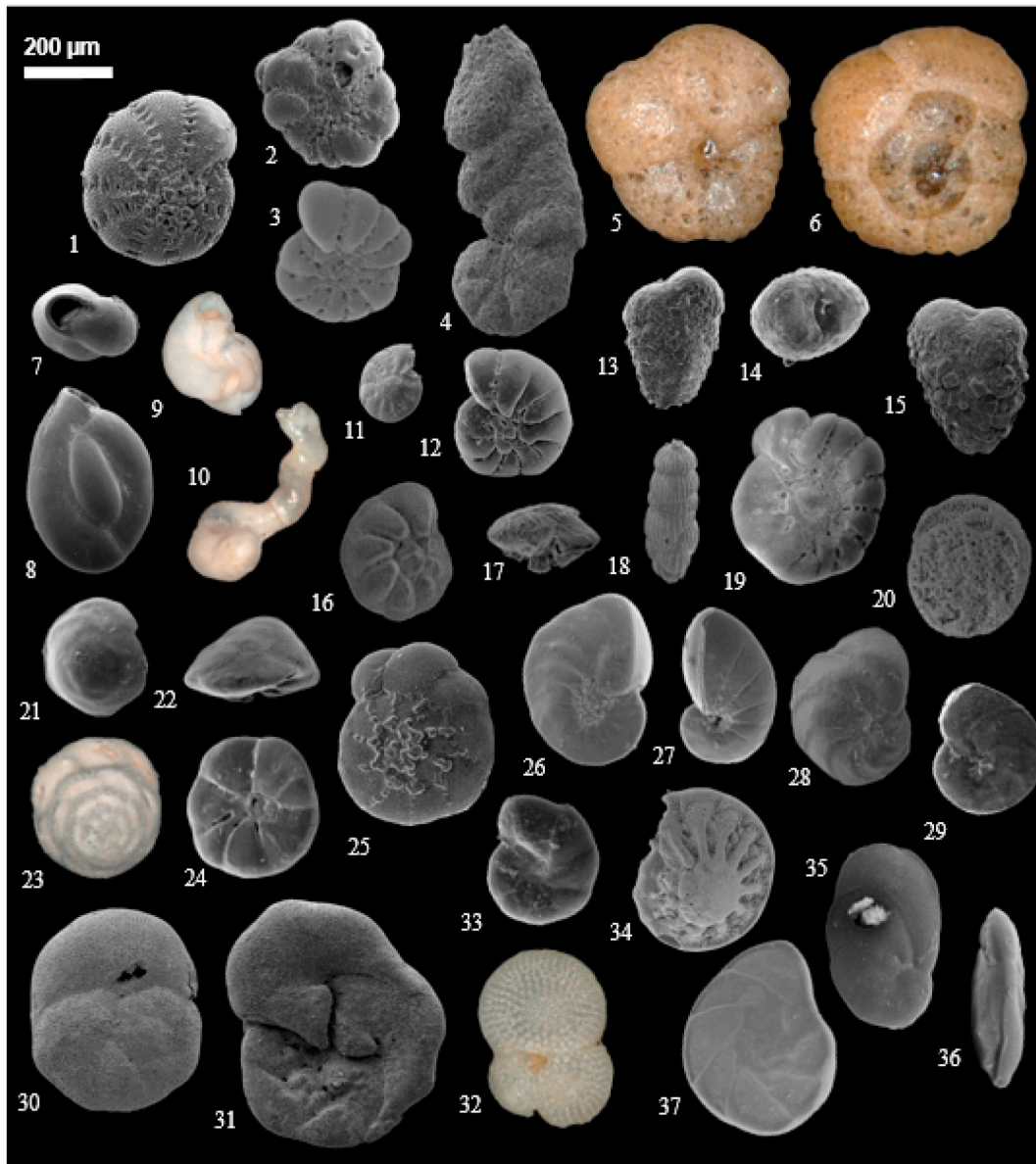


Fig. 3. Foraminifer taxa of Keta Lagoon and Densu Estuary. All photos are side views in SEM pictures if not otherwise stated, light microscope photos are given with LM. (1–2) *Criboelphidium gunteri* (Cole, 1931), 2 deformed test, sample GH 15; (3) *Criboelphidium articulatum* (d'Orbigny, 1839), slightly deformed, sample GH 14; (4) *Ammotium morenoi* (Acosta, 1940), apertural neck broken, sample GH 16; (5–6) *Trochammina inflata* (Montagu, 1808), LM; umbilical and spiral view, sample GH 28; (7–10) *Quinqueloculina* spp., 7 apertural view, 9–10 deformed tests, LM, sample GH 15; (11) *Elphidium "pereirum"* sensu Schmidt-Sinns (2008), sample GH 15; (12) *Criboelphidium sandiegoense* (Lankford, 1973); (13–14) *Textularia* sp., side and apertural view; (15) *Dorothia* sp., sample GH 22; (16–17) *Pararotalia* sp., umbilical and side view, sample GH 20; (18) *Rectuvigerina* cf. *nicoli* Mathews, 1945, sample GH 14; (19) *Criboelphidium sandiegoense*? (Lankford, 1973), deformed test, sample GH 15; (20) *Discorbia* sp., spiral view, sample GH 22; (21–24) *Neoponides schreibersii* (d'Orbigny, 1846); 21 spiral view, 22 side view, 23 spiral view, LM, 24 umbilical view, sample GH 14; (25) *Ammonia* sp., spiral view, sample GH 15; (26–27) *Nonion fabum* (Fichtel and Moll, 1798), sample GH 22; (28–29) *Hanzawaia concentrica* (Cushman, 1918), spiral and umbilical view, sample GH 15; (30–31) *Rosalina bradyi* (Cushman, 1915), spiral and umbilical view, sample GH 22; (32) Globigerininae, LM, sample GH 22; (33) *Haplophragmoides* sp., sample GH 22; (34) *Elphidium* cf. *fimbriatulum* Cushman, 1918, sample GH 16; (35–36) *Cancris oblongus* (Williamson, 1858), spiral and side view, sample GH 14; (37) *Eponides cribrorepandus* (Asano and Uchio, 1951), spiral view, sample GH 15.

