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Reconstruction of the Littorina Transgression in the Western Baltic Sea

by

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In memory of Wolfram Lemke

Contents

Abstract

Due to the early Holocene global sea-level rise marine water masses were entering the Baltic Basin and led to one of the most dramatic environmental changes in the post-glacial history of the Baltic Sea - the Littorina transgression. While the general evolution is well-known, many details remain controversial. This concerns for example the dating with the event being apparently younger than presumed, and the detailed description of the transgression.

New cores were drilled west and east of the Darss Sill, the Mecklenburg Bay and the Arkona Basin, to investigate the transition from the fresh water conditions of the Ancylus Lake to the marine-brackish conditions of the Littorina Sea in a high spatial and temporal resolution. Sediment-physical, sedimentological, geochemical and palaeontological analyses were conducted in order to define proxy parameters that are indicative of this transgression event.

In general, Arkona Basin sediments display more abrupt shifts in the proxy parameter at the transition from Ancylus Lake to Littorina Sea stage material than those from the Mecklenburg Bay. Radiocarbon dating on calcareous material indicates that marine waters entered the Mecklenburg Bay first at c. 7,500 ^{14}C yr BP and the Arkona Basin approximately 1,000 years later at c. 6,500 ^{14}C yr BP. These results therefore suggest a transgression pathway via the Great Belt into the Mecklenburg Bay and then into the Arkona Basin.

Kurzfassung

Infolge des globalen Meeresspiegelanstieges im Frühholozän drangen marine Wässer in das Ostseebecken ein und lösten eine der dramatischten Umweltveränderungen in der post-glazialen Entwicklungsgeschichte der Ostsee aus - die Littorina Transgression. Die generelle Entwicklung ist bekannt, jedoch bleiben viele Details widersprüchlich. Dies bezieht sich nicht nur auf den Beginn der Transgression, welcher jünger scheint als bisher angenommen, sondern auch auf die Details der Entwicklung der Transgression an sich.

Neue Kerne wurden westlich und östlich der Darßer Schwelle in der Mecklenburger Bucht und im Arkona Becken gewonnen, um den Übergang von den Süßwasser-Bildungen des Ancylus Sees zu den marinen-brackischen Bildungen des Littorina Meeres räumlich und zeitlich hochauflösend zu untersuchen. Sedimentphysikalische, sedimentologische, geochemische und paläontologische Analysen sind durchgeführt worden, um die für dieses Transgressionsereignis indikativen Proxy-Parameter zu definieren.

Im Allgemeinen zeigen die Sedimente des Arkona Beckens gegenüber der Mecklenburger Bucht abruptere Veränderungen in den Proxy-Parametern am Übergang vom Ancylus See zum Littorina Meer. Radiokarbonalter (kalkhaltiges Material) deuten darauf hin, dass marine Wässer zuerst in die Mecklenburger Bucht um ca. 7500 ^{14}C a BP gelangten und das Arkona Becken ungefähr 1000 Jahre später um ca. 6500 ^{14}C a BP erreichten. Diese Ergebnisse favorisieren einen Transgressionsweg über den Großen Belt in die Mecklenburger Bucht und danach in das Arkona Becken.

1 Introduction

The following work was initiated by Dr. habil. W. Lemke and is a contribution to the SINCOS subproject 1.2: "Littorina transgression in the western Baltic Sea: pathways, timing, and possible implications for human settlement".
The project "Sinking Coasts: Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea" (SINCOS), financially supported by the German Science Foundation (DFG), was founded as a German Research Unit, running from 2002 to 2005 (HARFF ET AL. 2005). The general target of SINCOS is the development of a model of relationships between the geosystem, eco-system, climate and socio-economic system for sinking coasts of tideless seas to be established as an example for the southern Baltic Sea since the Atlanticum (since 8000 calendar years BC).
The Littorina transgression caused one of the most dramatic environmental changes that occurred during the post-glacial history of the Baltic Sea. Due to the Holocene eustatic sea level rise marine water entered the Danish Straits and flooded the Baltic basin. The hydrographic system as well as the coastal configuration of the entire Baltic region changed completely. Inflowing saline waters transformed the freshwater Ancylus Lake into the brackish-marine Littorina Sea. The general picture of this development is known, many details, however, remain contradictory and/or controversial. These details relate to:

(i) the sediment proxy changes that are indicative of this event,
(ii) the accurate timing of the Littorina transgression,
(iii) the chronological order in which the thresholds of the Belts and the Öresund were flooded.

Aiming at a detailed reconstruction of the Littorina transgression in the western Baltic Sea, these scientific goals (i-iii) were tackled implementing two different approaches:

1. characterization of the initial main trangressive phase by a multi-proxy-methodic work program that involves physical, sedimentological, geochemical and palaeontological investigations,
2. precision of the beginning of the Littorina transgression using radiocarbon dating.

Investigations were focussed on two basin areas west and east of the Darss Sill, the Mecklenburg Bay and the Arkona Basin.

2 Setting of the study area

2.1 The Baltic Sea and its western basins, the Mecklenburg Bay and the Arkona Basin

The Baltic Sea is an intracontinental estuarine marginal sea of the Atlantic Ocean and known as the biggest brackish water body in the world, almost land-locked (Fig. 1). It occupies an area of 412,560 km^2 and a volume of 21,631 km^3 (SEIFERT & KAYSER 1995). Its extension is approximately 1,300 km from north to south and about 1,000 km from west to east. The catchment area is four times bigger. The basin has an average depth of 52 m and reaching 459 m at its deepest point (Landsort Deep). It is subdivided into shallow sills and basins (Fig. 1).
The estuarine circulation in the Baltic Sea is expressed by the inflow of denser saline bottom waters from the North Sea (approximately 900 km^3/yr) and an outflow of low salinity surface water (< 15‰) over the Little Belt (9% of the outflow), the Great Belt (64% of the outflow) and the Öresund (27% of the outflow; GERLACH 1994). Its modern hydrography is characterised by a pronounced continental influence. The river water inflow amounts approximately 479 km^3/yr (GERLACH 1994). The surplus of precipitation over evaporation is around 1800 $m^3\ s^{-1}$ (e.g. EMEIS ET AL. 2003). The surface water salinity records a west to east decreasing gradient with 25‰ in the Kattegat, 6-8‰ in the central Baltic Sea and < 2‰ in the Finnish Bay and the Bothnian Bay (MATTHÄUS 1996). The sills control the inflow and outflow of the water masses into the Baltic Sea (e.g. EMEIS ET AL. 2003). Almost the entire water exchange, approx. 70% according to LASS ET AL. (1987), is

The Western Baltic Sea

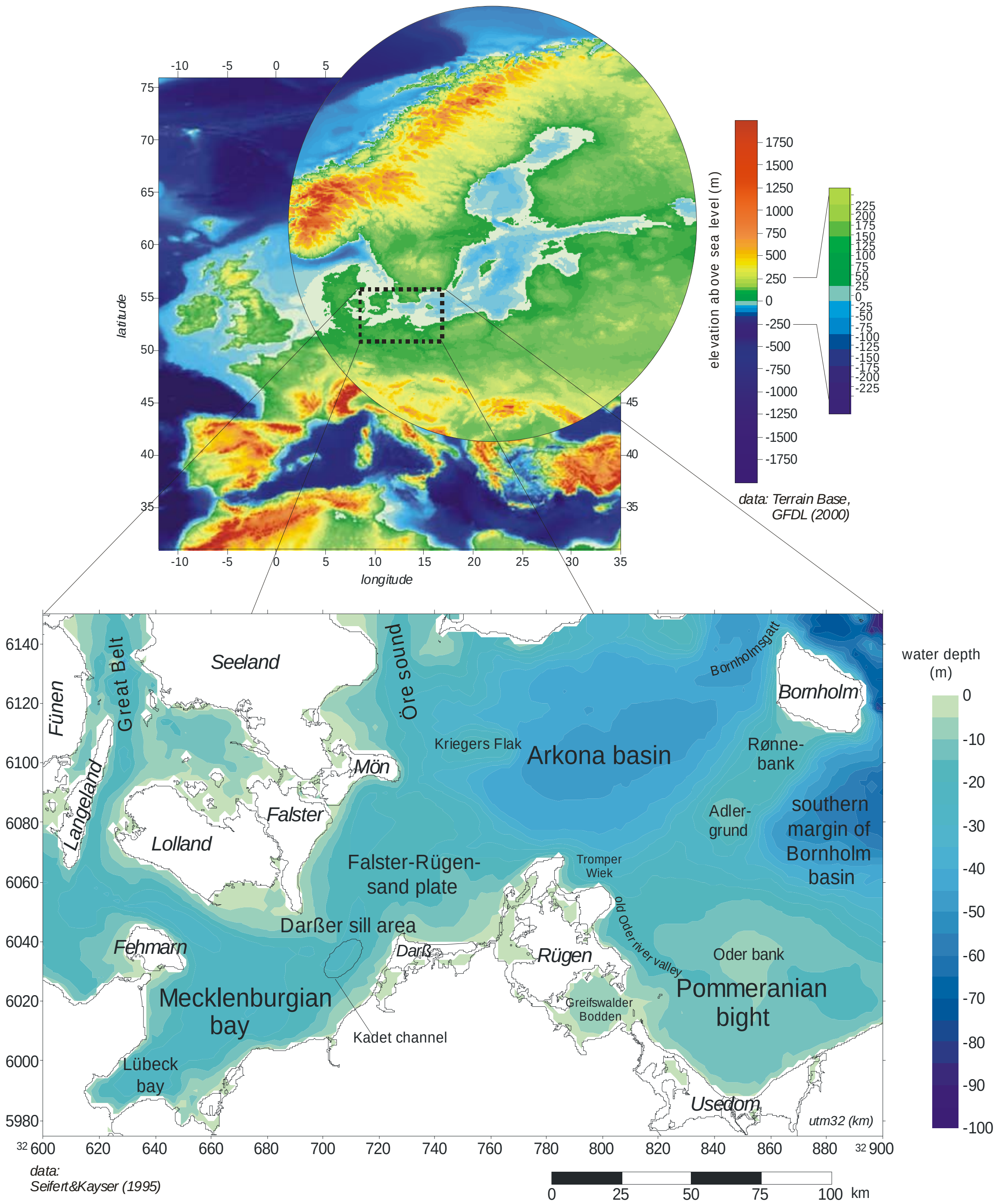


Fig. 1. Bathymetric map of the Western Baltic Sea (Bobertz 2000).

Abb. 1. Bathymetrische Karte der Westlichen Ostsee (Bobertz 2000).

restricted to the pathway between the Kattegat and the Arkona Basin. Considering the hydrodynamic situation, the Darss Sill (24 meter below sea level [mbsl]; LEMKE 1998) acts as a last shallow obstacle in front of the Arkona Basin (Fig. 1). The Darss Sill itself was defined by KOLP (1965) as a 6 sm wide area between the Fischland-Darß Peninsula and the Falster Island, characterised by morains (RICHTER 1937).
The salinity and temperature gradients between the surface waters and the deeper waters lead to a stable stratification in the basinal water columns. The midwater halocline has depths of < 20 m in the Kattegat, 30 m in the Arkona Basin, 60 m in the Bornholm Basin and around 80 m in the Gotland Basin. The permanent haloclines act as a physical border, preventing vertical mixing and thus ventilation of the deep water layers. More detailed information describing the modern hydrography of the Baltic Sea is given in e.g. LASS & MATTHÄUS (1996), LEMKE (1998), EMEIS ET AL. (2003).

According to WATTENBERG (1949), the Mecklenburg Bay and the Arkona Basin are part of the Belt Sea and the Arkona Sea, separated by the Darss Sill (Fig. 1).
The Mecklenburg Bay covers an area of 3,536 km^2 water (KOLP 1965). It is a shallow basin with a varying water depth of 24 to 25 m on average in its centre. The deepest parts occur near the Trollegrund (28 mbsl). Steep margins rising from 20–10 mbsl limit the basin to the north, east and west and are locally shaped like terraces. A connection is established between the northwestern part of the Mecklenburg Bay and the Kiel Bay as well as the Danish Belts through the Fehmarn Belt (KOLP 1965, LANGE 1984). The Darss Sill is located at its eastern margin (Fig. 1). The bottom water has a higher salinity (19-21‰) than the surface water (12-14‰). It is separated from the overlying water by a halocline situated at a water depth of 10 to 20 m.
The Arkona Sea, known as the most western part of the central Baltic Sea, occupies an area of about 18,700 km^2 (NEUMANN 1981). The basin has an average depth of 40 to 45 m, with the greatest depth of 53 m occurring in the Arkona Deep. Areas situated below the 30 m isobath are defined as the actual “Arkona Basin” and cover a quarter of the whole Arkona Sea. The centre of the Arkona Basin is a hollow, surrounded by shallow margins (NEUMANN 1981). In the NE the Bornholmsgat connects the Arkona Basin with the Bornholm Sea. The Arkona Basin is bordered by the Southern-Swedish coast in the N, the Bornholm Island and the shallows Rønnebank and Adlergrund in the E and the SE, the Odra Bank and the Rügen Island in the S and the Falster-Rügen-sand plain in the W (Fig. 1). The halocline is situated at a water depth of 30 m. The salinities of the bottom and surface water contain 16‰ and 12‰ (CRUISE REPORT R/V “GAUSS” 2005).

2.2 The Pre-Quaternary basement

The Pre-Quaternary basement of the western Baltic Sea is strongly structured and affected by tectonics. Especially the Tornquist zone has to be mentioned here due to its important tectonic role. The Tornquist zone is an intra-continental NW-SE trending tectonic lineament separating the Eastern European Platform from the Central European Platform (e.g. WINTERHALTER ET AL. 1981, HARFF ET AL. 2001). The fault zone is approximately 2,000 km long and extends from the Skagerrak in the eastern North Sea Basin in the northwest to the Black Sea in the southeast (Fig. 2). According to KRAUSS (1994), it outlines the southwestern boundary of the Eastern European Platform. It is divided into the Sorgenfrei-Tornquist-Zone (northwestern part) and the Teisseyre-Tornquist-Zone (southeastern part), which are displaced along the Rønne-Graben (Fig. 3). Thus, the study areas cover parts of the Eastern and Western European Platforms.
The Pre-Quaternary development is described in the following, regarding to the study areas. The palaeocontinent Baltica, also known as the East European Craton, was formed during the Neo-Proterozoic. In the early Ordovician crustal segments (Avalonia) separated from Gondwana and drifted to the North. The movement of Avalonia towards Baltica caused the subsequent closure of the Tornquist Ocean. The accretion of sediments of the ocean followed by thrusting onto Neo-

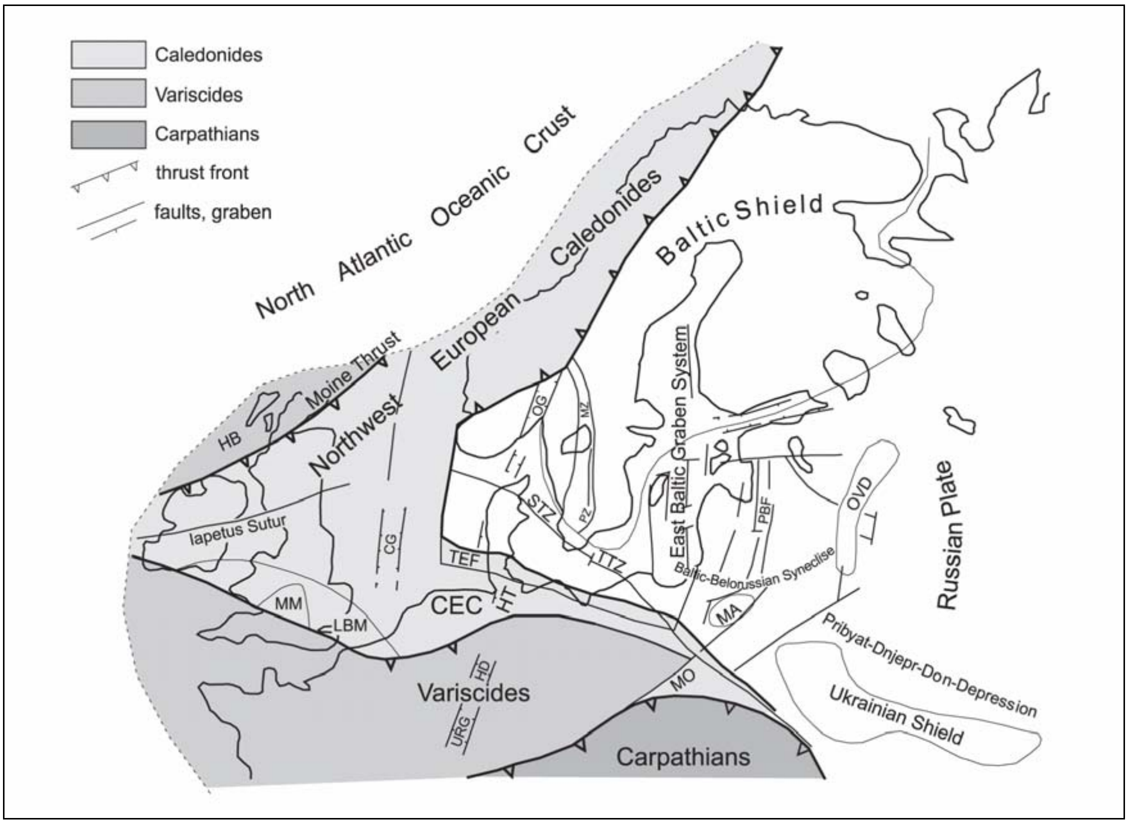


Fig. 2. Regional tectonic units of northern Europe (according to HARFF ET AL. 2001).

HB: Hebridic Shield, MM: Midland Massif, LBM: London Brabant Massif, CG: Central Graben, URG: Upper Rhein Graben, HD: Hessian Depression, HT: Hamburg Trog, OG: Oslo Graben, MZ: Mylonite Zone, PZ: Protegin Zone, MA: Masurian Anteclise, OVD: Orsha-Valday-Depression, PBF: Pribaltic Faults, MO: Moravosilesian, STZ: Sorgenfrei-Tornquist Zone, TTZ: Teisseyre-Tornquist Zone, TEF: Transeuropean Fault.

Abb. 2. Regionaltektonische Einheiten Nord-Europas (aus HARFF ET AL. 2001).

HB: Hebridic Shield, MM: Midland Massif, LBM: London Brabant Massif, CG: Central Graben, URG: Upper Rhein Graben, HD: Hessian Depression, HT: Hamburg Trog, OG: Oslo Graben, MZ: Mylonite Zone, PZ: Protegin Zone, MA: Masurian Anteclise, OVD: Orsha-Valday-Depression, PBF: Pribaltic Faults, MO: Moravosilesian, STZ: Sorgenfrei-Tornquist Zone, TTZ: Teisseyre-Tornquist Zone, TEF: Transeuropean Fault.