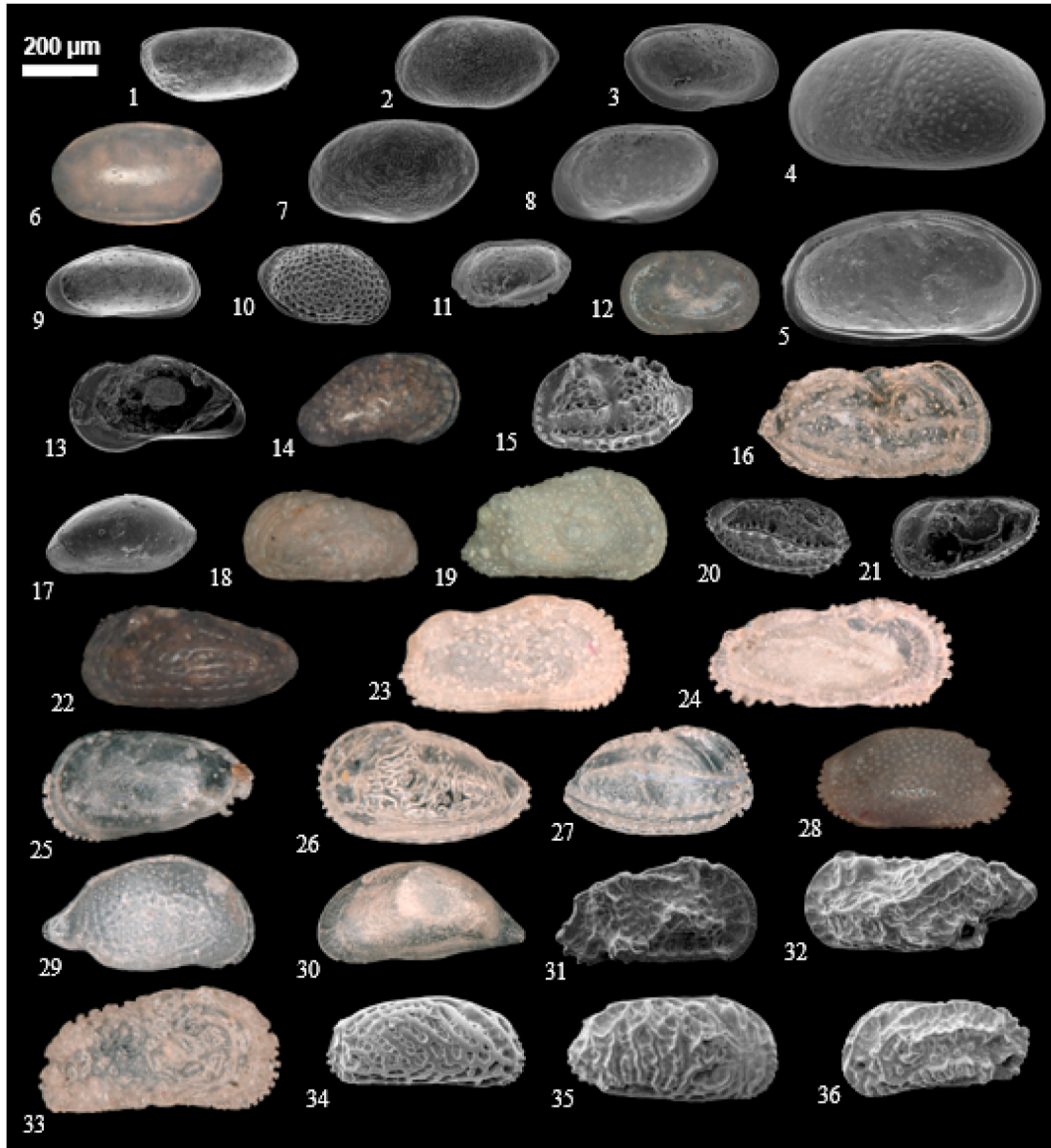


Fig. 4. Ostracod taxa of Keta Lagoon and Densu Estuary. All pictures are giving external views if not stated otherwise; they are SEM pictures and light microscope photos (LM). (1) *Basslerites (Loculiconcha) punctata* Omatsola, 1970, carapace from right side, sample GH 22; (2–3) *Pseudoconcha* sp., LVs, external and internal view, sample GH 24; (4–5) *Cyprideis remanei* Klie, 1940, female LV, external and internal view, sample GH 17; (6) *Cytherella hanaii* Omatsola, 1970, RV, LM, sample GH 14; (7–8) *Pseudoconcha hartmanni* (Omatsola, 1970), 7 LV, 8 RV, internal view, sample GH 20; (9) *Pontocythere* sp., RV; internal view, sample GH 20; (10–11) *Loxoconcha lacunensis* Omatsola, 1970, RVs, external and internal view, sample GH 17; (12) *Cytherelloidea lobitoensis?* Hartmann (1974), juvenile, LV, LM, sample GH 14; (13–14) Eucytheridea, gen. et sp. inc., RVs, 14 internal view, LM, sample GH 14; (15–16) *Neomonoceratina ikoroduensis* Omatsola 1970, LV; RV, LM, sample GH 20; (17) *Paradoxostoma* sp., RV, internal view, sample GH 22; (18) *Reymenia ijebuorum* Omatsola 1970, male LV, LM, sample GH 14; (19) *Hermanites* sp., RV, LM, sample GH 24; (20–21) *Neomonoceratina* cf. *ikoroduensis* Omatsola 1970, RVs, 21 internal view, sample GH 20; (22) *Neocaudites lindersae* Witte, 1993, LV, LM, sample GH 14; (23–24) *Neocaudites* aff. *lindersae* Witte, 1993, 23 RV, LM, sample GH 20, 24 RV, LM, sample GH 20; (25) *Ruggieria nigeriana?* Omatsola 1970, juvenile LV, LM, sample GH 22; (26–27) *Chrysocythere foveostriata* (Brady, 1870), RVs, LM, 25 internal view, sample GH 22; (28) *Neonesidea* sp., LV, LM, sample GH 22; (29) *Perissocytheridea (Kroemmelbeinella) libidinosa* Witte, 1993, RV, LM, sample GH 22; (30) *Gibboborchella kuznetsovae* (Omatsola, 1970), LV, LM, sample GH 22; (31) *Hermanites* cf. *foveolata* Omatsola 1970, RV, sample GH 22; (32) *Paracytheridea* sp. A sensu Witte 1993, LV, sample GH 21; (33) *Puriana trituberculata* Omatsola, 1972, RV, LM, sample GH 20; (34) *Puriana* aff. *interrasilis* Omatsola, 1972, RV, sample GH 20; (35) *Puriana* cf. *rugosa* Omatsola, 1972, RV, sample GH 14; (36) *Puriana mediocostata* Omatsola, 1972, LV, sample GH 20.

- Phylum **Foraminifera** d'Orbigny, 1826
- Class **Globothalamia** Pawlowski, Holzmann, Tyszka, 2013
- Order **Lituolida** Lankester, 1885
- Superfamily **Lituoloidea** Blainville, 1827
- Family **Lituoloidea** Blainville, 1827
- Ammotium morenoi* (Acosta, 1940)
- Trochammina inflata* (Montagu, 1808)*
- Family **Haplophragmoididae** Maync, 1952
- Haplophragmoides* sp.
- Order **Rotaliida** Delage & Hérouard, 1896
- Superfamily **Discorboidea** Ehrenberg, 1838
- Family **Cancriidea** Chapman, Parr, Collins, 1934
- Cancris oblongus* (Williamson, 1858)
- Family **Eponididae** Hofker, 1951
- Eponides cribroripandus* (Asano & Uchio, 1951)
- Family **Discorbidae** Ehrenberg, 1838
- Neoeponides schreibersii* (d'Orbigny, 1846)*
- Family **Rosalinidae** Reiss, 1963
- Rosalina bradyi* (Cushman, 1915)
- Superfamily **Rotalioidea** Ehrenberg, 1839
- Family **Rotaliidae** Ehrenberg, 1839
- Ammonia* sp. [a new species to be described in a later paper]*
- Superfamily **Cassidulinoidea** d'Orbigny, 1839
- Family **Cassidulinidae** d'Orbigny, 1839
- Cassidulina* sp.
- Familie **Elphidiidae** Galloway, 1933
- Criboelphidium "erraticum"* sensu Schmidt-Sinns (2008)
- Criboelphidium articulatum* (d'Orbigny, 1839)
- Criboelphidium gunteri* (Cole, 1931)*
- Criboelphidium sandiegoense?* (Lankford, 1973)
- Elphidium* cf. *fimbriatulum* Cushman, 1918
- Elphidium "pereirum"* sensu Schmidt-Sinns (2008)
- Superfamily **Planorbuloidea** Schwager, 1877
- Family **Cibicididae** Cushman, 1927
- Discorbia* sp.
- Superfamily **Globigerinoidea** Carpenter et al., 1862
- Family **Globigerinidae** Carpenter et al., 1862
- Globigerina* sp.
- Superfamily **Chilostomelloidea** Brady, 1881
- Family **Anomalinidae** Cushman, 1927
- Hanzawaia concentrica* (Cushman, 1918)
- Family **Trichohyalidae** Saidova, 1981
- Buccella* sp.
- Superfamily **Nonionioidea** Schultze, 1854
- Family **Nonionidae** Schultze, 1854
- Nonion fabum* (Fichtel and Moll, 1798)*
- Superfamily **Calcarinoidea** Schwager, 1876
- Family **Calcarinidae** d'Orbigny, 1826
- Pararotalia* sp.
- Superfamily **Buliminioidea** Jones, 1875
- Family **Siphogenerinoididae** Saidova, 1981
- Rectuvigerina* cf. *nicoli* Mathews, 1945
- Order **Textulariida**
- Superfamily **Eggerelloidea** Cushman, 1937
- Family **Eggerellidae** Cushman, 1937
- Dorothia* sp.
- Superfamily **Textularioidea** Ehrenberg, 1838
- Family **Textulariidae** Ehrenberg, 1838
- Textularia* sp.
- Order **Nodosariida** Calkins, 1926
- Superfamily **Nodosarioidea** Ehrenberg, 1838
- Family **Lagenidae** Reuss, 1862
- Lagena perlucida* (Montagu, 1803)
- Exsculptina* sp.
- Class **Tubothalamia** Pawlowski, Holzman, Tyszka, 2013
- Order **Miliolida** Delage and Hérouard, 1896
- Superfamily **Milioloidea** Ehrenberg, 1839
- Family **Hauerinidae** Schwager, 1876
- Quinqueloculina* spp.*
- Class **Foraminifera incertae sedis**
- ? *Stictogonylus*
- Order **Podocopida** Sars, 1866
- Superfamily **Cytheroidea** Baird, 1850
- Family **Cytherideidae** Sars, 1925
- Cyprideis remanei* Klie, 1940*
- Family **Cytherideidae** Sars, 1925
- Perissocytheridea ebutegettaensis* (Omatsola, 1970)
- Perissocytheridea (Kroemmelbeinella) libidinosa* (Witte, 1986)
- Family **Cytheridae** G. W. Müller, 1894
- Cytheropteron* sp.
- Cytherura* sp.
- Semicytherura duracina* Witte, 1993
- Family **Eucytheridae** Puri, 1954
- Eucytheridea** gen. et sp. inc.
- Family **Trachyleberididae** Sylvester-Bradley, 1948
- Basslerites (Loculiconcha) punctata* Omatsola, 1970
- Chrysocythere foveostriata* (Brady, 1870)
- Chrysocythere boldi* Omatsola, 1970
- Reymentia ijebuorum* Omatsola, 1970
- Ruggieria nigeriana?* Omatsola, 1970
- Soudanella africana* Omatsola, 1972
- Family **Loxococonchidae** Sars, 1925
- Loxoconcha lacunensis* Omatsola, 1970
- Pseudoconcha hartmanni* (Omatsola, 1970)*
- Pseudoconcha* sp.*
- Family **Cytheridae** Baird, 1850
- Gibborchella kuznetsovae* (Omatsola, 1970)
- Family **Schizocytheridae** Howe, 1961
- Neomonoceratina ikoroduensis* Omatsola, 1970
- Neomonoceratina cf. ikoroduensis* Omatsola, 1970
- Family **Hemicytheridae** Puri, 1953
- Hermanites* cf. *foveolata* Omatsola, 1972
- Hermanites* sp.
- Puriana* aff. *interrasilis* Omatsola, 1972
- Puriana* cf. *rugosa* Omatsola, 1972
- Puriana mediocostata* Omatsola, 1972
- Puriana trituberculata* Omatsola, 1972
- Neocaudites lindersae* Witte, 1993
- Neocaudites* aff. *lindersae* Witte, 1993
- Family **Paracytheroidea** Puri, 1957
- Paracytheridae** gen. et sp. inc.
- Paracytheridae* sp. A sensu Witte, 1993
- Family **Paradoxostomatidae** Brady and Norman, 1889
- Paradoxostoma* sp.
- Superfamily **Bairdioidae** Sars, 1865
- Family **Bairdiidae** Sars, 1865
- Neonesidea* sp.
- Family **Cushmaniidae** Puri, 1974
- Pontocythere* sp.*
- Subclass **Platycopa**
- Order **Platycopina** Sars, 1866
- Superfamily **Cytherelloidea** Sars, 1866
- Family **Cytherellidae** Sars, 1866
- Cytherella hanaii* Omatsola, 1970
- Cytherelloidea lobitoensis?* Hartmann, 1974