Proterozoic Baltica, led to the development of the Caledonian Deformation Front (CDF; Fig. 3).

Wells drilled in the areas of Blekinge, Bornholm and NE of the Rügen Island, north of the CDF, reached undisturbed Palaeozoic deposits below 1 km thick Mesozoic layers. Thus this region is related to the Baltic Shield or the East European Craton. According to KRAUSS (1994), the area situated south to the Caledonian Deformation Front (CDF) can be associated with the transition zone between the Precambrian Shield in the North (Baltic Shield or East European Craton) and the North-German-Polish Trough in the South (Fig. 3). The study area therefore covers parts situated north and south of the Caledonic Deformation Front, i.e. parts of the Eastern and Western European Platforms (see above).
South of the CDF, thick Ordovician deposits were found in drillings on the Rügen Island. Above an angular unconformity (PISKE & NEUMANN 1990) Devonian and Carboniferous sediments follow. The subsequent Variscan orogenesis caused intensive fracturing of the basement, which is discordantly overlain by Westphalian rocks. During the Autun, intensive volcanism led to the intrusion of sills and dykes into Ordovician, Devonian and Carboniferous sediments. Examples of these are manifested by basic effusive products on the Northern Rügen Island. Permian and Mesozoic sediments, characterised by unconformities, cover these deposits. The post-variscian

deposits reached thicknesses up to 10 km, as for example KRAUSS & MÖBUS (1981) assumed for the Mecklenburg Bay.
The Sorgenfrei-Tornquist-Zone (northwestern part) developed during the Permo-Triassic. Due to the Kimmerian orogenesis the Rønne Fault System was established. According to KRAUSS (1994) the formation of the Teisseyre-Tornquist-Zone (southeastern part) was connected to the Alpine orogenesis (Upper Cretaceous and Early Tertiary).
Cretaceous deposits were drilled on the Darss Peninsula (Campanian deposits according to HOTH ET AL. 1993) and on the mainland (Maastrichtian deposits according to LEMKE 1998).
WINTERHALTER ET AL. (1981) described that Tertiary sediments are deposited southwest of a line between Fischland and Falster. HOTH ET AL. (1993) retrieved Palaeogene sediments (drill Rostock 1/1968) and Neogene sediments (near Grevesmühlen) beneath Pleistocene deposits.
A widespread river system, the so-called Baltic Mainstream, cut through the Tertiary landscape and culminates in the Baltic area. It transported clastic material from southern and central Sweden to the southern North Sea, eroding pathways for Pleistocene glaciers (KÖNIGSSON 1979). Quaternary rocks overlying the Pre-Quaternary basement in the study area less than 100 m thick.

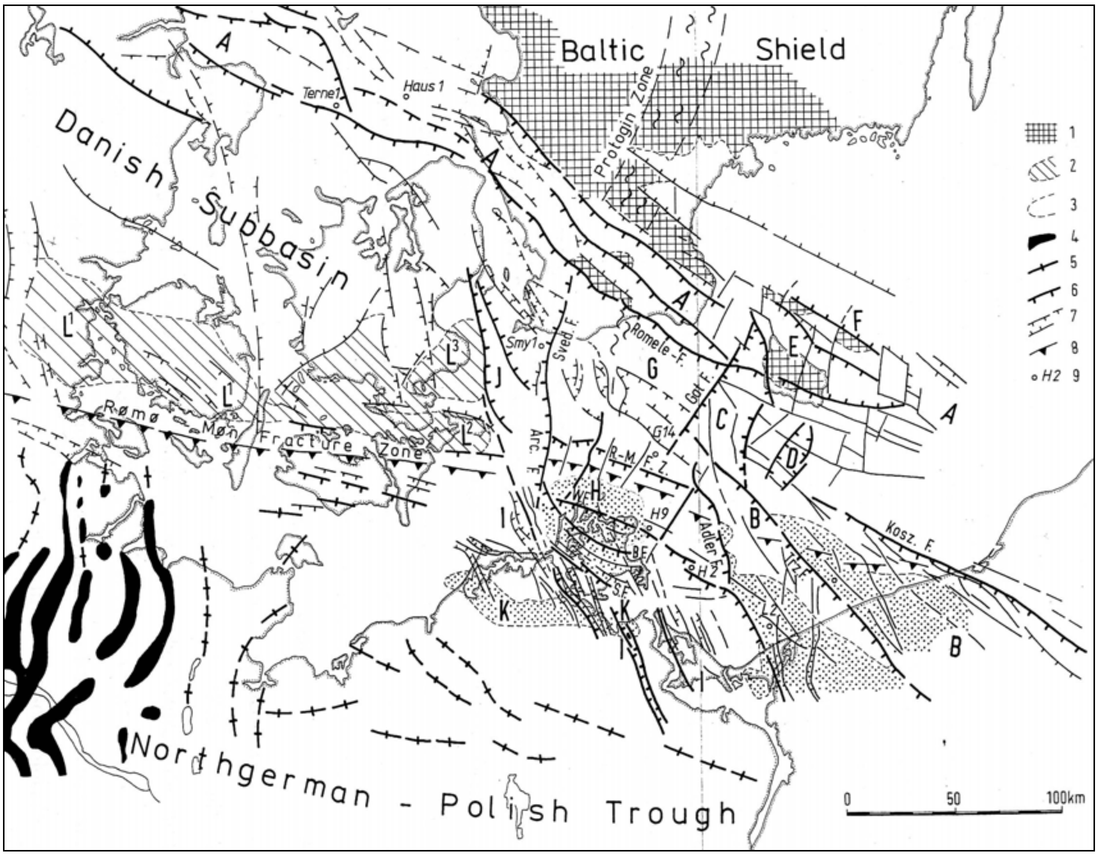


Fig. 3. The structural pattern below the southern Baltic Sea and the adjacent land areas (according to KRAUSS 1994).

1 - crystalline basement; 2 - uplift of the basement below the cover; 3 – swell in the Mesozoic cover; 4 - salt diapir; 5 - salt ridge; 6 - main faults; 7 - faults; 8 - Caledonian Deformation Front (CDF); 9 - offshore boreholes; A - Sorgenfrei-Tornquist Zone; B-Teisseyre-Tornquist Zone; C - Rønne and D - Arnager Fault System; E - Bornholm and F - Christiansø uplift; G - Skurup- and H - Rügen swell; I - Vorpommern and J - Øresund Fault System; K - Grimmen wall; L - Ringkøbing-Fyn-Møn-Swell.

Abb. 3. Struktureller Bau des südlichen Ostseeraumes und der angrenzenden Gebieten (nach KRAUSS 1994).

1 - kristalliner Untergrund; 2 - Hochlage des Kristallins unter dem Deckgebirge; 3 - Schwelle im mesozoischen Deckgebirge; 4 - Salzdiapir; 5 - Salzkissen; 6 - Hauptstörungen; 7 - Störungen; 8 - Kaledonische Deformationsfront (CDF); 9 – Bohrungen im offshore-Bereich; A - Sorgenfrei-Tornquist Zone; B-Teisseyre-Tornquist Zone; C - Rönne und D - Arnager Störungssystem; E - Bornholm und F - Christiansö-Aufragung; G - Skurup- und H – Rügen-Schwelle; I - Vorpommern und J – Öresund-Störungssystem; K - Grimmener Wall; L - Ringköbing-Fyn-Mön-Schwelle.

2.3 The Quaternary development

Climatic fluctuations influenced the Quaternary system in Europe (e.g. West 1977, Donner 1995). During the Quaternary, Scandinavian glaciers moved southwards to Central and Western Europe through the Baltic Sea trough leaving behind glacial sediments. Those glacial deposits were overrun several times by large inland ice. Hardly any evidences of pre-Weichselian glaciations are found in the study area (Lemke 1998). Following, the reconstruction of Elsterian, Holsteinian, Saalian and Eemian deposits within the study area proves to be difficult. Proof for their extension, however, is mainly derived from mainland outcrops, resulting in several local stratigraphic successions of Pleistocene. Table 1 illustrates the subdivision of the Pleistocene in Mecklenburg-Vorpommern:

Tab. 1. Stratigraphy of the Quaternary in Mecklenburg-Vorpommern (modified from Schulz 2003).

Tab. 1. Stratigraphie des Quartärs in Mecklenburg-Vorpommern (verändert nach Schulz 2003).

Holocene		Ages in ^{14}C kyr BP:
		12
Weichselian glacial	Pommeranian advance	
		15
	Frankfurtian advance	
		18
	Brandenburgian advance	
		25
	several interstadials	
		80
Eem-interglacial		
		125
Saalian glacial	Warthe-advance Drenthe-advance	
		200
Holsteinian interglacial		
		250
Elsterian glacial		
		400
Older glacials and interglacials		
		2000
Pliocene		

Deep Pre-Quaternary channels are typical features of the Elsterian glaciation and can be found e.g. in the southwestern Mecklenburgian area (Müller 2004, Müller et al. 2000, Müller & Rühberg 1995, v. Bülow 1967), in the Arkona Basin (Wegerdt et al. 1994) or around Hamburg (Ehlers et al. 1984). They are filled with Elsterian glacial sediments. In southwestern Mecklenburg two Elsterian tills were formed. The so-called Lauenburger glay (glacial layered clay) represents the end of this glacial period (Müller 2004).

The Elsterian glacio-lacustrine Lauenburg clay in the deep channels is covered by limnic, marine and fluvial Holsteinian sediments (LINKE 1986). Due to a climatic optimum in the beginning of this warm stage a transgression covered an extensive area stretching from the Mecklenburgian mainland to the northwest of Brandenburg into the southern Baltic Sea. The Holsteinian transgression recorded the highest sea level rise during the Quaternary (MÜLLER 2004).
The Holsteinian warm stage was followed by the Saalian cold stage, the period during which the glaciation was more extensive than during the previous Elsterian glacial. Exaration by Saalian glaciers formed the Baltic Sea trough. Two glacial advances, mirrored by the Drenthe and Warthe tills, were formed during the Saalian glacial period.
The following transgression of the Eem interglacial ran over the southern Jutland into the southern Baltic Sea and adjacent bays and river mouths (Lübeck Bay, Trave, Wismar Bay, Warnow, Peene). Marine sediments were deposited in the underflows of the Warnow and Trave rivers, limnic ones in the vicinity of the recent Schwerin Lake and the Trollense Lake.
At least one glaciation (Warnow glaciation) is assumed between the Eemian interstadial and Weichselian glacial, interpreted as a connection between the Danish, Schleswig-Holsteinian and Polish Weichselian advances (MÜLLER 2004).
During the Late Weichselian glacial the inland ice advanced several times forming end moraines in front of the retreating ice margin and related ground moraines. The subdivision of the Weichselian glacial includes the following advances (according to DUPHORN ET AL. 1995):

(i) <u>Brandenburgian/Frankfurtian advance (W1)</u>

A maximal age of 20,000 ^{14}C yr BP is assigned to the Brandenburgian advance. Glaciers of the following Frankfurtian advance overran previous ones between 18,500 - 17,000 ^{14}C yr BP (SCHULZ 1967), leaving more concise morphological features. During the Blankenburgian interstadial inland ice retreated up to the southern Baltic Sea.

(ii) <u>Pommeranian advance (W2)</u>

The maximal advance was dated to 15,200 - 14,800 ^{14}C yr BP and separated into two thick ground moraines (W2u, W2o). Between 14,800 - 13,200 ^{14}C yr BP, glaciers melted culminating in a warm stage around 13,600 - 13,500 ^{14}C yr BP. This interstadial is correlated to the Lockarp interstadial in southern Sweden.

(iii) <u>Mecklenburgian advance (W3)</u>

The term Mecklenburgian advance was introduced by EIERMANN (1984). RÜHBERG (1987) recorded its widespread distribution in Mecklenburg-Vorpommern. This advance is subdivided into smaller advances: Rosenthal, Velgast and Nordrügen “Staffel”. The existence of the "Nordrügen Staffel", however, is still controversial (RÜHBERG ET AL. 1995). A time-related classification and the correlation of this advance with other advances in neighbouring regions of the southern Baltic Sea were discussed in e.g. LEMKE & NIEDERMEYER (2004), DUPHORN ET AL. (1995), STEPHAN (1994), RÜHBERG (1987), LANGE (1984) and WINN ET AL. (1982).

Generally, the advances of Late Weichselian age formed the present landscape in Northern Germany. The Late Weichselian was interrupted by several interstadials of short duration (Meiendorf-, Bølling-, Allerød-Interstadial). Periods of colder phases are referred to as Oldest, Older and Younger Dryas (e.g. DONNER 1995). The melting of the high-glacial inland ice occurred around 13,000 ^{14}C yr BP. The margin of the inland ice retreated to the North, exposing the young moraine landscape. Tundra and permafrost disappeared resulting in the establishment of forests, lakes and marshes. These developments marked the commencement of the Holocene period.

2.4 The post-glacial history of the Baltic Sea

Generally, four major stages in the post-glacial development of the Baltic Sea have been identified in litho- and biostratigraphic records: the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Littorina Sea stage (e.g. MUNTHE 1940, ERONEN 1974, GUDELIS & KÖNIGSSON 1979). They were mainly influenced by oscillating sea level (water level high stands and low stands), furthermore by glacio-isostasy (uplift and subsidence). A detailed description of these Baltic Sea stages, covering the Late Pleistocene and the Early Holocene, is given by e.g. BJÖRCK (1995), JENSEN ET AL. (1997) and BENNIKE & JENSEN (1998).
MOROS (1998) and MOROS ET AL. (2002) observed sandy layers (S_{ab} - S_{ef}), reflected by sharp spikes in the variation of the weight percentage (wt%) of the grain-size fraction > 63 µm in the Arkona Basin. The sandy layers were interpreted to reflect episodes of basin-wide water-level low stands, resulting from water-level drops during the early stages of the Baltic Sea's history. In the following, the development of the Baltic Sea stages are correlated to these sandy layers with regard to the study areas (Tab. 2).
Note that all ages are given as uncorrected ^{14}C ages in this PhD work.

2.4.1 The early stages: The Baltic Ice Lake, the Yoldia Sea and the Ancylus Lake stage

The Baltic Ice Lake (13,500 – 10,300 ^{14}C yr BP)

The margin of the inland ice (Fig. 4a, 4b) retreated rapidly back to the North between 13,500-13,000 ^{14}C yr BP (e.g. LUNDQUIST 1986, BJÖRCK 1995) resulting in the formation of meltwater lakes and glaciers, described as the little known "embryonal" Baltic Ice Lake (BIL; LEMKE 1998). BJÖRCK (1995) assumed a connection between the southern Baltic and Kattegat via the Öresund for this early Baltic Ice Lake stage.
According to BERGSTEN & NORDBERG (1992) this connection existed furthermore between 12,600-12,000 ^{14}C yr BP. They documented high sedimentation rates in the southeastern Kattegat due to erosion of the Öresund threshold area, as a result of its isostatic uplift. Large parts of the southern Baltic, as well the study area, became ice-free. In the period 12,500 ^{14}C yr BP the Baltic Ice Lake covered the Hanö Bay in the NE, the Bornholmsgat and the northern part of the Arkona Basin (JENSEN 1992). According to e.g. JENSEN ET AL. (1997) and LEMKE (1998) it extended up to the Darss Sill.
At around 12,000 ^{14}C yr BP (BJÖRCK 1995) the isostatic uplift of the Öresund threshold could no longer be compensated by erosion as the Cretaceous bedrock, resistant against erosion, had already been reached (at approximately 8 mbsl in the southern Öresund). The water level of the Baltic Ice Lake rose. According to MOROS (1998) and LEMKE (1998) sediments of clay were deposited in the Mecklenburg Bay and the Arkona Basin (corresponding to Baltic Ice Lake I or *LStU* AI in Tab. 2).
A new connection between the Kattegat and the Baltic Ice Lake caused a drainage of the Baltic Ice Lake at Mt. Billingen in southern central Sweden at the end of the Alleröd around 11,200 ^{14}C yr BP (BJÖRCK 1995). The so-called *Billingen-1* drainage (according to BODÉN ET AL. 1997) is reflected by a characteristic sandy layer subdividing the clayey deposits of the Baltic Ice Lake into the units AI and AII (see Tab. 2). Several studies (e.g. BJÖRCK 1979, GUDELIS 1979, KESSEL & RAUKAS 1979, SVENSSON 1989) report a rapid fall of the water level in the Baltic Ice Lake. The range for the amount of the fall differs between 5 and 60 m.
Owing to a Younger Dryas glacial re-advance of the Scandinavian ice sheet the *Billingen-1* outlet was closed around 10,800 ^{14}C yr BP. It led to a renewed damming of the Baltic Ice Lake (Fig. 4c) up to e.g. 13 mbsl in the Faxe-Bay (JENSEN 1992). In the Arkona Basin the deposition of sediments with a more distal character began (corresponding to Baltic Ice Lake II or *LStU* AII in Tab. 2). For the first time the Baltic Ice Lake reached the Darss Sill from the eastern side (LEMKE 1998).

Tab. 2. Late Pleistocene and Holocene development of the Mecklenburg Bay and the Arkona Basin: an overview (modified by LEMKE 1998 and MOROS 1998). Baltic Sea stages according to BJÖRCK (1995), chronozones according to DUPHORN ET AL. (1995), seismo-stratigraphic units (*SstU*) according to LEMKE (1998) and lithostratigraphic units (*LStU*) according to MOROS (1998) and MOROS ET AL. (2002). Ages are given as uncorrected ^{14}C ages (^{14}C yr BP).

Tab. 2. Spätpleistozäne und holozäne Entwicklung der Mecklenburger Bucht und des Arkona Beckens: Ein Überblick (verändert nach LEMKE 1998 und MOROS 1998), der die Ostsee-Stadien (BJÖRCK 1995), die Chronozonen (DUPHORN ET AL. 1995), seismostratigraphische Einheiten (*SstU*; LEMKE 1998) und lithostratigraphische Einheiten (*LStU*; MOROS 1998, MOROS ET AL. 2002) umfaßt. Die Altersangaben beziehen sich auf unkalibrierte ^{14}C Alter (^{14}C a BP).