4. Results

4.1. Environmental and sediment data

The ranges and medians of measured environmental data for both study areas are given in Table 1. Salinity data covers mesohaline to hyperhaline ranges (Table 1) following the Venice System (Symposium on the Classification of Brackish Waters, 1958). The total organic carbon content of the surface sediment varied considerably (1.8–17.5%), the thickness of the oxygenated surface layer was very variable as well (Table 1). The highest organic carbon contents were observed in Keta Lagoon (GH 10: 17.5%) and in Densu estuary very close to the village (GH 14: 12.4%). The mean value for LOI in Densu is 6.3% (SD 3.2%), for Keta the mean value is slightly lower (5.1%) but more variable. Keta samples consisted mostly of blackish muddy/silty sediment as well as sandy fine grained grayish to brownish sediment with common shells and living snails. Densu lagoon sediments consisted mostly of black mud but of sand in the western part close to the sand barrier. No submerged phytal areas were encountered during sampling.

Table 1

Measured environmental factors and documented ranges for quantitative data for Keta and Densu estuarine systems.

Parameter	Range	Median	Number of samples
Salinity	17.5–70.0	27.9	22
Water temperature [°C]	27.1–32.7	30.2	22
Oxygenated surface sediment [mm]	1 - >2	5.6	15
O ₂ concentration [ml/l]	7.2–18.14	12.8	21
pH	8.28–9.02	8.7	22
LOI [%]	1.8–17.5	6.3	14
Water depth [m]	0.2–1.8	0.9	21

Table 2

Heavy metal content (µg/g) in sediments from Densu Estuary and Keta Lagoon. Critical values are marked according to limits given in Crommentuijn et al. (1997).

Sample	As	Cd	Co	Cr	Cu	Ni	Pb	Zn
GH 10	13.00	0.37	16.70	88.10	38.42	36.28	32.80	163.00
GH 11	0.96	0.12	2.40	4.30	2.18	3.71	3.54	11.40
GH 12	1.00	0.14	2.13	2.81	1.86	3.39	3.40	8.74
GH 13	1.80	0.15	1.98	3.20	2.45	3.30	4.49	10.10
GH 14	6.40	0.44	5.87	40.00	19.80	12.30	18.00	133.10
GH 15	5.40	0.29	4.26	10.12	11.50	9.00	12.46	61.80
GH 16	4.20	0.15	4.41	17.30	7.31	9.30	10.18	38.80
GH 17	1.60	0.05	1.32	2.76	0.98	2.56	3.30	12.80
GH 18	1.30	0.08	1.49	3.00	2.19	2.82	3.04	14.10
GH 19	1.27	0.05	0.99	1.71	0.98	1.40	1.76	15.00
GH 20	8.62	0.28	5.51	15.18	7.57	10.65	7.79	36.00
GH 21	5.80	0.17	8.46	28.90	13.80	19.70	9.63	49.00
GH 22	6.90	0.25	4.90	13.50	6.67	9.50	10.20	33.90
GH 24	6.80	0.28	8.88	37.50	16.20	19.80	18.40	65.90

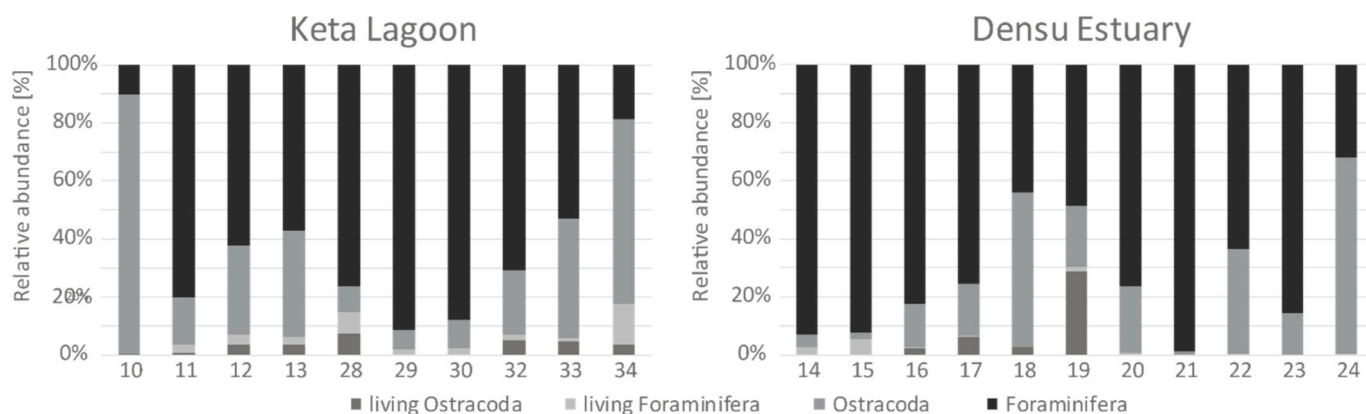


Fig. 5. Relative abundances of living and dead Ostracoda and Foraminifera in Densu Estuary and Keta Lagoon. (Here the data of the samples is presented where the number of counted microfossils was >300. No microfossils were found in sample GH31). The numbers below the columns are referring to the sample numbers.

20 in Densu estuary with a high abundance of *Hanzawaia concentrica* and *Nonion fabum* is very different from those of the other samples.

The cluster analyses of Foraminifera and Ostracoda of the 21 samples of both study areas shows five different major cluster groups (Fig. 6, Table 3). Cluster A is present only in Densu estuary with dominant *Discorbia* sp., but also *Ammonia* sp., *Nonion fabum* and Globigerininae

and represents high salinity and a thick oxidized sediment surface layer. Cluster B is characterized by water temperature and a very high abundance of *Ammonia* sp. and *Trochammina inflata*. Cluster C does not have clear common characteristics; however, all samples have very low species diversity as well as abundances. Cluster D displays marine salinity ranges with dominant *Ammonia* sp., and high abundance of

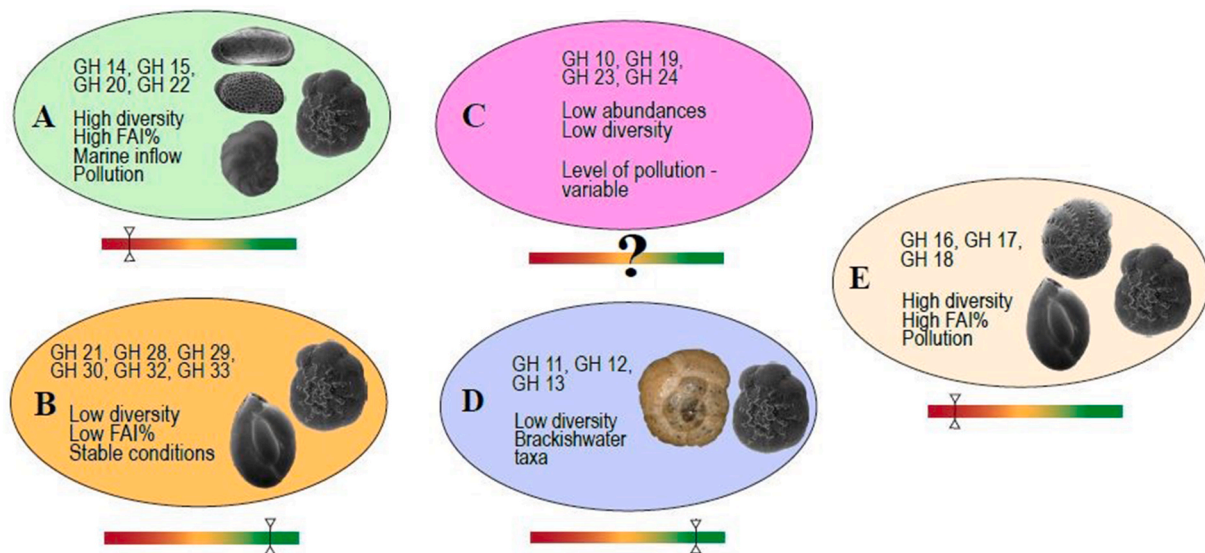


Fig. 6. Groups of samples according to microfossil distribution. The color-coding is referring to the map (Fig. 8) of cluster distributions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Clusters according to foraminifer and ostracod distributions with associated environmental factors and characteristic taxa. FAI stands for the percentage of malformed foraminifer tests. Sample GH 31 was not containing any microfossils.