	^{14}C yr BP	Chronozones according to Duphorn et al. (1995)	Baltic stages according to Björck (1995)	Mecklenburg Bay, according to Lemke (1998): *SstU*	Sediments	Palaeo-geography	Arkona Basin, according to Lemke (1998): *SstU*	Sediments	Palaeo-geography	according to Moros (1998): *LStU*	Sandy layer
Holocene			Mya Sea								
	1000	Subatlanticum	Lymnaea Sea								
	2000				mud, sandy in marginal areas	brackish-marine basin		mud, fine sandy in marginal areas	brackish-marine basin	F	
	3000	Subboreal					E5				
	4000		Littorina Sea	W5	sand above 20 m water depth						
	5000										
	6000	Atlanticum									S_{ef}
	7000		Mastogloia Sea		silt, sand, partly with humous layers	local fresh-water lake with occasional marine intrusions	E4		freshwater lake with occasional marine intrusions	E	
	8000	Boreal	Ancylus Lake	W4	silt, peat, peat gyttja, calcareous silt, lake marl, sand	local fresh-water lake		silt, silty clay, peat gyttja in marginal areas	freshwater lake		
	9000					short connection to Arkona Basin				D	S_{de}
		Preboreal	Yoldia Sea			local fresh-water lake			freshwater lake	C	S_{cd}
	10000					short connection to Arkona Basin	E3	fine sand, clay, silty, silt in marginal area		B	S_{bc}
Pleistocene		Younger Dryas								AII	S_{ab}/ Billingen-2
	11000	Alleröd-Interstadial	Baltic Ice Lake proper	W3	clay, sand, peat and peat gyttja at marginal basin	local fresh-water lake		fine sand	freshwater lake		Sand/ Billingen-1
	12000	Older Dryas; Bölling-Interstadial; Oldest Dryas; Meiendorf-Interstadial		?; W2	clay, sand, gravel	local fresh-water lake	E2	clay, local grain sand and gravel	freshwater lake	AI	
	13000	Mecklenburgian Stadium; Lockarp-Interstadial	First Baltic Ice Lake stage	W1	till		E1	till			

Around 10,300 ^{14}C yr BP a final drainage (*Billingen-2*), characterised by a rapid 25 m fall of the BIL water-level, ended the Baltic Ice Lake stage at the Younger Dryas – Preboreal boundary (Pleistocene – Holocene boundary; Fig. 4d).

BODÉN ET AL. (1997) also assumed a 25 m fall of the water level in the Arkona Basin caused by a connection to the Bornholm Basin via the Bornholmsgat. The drastic regression resulted in the formation of the most prominent sandy layer S_{ab} (according to MOROS ET AL. 2002) in the Arkona Basin (Tab. 2).

LEMKE (1998) described the isolation of a local lake in the Mecklenburg Bay (water level: 23 mbsl) due to the finale drainage of the Baltic Ice Lake (Fig. 4d) and its drainage into the Arkona Basin (water level: 35 mbsl) through a flat channel system, which was incised into the sandy Falster-Rügen-Plane.

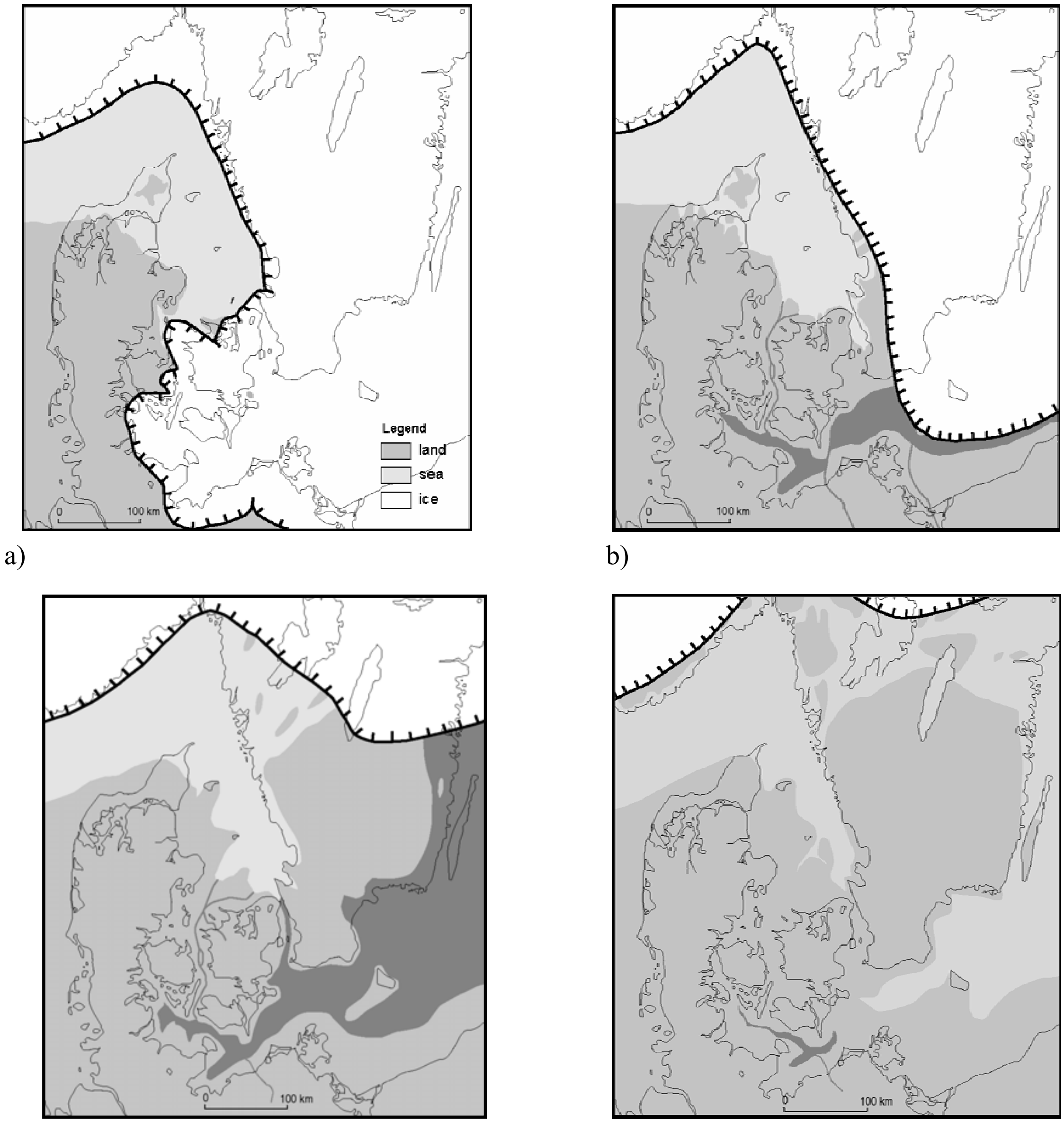


Fig. 4. Palaeogeographical maps with a) Weichselian Late glacial, b) Baltic Ice Lake formation c) Baltic Ice Lake and d) Finale drainage of the Baltic Ice Lake - beginning of the Yoldia Sea (after JENSEN ET AL. 2002).

Abb. 4. Paläogeographische Karten: a) Weichsel-Spätglazial, b) Bildung des Baltischen Eisstausees, c) Baltischer Eisstausee und d) Finale Drainage des Baltischen Eisstausees - Beginn des Yoldia Meeres (nach JENSEN ET AL. 2002).

The Yoldia Sea (10,300 – 9,500 ^{14}C yr BP)

According to ALLEY ET AL. (1993) a rapid and global warming (= Holocene warming) characterised the beginning Yoldia Sea stage. Until 10,000-9,900 ^{14}C yr BP no evidence for marine waters entering the Baltic was found. Arctic *Portlandia (Yoldia) arctica* shells and diatoms reflected the intrusion of salinar waters through the south-central Swedish lowlands for a short brackish phase (BJÖRCK 1995). According to STRÖMBERG (1989) and WASTEGÅRD ET AL. (1994) this brackish phase lasted 100-200 years (with respect to clay-varve stratigraphy). It occurred along the Swedish coastline down to the Hanö Bay (BJÖRCK ET AL. 1990), but is also known from other studies in Finland (e.g. ERONEN 1974), Estonia (e.g. KESSEL & RAUKAS 1979) and Latvia (e.g. VEINBERGS 1979). Several authors doubt that marine waters entered other Baltic areas out of the Swedish coastal waters (RAUKAS 1990, 1991). For example ABELMANN (1985, 1992) and BENNIKE & LEMKE (2001) found no indications of marine influences in the Bornholm Basin and Arkona Basin, respectively. The occurrence of the short brackish phase and the extension of the Yoldia Sea are still under discussion.
In the southern and western Baltic areas environmental conditions changed considerably after the final Baltic Ice Lake drainage (LEMKE 1998). Due to the ending outlet-function of the Öresund, a large land-bridge was formed between today's northern parts of Germany, the Danish islands and Skåne during the Yoldia Sea stage (BJÖRCK 1995). Bornholm was connected to today's German mainland (Fig. 4d). Only the deepest parts of the Arkona Basin were still covered with water (JENSEN ET AL. 1997, LEMKE 1998). The sedimentation in the Arkona Basin reflects stagnant or slightly rising water levels and a generally low water level during the deposition of the lithostratigraphic units B and C, respectively (MOROS 1998; Tab. 2). According to MOROS ET AL. (2002) the sandy layer S_{bc} is less distinct than S_{cd}. The latter seems to reflect the Yoldia regression as described by GLÜCKERT (1995) and BJÖRCK (1995).
Glacio-isostatic uplift closed the south-central Swedish connection between the Baltic Sea and the ocean (BJÖRCK 1995). Around 9,500 ^{14}C yr BP the Baltic Sea was re-dammed again. A new stage, the Ancylus Lake stage, named after the mollusc *Ancylus fluviatilis,* began (*LStU* D and E in Tab. 2).

The Ancylus Lake (9,500 – 8,000 ^{14}C yr BP)

Except for the northern territories of the Baltic Sea, the isostatic uplift in the southern Baltic area had almost ceased or turned into land subsidence. The damming up of the Ancylus Lake, between 9,500 and 9,200 ^{14}C yr BP (BJÖRCK 1995), created a significant trangression in the southern Baltic (*LStU* D in Tab. 2; Fig. 5a). SVENSSON (1989) and BJÖRCK (1995) characterised this transgression as being fast, (i.e. a rise of water level of 5-10 m in 100 years) and thus flooded large areas, causing significant changes of the coastline. Several publications presented different highlevel water depths for the Ancylus Lake, e.g. 20 mbsl (KOLP 1965, BJÖRCK 1995), 18 mbsl (JENSEN ET AL. 1997, LEMKE 1998), 12 mbsl (KOLP 1986, ERONEN ET AL. 1990), 8 mbsl (KLIEWE & JANKE 1982, 1991). LEMKE (1998) stated that a short connection between the Mecklenburg Bay and Arkona Basin might have existed.
A regression around 9,300 ^{14}C yr BP (SVENSSON 1991), 9,200 ^{14}C BP (BJÖRCK 1995) or 8,700 ^{14}C BP (KLIEWE & JANKE 1982, 1991) caused a rapid fall of the Ancylus Lake's water level (S_{de} in Tab. 2; Fig. 5b). Data differ between a 10 and 25 m water level fall (e.g. GUDELIS 1979, ERONEN 1983, KESSEL & RAUKAS 1979, SVENSSON 1989, 1991). The discussions with regard to the drainage path of the Ancylus Lake are still controversial (e.g. BJÖRCK ET AL. in prep.). The water level of the Ancylus Lake dropped in 200 years (BJÖRCK 1995). Following, a connection between the Ancylus Lake and Kattegat must have existed. KOLP (1986) and BJÖRCK (1995) favoured a drainage pathway for the Ancylus Lake over the Darss Sill, the Fehmarn Belt and the Great Belt into the Kattegat. According to VON POST (1929) the water must have been discharged through the so-called Dana River. BENNIKE ET AL. (1998), LEMKE (1998), JENSEN ET AL. (1999) and LEMKE ET

AL. (1999) disagreed with this Dana River concept. Their results did not confirm the draining of the Ancylus Lake through the Dana River. They argue that river deposits must have been incised to a depth level of 32 mbsl if the Dana River drained along the described pathway of the other authors (see above). During the regression, the water level of the Ancylus Lake dropped to 23 mbsl (LEMKE 1998). The Mecklenburg Bay is characterized by fine-grained basin deposits and shows no signs of prograding systems and/or progressive incision as a result of a catastrophic overflow of the Darss Sill by the Dana River (JENSEN ET AL. 1997). Therefore LEMKE (1998) suggested to search for a drainage pathway in other places rather than in the Darss Sill area.
Between 9,000 and 8,000 ^{14}C yr BP a connection between the Ancylus Lake and the Kattegat existed, broad enough to prevent a new damming of the Ancylus Lake (*LStU* E in Tab. 2). Apart from the Arkona Basin and a lake situated in the deepest part of the Mecklenburg Bay, former large coastal areas were again connected to the mainland and were covered by small lakes and swamps (LEMKE 1998).

a) 

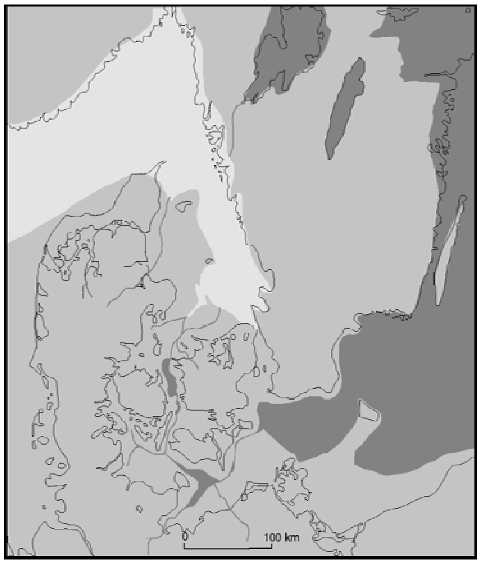
b) 

Fig. 5. Palaeogeographic maps with a) Ancylus Lake transgression – maximal extension and b) Ancylus Lake regression (according to JENSEN ET AL. 2002).

Abb. 5. Paläogeographische Karten: a) Höchststand des Ancylus Sees und b) Situation nach der Regression des Ancylus Sees (nach JENSEN ET AL. 2002).

2.4.2 The Littorina transgression, the Littorina Sea and the post-Littorina Sea

LINDSTRÖM (1886) introduced the term “Litorina-Sea” for the first time, discussing two postglacial deposits in the Gotland Basin, (i) the older Littorina and (ii) the younger Lymnaea deposits, derived from findings of molluscs *Littorina littorea* and *Lymnaea ovata*. First data referring to the Littorina Sea stage are published in Swedish papers by DE GEER (1882, 1890), MUNTHE (1910) and VON POST (1933).

The Holocene climatic optimum (HYVÄRINEN ET AL. 1988, DAVIS ET AL. 2003) was responsible for the changing global ice volume, the sea level rise, the continued land uplift in Scandinavia and the subsidence in the southern Baltic Sea area during the middle Holocene. It caused a rapid flooding of the Baltic Sea, the so-called Littorina transgression (e.g. YU 2003). The partial collapse of the Antarctic ice sheet probably initiated an increased meltwater discharge (BLANCHON & SHAW 1995), resulting in a global sea level rise. A connection with the sea through the Danish Straits was

opened due to this eustatic sea level rise and the subsidence (BJÖRCK 1995). The Danish Straits were submerged, brackish water entered the Baltic basin and the Littorina Sea was formed.
The inflow of saline waters, i.e. the Littorina transgression, caused a transformation of the entire Baltic Basin´s hydrography from the fresh-water Ancylus Lake into the brackish-marine basin of the Littorina Sea. In this context, the Mastogloia Sea stands for as a transitional phase between these two stages (KROG 1979, HYVÄRINEN ET AL. 1988). This phase is named after the diatom genus *Mastogloia* Thwaites (SUNDELIN 1922, MILLER & ROBERTSSON 1979). Stratigraphically the Mastogloia phase is poorly defined, i.e. evidences have been found in coastal area but not in deeper basin sediments (WINTERHALTER ET AL. 1981, IGNATIUS ET AL. 1981). Brackish-water diatoms, including several species of the genus *Mastogloia*, indicate the development of low surface salinity there (e.g. BERGLUND 1964, BERGLUND ET AL. 2005). Many investigators do not recognise the Mastogloia phase as an independent or existent unit (e.g. KESSEL & RAUKAS 1979). In some studies of deeper basin sediments (e.g. ANDRÉN ET AL. 2000) the term "Initial Littorina Sea" was introduced and used as a phase between first marine inflows into the Baltic Sea and the establishment of full brackish conditions around 1,000 years later (HYVÄRINEN 1988).
Several studies (e.g. SOHLENIUS ET AL. 1996, SOHLENIUS & WESTMAN 1998, ANDRÉN 1999) describe an increase in salinity in the early phase of the Littorina Sea, accompanied by changes in diatom assemblages and a rapid increase in organic carbon content.
The onset of the Littorina Sea is a metachronous event (HYVÄRINEN ET AL. 1988). In several publications (e.g. HYYPPÄ 1937, SAURAMO 1940, 1958, DONNER 1964, 1965, 1966, 1969, CHRISTENSEN 1995, DUPHORN ET AL. 1995, YU 2003) the term "Littorina transgression" is assigned to a number of sub-phases, differing between two to six transgressions. On the other hand ERONEN (1974) concluded that only one major transgression for the whole Baltic basin took place.
Previous investigations report a wide range of dates regarding the timing of the Littorina transgression. Thus, BERGLUND ET AL. (2001, 2005) claim that first signs of brackish conditions are dated back to 8,900 ^{14}C yr BP in Blekinge, SE Sweden. According to these investigations full marine conditions were established in Blekinge already at 7,750 ^{14}C yr BP. ANDRÉN ET AL. (2000) documented that the first inflows of marine waters into the Bornholm Basin occurred around 8,900 ^{14}C yr BP, too. According to BJÖRCK (1995) "a sea level dependent marine transgression over the Öresund threshold" caused "the first saline influence of the Baltic after the Ancylus transgression", recorded around 8,200 ^{14}C yr BP. His conclusion was based on studies by MÖRNER (1979), which showed that the uplift in this region ceased, and FAIRBANKS (1989), that a rapid sea level rise of > 1 cm/yr inundated the Öresund threshold. A distinct increase in the number of marine diatoms, thus indicating the onset of the marine-brackish Littorina Sea stage, has been dated to 8,500-8,000 ^{14}C yr BP in the Mecklenburg Bay. These data were derived from the pollen stratigraphy of a core situated in the central part of this basin (ERONEN ET AL. 1990). Furthermore, LANGE (1984) reported first brackish-marine influences in the Mecklenburg Bay from around 8,300 ^{14}C yr BP (bulk dates). Peat layers found in the cores of the Kiel Bay are thought to mark the oldest possible age of a marine influence and are dated to 7,700 ^{14}C yr BP (WINN ET AL. 1986). JENSEN ET AL. (1997, 2005) and BENNIKE ET AL. (2004) identified a first marine ingression in the central Store Belt area, i.e. between the fully marine Kattegat and the brackish Baltic basin, at 7,700 ^{14}C yr BP (dated on marine shells).
In addition, relative sea level (RSL) and eustatic sea level (ESL) curves (Fig. 6) demonstrate a sharp increase of the water level from deeper than 20 mbsl to 5 mbsl between 8,000 and 6,000 ^{14}C yr BP in the south-western Baltic Sea (e.g. KÖSTER 1961, MÖRNER 1976, KROG 1979, DUPHORN 1979, KLIEWE & JANKE 1982, 1991, JANKE & LAMPE 2000, KOLP 1986), an area where the modern glacio-isostatic uplift is nearly negligible. The shape and the gradient of the several curves vary strongly (Fig. 6). However, they reflect a steep sea level rise linked to the Littorina transgression (LEMKE 1998).