Cluster	Sample	Environmental factors	Shannon (H) diversity index	Foraminifera	Ostracoda
A	GH 14	± marine (27.9–32.5); mud and muddy sand with high LOI (6.1–7.7%); thick oxidized surface sediment layer (1 cm) and highly variable O ₂ concentration; water temperature high (>30 °C); critical As and Ni concentrations	highest (1.5–2.9)	<i>Discorbia</i> sp. <i>Quinqueloculina</i> spp. <i>Hanzawaia concentrica</i> Globigerininae <i>Elphidium "pereirum"</i> <i>Criboelphidium gunteri</i> <i>Nonion fabum</i> <i>Neoponides schreibersii</i> <i>Textularia agglutinans</i> <i>Eponides cribrorepandus</i> <i>Pararotalia</i> sp. <i>Ammonia</i> sp. high FAI (5–9%)	<i>Pontocythere</i> sp. <i>Loxococoncha lacunensis</i> <i>Pseudoconcha hartmanni</i> <i>Chrysoocythere foveostriata</i> <i>Cytherella hanaii</i> <i>Neomonoceratina</i> sp.
	GH 15				
	GH 20				
	GH 22				
B	GH 21	organic rich mud and fine sands; salinity and oxygen availability variable; water temperature low (26.8–29.5 °C); no data on heavy metals	low (0.8–1.3)	<i>Ammotium morenoi</i> <i>Ammonia</i> sp. <i>Trochammina inflata</i> very low FAI (<1%)	no characteristic taxa
	GH 28				
	GH 29				
	GH 30				
	GH 32				
	GH 33				
C	GH 10	highly variable parameters	variable (0.4–2.1)	no characteristic taxa, low species abundances and diversity	
	GH 19				
	GH 23				
	GH 24				
D	GH 11	variable substrate and TOC; marine (34.2–35); thin oxidized surface layer (1–5 mm); variable water temperature; moderate heavy metal pollution	low (0.9–1.0)	<i>Ammonia</i> sp., <i>Quinqueloculina</i> spp. many living individuals low FAI (<2%)	no characteristic taxa
	GH 12				
	GH 13				
E	GH 16	variable substrate, TOC and O ₂ availability; brackish (17.5–23.1) water temperature high (>31 °C); moderate to low heavy metal pollution	high (1.3–2.2)	<i>Criboelphidium gunteri</i> <i>Neoponides schreibersii</i> high FAI (7–16%)	<i>Pseudoconcha hartmanni</i> <i>Chrysoocythere foveostriata</i> <i>Pontocythere</i> sp.
	GH 17				
	GH 18				

Quinqueloculina spp., *Cyprideis remanei* and *Pseudoconcha hartmanni*, living Foraminifera and Ostracoda. Cluster E has a mesohaline-polyhaline salinity range with high abundances of *Quinqueloculina* spp., *Cyprideis remanei*, *Pseudoconcha hartmanni*, *Cribrorhynchium gunteri*, *Neoponides schreibersii* and *Chrysocythere foveostriata* and a high rate of malformations.

5. Discussion

5.1. Salinity

Salinity is one of the most important ecological factors in brackish water systems (Remane, 1958). It is therefore important to recognise salinity effects on assemblages to differentiate between natural and anthropogenic impacts.

In the lower part of the Densu river basin where the estuary forms, the stream meets the ocean with an exchange of fresh and saline water and silt settles. It is important to consider that sampling in Densu was performed exclusively during the dry season in March 2017. Two sampling points close to the village (GH 14 and GH 15) show high values close to the marine range with 29.9 and 28.9, despite being far from the outlet (Fig. 7), consequently evaporation is the major cause of salinization in this case. An intrusion of ocean water through the relatively narrow sand barrier can be also a reason. Going further east, GH 16, GH 17 and GH 24 salinity decreases to the mesohaline-polyhaline transition at a salinity of around 18, because of the freshwater influx from upstream. Further west the salinity gradually increases from polyhaline to euhaline, reaching marine ranges up to 32.5 and 34.7 close to the mouth of the estuary.

Keta Lagoon has no outlets at the present time, but they were present in the 1960s (e.g. Sørensen et al., 2003). The salinity range of our measurements varies from 34 to 70 during the dry season in March and from 19.6 to 25.5 during the wet season in September. The peak hyperhaline value of 70 in GH 10, in an isolated pond near a village, is driven by evaporation. The three other samples obtained during the dry season, GH 11, GH 12 and GH 13, have very similar salinity values from 34 to 35.2. During the wet season, six samples were taken in two different areas in Keta Lagoon. One area (GH 28–30) is located near Kodzi village with lower salinity due to the freshwater influx. The relatively high salinity (25.5) of GH 31 can be explained by evaporation, which has a strong impact in shallow water depths. The other samples showed relatively similar values of ca. 23. The second sampling area includes GH 32–34 close to the Kedzi village showing relatively low salinity around 20, which can be influenced by regular inflow of the Aka,

the Tordzi River and Belikpa stream, that are entering the lagoon from the north.

5.2. Organic pollution

High values of organic carbon within the sediment can be due to excessive anthropogenic organic pollution that is increasing the trophic state of the water bodies. Because of the enrichments of nutrients (nitrogen and phosphorus) in the water bodies, planktic algal blooming accelerates in the upper water column eventually producing anoxia. The peak LOI values of 17.5% (GH 10) in Keta and 12.4% and 10.4% (GH 14) in Densu suggest anthropogenic impact.

In Keta, the location of sample GH 10 was in an isolated pond (ca. 2.2 km diameter) near a village. The stagnant water regime sustains a very high accumulation of organic matter with additional discharges from the village during the dry season. The lack of an outlet especially increases a threat from disposal of human waste together with poor access to toilet facilities. Another risk is associated with intensification and expansion of agriculture and increased use of pesticides and herbicides (Finlayson et al., 2000). Considering the peak LOI sites of Densu, GH 14 is located right at the shore of the village and GH 24 could be affected by organics from the city's outflow. The Densu River Basin is considered as one of the largest agricultural areas in Ghana, the pesticide contamination (Fiango et al., 2011) and nitrogen fertilizers (Ansa-Asare and Asante, 1998) are among the main concerns and health risks. Moreover, the results from the water quality assessment in the Densu basin in 2003–2004 by Karikari and Ansa-Asare (2006) showed that the faecal coliforms ranged between 336 and 739 CFU/100 ml but should be equal zero to have no risk for human health (WHO, 1987). The groundwater quality is critical for people in the surrounding areas. Therefore, there is an urgent need to reform and establish a cost-efficient water quality monitoring to control discharges of pollutants into the Densu River (Fiango et al., 2011).

5.3. Heavy metals

Overall metalloids, five of them have very high values in localities of Keta and Densu (Table 2). The data are compared with the Dutch ecologists' criteria (Crommentuijn et al., 1997), where experiments on the sensitiveness of the biota and plants to the high hazardous values of metalloids were made (Table 2). They represent the maximum permissible addition (MPA), which stands for "no observed effect concentration", so the highest concentration with which there were no observed changes in reproduction and growth of the organisms studied.

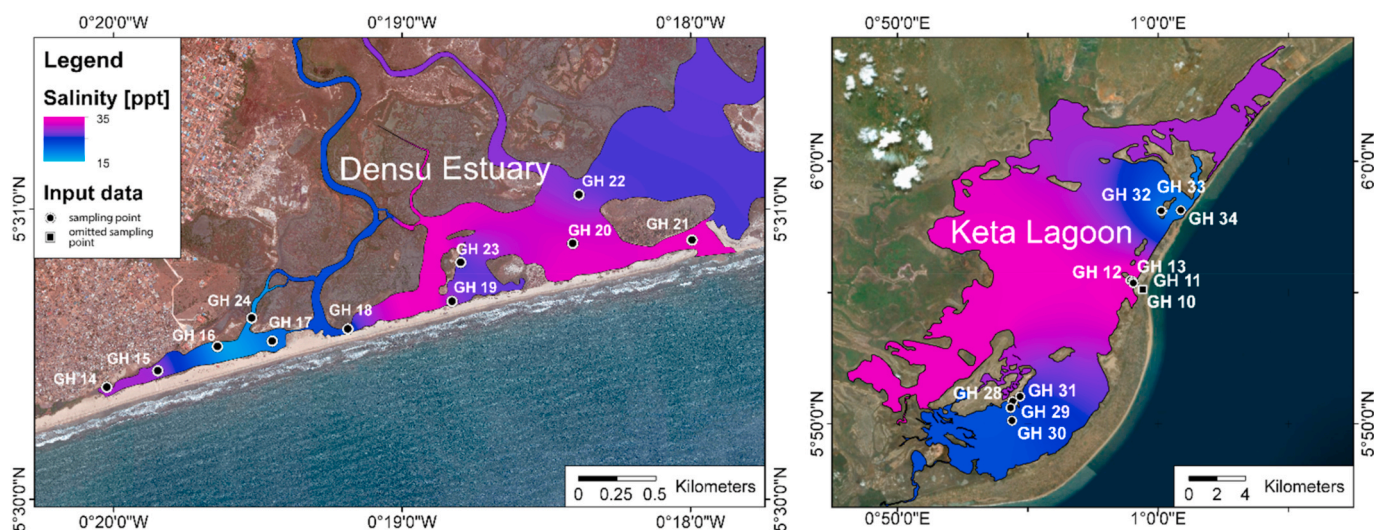


Fig. 7. Salinity variation along Densu estuary and Keta lagoon, Gulf of Guinea, Ghana (GH 10 with a salinity of 70 was omitted).

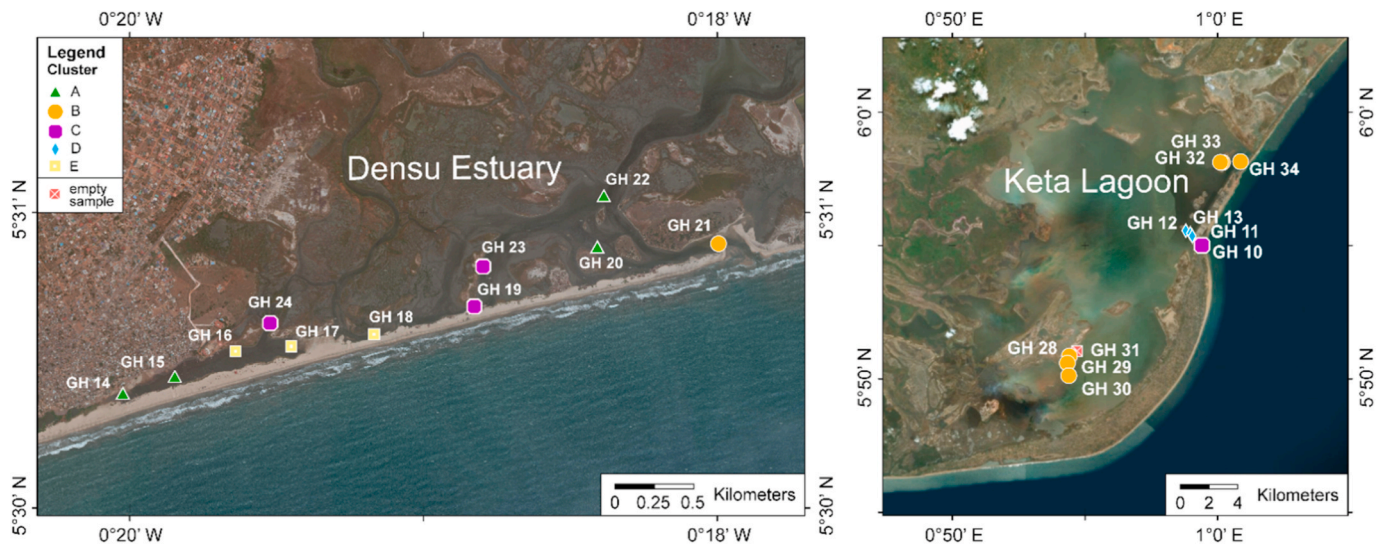


Fig. 8. Clusters distribution in Densu Estuary and Keta Lagoon.

Additionally, the natural input of heavy metals into the ground and surface water was considered.

Densu river is running through the densely populated outskirts of Accra, including smaller industrial areas. The wetland of the estuary is framed by housings and a lower number of settlements within the wetland itself. Possible sources of contamination, because of an expanding population along the Densu basin, are the buildings, effluent discharges, municipal and agricultural activities. In the catchment there are cultivation activities of crops such as cocoa, maize, cassava, vegetables, pineapples and cocoyam as well as the raising of livestock and fishing (Karikari and Ansa-Asare, 2006). The data by Hagan et al. (2011) on heavy metals from Densu showed Fe values being above WHO's standards for drinking water and enrichment factor computation for the soil sediments showed a moderate contamination by Mn and Fe that could come with the emissions from exhaust fumes of tractors and the pesticides used on the farms on the banks of the river (Hagan et al., 2011). Another study in Densu showed values of Fe in the water that exceeded the background level as well as WHO standards, however, that can be because the Densu basin is basically granite, a potential source of Fe in the drinking water. In this study, the levels of Mn acceded the background values, but it was suggested to be due to the weathering of the rocks in the basin (Karikari and Ansa-Asare, 2006). Karikari and Ansa-Asare (2006) also showed that the dominance of chloride over sulfate is probably because of the domestic discharges resulting from household effluents, fertilizer use and anthropogenic sources. It is important to note, that Karikari and Ansa-Asare (2006) also recommended a better control for the farmers by the Ministry of Food and Agriculture, since they are using pesticides, nematicides, fungicides and herbicides, in order to avoid high nutrients loads into the river (Karikari and Ansa-Asare, 2006). The study of Dadzie (2012) showed that upstream, close to Weiija Dam, the leachate from the Oblogo landfill site substantially increases the heavy metal concentration in the Densu River. The values of As, Pb, Hg and Cd in the leachate were high and exceeded the permitted levels set by the WHO, EU and USEPA (Dadzie, 2012), which correlates with our results.

Keta Lagoon is a part of the Volta system and is fed from several rivers up north with unknown discharges (Sørensen et al., 2003). The major occupations of the communities around the lagoon are fishing and farming, with an intensive onion production on the barrier separating the lagoon from the sea (Sørensen et al., 2003). Seasonal changes are explained as a result of high evaporation together with reduced run-off from land drainages (Lampthey and Armah, 2008). The industrial development is relatively low at Keta Lagoon and there are no mineral

deposits with a high metal content. The investigations of water samples for metalloids showed low values in Finlayson et al. (2000). Human waste is among the crucial pollution sources because of an open defecation. It is especially critical in shallow groundwater resources along the coast. Within the wetland areas the biggest issues arise concerning the sludges and liquid waste management. Finlayson et al. (2000) also stated that about 80% of refuse generated was of domestic origin and industrial sawdust was produced by boat builders and carpenters. Furthermore, a survey carried out for the Volta River Authority in the Lower Volta (VBRP, 1996) showed that many chemicals are in use by farmers (Finlayson et al., 2000). Lampthey et al. (2013) also indicated a high load of nutrients with a use of manure and fertilizers because of the production of shallot horticulture system on the Keta sand spit. Other typical vegetable production systems of the surrounding area are pepper, okra, tomatoes and carrots (Lampthey et al., 2013). As a consequence, this system is highly depended on the use of pesticides and herbicides, especially in Anloga, where fertilizers (NPK - nitrogen, phosphorus and potassium) are used for crop farming with nitrogen compounds, manure and, to a small extent pesticide (Lampthey et al., 2013). That corresponds with our high values for Ni and can explain high values of Zn and Cu in case of use of Zinc and Copper Sulfate fertilizers. The results of WQI (Water Quality Index) of the wells, lagoon, and floodplains from Lampthey et al. (2013) indicated either poor water quality or unsuitable for drinking.

5.4. Fauna

The low proportion of living individuals within the documented fauna indicates a low destruction rate of skeletons by dissolution or mechanical fragmentation (Fig. 5).

Fauna in Densu estuary and Keta lagoon was classified into five associations according to distribution of taxa and common environmental factors (Fig. 8).

The outlet of Densu estuary shifted from the most western point close to the village to the eastern part of the sand bar separating the estuary from the open sea in 2013. There, at the mouth of the estuary (GH 20, GH 22), and close to the old outlet (GH 14, GH 15), cluster A is located (Fig. 8). Salinity lies in the range of 27.9–32.5. Despite the switch of the outlet happened already in 2013, we can still observe a similarity of taphocoenoses in the samples close to the present and the old outlet. The Shannon diversity index (H) is the highest in this cluster (1.5–2.9), very likely due to high impact of marine water inflow sustaining high salinity and transporting marine taxa into the taphocoenoses, including open

marine planktic foraminifers. Ostracods identified as marine-brackish like *Pontocythere* (e.g. Dolu et al., 2007), *Loxocochoa* (Swain, 1955; Kruit and van Andel, 1955), *Pseudoconcha hartmanni* (Omatsola, 1970a), *Cytherella hanaii* (Omatsola, 1972), *Neomonoceratina* sp. (Omatsola, 1970a) are characteristic (Table 3). There are marine shelf taxa as well, as *Chrysocythere*, a typical West African genus and one of the most abundant ostracods from Nigeria to Senegal (Omatsola, 1972). Foraminifera are represented with high abundance of *Quinqueloculina*, a genus known to live in restrained environments under high anthropogenic pressure (Alve, 1995; Debenay et al., 2000, 2001) being tolerant to chemical, metalloids and coal pollution (Setty, 1982; Yanko et al., 1994). We also observed a high rate of malformations in *Quinqueloculina*, which is commonly recognized as a response to anthropogenic pressure or to strong salinity variations which can disturb test construction (e.g., Sgarrella and Barra, 1985; Yanko et al., 1994; Geslin et al., 2000; Geslin et al., 2002). Another typical foraminifer for this cluster, *Ammonia* sp., belongs to a cosmopolitan marginal-marine genus well-known for its tolerance to organic enrichment (e.g. Sgarrella and Moncharmont Zei, 1993). The concentration of organic carbon is high for the sites of association A (LOI% values 6.2–12.3). Furthermore, concentrations of As and Ni are exceeding limits given in Crommentuijn et al. (1997). Salinity variation alone can cause up to 10% malformed tests in estuarine associations (Geslin et al., 2002), but higher values are only reached via anthropogenic pressure as through heavy metal contamination (e.g. Polovodova and Schönfeld, 2008) or in athalassic lakes (Pint et al., 2017). Therefore, the medium to very high FAIs of 2.0–17.5% of cluster A are interpreted as reflecting mainly heavy metal pollution.