As mentioned in the beginning, the general picture of this development is known, but many details regarding the onset of the Littorina transgression, the search for well-dated palaeo-environmental proxies that are indicative of this event and the question of which passage was opened first for the inflowing marine waters from the Kattegat are still controversial.

Between 7,900 and 7,300 ^{14}C yr BP the global sea level rose rapidly and is reflected as a fast water level rise of 2.5 cm per year in the southern and western Baltic Sea (KLIEWE & JANKE 1982, KLIEWE 2004). It caused extreme environmental changes and influenced the coastal configuration there. Until 5,700 ^{14}C yr BP the sea level rise slowed down to 0.3 cm per 100 years (KLIEWE & JANKE 1982). At that time, the Baltic Sea water level was 1 m less than the recent ones (LEMKE 1998). Afterwards no stronger significant water level changes occurred.

Findings of *Littorina littorea* record the higher salinity compared to the recent ones during the Littorina Sea stage 8,000-2,000 ^{14}C yr BP (EKMAN 1953). The salinity in the Baltic Sea decreased around 2,000 ^{14}C yr BP, defining a new phase referred to as the Lymnaea Sea, named after the mollusc *Lymnaea ovata baltica* (SAURAMO 1958). The present Baltic Sea has been called the Mya Sea (HESSLAND 1945) after the mollusc *Mya arenaria*. This phase started 500 years ago (e.g. LEMKE 1998). New investigations prove the existence of *Mya arenaria* for a much longer period than believed so far. Records show that they must have lived in the Baltic Sea for the last 1,000 years (PETERSON ET AL. 1992, BEHRENDS ET AL. 2005).

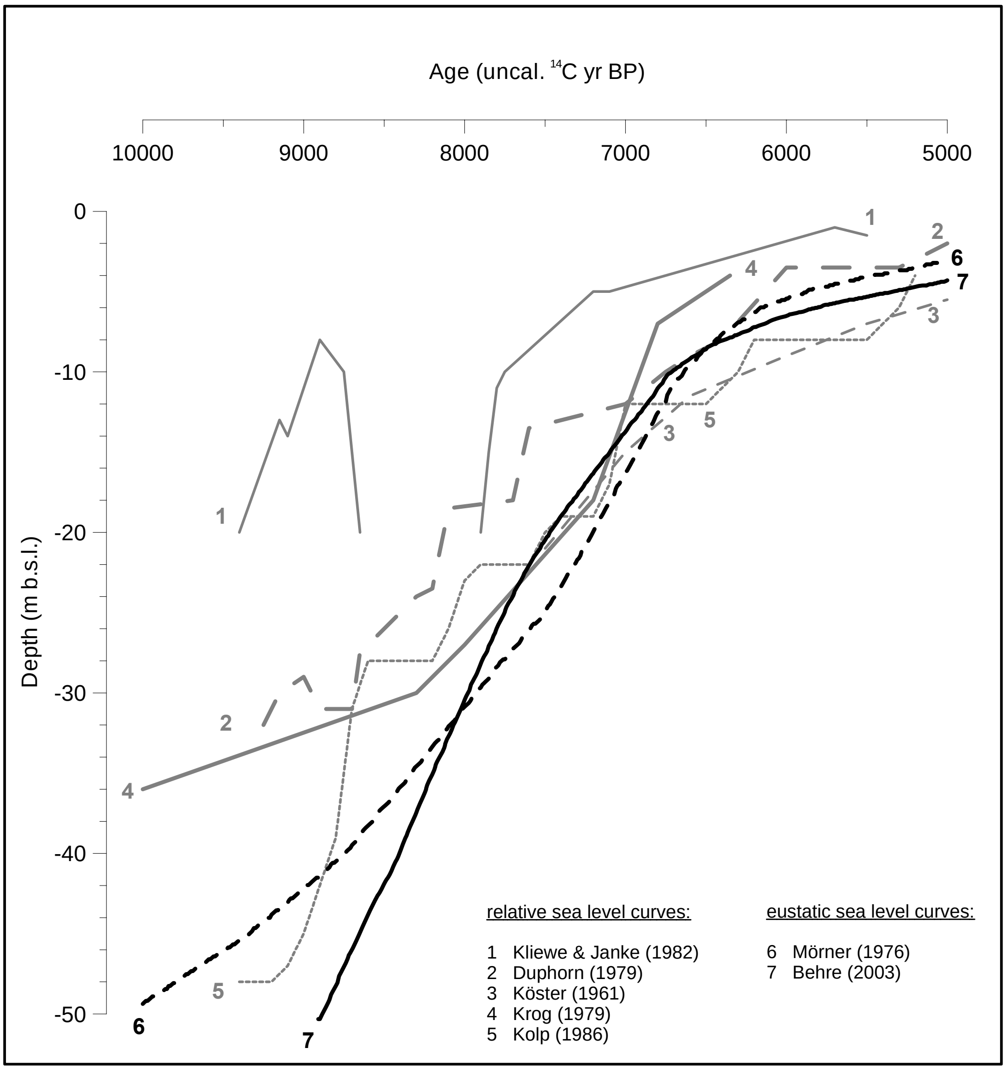


Fig. 6. Published relative and eustatic sea level curves from the south-western Baltic Sea. Modified according to LEMKE (1998).

Abb. 6. Veröffentlichte relative and eustatische Meeresspiegelkurven der südwestlichen Ostsee. Verändert nach LEMKE (1998).

3 Methods

3.1 Work program and material

The objective of the study aims at a detailed reconstruction of the Littorina transgression in the western Baltic Sea in a high spatial and temporal resolution. Therefore well-dated palaeo-environmental proxies should be searched to tackle this problem. WEFER ET AL. (1999) define proxy variables (short: “proxies”) as measurable descriptors for desired (but unobservable) variables. They deliver information for reconstructing environmental parameters (target parameters) such as surface water temperature, salinity, nutrient content, oxygen content, carbon dioxide concentration, wind speed, and productivity (WEFER ET AL. 1999). Estimating a single target parameter by using more than one proxy describes the so-called multi-proxy approach. Table 3 shows the concept of the multi-proxy approach set up for this PhD thesis. Care should be taken when interpreting proxies because evolutionary change of biotic signal carriers or assemblages as well as post-depositional processes (e.g. dissolution, bioturbation, redox reaction) can occur (WEFER ET AL. 1999).

Tab. 3. Concept of the multi-proxy approach for this work (modified after WEFER ET AL. 1999).

Tab. 3. Abriß des verwendeten Multi-Proxie-Ansatzes in Anlehnung an WEFER ET AL. (1999).

Target parameter	*Proxy*	*Basic assumption(s)*
Bottom transport/ dynamic pattern	Distribution of grain size fraction > 63 µm Bulk density Water content GRAPE density Mineral magnetic properties	Variations are displayed in composition of sediments (e.g. deposition of coarser material due to changed current pattern). Displacement of particles occur.
	Si content	Conclusion to sand content by excluding biota Si-components
	$\delta^{13}C$ of bulk	Admixture of terrestrian organic carbon
Biological production/ productivity	TOC content	Organic carbon accumulation rate is proportional to organic carbon flux and production.
	Transfer function	The benthic community depends on organic matter input from surface. The impact of food supply dominates small physicochemical changes.
	$\delta^{13}C$ of bulk	CO_2 fixing enzyme of marine phyto-plankton has a higher affinity for ^{12}C. Hence, increased primary production enriches ocean surface waters in ^{13}C.
	Biota distribution (micro- and macrofossil assemblages): e.g. accumulation of benthic foraminifers	Accumulation or blooms indicate high productivity.
	P content	P-flux is related to organic carbon flux.
	Carbonate content	Carbon flux is related to the carbonate flux and therefore to productivity. A regional quantitative correlation between $CaCO_3$ and TOC can be assumed.
Salinity	Biota distribution (micro- and macrofossil assemblages): e.g. diatoms, foraminifers, plants	Affinity to brackish- marine or limnic conditions is shown.
	C/S	According to Berner & Raiswell (1984) a mean C/S ratio of 2.8 identifies marine conditions.
	Elemental distribution (e.g. Mg)	Changes in elemental concentrations reflect changes in water chemistry.
Terrestrial input	Pollen	Representation of the vegetation
	Freshwater diatoms and limnic water plant/plant remains	Extent of lakes and mainland, Fluvial input
Marine vs. terrestrial productivity	$\delta^{13}C$ of bulk	C3 (mainly marine) and C4 (mainly terrestrial) plants differ in their isotopic composition: -20% for marine and -27% for terrestrial C_{org}.
	C/N	Organic matter of terrestrial origin generally has C/N ≥ 15; marine organic matter usually has C/N = > 5.

Sediment-physical, sedimentological, geochemical and palaeontological investigations based on detailed sub-sampling of crucial core sections were planed (Fig. 7) in order to provide information

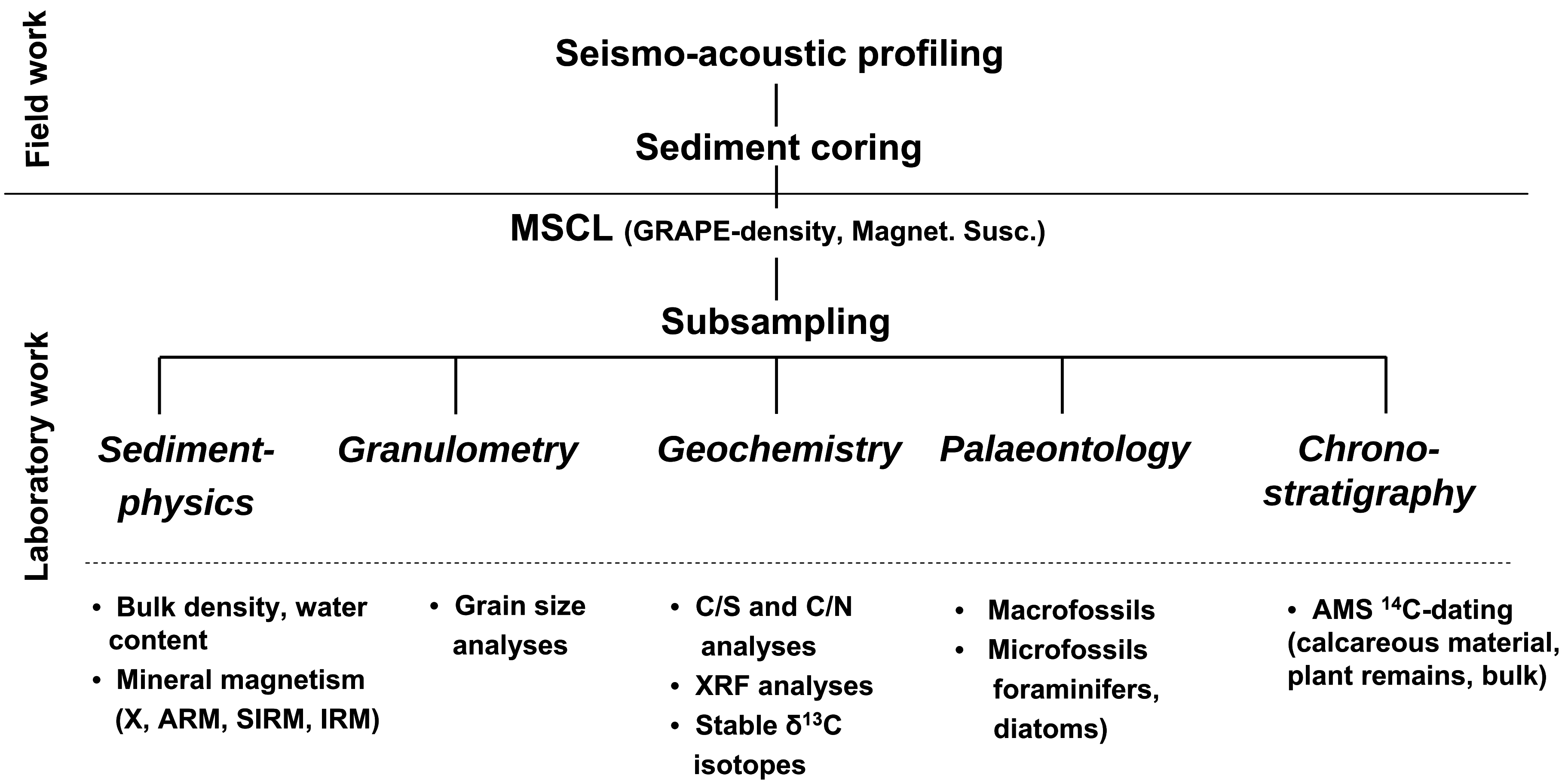


Fig. 7. Work program, subdivided into different fields and methods.

Abb. 7. Das Arbeitsprogramm, unterteilt in die verschiedenen Arbeitsfelder mit den angewandten Methoden.

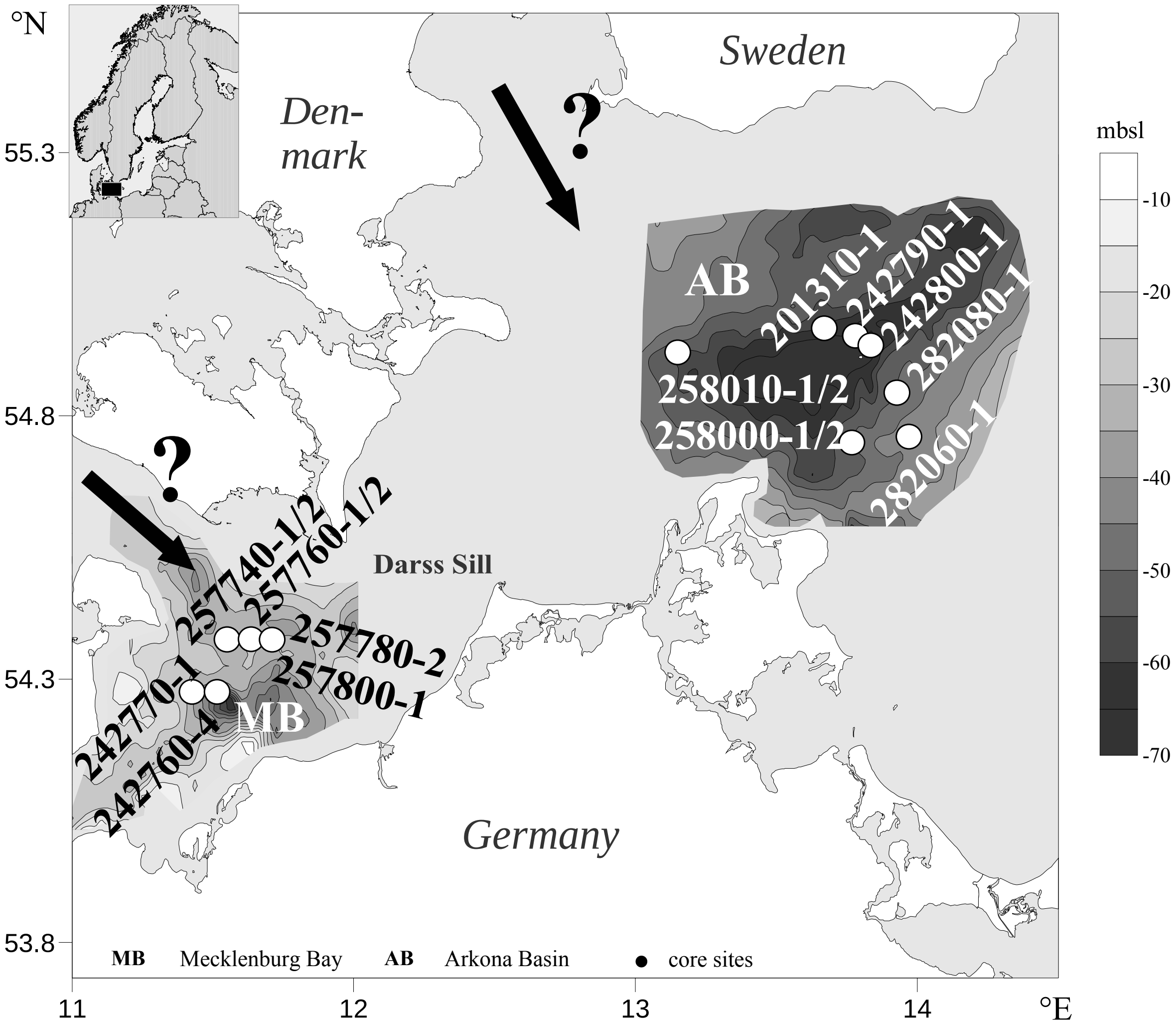


Fig.8. Investigation area with the core sites (points) from the Mecklenburg Bay (western part) and the Arkona Basin (eastern part; Tab. 4 includes the core locations), which is also shown as the black box in the small map. Black arrows show possible pathways of the Littorina transgression, which should be defined during this work. The depth of the uppermost till surface (isolines in mbsl) is included (according to LEMKE 1998).

Abb. 8. Das Arbeitsgebiet mit den Kernstationen (Punkte) in der Mecklenburger Bucht (westlicher Teil) und im Arkona Becken (östlicher Teil; Tab. 4 enthält die jeweiligen Kernpositionen), welches ebenfalls in der kleinen Übersichtskarte als schwarze Box dargestellt ist. Schwarze Pfeile zeigen mögliche Pfade der Littorina Transgression an, welche im Rahmen dieser Arbeit untersucht werden sollen. Weiterhin ist die Tiefenlage des obersten Geschiebemergels gemäß nach LEMKE (1998) enthalten.

about the transgressive event, i.e. to find and date the boundary between limnic and marine deposits as accurately as possible. For dating purposes transport-resistant (in-situ) material (e.g. remains of macrofossils, intact molluscs, foraminifers) as well as bulk samples were sampled in order to determine the onset of stable marine conditions. The used methods are displayed schematically in Figure 7.

17 four-, six- or twelve meter long gravity cores or vibrocores were retrieved in different basins of the western Baltic Sea, namely the Mecklenburg Bay and the Arkona Basin. The core sites as well as the analyses are listed in Table 4 and the locations are shown in Figure 8.

Tab. 4. Core list with geographic coordinates, water depth, coring device, core location related to uppermost till surface and conducted studies.

Tab. 4. Kernliste mit Positionen der Sedimentkerne, Wassertiefe, Geräteeinsatz, Positionierung der Kerne bzgl. des oberen Geschiebemergels und durchgeführte Untersuchungen.

Area	Core	Latitude	Longitude	Water depth (mbsl)	Coring device	Location rel. to uppermost till surface	PVC-liner/foil	MSCL-logging	Water content (W %)	Bulk density (g/cm^3)	Mineralmagnetism	Sieving (> 63 µm)	TC/S	TIC	C/N	XRF	Isotopes (^{13}C)	Foraminifers	Diatoms	Palaeontology (foils)	AMS ^{14}C-dating
MB	257740-1	54°22.472	11°54.920	23.4	VKG	marginal	foil		66	66		66	66	66						x	5
MB	257740-2	54°22.472	11°54.920	23.4	VKG	marginal	liner	x	252	252	252	396	252	252	182	73		61			1
MB	257760-1	54°22.534	11°38.080	24.0	VKG	marginal	foil		71	71		71						22		x	1
MB	257760-2	54°22.538	11°38.084	24.0	VKG	marginal	liner	x	138	138	138	345	138	138		33		77			
MB	257780-2	54°22.520	11°42.574	23.8	VKG	marginal	liner	x	244	244	244	243	244	244	244						
MB	257800-1	54°22.465	11°42.608	23.7	VKG	marginal	foil													x	3
MB	242760-4	54°16.500	11°31.050	23.0	GC	central	liner	x	207	207	79	234	78	78				?			7
MB	242770-1	54°16.530	11°25.550	24.0	GC	central	liner	x	270	270	63	149	68	68	65		65	16			3
AB	258010-1	54°55.180	13°09.077	42.4	VKG	marginal	foil													x	2
AB	258010-2	54°55.177	13°09.080	42.4	VKG	marginal	liner	x	254	254	254	417	254	254	254	33		25			1
AB	201310-1	54°57.960	13°40.020	46.0	GC	marginal	liner	x													1
AB	242790-1	54°57.100	13°47.130	45.0	GC	central	liner	x	234	234	234	187	91								
AB	242800-1	54°56.000	13°50.030	45.0	GC	central	liner	x	208	208	208	128	69	69	69		36	11			5
AB	258000-1	54°45.005	13°45.876	39.5	VKG	marginal	foil												93	x	
AB	258000-2	54°45.004	13°45.874	39.5	VKG	marginal	liner	x	245	245	245	552	245	245	245	48		58			2
AB	282080-1	54°50.717	13°55.509	44.0	VKG	marginal	foil														1
AB	282060-1	54°45.683	13°58.377	38.9	VKG	marginal	foil														1

MB Mecklenburg Bay AB Arkona Basin VKG vibrocorer GC gravity corer

3.2 Field work

3.2.1 Seismo-acoustic profiles

Shallow seismic surveys were performed during the joint cruises of Danish (GEUS) and German (IOW) geologists in the years 1993, 1994 and 2002 to 2004 aboard the R/Vs "Prof. A. Penck", "A. v. Humboldt" and "Poseidon" (Appendix A). The following seismo-acoustic equipments were used:

- Boomer (Uniboom 0.8-16 kHz)
- high frequency Sparker system (about 0.4-14 kHz)
- side scan sonar (Edo Western 100 kHz)
- 15/210 kHz sediment echo-sounder (DESO25) of the two research vessels.

3.2.2 Sediment coring

The sampling devices used were:

- 6 m vibrocorer (VKG-6; liner-diameter 120 mm)
- 4 m vibrocorer (VKG-4; liner-diameter 120 mm)
- 12 m gravity corer (GC; liner-diameter 120 mm).

The vibrocorers are designed to sample sediment in shallow seas. They are made up of a base frame, leverage with a hollow tube pipe and an electrical vibration head (Fig. 9). After placing the vibrocorer on the seafloor, the electrical vibration head drives the pipe into the seafloor. This equipment is particularly suitable for coring in harder layers (e.g. sandy units).

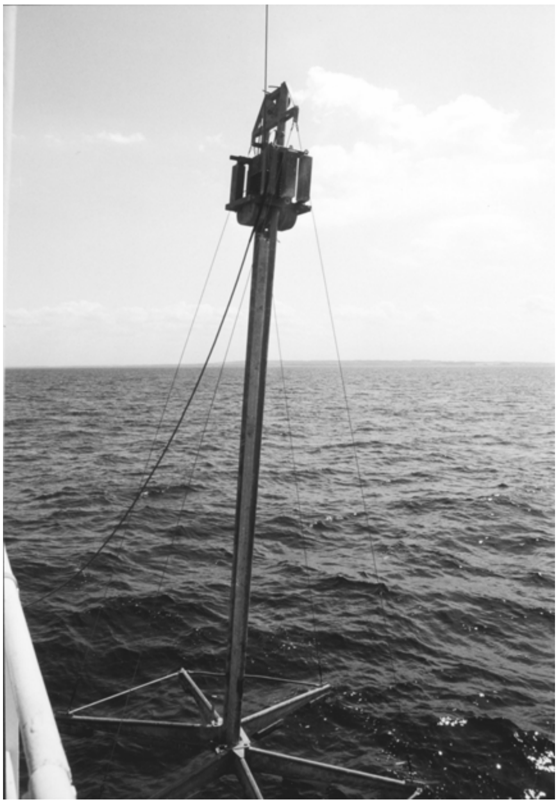


Fig. 9. Vibrocorer (VKG-4)

Abb. 9. Vibrationskerngerät (VKG-4)

Fig. 10. Gravity corer (GC)

Abb. 10. Schwerelot (SL)

To recover long cores within the deeper basins a gravity corer was taken (Fig. 10). Using the effect of gravitation of falls the gravity corer consisting of a hollow tube pipe is able to punctuate the sea bottom.
For both the vibrocorer and the gravity corer a metal core catcher at the end of the tube keeps the sediment in the pipe, as does the partial vacuum created by a flapper valve closing the top, while lifting up the tube. Aboard the ship, the cores were rotated to a horizontal position to facilitate the removal of the PVC liner (Fig. 11) or foil (Fig. 12) within the tube. All PVC liners were cut into one-meter sections, sealed and labelled to guarantee an oriented sampling in the laboratories afterwards.

Fig. 11. PVC-liner

Abb. 11. PVC-Liner

Fig. 12. Foil

Abb. 12. “Folien-Kern”

3.2.3 Sediment sampling on board

Foils were opened in the wet-sieving laboratory on board. They were split lengthwise and documented using a digital camera. They were described in detail in terms of sediment type, sediment colour (Munsell-Rock-Color-Chart), textural parameters, carbon content and presence of fossils (e.g. plants, molluscs etc.). Depending on their lithologic variability and the following laboratory analyses the cores were sub-sampled in different intervals. In general, sieving samples consist of 3 to 5 cm thick slices taken every five centimeters. Samples aimed at determining the diatom associations and foraminiferal assemblages were taken in intervals of ten and twenty centimeters. The thickness of the samples ranges between two and three centimeters. For macrofossil purposes 10 cm thick contiguous sediment samples were put into plastic bags.

3.3 Laboratory work

3.3.1 Sediment sampling in the laboratory

Like the foils described in paragraph 3.2.3, the PVC liners were split lengthwise and documented by using a digital camera or scanned with the Multi Sensor Core Logger (MSCL) at the IOW and described with regard to their lithologic characteristics.
Sediment successions presenting the transgression horizon were sliced in one or two centimetre thick discs and used for both sieving and micropalaeontological investigations. Plastic cubes

(volume approximately 7 cm^3) were sub-sampled contiguously in order to provide samples for the calculation of the water content and the bulk density. After freeze-drying, they were utilised for magnetic and geochemical analyses. Table 4 lists the numbers of sub-samples related to the type of measurements used for each core.

3.3.2 Physical sediment properties

3.3.2.1 Multi-Sensor Core Logging (MSCL)

At first, the PVC liners were logged with the Multi Sensor Core Logger (MSCL) of the IOW and afterwards sub-sampled (chapter 3.3.1). The MSCL was constructed by GEOTEK, a British company (SCHULTHEISS ET AL. 1988, WEAVER & SCHULTHEISS 1990). Changes in physical properties within the core can be traced by the Multi Sensor Core Logging with great sensitivity. It allows simultaneous measurements of several parameters on unopened sedimentary core-liners (CHI 1995, MOROS 1998). The advantages of this method are the high logging resolution and the retrieval of undisturbed PVC-liner itself.
The P-wave velocity (v_p), the GRAPE (Gamma Ray Attenuation Porosity Evaluator) density and the magnetic susceptibility (χ) are measured in intervals of 0.5 cm with the aid of the MSCL. The apparatus is also equipped with a colour-scanner. These measurements were conducted at the IOW. All parameters are measured vertically to the PVC-liner, and thus almost parallel to the layering.
The P-wave velocity (v_p) corresponds to the propagation velocity of the longitudinal compound of an acoustic signal through a medium (TOPERCZER 1960).

(eq. 1) $v = s/t$

v	velocity
s	distance
t	travel time

The GRAPE-density is comparable to the sediment bulk density (paragraph 3.3.2.2). It is calculated from the attenuation of gamma ray radiation, which is emitted by a ^{137}Cs source (CHI 1995). The attenuation depends on the density of the radiated medium. According to CHI (1995) the following equations were used to calculate the density of the radiated medium (ρ_{GRAPE}):

(eq. 2) $A/A_0 = e^{-\rho GRAPE\ \mu s_\gamma}$

A	activity of gamma-ray before attenuation
A_0	activity of gamma-ray after attenuation
ρ_{GRAPE}	density of the radiated medium
μ	mass attenuation coefficient of the material
s_γ	distance of gamma-ray-radiation

(eq. 3) $\rho_{GRAPE} = 1/-\mu s * \ln A/A_0$

The magnetic susceptibility (χ) is a parameter to determine the magnetic property of a material, caused by iron-bearing minerals in soils, rocks, dusts and sediments. It reflects the concentration of ferrimagnetic, diamagnetic and paramagnetic minerals in a sample, with the ferrimagnetic minerals being the most common ones. Magnetization (M) is created within a medium by an induced magnetic field (H) and thus the magnetic susceptibility can be calculated as follows:

(eq.4) $\chi = M/H$

The measurement was done in a low magnetic field (80 A/m) with a frequency of 0.565 kHz, caused by an alternating current within an electrical spool. The data obtained from the magnetic susceptibility system provides mass specific magnetic susceptibility (χ) expressed in SI units ($10^{-8} m^3/kg$).

3.3.2.2 Bulk density and water content

Samples with known volumes (cubic boxes: 6.859 cm^3) were taken and weighed for bulk density analysis. The bulk density (ρ_w; in g/cm^3) was calculated from fresh samples as follows:

(eq. 5) $\rho_w = m_w/V$

with m_w being the mass (g) and V the volume of the wet sample (cm^3).

Bulk densities of extremely sandy material are sometimes too low as complete water saturation was hindered (e.g. due to sampling procedure).
The wet weight and after freeze-drying classified as the dry weight of the sediment samples were measured. The water content (W) was calculated as follows:

(eq. 6) $W = ((m_w-m_d)/m_d)*100$

with m_w as the mass of the wet sample (g) and m_d as the mass of the dry sample (g).

3.3.2.3 Mineral magnetic properties

Analyses of the magnetic mineral concentration and the magnetic mineral grain-size provide parameters that are interpreted, amongst others, as proxies for erosion processes, current velocities and (bio)-chemical conditions. In agreement with Swedish colleagues and to guarantee comparisons with other mineral magnetic works done on Baltic Sea sediments (e.g. MOROS ET AL. 2002, YU 2003), the following parameters were measured on the freeze-dried sediments in cubic boxes at the Palaeomagnetic and Mineral Magnetic Laboratory of Lund University, Sweden, following the procedures described by e.g. SANDGREN ET AL. (1999):

- magnetic susceptibility (χ)
- anhysteretic remanent magnetization (ARM)
- saturation isothermal remanent magnetization (SIRM)
- isothermal remanent magnetization (IRM)

Furthermore, the ARM/χ, the SIRM/χ, the ARM/SIRM, and the S-ratio (Saturation-ratio) were calculated.

The mass specific magnetic susceptibility (χ; in $10^{-6}m^3kg^{-1}$) was determined using a Geofyzika Brno KLY-2 KAPPA bridge. It depends mainly on the concentration of ferrimagnetic iron oxides in the sediment (THOMPSON ET AL. 1975).

(eq. 7) $\chi = (\text{measured value}/100)/m_d$
m_d mass of the dry sample (freeze-dried cubic box in g)

Anhysteretic remanent magnetization (ARM; in mAm^2kg^{-1}) is produced by a decreasing alternating field demagnetisation at the ARM Magnetizer Model 615. It was applied in a 100 milli-Tesla (mT) demagnetizing field. The ARM is sensitive to fine magnetic grains (0.05 to ~ 1 µm) of low-coercivity minerals like magnetite and maghemite.

(eq. 8) $ARM = ((\text{measured value}*12.87)/1000)/ m_d$
m_d mass of the dry sample (freeze-dried cubic box in g)

After ARM measurements, each sample was placed in a 1.06 Tesla (T) magnetic field, induced by a Redcliff BSM-700 pulse magnetizer, in order to saturate the samples magnetically. The saturation isothermal remanent magnetization (SIRM; in mAm^2kg^{-1}) is, like magnetic susceptibility, a measure of the concentration of ferrimagnetic minerals (e.g. magnetite, maghemite, and hematite), but SIRM is also influenced by grain-size differences and antiferromagnetic minerals.

(eq. 9) SIRM = ((measured value*12.87)/1000)/ m_d

m_d mass of the dry sample (freeze-dried cubic box in g)

ARM and SIRM are laboratory-induced magnetic remanences. Values were measured with a Molspin Minispin magnetometer.

The S-ratio, ranging from +1 to -1, is a measure of the relative proportions of ferrimagnetic to antiferromagnetic minerals. Increasing ratios (less negative, more positive) represent a relative increase in the proportion of antiferromagnetic minerals (SANDGREN ET AL. 1990). It was calculated by dividing a backfield IRM value (e.g. exposing the samples to a reversed field of 100 mT, IRM_{-100mT}) by SIRM (at 1.06 T). The S-ratio is based on the fact that ferrimagnetic minerals such as magnetite will have saturated in fields below 100 mT and the major difference in high field remanence will be due to imperfect antiferromagnetic minerals such as hematite and goethite (THOMPSON & OLDFIELD 1986). It represents a measure of the ease by which a SIRM can be reversed.

(eq. 10) S-ratio = IRM_{-100mT}/SIRM

As described in SNOWBALL (1995) low values (e.g. -0.8) indicate magnetically soft minerals, like magnetite or greigite and high values (e.g. 0.5) magnetically hard minerals, like hematite or pyrrhotite.

Calculating different mineral magnetic ratios provide information about the magnetic bearing minerals and their grain size distribution within the samples. The following ratios are the most common described in the literature (e.g. SNOWBALL 1995, SOHLENIUS 1996, SANDGREN ET AL. 1999, YU 2003):

- ARM/χ is influenced by the magnetic grain size; but even by diamagnetic and paramagnetic materials due to their contribution to χ.
- Calculating the SIRM/χ-ratio renders the determination of the causative mineral type and the dominating magnetic grain size possible, but only when there is no significant influence of paramagnetic and diamagnetic minerals on magnetic susceptibility.
- ARM/SIRM is sensitive to the grain size distribution when there is only one dominant magnetic mineral present in a sample.

3.3.3 Grain size analyses

Sieve analyses to determine grain sizes were carried out at the sedimentary laboratory of the Institute of Baltic Sea Research Warnemünde (IOW). The sediment samples were disintegrated by wet sieving with 63 µm and 125 µm sieves using tap water. To safeguard the comparability of the sieving results with other published data, analyses were restricted to the grain size fraction > 63 µm (wt%). Several works (e.g. LEMKE 1998, MOROS 1998) emphasise the importance of the wt% > 63 µm, describing it as the most sensitive parameter to determine lithostratigraphic boundaries.

3.3.4 Geochemical analyses

3.3.4.1 C/S- and C/N-analyses

To reconstruct the transgression from its geochemical side analyses on total carbon (TC), nitrogen (N) and sulphur (S) contents were performed at the IOW, using the Elemental Analyzer multi EA 2000 CS and the Elemental Analyzer EA 1110.
The total contents of carbon (TC) and sulphur (S) were determined on freeze-dried material by an infrared analyser, the Elemental Analyzer multi EA 2000 CS, with a precision of ± 1.0%. Sub-samples out of the cubic boxes were homogenized and weighed into ceramic containers for a combined analysis of TC/S. High-temperature oxidation (1400°C) allowed the complete digestion of the sediment samples. They were oxidised to CO_2 and SO_2 and transported to the infrared detector by oxygen. The determination of inorganic carbon (TIC) was carried out by a phosphoric acid dissolving (6 ml 50% H_3PO_4). After every tenth sample a standard deviation for carbon (12% C) and sulphur (1.56% S) of < 0.2% was calculated. A synthetic standard from Eltra was applied for calibration purposes, using Eltra 90810 calcium carbonate and Eltra 92510-6 sulphur.
Total contents of carbon (TC) and nitrogen (N) were measured with the Elemental Analyzer EA 1110 with a precision of ± 0.5%. At first the sediment samples were homogenized, weighed into a tin container and later pressed into a tin bowl. Once they were loaded into an auto-sampler, the samples were moved into a sample room and vaporised with helium. They were burned at 1020°C in a combustion tube. The combustion gases were swept through the reduction reactor where the nitrogen oxides and carbon oxides were converted into elemental nitrogen, carbon dioxide, and water. Then the reduced gases N_2, CO_2 and H_2O were separated by the chromatographic column and detected by a thermal conductivity detector resulting in the determination of the total carbon (TC) and total nitrogen (N) values.