Cluster B is located mainly in Keta Lagoon but with one sample at the mouth of Densu Estuary as well (Fig. 8). It is characterized by a high abundance of the tolerant brackish water species *Trochammina inflata* and *Ammotium morenoi* and the marginal marine *Ammonia* sp. The Shannon diversity index (H) is variable and does not show a clear pattern, with low diversity of 0.4 up to a high diversity index of 2.1. FAI is very low. Except for GH 21 all sites are sheltered brackish water habitats and less impacted by anthropogenic pollution. GH 21 is situated at the present-day mouth of Densu Estuary, but we sampled a dark clay eroded at its surface pointing to a sub-recent association of the time this site was much more isolated. This situation also explains the exceptionally low FAI within the Densu estuary. The high proportion of agglutinated foraminifers and living individuals points to partial dissolution of calcareous shells within the sediment (Buzas-Stephens and Buzas, 2005).

Cluster C (Fig. 8) does not have characteristic taxa neither of Ostracoda nor of Foraminifera. Low species abundances as well as diversity are grouping these samples. A decline in the abundance of Ostracoda together with Foraminifera can be interpreted as ecological stress in the environment (e.g. Yasuhara and Yamazaki, 2005; Tsujimoto et al., 2006). According to severe organic and heavy metal pollution (Table 2), this could be a reason for samples GH 10 and GH 24, however, GH 19 is not contaminated (data on heavy metals for GH 23 are missing). Interestingly, GH 10 and GH 24 contain abundant *Cyprideis remanei*, an opportunistic brackish ostracod taxon (Hartmann, 1974). The high variability of environmental factors is driven by the pronounced confinement of the sampling locations. The Shannon diversity index (H) for GH 10 and GH 24 is 0.40 and 1.1, which is relatively low and could again point to its very high level of contamination. Thus, non-contaminated GH 19 has a higher diversity with 2.1 Shannon (H) index. Summarizing, the fauna of relatively heterogeneous cluster C is impacted by ecological stress through pollution or high variability of environmental factors.

Cluster D (Fig. 8) is situated in less polluted Keta Lagoon, which lays immediately behind sand barriers close to the open sea. The cluster represented by *Quinqueloculina* and *Ammonia* sp., both marginal marine tolerant taxa (den Dulk et al., 2000; Murray, 2006). The distribution of species in cluster D and E coincides with species diversity, however, is

defined by salinity variation. The Shannon diversity index (H) is lower in cluster D (0.9–1.0) compared to cluster E (1.3–2.2).

Cluster E (Fig. 8) is completely situated in Densu Estuary and has a salinity range of 17.5–23.1 with a high rate of malformations in Foraminifera. It represents high abundances of *Criboelphidium gunteri*, *Neoponides schreibersii* and *Chrysocythere foveostriata*. *Criboelphidium gunteri* is a coastal marine-brackish foraminifer (e. g. Patterson, 1990) but was also found in salinities of up to 290 (Poag, 1978). *Neoponides schreibersii* and *Chrysocythere* are coming from open marine environments (Goubert et al., 2001; Keen, 2004) pointing to input of open marine material during storms. Such an input of allochthonous material could explain the higher diversities, despite having a lower salinity and higher FAI. The latter is probably caused by both high salinity variation and pollution because it is rising sometimes above 10%. Because the level of heavy metal pollution in cluster E is in average lower than in D, we expect elevated concentrations of additional pollutants, probably POPs, in Densu Estuary compared to Keta Lagoon.

Summing up faunistic and environmental patterns of associations from Densu Estuary and Keta Lagoon we get the following picture: Association A, characterized by high diversity and many marine taxa including planktic foraminifera, is an outer-estuarine association strongly impacted by allochthonous marine microfossils. Its high FAI is partly driven by high salinity variation but is also caused by organic and heavy metal pollution which is hard to differentiate with our limited dataset alone. Association B shows low diversity and dominance of true brackish water taxa like *Ammotium* and *Trochammina* due to its more sheltered position within the studied estuarine systems. Pollution effects are not recognizable. Association C shows low abundance and diversity caused by variable natural and anthropogenic stressors which are not specifiable with such a low number of samples and some missing parameters. The two sites with highest organic and heavy metal pollution, however, show a dominance of *Cyprideis remanei*, a potential indicator species for pollution. Association D yields a low diversity association dominated by *Ammonia* and *Quinqueloculina* but with low FAI indicating stable lagoonal conditions with a low pollution level. Association E is characterized by a higher diversity with brackish water ostracods, *Criboelphidium gunteri* and a high FAI pointing to estuarine settings and a higher pollution level.

6. Conclusions

This study provides the first overview on marginal marine Ostracoda and Foraminifera of Ghana and contributes new data to the sparse knowledge on biogeographical distribution and ecology of these taxonomic groups in Western Africa.

Foraminiferal Abnormality Index (FAI) is known to be a response to variable environmental parameters or anthropogenic pressure (e.g. Geslin et al., 2002). In our case, the highest FAI results to be associated with high heavy metal concentrations and variable salinity. Additionally, we found indication for other pollutants causing increased levels of malformation.

Each species of Ostracoda and Foraminifera has its own tolerance to different environmental parameters and to different types of pollution. The dominance of tolerant taxa as *Quinqueloculina*, *Ammonia* sp., *Criboelphidium gunteri* and *Cyprideis remanei* is commonly encountered in anthropogenically impacted areas. *Quinqueloculina* is known to live in stressed environments (Alve, 1995; Debenay et al., 2000, 2001) and to be tolerant to different pollutants (Setty, 1982; Yanko et al., 1994). Moreover, *Quinqueloculina* showed a high rate of test abnormalities in many studies which points to an anthropogenic pressure or to strong salinity variations (e.g. Sgarrella and Barra, 1985; Yanko et al., 1994; Geslin et al., 2000; Geslin et al., 2002), as it was mentioned before. Another opportunistic marginal-marine foraminifer genus is *Ammonia*, which is also well-known for its tolerance to organic enrichment (e.g. Sgarrella and Moncharmont Zei, 1993). *Criboelphidium gunteri* is a coastal marine-brackish foraminifer (e. g. Patterson, 1990) preferring

mud with high organic content (van Voorthuysen, 1960). The only dominant ostracod is *Cyprideis remanei*, which is also an opportunistic brackish ostracod (Hartmann, 1974). Besides that, *Ammotium morenoi* is associated with confined areas, and *Ammonia* sp. and *Cribrorhynchium gunteri* characterize the most marine-influenced areas.

Our results show that the higher LOI content is associated with higher Shannon (H) diversity index and density of total fauna (Cluster A), especially in stations closer to villages, with a lower speed of tidal currents and turbulence. This is different, however, for sample GH 10 in Keta lagoon; there, diversity is low because of the hyperhaline water despite high LOI values and muddy sediment. General comparison of species richness between associations in the two estuarine systems indicates productivity, hydrographic regime, including transport of allochthonous material, and pollution to be the drivers of faunistic patterns.

The concentrations of the heavy metals are exceeding some thresholds in Keta Lagoon and Densu Estuary. According to the heavy metal distribution, the greatest degree of anthropogenic pollution is found close to settlements or its outflows.

Most importantly, in contrast to a usual diversity trend reflecting high levels of pollution by lower diversity, the results from the studied estuarine systems show higher diversity associated with sites of higher pollution levels. Reasons are the close to marine salinity of these sites supporting higher species numbers and the accumulation of allochthonous specimens coming from the open sea. These observations underline the need to understand salinity levels and transport processes if using microfossils as tracers of anthropogenic impacts.

A more complete dataset on nutrition loads and heavy metals in this area will improve our ability to draw explicit conclusion and see a clear correlation between microfaunal associations and the effect of pollution in the studied estuaries. Nonetheless, the combined use of Ostracoda and Foraminifera demonstrated complex patterns in relation to anthropogenic impact, as already proven in various studies on Ostracoda and Foraminifera showing a great potential as sentinels for environmental stress (e.g. Ruiz et al., 2005; Schornikov and Zenina, 2014).

Data availability

The data used and created in this paper are available through PAN-GAEA (<https://www.pangaea.de/>).

CRediT authorship contribution statement

Olga Gildeeva: Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Data curation. **Lailah Gifty Akita:** Conceptualization, Investigation, Writing – review & editing. **Johannes Biehler:** Formal analysis, Investigation, Data curation. **Peter Frenzel:** Conceptualization, Supervision, Methodology, Validation, Investigation, Writing – review & editing. **Mauro Alivernini:** Conceptualization, Supervision, Methodology, Validation, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank our colleagues from the Department of Marine and Fisheries Sciences, University of Ghana for their support during the fieldwork. We are grateful to Dr. Edem Mahu (University of Ghana) for providing logistic support during the expeditions. We also thank M.Sc. Thomas Biehl (Friedrich Schiller University Jena, Germany) for his contribution to field work. We thank the fishermen at Keta Lagoon and

Densu Estuary for their assistance with providing a boat for sampling on the coastal waters. We also would like to express our gratitude to Dr. Bruce Hayward (Geomarine Research, University of Auckland) for checking our *Ammonia* species. This contribution was made possible thanks to a grant from the Journal GEO (Expeditionsstipendium) and the support by Volkswagen Stiftung (Grant No. 89371).

References

- Altınışık, S., Griffiths, H.I., 2001. The freshwater ostracods *Hungarocypris* and *Leucocythere* from Turkey. *Crustaceana* 74, 681–688.
- Alvarez Zarikian, C.A., Swart, P.K., Gifford, J.A., Blackwelder, P.L., 2005. Holocene paleohydrology of Little Salt Spring, Florida, based on ostracod assemblages and stable isotopes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 225, 134–156.
- Alve, E., 1995. Benthic foraminiferal responses to estuarine pollution: a review. *J. Foraminif. Res.* 25, 190–203.
- Alve, E., Lepland, A., Magnusson, J., Backer-Owe, K., 2009. Monitoring strategies for reestablishment of ecological reference conditions: possibilities and limitations. *Mar. Pollut. Bull.* 59, 297–310.
- Anadón, P., Utrilla, R., Julià, R., 1994. Palaeoenvironmental reconstruction of a Pleistocene lacustrine sequence from faunal assemblages and ostracod shell geochemistry. Baza Basin, SE Spain. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 111, 191–205.
- Appiah-Opoku, S., 2001. Environmental impact assessment in developing countries: the case of Ghana. *Environ. Impact Assess. Rev.* 21 (1), 59–71.
- Ansa-Asare, O.D., Asante, K.A., 1998. A comparative study of the nutrient status of two reservoirs in southeast Ghana. *Lakes Reservoirs Res. Manag.* 3, 205–217.
- Bentum, J.K., Anang, M., Boadi, K.O., Koranteng-Addo, E.J., Owusu Antwi, E., 2011. Assessment of heavy metals pollution of sediments from Fosu lagoon in Ghana. *Bull. Chem. Soc. Ethiop.* 25 (2), 191–196.
- Boomer, I., Horne, D.J., Slipper, I.J., 2003. The use of ostracods in palaeoenvironmental studies, or what can you do with an ostracod shell? *Paleontol. Soc. Pap.* 9, 153–180.
- Bouchet, V.M.P., Debenay, J.-P., Sauriau, P.-G., Radford-Knoery, J., Soletchnik, P., 2007. Effects of short-term environmental disturbances on living benthic foraminifera during the Pacific oyster summer mortality in the Marennes-Oleron Bay (France). *Mar. Environ. Res.* 64, 358–383.
- Buzas-Stephens, P., Buzas, M.A., 2005. Population dynamics and dissolution of foraminifera in Nueces Bay, Texas. *J. Foraminif. Res.* 35 (3), 248–258.
- Crommentuijn, T., Polder, M.D., van de Plassche, E.J., 1997. Maximum Permissible Concentrations and Negligible Concentrations for Metals, Taking Background Concentrations into Account. Report no. 601501001. National Institute of Public Health and the Environment, Bilthoven, The Netherlands, 260 pp.
- Curry, B.B., 1999. An environmental tolerance index for ostracodes as indicators of physical and chemical factors in aquatic habitats. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 148, 51–63.
- Dadzie, E.S., 2012. Assessment of Heavy Metal Contamination of the Densu River, Weija from Leachate. Master thesis. The Department of Environmental Science, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, unpublished.
- De Deckker, P., Forester, R.M., 1988. The use of ostracodes to reconstruct continental palaeoenvironmental records. In: De Deckker, P., Colin, J.-P., Peypouquet, J.P. (Eds.), *Ostracoda in the Earth Sciences*. Elsevier, New York, pp. 175–199.
- Debenay, J.P., Guillou, J.J., Redois, F., Geslin, E., 2000. Distribution trends of foraminiferal assemblages in Paralic environments. In: Martin, R.E. (Ed.), *Environmental Micropaleontology*. Topics in Geobiology, 15. Kluwer Academic/Plenum Publishers, New York, pp. 39–67.
- Debenay, J.-P., Tsakiridis, E., Soulard, R., Grosse, H., 2001. Factors determining the distribution of foraminiferal assemblages in Port Joinville Harbor (Ile d'Yeu, France): the influence of pollution. *Mar. Micropaleontol.* 43, 75–118.
- den Dulk, M., Reichert, G.J., van Heyst, S., Zachariasse, W.J., van der Zwaan, G.J., 2000. Benthic foraminifera as proxies of organic matter flux and bottom water oxygenation? A case history from the northern Arabian Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 161 (3–4), 337–359.
- Denoyelle, M., Jorissen, F.J., Martin, D., Galgani, F., Miné, J., 2010. Comparison of benthic foraminifera and macrofaunal indicators of the impact of oil based drill mud disposal. *Mar. Pollut. Bull.* 60, 2007–2021.
- Dolu, E., Gökaşan, E., Meriç, E., Ergin, M., Görüm, T., Tur, H., Ecevitöglu, B., Avşar, N., Görmüş, M., Batuk, F., Tok, B., Çetin, O., 2007. Quaternary evolution of the Gulf of İzmit (NW Turkey): a sedimentary basin under control of the north Anatolian fault zone. *Geo Mar. Lett.* 27, 355–381.
- Fajemila, O.T., Langer, M.R., 2017. Spatial distribution and biogeographic significance of foraminiferal assemblages from Sao Tome and Principe, Gulf of Guinea, West Africa. *Neues Jahrbuch Geol. Palaontol. Abhand.* 285, 337–360.
- Feldt, T., Fobil, J.N., Wittsiepe, J., Wilhelm, M., Till, H., Zoufaly, A., Burchard, G., Göen, T., 2014. High levels of PAH-metabolites in urine of e-waste recycling workers from Agbogboshie, Ghana. *Sci. Total Environ.* 466/467, 369–376.
- Fianko, J.R., Donkor, A., Lowor, S.T., Yeboah, P.O., Glover, E.T., Adom, T., Faanu, A., 2011. Health risk associated with pesticide contamination of fish from the Densu river basin in Ghana. *J. Environ. Protect.* 2 (2), 115–123.
- Finlayson, C.M., Gordon, C., Ntiama-Baidu, Y., Tumbulto, J., Storrs, M., 2000. Supervising Scientist Report. The Hydrobiology of Keta and Songor Lagoons: Implications for Coastal Wetland Management in Ghana, vol. 152. Supervising scientist, Darwin, p. 116.