Mean values of TC (TC_{mean}) were derived from the carbon measurements of the two analysers Elemental Analyzer multi EA 2000 CS ($TC_{EA2000CS}$) and the Elemental Analyzer EA 1110 (TC_{EA1100}):

(eq. 11) $$TC_{mean}\,(wt\%) = (TC_{EA2000CS}\,(wt\%) + TC_{EA1100}\,(wt\%))/2$$

The content of total organic carbon (TOC) was calculated by subtracting the total inorganic carbon (TIC) from the total carbon content (TC_{mean}):

(eq. 12) $$TOC\,(wt\%) = TC_{mean}\,(wt\%) - TIC\,(wt\%)$$

Multiplying inorganic carbon (TIC) by 8.33 yielded the carbonate content ($CaCO_3$):

(eq. 13) $$CaCO_3\,(wt\%) = TIC\,(wt\%)*8.33.$$

3.3.4.2 X-ray fluorescence (XRF) analyses

For the conduction of XRF analyses suitable glass discs had to be prepared at first. This procedure is described in the following paragraph, carried out at the geochemical laboratory at the IOW:

At first the weight percentage of loss on ignition was determined to measure and destroy the organic content in the sediment. Therefore the freeze-dried and grinded sediment samples were weighed to 0.8 g net weight in crucibles (net dry $weight_{800}$), put in the furnace and kept at 1030°C for one hour. Then the samples were placed in a desiccator to cool fully before re-weighing as the dry weight of the sample after heating to 1030°C (the net dry $weight_{1030}$).
Subsequently the percentage of the dry weight loss on ignition (LOI; % DM) was calculated (used Standards: ABSS, MBSS, BCSS, Skagerak, “Hausstandard” (Inhouse Standard)):

(eq. 14) $$LOI\ (\%\ DM) = ((\text{net dry weight}_{800}\ (g) - \text{net dry weight}_{1030}\ (g)) / \text{net dry weight}_{800}\ (g))*100$$

The remaining ash samples were taken for the production of homogeneous glass discs with the fusion system OxiFlux and used for subsequent X-ray fluorescence analyses. The samples never actually melt. They are merely dissolved into a solvent. Thus ash samples were mixed with a solvent, a lithium borate flux, consisting of 2 g lithium metaborate ($LiBO_2$) and 1.932 g lithium tetraborate ($Li_2B_4O_7$). This solvent is solid at room temperature and must be liquefied to dissolve existing solid particles. This is the only reason why the whole process requires heat. Lithium tetraborate melts at 920°C and has the highest melting point of common fluxes. Lithium metaborate melts at 845°C. The blend (mixture of ash sample and solvent) was put into Pt-crucibles and melted, using the fusion system OxiFlux. The system consists of five burners and one blower for cooling. During the analyses, only burner 4 (1050°C) and 5 (1150°C) were used, fusing 9 min at each flame. To obtain the right consistency of the melt, a few milligrams of J_2O_5 were added three minutes prior to cooling. The melt was filled into a coquille and cooled down to obtain glass discs for further X-ray fluorescence analyses.

X-ray fluorescence (XRF-) analyses were performed by Dr. J. Eidam in a high vacuum with the sequential X-ray spectrometer PW 2404 in the geochemical laboratory at the Ernst-Moritz-Arndt-University in Greifswald. The measurements ranged from 60 kV/66 mA to 32 kV/125 mA. The measurement period averaged 54 min per sample to determine the distribution of main and trace elements in a quantitative way.

3.3.4.3 Stable $\delta^{13}C$ isotope analyses

The analyses of stable $\delta^{13}C$ isotopes were carried out in an Isotope Ratio Mass Spectrometer (IRMS) at the IOW. Freeze-dried samples were homogenized, acidified with H_3PO_4 and filtered. Afterwards the filters were dried and the residues scratched from the filter into sample glasses. Sub-samples were weighed into tin capsules for the determination of $\delta^{13}C$ values.
Dr. B. Deutsch did measurements at the IRMS. The samples were combusted with oxygen at 1020°C in an elemental analyser. Resulting CO_2 gases were transported by a helium flow through a reduction tube and led over a water trap into a gas-chromatography column. The amount of CO_2 was reduced to approximately 1% by a split interface and reached the IRMS. The gases were ionised with electrons and accelerated, entering the magnetic sector afterwards. At a collector, the ions were separated due to their masses and counted. According to DEUTSCH (2006), isotope values of every sample were controlled by measurements of reference gases (CO_2, CO), which were calibrated against international standards (as reported in DEUTSCH 2006 for $\delta^{13}C$ [‰]: IAEA C6 (sucrose) with -10.43 ± 0.13, NBS 22 (oil) with -29.74 ± 0.12, USGS 24 (graphite) with -15.99 ± 0.11).

3.3.5 Palaeontological investigations

3.3.5.1 Macrofossil analyses

Sediment samples were disintegrated by wet sieving using tap water. The samples weighed approx. 1 kg. They were wet-sieved with 0.4, 0.2 and 0.1 mm sieves to obtain remains of macrofossils (both flora and fauna) for palaeoenvironmental reconstructions. The residue left on the sieves was analysed using a dissecting microscope. Sediment types like lake marl and peat had to be soaked in NaOH before sieving. These analyses were carried out by O. Bennike at the Geological Survey of Denmark and Greenland (GEUS).

3.3.5.2 Microfossil analyses

Residues of sieving samples (grain size fraction > 63 µm) were examined with a binocular microscope in order to obtain calcareous microfossils. In deep-water cores carbonate-rich units were especially investigated to determine the presence of foraminifers and ostracods. These deliver information suitable for the identification of changes in bottom water conditions and further enhances the possibility of finding datable material.

Cores MB 257740-1 and MB 257760-1 were investigated by Dr. J. Bartholdy and Dr. P. Frenzel in order to determine mainly the occurrence of foraminifers and ostracods, as well as for the description of other significant remains. Their sample preparations were similar to the ones described by FRENZEL (1991, 1993) and FRENZEL ET AL. (2005).

Investigations on diatom assemblages were envisaged to provide information on salinity changes. Diatom analyses were restricted to cores AB 258000-1 (STEYER 2004).

3.3.6 Radiocarbon dating

The radiocarbon method is a standard method for determining conventional ^{14}C ages of e.g. organic matter, mollusc shells, secondary carbonate, sediment, groundwater and ice (e.g. GEYH & SCHLEICHER 1990). The determinable age ranges from 300 to 50,000 years. The concept is based on the radiocarbon (^{14}C) decay by measuring the ratio of the carbon isotopes ^{14}C to ^{12}C.
Accelerator mass spectrometry (AMS) radiocarbon dating was performed at the Leibniz-Laboratory for Radiometric Dating and Isotope Research of the Kiel University. Compared to decay counting techniques the decisive advantage of the AMS technique is the possibility to measure the atom ratios of up to 10^{-17} with sample sizes < 1 mg (GEYH & SCHLEICHER 1990).
According to the dating-reports of the Leibniz-Laboratory the following technique was applied by Prof. P.M. Grootes and his colleagues: First, the samples were checked and mechanically cleaned under the microscope. The residual material was then extracted with 1% HCl, 1% NaOH (at 60°C) and again 1% HCl. The ^{14}C concentration of the samples was measured by comparing the simultaneously collected ^{14}C, ^{13}C, and ^{12}C beams of each sample with those of Oxalic Acid standard CO_2 and coal background material. Conventional ^{14}C ages were calculated according to STUIVER & POLACH (1977) with a $\delta^{13}C$ correction for isotopic fractionation based on the $^{13}C/^{12}C$ ratio measured by their AMS-system simultaneously with the $^{14}C/^{12}C$ ratio.
Normally no corrections for the reservoir ages were applied, as the preferred local value may be different (e.g. WINN ET AL. 1998, ERONEN ET AL. 1990). Thus ages are given in uncalibrated ^{14}C yr BP mainly. Only few dates have been corrected for the seawater reservoir effect (400 years) according to dendro-chronological data using Calib 5.0.1 (STUIVER ET AL. 2005). Such calibrated data are only presented in Table 8.

4 Results

Before presenting the results it should be noted that the depth of the uppermost till surface determines the distribution and thickness of the overlaying sediments (e.g. LEMKE 1998, MOROS ET AL. 2002). Hence, thick accumulations of Littorina Sea stage sediments are found in areas with till surface troughs and thin accumulations in areas with a shallower depth of the till surface. The terms “marginal” or “central” are used for site locations depending on the depth of the uppermost till surface. Shallow depths of the uppermost till surface refer to “marginal” cores and deeper depths to “central” cores. These terms do not represent present-day water depths.
All results, as shown in Table 5, are presented in the same order; i.e. beginning with the uppermost Ancylus Lake sediments (unit E), extending progressively over the transition zone, represented by the Ancylus Lake stage to the Littorina Sea stage (boundary E/F), and finishing with the lowermost Littorina Sea sediments (unit F). In the following, the results of each parameter are reported, starting with the Mecklenburg Bay and finishing with the Arkona Basin.

Tab. 5. Order of result presentation related to the Baltic Sea stage and lithostratigraphic units.

Tab. 5. Reihenfolge der Abhandlung der Ergebnisse im Bezug zu den Ostsee-Stadien und den lithostratigraphischen Einheiten

Order	Baltic Sea stage	Lithostratigraphic unit
1.	Ancylus Lake stage	unit E
2.	transition Ancylus Lake stage/ Littorina Sea stage	boundary E/F
3.	Littorina Sea stage	unit F

Lithostratigraphic units E (Ancylus Lake stage) and F (Littorina Sea stage) were coloured differently in figures to highlight the beginning Littorina transgression (boundary E/F). Evaluations of the results of all measurements showed that the onset of the TOC increase is mainly established as the steepest and clearest change in all cores. Therefore, the conspicuous increase of the total organic carbon content (TOC) was used to define the boundary between the units E and F in the figures. Consequently, the geochemical results are presented before the sediment physical properties, grain size analyses and palaeontological investigations.

4.1 Seismo-acoustic profiles

Seismo-acoustic records were obtained by different shallow seismic systems (see methods, chapter 3.2.1). Seismo-acoustic profile tracks referring to the investigation areas are plotted in a map, presented in the Appendix A1.
Here, one example is selected showing one part of a seismo-acoustic profile from the Mecklenburg Bay. In Figure 13 the position of the Mecklenburg Bay core MB 242760-4 is plotted into the seismo-acoustic profile. Focussing on the transition from Ancylus Lake (unit E) to Littorina Sea deposits (unit F) no remarkable changes occur in this seismogram. Compiling seismo-acoustic data of other core sites displayed similar results.

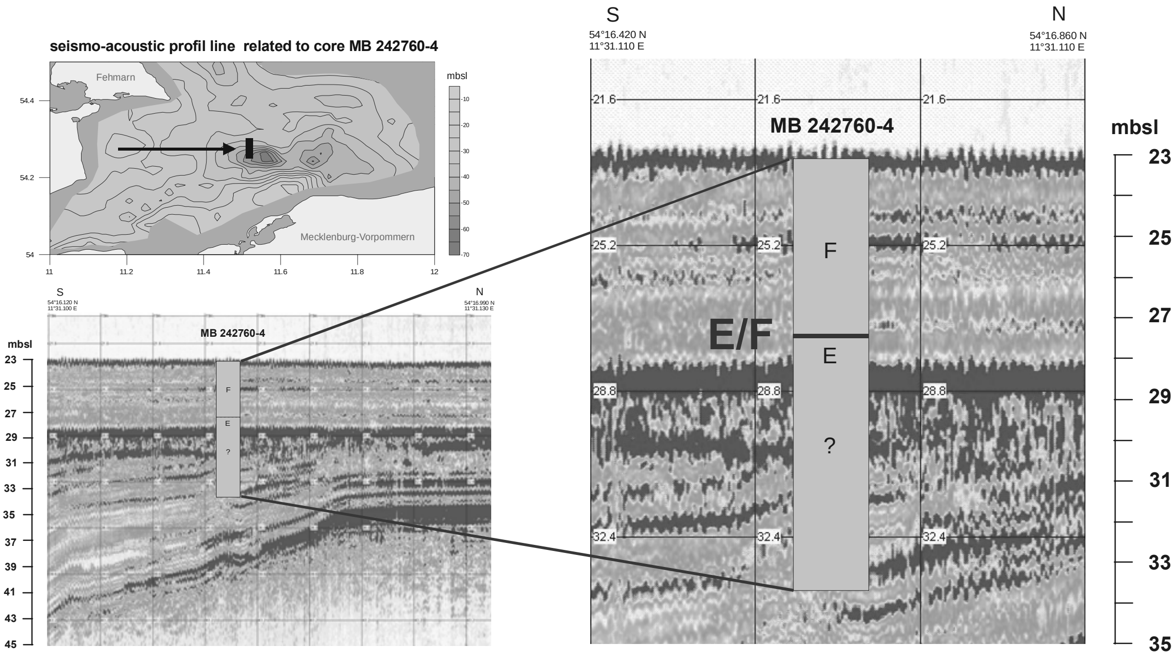


Fig. 13. Example of a seismo-acoustic profile from the Mecklenburg Bay combined with the core MB 242760-4. The position of the profile line is shown in a map, which refers to the depth of the uppermost till surface (after LEMKE 1998). All depths are given in meter below sea level (mbsl). The lithostratigraphic units E and F are related to the deposits of the Ancylus Lake stage and Littorina Sea stage. Thus, the boundary E/F marks the onset of the Littorina transgression defined by the significant TOC increase. The seismo-acoustic data itself show no variation in the transgression horizon.

Abb. 13. Beispiel eines seismoakustischen Profilausschnittes aus der Mecklenburger Bucht, kombiniert mit der Lage des Kernes MB 242760-4. Die Position der Profillinie ist in der Karte angezeigt. Die Karte selbst bezieht sich auf die Tiefenlage des obersten Geschiebemergels (nach LEMKE 1998). Alle Tiefenangaben sind in Höhe unterhalb des Meeresspiegels angegeben (mbsl). Die lithostratigraphischen Einheiten E und F beziehen sich auf die Ablagerungen des Ancylus Sees und des Littorina Meeres. Dementsprechend markiert die Grenze E/F den Beginn der Littorina Transgression, welcher durch einen signifikanten Anstieg im TOC definiert wurde. Es sind keine Veränderungen im Transgressionsbereich innerhalb des seismoakustischen Datensatzes festzustellen.

4.2 Lithology

4.2.1 Introductory notes: Lithostratigraphic classification

The macroscopic core description bases on earlier published lithostratigraphic subdivisions for sediments of the Mecklenburg Bay (LANGE 1984, JENSEN ET AL. 1997, LEMKE 1998) and the Arkona Basin (NEUMANN 1981, JENSEN ET AL. 1997, LEMKE 1998, MOROS 1998, MOROS ET AL. 2002).

Focussing on the transition from the limnic deposits of the Ancylus Lake stage to the brackish-marine deposits of the Littorina Sea stage as the main topic of this work, the classification of these two lithostratigraphic units relates to MOROS ET AL. (2002; see Fig. 14). Unit F corresponds to muddy sediments of the Littorina Sea stage and unit E to clayey-silty sediments of the Ancylus Lake stage there. Note that the lithostratigraphic units of MOROS ET AL. (2002) refer to the Arkona Basin sediments. To treat core descriptions and evaluation of all measurements as uniformly as possible, the lithostratigraphic subdivision in units E and F is adopted for the Mecklenburg Bay sediment classification.

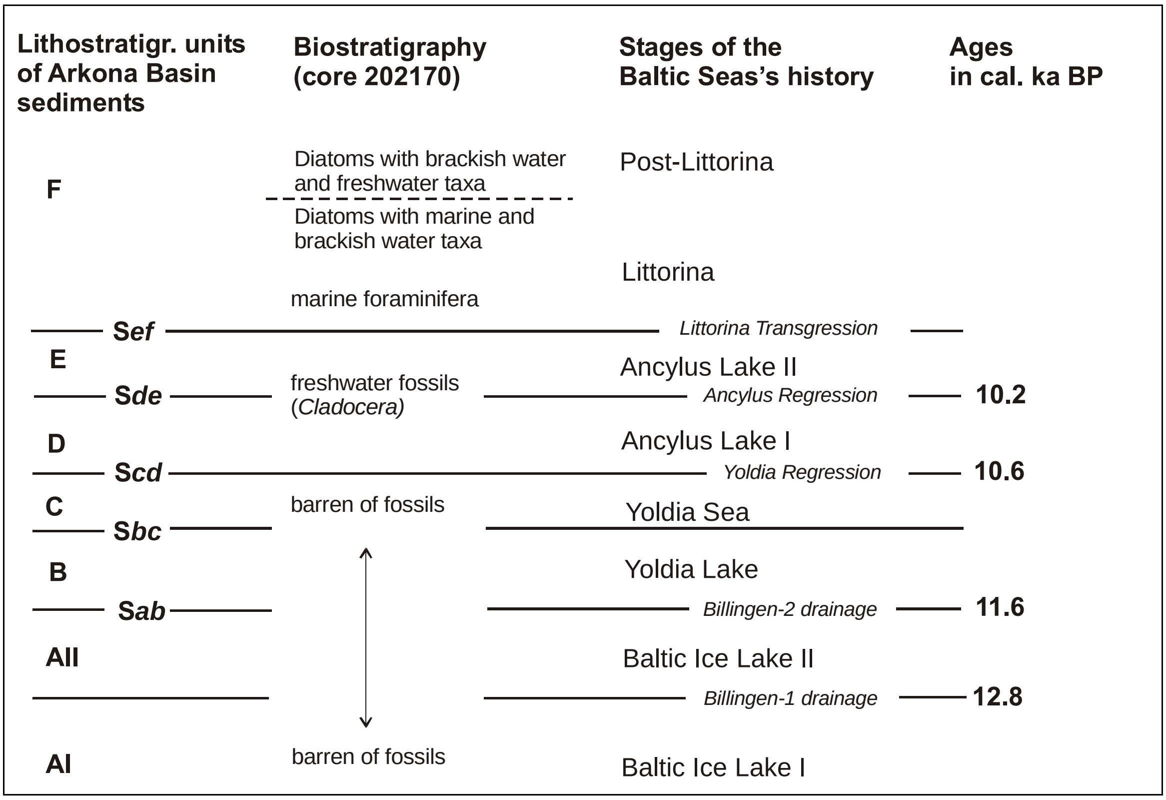


Fig. 14. Lithostratigraphic units of the Arkona Basin (according to MOROS ET AL. 2002).

Abb. 14. Lithostratigraphische Einheiten des Arkona Beckens (aus MOROS ET AL. 2002).

4.2.2 Macroscopic features

In cores from the deeper Mecklenburg Bay, the transgression is characterised by a continuous transition from clayey Ancylus Lake stage deposits (unit E) to muddy Littorina Sea stage sediments (unit F). Sediment colours change gradually from olive grey 5Y 4/1 (Ancylus Lake stage) to olive grey 5Y 3/2 (Littorina Sea stage) in the Mecklenburg Bay. The remains of molluscs (*Arctica islandica, Mytilus edulis*, *Macoma baltica*, gastropods) are common in the lowermost part of the muddy sediments, accompanied by foraminifers macroscopically visible. Similar lithologic successions are found in cores from marginal areas of the Mecklenburg Bay (Fig. 15). However, the marginal cores seem to be depleted in fossil content in the transgression horizon in contrast to the central cores.

Typical for the muddy Littorina Sea stage deposits in the Arkona Basin is the very distinct H_2S scent. A clearly visible colour change like in core AB 242800-1 from dark greenish grey 5GY 4/1 to olive grey 5Y 4/1 sediments marks the transition from clay (unit E) to mud (unit F) in the deeper basin (Fig. 15). Significant for the lower part of unit F is an accumulation of shell types like *Arctica islandica* and *Mytilus edulis* as well as foraminifers.

In sections of the cores from the marginal Arkona Basin separating unit E (Ancylus Lake stage) and F (Littorina Sea stage) a clearly discernible change in the colour and sediment material is observed. Thus this area is represented by a sediment colour change from dark greenish grey 5G 4/1 (unit E) to olive-grey 5Y 3/2 or olive grey 5Y 4/1 (unit F) coinciding with fine grain to medium grain sandy layers at the boundary E to F. Table T1 in the Appendix contains all macroscopic core descriptions.

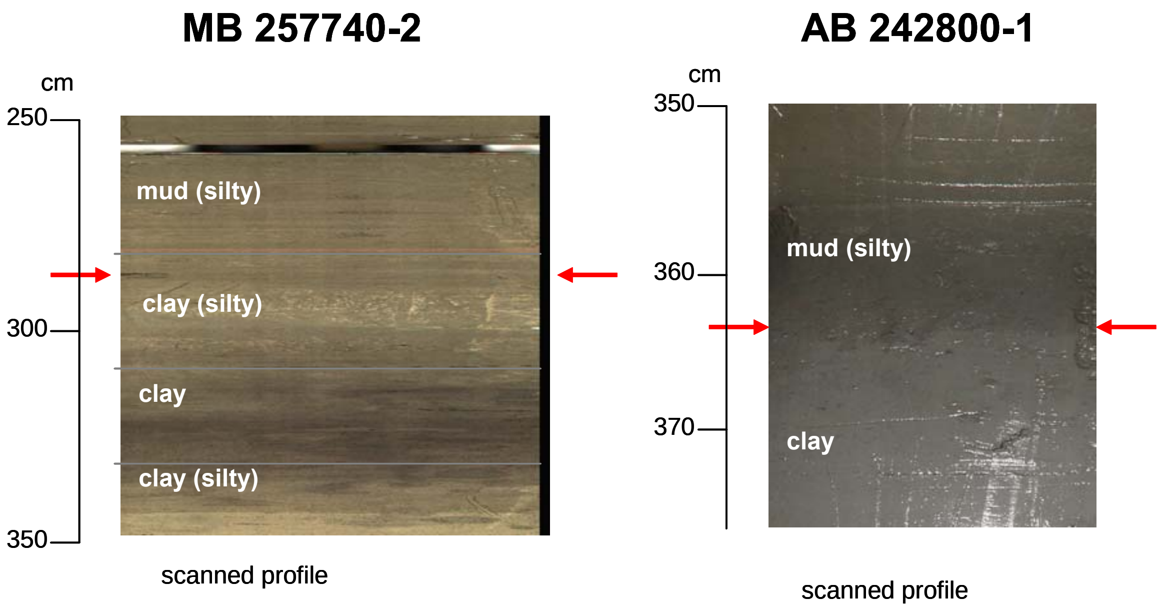


Fig 15. Sedimentary successions and their lithological description of MB 257740-2 and AB 242800-1. Red arrows mark the "possible" position of the Littorina transgression. Note the typical discernible sediment colour change from dark greenish grey 5GY 4/1 to olive grey 5Y 4/1 at the boundary E/F in the Arkona Basin core (AB 242800-1). No clear changes are displayed in the Mecklenburg Bay core (MB 257740-2).

Abb. 15. Sedimentabfolgen mit entsprechender lithologischer Beschreibung der Kerne MB 257740-2 und AB 242800-1. Die roten Pfeile kennzeichnen die wahrscheinliche Position der Littorina Transgression in den Kernen. Ein typischer Sedimentfarbwechsel von dark greenish grey 5GY 4/1 zu olive grey 5Y 4/1 tritt an der Grenze E/F des Arkona Becken Kernes (AB 242800-1) auf. Es sind keine makroskopisch sichtbaren Veränderungen im Mecklenburger Kern (MB 257740-2) enthalten.

4.3 Geochemistry

4.3.1 Evaluation of C/S- and C/N analyses

Organic carbon content (TOC)

Organic carbon contents (TOC) decrease on average from 4.5% to 2.3% in the first e.g. 10 cm of the uppermost part of unit E (Ancylus Lake stage) in the Mecklenburg Bay. At the E/F boundary a marked increase from approximately 2.3% TOC in the uppermost parts of the unit E to ~3.1% TOC in the first 10-15 cm of the unit F was recorded (Fig. 16a, Appendix A2-A3).
As depicted in the Mecklenburg Bay similar results for the stratigraphically older parts of unit E (uppermost centimetres) were observed in the Arkona Basin, too. These parts (Ancylus Lake stage sediments) show decreasing and/or low contents in organic carbon (Fig. 16b, Appendix A2-A3), e.g.:

(i) marginal core AB 258010-2, between 380-368 cm in unit E: from 3.0% to 1.7% TOC
(ii) central core AB 242800-1, between 380-368 cm in unit E: constant low TOC values of 1.2%.

In an upward direction from the boundary E/F, organic carbon content increases rapidly to 3.5-4% within the first 10-30 cm of unit F (Littorina Sea stage). This steep increase is recorded best in the central core AB 242800-1 (Fig 16b). It shows organic carbon contents ranging from 1.2% TOC at 368 cm (boundary E/F) to 3.8% at 330 cm (unit F). The rapid TOC increase corresponds well to the macroscopically visible colour change in the Arkona Basin cores (see chapter 4.2, Appendix T1: core descriptions).

Generally, the transition from unit E (Ancylus Lake sediments) to unit F (Littorina Sea sediments) in both the Mecklenburg Bay and the Arkona Basin is characterised by a clear increase in organic carbon content.

Carbonate content ($CaCO_3$)

The results of the carbonate content ($CaCO_3$) measurements as shown in Figure 16a and Appendix A2-A3 demonstrate a similar trend as the TOC in the Mecklenburg Bay. The carbonate content displays low values at the boundary E/F with < 2.5% $CaCO_3$ in marginal cores and < 1% $CaCO_3$ in central cores. It increases clearly in the overlaying sediments of unit F recording an approximate rise of 2-3.5%, i.e. 3-6% $CaCO_3$ contents in the marginal cores and 2.5-5% $CaCO_3$ contents in the central cores.
Carbonate content evolutions in the Arkona Basin (Fig. 16b, Appendix A2-A3) also demonstrate a significant increase from unit E (Ancylus Lake stage) with < 1% to ~2.5% in core AB 258010-2 to ~4.8% in core AB 242800-1 of unit F (Littorina Sea stage).
In contrast to carbonate results in the Mecklenburg Bay, a significant carbonate maximum is recorded in Littorina Sea deposits of the central Arkona Basin. Here average values reach 5% $CaCO_3$ (Fig. 16b, Appendix A2-A3). Line (2) in Figure 16b indicates the first carbonate maximum for the central Arkona Basin. Such a clear $CaCO_3$ peak, however, is neither recorded in any core of the marginal Arkona Basin nor in any core of the Mecklenburg Bay.

Like organic carbon contents, carbonate measurements also show a significant increase in the transition from Ancylus Lake deposits of unit E to Littorina Sea deposits of unit F within the Mecklenburg Bay and the Arkona Basin, with a clear carbonate maximum in the central Arkona Basin.

C/S ratio

TOC to TS refers to the ratio of total organic carbon (TOC) percentages to total sulphur (TS) percentages in the sediment. The C/S ratio is diminished by approximately 1-2% in the uppermost centimetres of unit E in the Mecklenburg Bay, as for example shown in following cores (Fig. 17a):

(i) Core MB 257740-2: C/S decreases from 2.4 (at 318 cm) to 1.4 (at 305 cm).
(ii) Core MB 242770-1: it falls from 2.3 (at 605 cm) to 1.5 (at 595 cm).

At the transition border between unit E and F, the C/S ratio shows a steep average increase to 2.2. Unit F shows C/S-ratios between 1.5-3.5 (Fig. 17a, Appendix A2-A3). Similar to the TOC- and $CaCO_3$-results, the C/S ratio also displays a clear increase at the boundary E/F in the Mecklenburg Bay cores (Fig. 17a).
The C/S ratio increases in the lowermost deposits of unit F in the Arkona Basin, best presented in the central core AB 242800-1 (Fig. 17b). There it increases from 1.3 to 2.2 between 368 cm (boundary E/F) and 357 cm (unit F). This coincides with the steep rise of TOC and $CaCO_3$ contents observed in the same core (Fig. 16b). Data of the other Arkona Basin cores display the same increase in the C/S ratio at the boundary E/F (Appendix A2-A3).

C/S ratios show a significant increase at the transition from Ancylus Lake sediments (unit E) to Littorina Sea deposits (unit F) in both basins. The values reflect a rapid and steep increase in the lowermost section of unit F (within the first 20-30 cm above E/F).

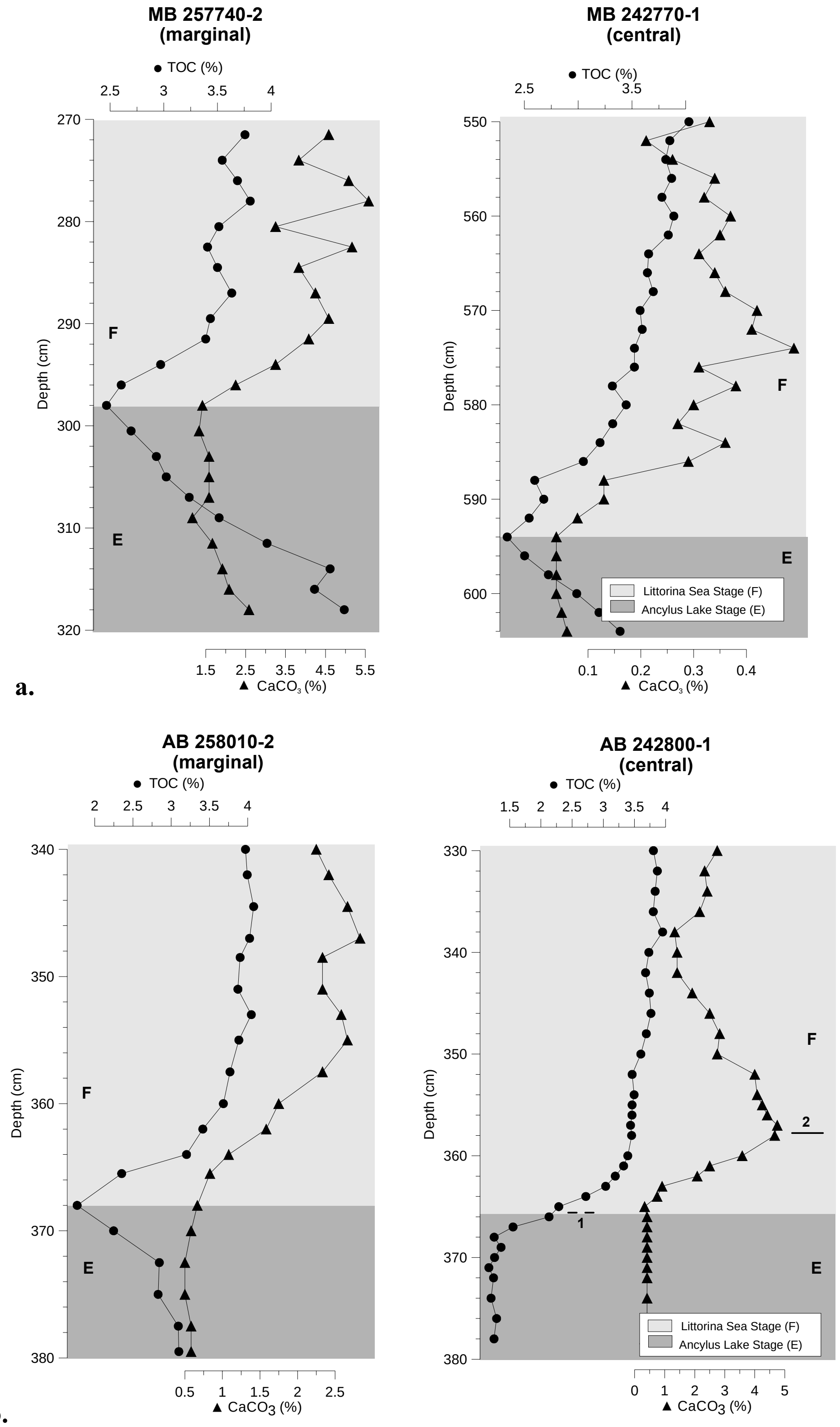
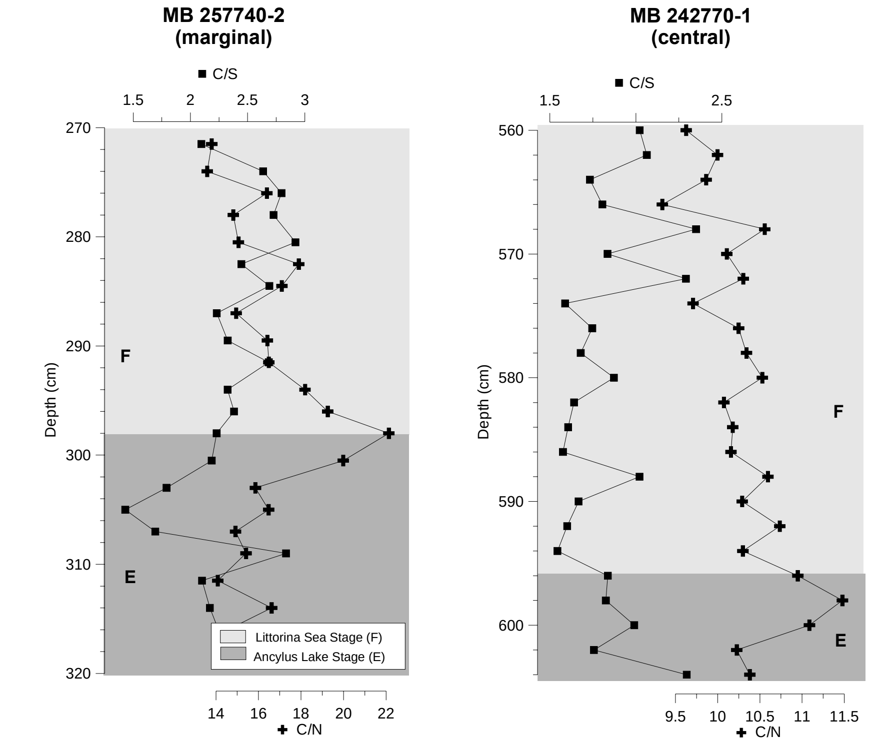
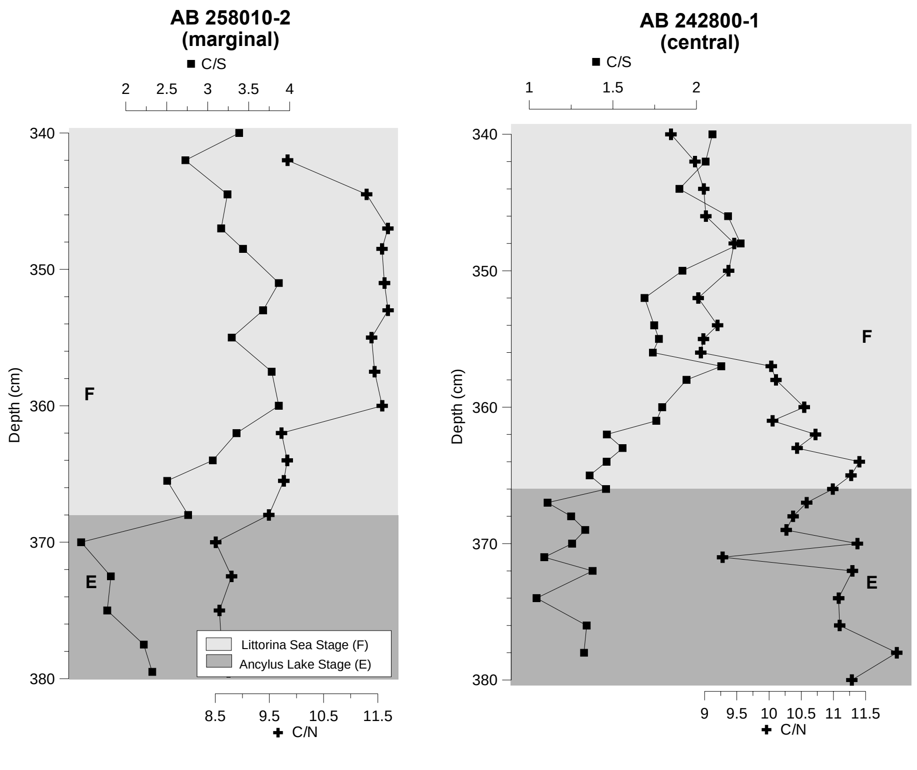


Fig. 16. Organic carbon content (TOC) and carbonate content ($CaCO_3$) for **a.** the Mecklenburg Bay, and **b.** the Arkona Basin. Note the clear increases at the boundary E/F. In **b.**: the black dashed line (1) marks the onset of the significant increase in organic carbon content. Black line (2) points out the first maximum in carbonate content. The terms marginal and central are related to the depth of the uppermost till surface.

Abb. 16. Organischer Kohlenstoffgehalt (TOC) und Karbonatgehalt ($CaCO_3$) für **a.** Mecklenburger Bucht, und **b.** Arkona Becken mit klaren Anstiegen an der Grenze E/F. In **b.** markiert die gestrichelte Linie (1) den Beginn des TOC-Anstieges. Linie (2) markiert das erste Maximum im Karbonatgehalt. Die Begriffe „marginal” und “central” beziehen sich auf die Tiefe des obersten Geschiebemergels.



a.



b.

Fig. 17. Increases in C/S and decreases in C/N ratios (exception: C/N ratio in AB 258010-2) at the boundary E/F for **a.** the Mecklenburg Bay, and **b.** the Arkona Basin. The boundary E/F refers to the TOC increase, caused by the Littorina transgression. The terms marginal and central are related to the depth of the uppermost till surface.