- Frenzel, P., Keyser, D., Viehberg, F.A., 2010. An illustrated key and (palaeo) ecological primer for Postglacial to Recent Ostracoda (Crustacea) of the Baltic Sea. *Boreas* 39 (3), 567–575.
- Frontalini, F., Coccioni, R., 2008. Benthic foraminifera for heavy metal pollution monitoring: a case study from the central Adriatic Sea coast of Italy. *Estuarine, Coastal and Shelf Science* 76, 404–417.
- Fürstenberg, S., Gründler, N., Meschner, S., Frenzel, P., 2017. Microfossils in surface sediments of brackish waters on the west coast of South Africa and their palaeoecological implications. *Afr. J. Aquat. Sci.* 42 (4), 329–339.
- Geslin, E., Debenay, J.-P., Duleba, W., Bonetti, C., 2002. Morphological abnormalities of foraminiferal tests in Brazilian environments: comparison between polluted and non-polluted areas. *Mar. Micropaleontol.* 45 (2), 151–168.
- Geslin, E., Stouff, V., Debenay, J.-P., Lesourd, M., 2000. Environmental variation and foraminiferal test abnormalities. In: Martin, R.E. (Ed.), *Environmental Micropaleontology. The Application of Microfossils to Environmental Geology*. New York, Springer. Topics in Geobiology 0275-0120 (15), 191–215.
- Goubert, E., Néraudeau, D., Rouchy, J.M., Lacour, D., 2001. Foraminiferal record of environmental changes: Messinian of the Los Yesos area (Sorbas basin, SE Spain). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 175 (1), 61–78.
- Griffiths, H.I., Holmes, J.A., 2000. Non-marine Ostracods and Quaternary Palaeoenvironments. Technical Guide No. 8. Quaternary Research Association, London, UK, p. 188.
- Hagan, G.B., Ofori, F.G., Hayford, E.K., Osa, E.K., Oduro-Afriyie, K., 2011. Heavy metal contamination and physico-chemical assessment of the Densu River basin in Ghana. *Res. J. Environ. Earth Sci.* 3 (4), 385–392.
- Hartmann, G., 1974. Zur Kenntnis des Eulitorals der afrikanischen Westküste zwischen Angola und Kap der Guten Hoffnung und der afrikanischen Ostküste von Südafrika und Mocambique unter besonderer Berücksichtigung der Polychaeten und Ostracoden. Die Ostracoden des Untersuchungsgebiets. Mitteilungen aus dem Hamburgischen Zoologischen Museum und Institut, Ergänzungsband 69, 229–520.
- Havel, J.E., Talbott, B.L., 1995. Life history characteristics of the freshwater ostracod *Cyprinotus incongruus* and their application to toxicity testing. *Ecotoxicology* 4, 206–218.
- Jorissen, F.J., Bicch, E., Duchemin, G., Durrieu, J., Galgani, F., Cazes, L., Gaultier, M., Camps, R., 2009. Impact of oil-based drill mud disposal on benthic foraminiferal assemblages on the continental margin off Angola. *Deep-Sea Research II* 56, 2270–2291.
- Karikari, A.Y., Ansa-Asare, O.D., 2006. Physico-chemical and microbial water quality assessment of Densu River of Ghana. *West African Journal of Applied Ecology* 10 (1), 1–10.
- Keen, M.C., 2004. The origin of the modern tropical West African marine Ostracod Fauna, with a description of the *Ruggieriini* n. tribe. *Boll. Soc. Paleontol. Ital.* 43 (1), 201–216.
- Kruit, C., van Andel, T.J.H., 1955. Sediments of the Rhone delta: Verhandelingen van het Koninklijk Nederlandsch Geologisch-Mijnbouwkundig Genootschap. *Geologische Serie* 15, 357–499.
- Kusimi, J.M., 2008. Stream processes and dynamics in the Morphology of the Densu river channel in Ghana. *The International Archives of the Photogrammetry. Remote Sensing and Spatial Information Sciences VXXXVII B8*, 1177–1182.
- Lamprey, E., Armah, A.K., 2008. Factors affecting Macro-benthic fauna in a tropical Hypersaline coastal lagoon in Ghana, West Africa. *Estuar. Coast* 31 (5), 1006–1019.
- Lamprey, M.A., Ofori-Danson, K.P., Abbenney-Mickson, S., Breuning-Madsen, H., Abekoe, K.M., 2013. The influence of land-use on water quality in a tropical coastal area: case study of the Keta Lagoon complex, Ghana, West Africa. *Open J. Mod. Hydrol.* 3 (4), 188–195.
- Lutze, G.F., Altenbach, A.V., 1991. Technik und Signifikanz der Lebendfärbung benthischer Foraminiferen mit Bengalrot. *Geol. Jahrbuch Reihe* 128, 251–265.
- Mischke, S., Kramer, M., Zhang, C., Shang, H., Herzschuh, U., Erzinger, J., 2008. Reduced early Holocene moisture availability in the Bayan Har Mountains, northeastern Tibetan Plateau, inferred from a multi-proxy lake record. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 267, 59–76.
- Murray, J.W., 2006. *Ecology and Applications of Benthic Foraminifera*. Cambridge University Press, Cambridge, UK, p. 426.
- Murray, J.W., Bowser, S.S., 2000. Mortality, protoplasm decay rate, and reliability of staining techniques to recognize living foraminifera: a review. *J. Foraminif. Res.* 30, 177–191.
- Nagy, J., Alve, E., 1987. Temporal changes in foraminiferal faunas and impact of pollution in Sandebukta, Oslo Fjord. *Mar. Micropaleontol.* 12, 109–128.
- Omatsola, M.E., 1970a. Podocypid Ostracoda from the Lagos lagoon, Nigeria. *Micropaleontology* 16 (4), 407–445.
- Omatsola, M.E., 1970b. On the occurrence of cytherellids (Ostr., Crust.) in a brackish-water environment. *Bull. Geol. Inst. Univ. Upps* 2 (10), 91–96.
- Omatsola, M.E., 1970c. Notes on three new species of Ostracoda from the Niger Delta, Nigeria. *Bull. Geol. Inst. Univ. Uppsala, N. Ser.* 2 (11), 97–102.
- Omatsola, M.E., 1972. Recent and subrecent Trachyleberididae and Hemicytheridae (Ostr., Crust.) from the western Niger delta, Nigeria. *Bull. Geol. Inst. Univ. Upps* 3 (114), 38–110.
- Patterson, R.T., 1990. Intertidal benthic foraminiferal biofacies on the Fraser River delta, British Columbia: modern distribution and paleoecological importance. *Micropaleontology* 36 (3), 1–229.
- Pint, A., Engel, M., Melzer, S., Frenzel, P., Plessen, B., Brückner, H., 2017. How to discriminate athalassic and marginal marine microfaunas: foraminifera and other fossils from an early Holocene continental lake in northern Saudi Arabia. *J. Foraminif. Res.* 47 (2), 175–187.
- Poag, C.W., 1978. Paired foraminiferal ecophenotypes in Gulf Coast estuaries: ecological and paleoecological implications. *Gulf Coast Association of Geological Societies, Transactions* 28, 1–44.
- Polovodova, I., Schönfeld, J., 2008. Foraminiferal test abnormalities in the western Baltic sea. *J. Foraminif. Res.* 38, 318–336.
- Remane, A., 1958. Die Ökologie des Brackwassers. In: Remane, A., Schlieper, C. (Eds.), *Die Biologie des Brackwassers*, vol. 22. Die Binnengewässer, Stuttgart, p. 216.
- Rosenfeld, A., Ortal, R., 1983. Ostracodes as indicators of water pollution in Nahal Harod, northern Israel. In: Maddocks, R.F. (Ed.), *Applications of Ostracoda*, Proceedings of the 8th International Symposium on Ostracoda. University of Houston, Texas, pp. 229–237.
- Ruiz, F., Abad, M., Bodergat, A.M., Carbonel, P., Rodriguez-Lazaro, J., Yasuhara, M., 2005. Marine and brackish-water ostracods as sentinels of anthropogenic impacts. *Earth Sci. Rev.* 72, 89–111.
- Shannon, C.E., 1948. A mathematical theory of communication. *Bell System Technical Journal* 27 (3), 379–423.
- Scheren, P.A., Ibe, A.C., Janssen, F.J., Lemmens, A.M., 2002. Environmental pollution in the Gulf of Guinea—a regional approach. *Mar. Pollut. Bull.* 44, 633–664.
- Schmidt-Sinns, J., 2008. *Rezente benthische Foraminiferen im Bereich des Benguelastroms, Südwestafrika - Verbreitungsmuster und ihre steuernden Faktoren*. PhD thesis. University of Bonn, Germany, p. 261.
- Schönfeld, J., Alve, E., Geslin, E., Jorissen, F., Korsun, S., Spezzaferri, S., 2012. The FOBIMO (FORaminiferal Bio-Monitoring) initiative - towards a standardised protocol for soft bottom benthic foraminiferal monitoring studies. *Mar. Micropaleontol.* 94, 1–13.
- Schornikov, E.I., 2011. Loxocaudinae: a new subfamily in the ostracod family Loxoconchidae. *Russ. J. Mar. Biol.* 37 (3), 185–192.
- Schornikov, E.I., Zenina, M.A., 2014. Ostracods as Indicators of Conditions and Dynamics of Water Ecosystems (On the Example of Peter the Great Bay, Sea of Japan). *Dal'nauka, Vladivostok*, p. 334.
- Sgarrella, F., Barra, D., Improta, A., 1985. The benthic foraminifera of the Gulf of Policastro (southern Tyrrhenian sea, Italy). *Bollettino della Soc. dei Nat. Napoli* 92, 67–114.
- Sgarrella, F., Moncharmont Zei, M., 1993. Benthic foraminifera of the Gulf of Naples (Italy): systematics and autoecology. *Boll. Soc. Paleontol. Ital.* 32 (2), 145–264.
- Setty, M.G.A.P., 1982. Pollution effects monitoring with foraminifera as indices in the Thana Creek, Bombay area. *Int. J. Environ. Stud.* 18 (3–4), 205–209.
- Sørensen, T.H., Volund, G., Armah, A.K., Christensen, C., Jensen, L.B., Pedersen, J.T., 2003. Temporal and spatial variations in concentrations of sediment nutrients and carbon in the Keta lagoon, Ghana. *West African Journal of Applied Ecology* 4, 91–105.
- Symposium on the Classification of Brackish Waters, 1958. The Venice System for the classification of marine waters according to salinity. *Limnol. Oceanogr.* 3 (3), 346–347.
- Tsujimoto, A., Nomura, R., Yasuhara, M., Yamazaki, H., Yoshikawa, S., 2006. Impact of eutrophication on shallow marine benthic foraminifera over the last 150 years in Osaka Bay, Japan. *Mar. Micropaleontol.* 60 (4), 258–268.
- VBPR, 1996. *Environmental Impact Studies on the Volta Basin: Location, Population Size and Water Sources of Settlements*. Technical report 1/96. Volta Basin Research Project, Legon.
- van Voorthuysen, J.V., 1960. *Die Foraminiferen des Dollart-Ems-Estuarium*. Verhandelingen der Koninklijke Nederlandse Geologisch-Mijnbouwkundig Genootschap 19, 237–269.
- Watkins, J.G., 1961. Foraminiferal ecology around the Orange county, California. ocean sewer outfall: *Micropaleontology* 7, 199–206.
- Witte, L.J., 1993. *Taxonomy and biogeography of West African beach ostracods*. PhD thesis. In: *Taxonomy and Origin of Modern West African Shallow Marine Ostracoda: Taxonomy*. Free University of Amsterdam, pp. 13–105.
- WHO (World Health Organisation), 1987. *Guideline for Drinking Water*, vol. 1. WHO, Geneva.
- Yanko, V., Kronfeld, J., Flexer, A., 1994. Response of benthic foraminifera to various sources: implications for pollution monitoring. *J. Foraminif. Res.* 24, 1–17.
- Yasuhara, M., Yamazaki, H., 2005. The impact of 150 years of anthropogenic pollution on the shallow marine ostracode fauna, Osaka Bay, Japan. *Mar. Micropaleontol.* 55, 63–74.