Abb. 17. Steigende C/S- und abnehmende C/N-Verhältnisse (Ausnahme: C/N-Verhältnis in AB 258010-2) am Übergang E/F für **a.** die Mecklenburger Bucht, und **b.** das Arkona Becken. Die Grenze E/F bezieht sich auf den Anstieg im TOC, ausgelöst durch die Littorina Transgression. Die Begriffe “marginal” und “central” beziehen sich auf die Tiefenlage des obersten Geschiebemergels.

C/N ratio

Dividing the total organic carbon (TOC) by the total nitrogen (TN) content results in the C/N ratios. In the Mecklenburg Bay, C/N peaks with values > 10 mark the uppermost deposits of unit E or the boundary E/F in cores MB 242770-1, MB 257760-2 and MB 257740-2 (Fig. 17a, Appendix A2-A3). Afterwards, the values decrease rapidly in the first 20-40 cm of unit F. For example in core MB 257740-2 the C/N ratio drops from 22.1 (at 298 cm) to 15 (at 287 cm).
In contrast to the Mecklenburg Bay, the C/N ratios in the Arkona Basin show different trends with decreasing values towards unit F in the central and marginal cores. Considering the central core AB 242800-1 (Fig. 17b), the C/N ratio decreases from 11.3 at 380 cm (unit E) to 8.5 at 340 cm core depth (unit F). The C/N ratio drop at 357 cm corresponds to the observed carbonate maximum. On the other hand, increasing values from unit E to unit F with C/N ratios from < 9 to > 9.5 mark the transition in the marginal core AB 258010-2 (Fig. 17b).
Apart from the marginal Arkona Basin cores AB 258010-2 and AB 258000-2, the C/N ratio decreases clearly at the boundary E/F, and further continues into unit F in areas of both the Mecklenburg Bay and the central Arkona Basin.

4.3.2 X-ray fluorescence values

XRF analyses were carried out in order to determine the distribution of main and trace elements on two cores from the Mecklenburg Bay, namely MB 257740-2 and MB 257760-2, and on two cores from the Arkona Basin, AB 258000-2 and core AB 258010-2 (Appendix A4).
Here, only the results for MB 257740-2 are presented (Fig. 18), concentrating on the most

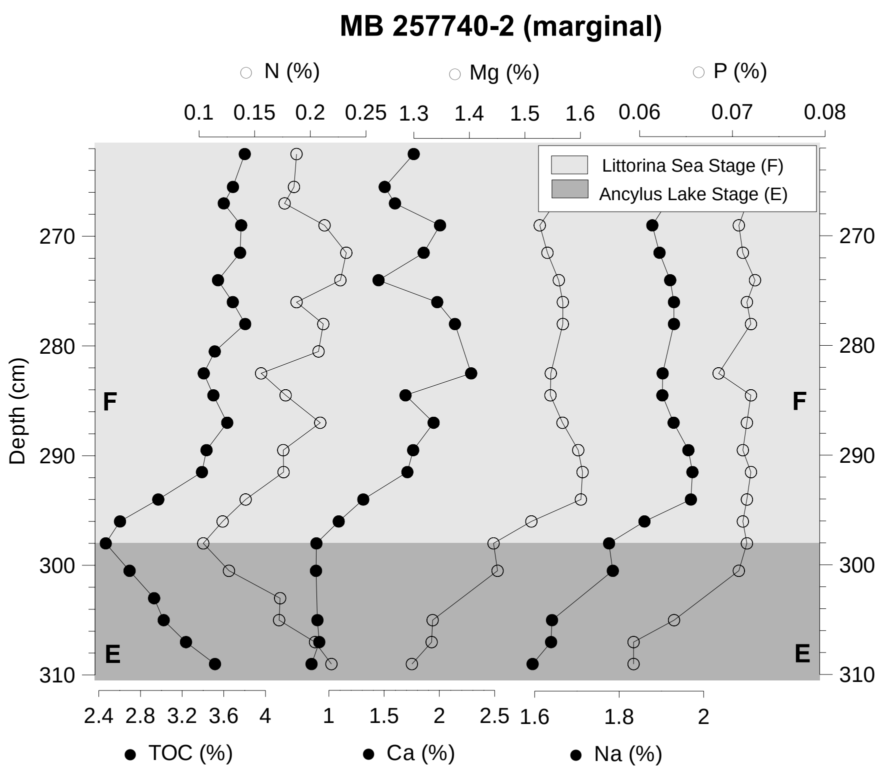


Fig. 18. XRF results, i.e. Ca, Mg, Na and P compared to TOC and TN values, recorded for the core MB 257740-2. Parameters increase from unit E (Ancylus Lake) to unit F (Littorina Sea).

Abb. 18. RFA-Analysen mit z.B. Ca-, Mg-, Na- und P-Gehalte im Vergleich zu den ermittelten TOC- und TN-Werten, bestimmt am Kern MB 257740-2. Alle gemessenen Parameter steigen in den Gehalten von Einheit E (Ancylus See) zu F (Littorina Meer) an.

significant changes observed in XRF analyses. There are higher contents of calcium (Ca), magnesium (Mg), sodium (Na) and phosphorous (P) in the lowermost Littorina Sea deposits (unit F, Fig. 19) compared to the transition base E/F in the Mecklenburg Bay. Generally, all curves show a slight increase from the Ancylus Lake to the Littorina Sea sediments, mostly between 0.1-0.2%, apart from phosphorous with only ~ 0.01% increase.
Sodium increases from 1.78% to 1.93%, magnesium from 1.44% to 1.57% and calcium from 0.89% to 1.95% between 298 cm (boundary E/F) and 287 cm (unit F). Calcium rises most significantly with about 1.06%. The high Ca content is due to the contribution from $CaCO_3$ (WASTEGÅRD ET AL. 1994). Phosphorous starts to increase in the uppermost Ancylus Lake deposits (0.06% at 310 cm) and displays constant values in the Littorina Sea sediments (on average 0.07% between 298 cm and 262 cm). The TOC as well as a TN increase coincide with these increased elemental contents in the lowermost parts of unit F (see discussion – chapter 5).

4.3.3 Stable $\delta^{13}C$ isotopes

Stable $\delta^{13}C$ isotope analyses of bulk material were carried out on bulk samples of central cores MB 242770-1 and AB 242800-1 from the Mecklenburg Bay and Arkona Basin, respectively, with regard to the transition from Ancylus Lake to Littorina Sea deposits (Fig. 19).
Bulk sediment stable $\delta^{13}C$ isotope values increase stepwise from -25.5‰ in unit E to -22.5‰ in unit F in the Mecklenburg Bay core MB 242770-1 (Fig. 19). Two significant $\delta^{13}C$ increases are observed: (i) between 598 cm and 594 cm on average from -25.5‰ to -24.6‰ and (ii) between 570 and 550 cm from -24.6‰ to - 22.7‰. The first jump corresponds to increasing organic carbon content, carbonate content and C/S ratio at the boundary E/F (Fig. 16a, 17a).

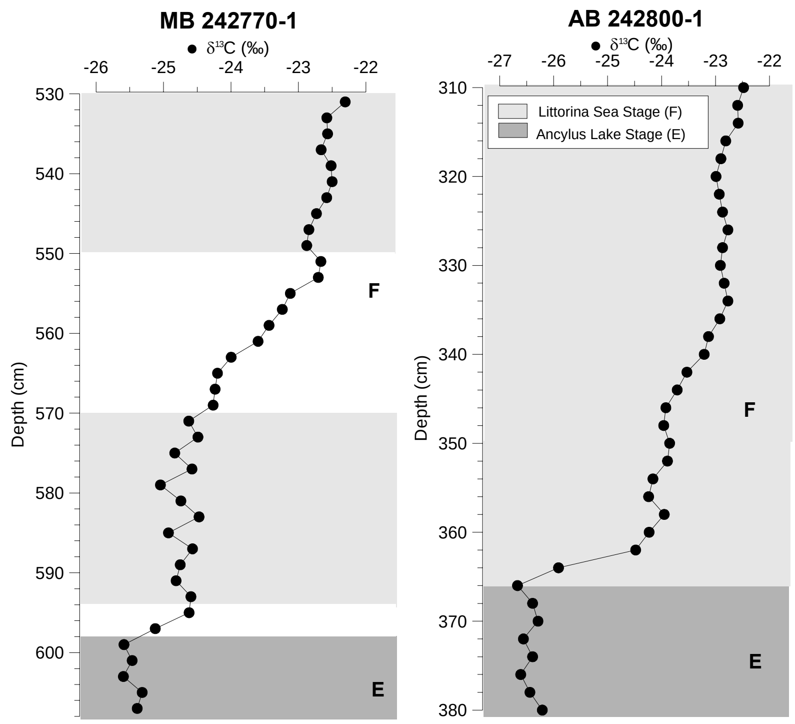


Fig. 19. Stable $\delta^{13}C$ isotopes of central cores MB 242770-1 and AB 242800-1 increase drastic from the Ancylus Lake (unit E) to the Littorina Sea (unit F) deposits. Note the stepwise increase in MB 242770-1 (white-coloured boxes).

Abb. 19. Die stabilen $\delta^{13}C$ Isotope der zentralen Kerne MB 242770-1 und AB 242800-1 steigen drastisch von den Ancylus See-Ablagerungen (Einheit E) zu den Sedimenten des Littorina Meeres (Einheit F) an, wobei der Anstieg im Kern MB 242770-1 schrittweise erfolgt (siehe weiße Flächen).

In the Arkona Basin core AB 242800-1 (Fig. 19) uniform low $\delta^{13}C$ values of about -26.5‰ were measured in the lowermost part between 380 and 366 cm, hence in Ancylus Lake stage sediments. The most striking feature recorded, is a sharp $\delta^{13}C$ increase to -24.5‰ at 362 cm core depth (unit F). In an upward direction from 360 cm the $\delta^{13}C$ values show a general increase to -22.5‰ at 310 cm (Fig. 19; Littorina Sea stage). The observed sharp $\delta^{13}C$ shift corresponds to marked increases in organic carbon content, carbonate content and C/S ratio in the lowermost part of unit F in core AB 242800-1 (Fig. 16b, 17b).

4. 4 Sediment physical properties

4.4.1 MSCL, bulk density and water content

The magnetic susceptibility (χ) and GRAPE density were logged with a Multi Sensor Core Logger (MSCL). The loggings of the Mecklenburg Bay cores show no clear variations within the lithostratigraphic units E and F (Fig. 20, Appendix A5). In general, the intensity of the magnetic susceptibility decreases upwards. GRAPE density values range from 1.1 to 1.5 g/cm^3. Bulk density (ρ_w) and water content (W) reflect no significant changes in the Mecklenburg Bay (Appendix A5-A6).

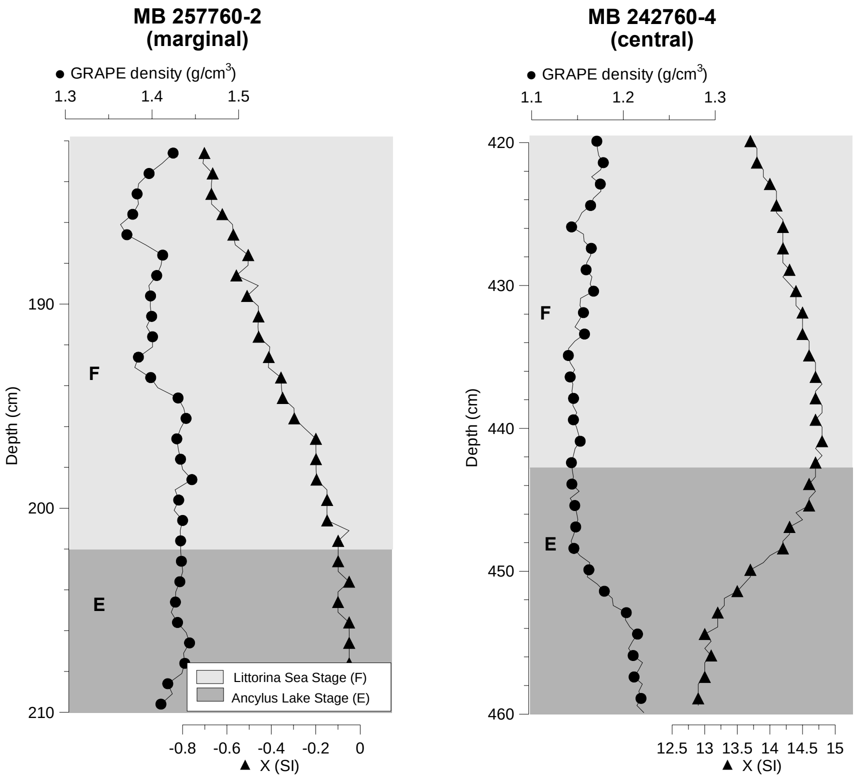


Fig. 20. GRAPE density and magnetic susceptibility (χ) of a marginal and a central Mecklenburg Bay core. Both parameters show no distinct changes at the transition E/F. Boundary E/F refers to the onset in TOC increase. The terms marginal and central relate to the depth of the uppermost till surface.

Abb. 20. GRAPE-Dichte und Magnetische Suszeptibilität (χ) eines marginalen und eines zentralen Kernes aus der Mecklenburger Bucht. Beide Parameter zeigen keine Veränderungen am Übergang E/F. Die Grenze E/F bezieht sich auf den Anstieg im TOC. Die Begriffe “marginal” und “central” beziehen sich auf die Tiefenlage des obersten Geschiebemergels.

GRAPE density peaks, marking the boundary between the units E/F, characterise the cores from the Arkona Basin. GRAPE density increases from lower Ancylus Lake sediments to

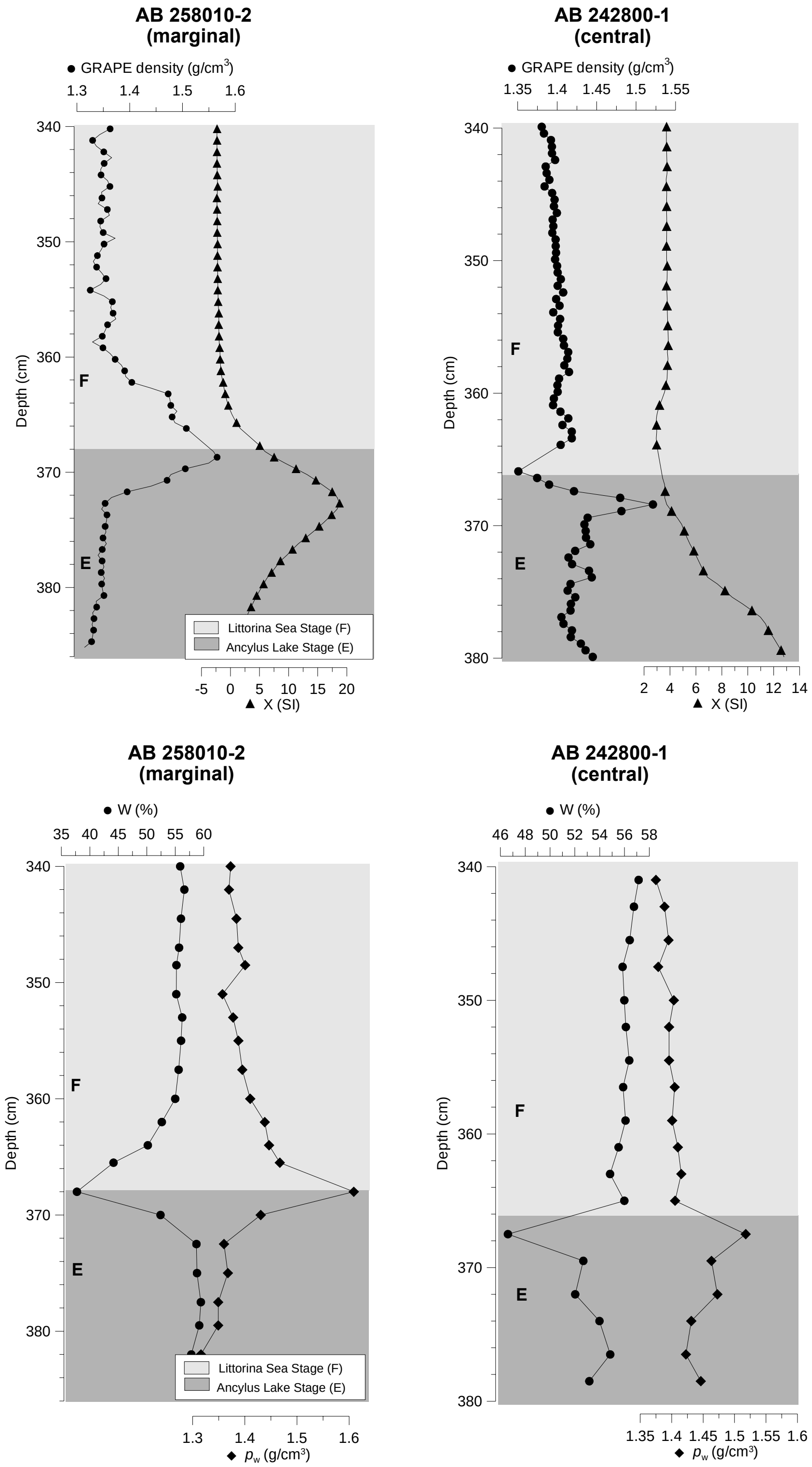


Fig. 21. GRAPE density, magnetic susceptibility (χ), water content (W) and bulk density (ρ_w) of a marginal (AB 258010-2) and a central (AB 242800-1) Arkona Basin core. All parameters vary significantly at the transition from unit E to unit F. The boundary E/F corresponds to the analysed TOC increase. Terms marginal and central refer to the depth of the uppermost till surface.

Abb. 21. GRAPE-Dichte, Magnetische Suszeptibilität (χ), Wassergehalt (W) und Bulkdichte (ρ_w) eines marginalen (AB 258010-2) und eines zentralen (AB 242800-1) Arkona Becken Kernes. Alle Parameter zeigen signifikante Änderungen am Übergang von der Einheit E zur Einheit F. Die Definition der Grenze E/F bezieht sich auf den gemessenen TOC-Anstieg. Die Begriffe “marginal” und “central” stehen im Bezug zur Tiefenlage des obersten Geschiebemergels.

an amount of 1.5 g/cm^3 at the boundary E/F, and decreases in upper Littorina Sea sediments (Fig. 21). The magnitude of the peaks correlates well with the wt% of material > 63 µm within these sections (see chapter 4.5). Thus increasing GRAPE density values are accompanied by coarsening of the deposited material. This coarsening is also recorded by the bulk density and water content results
(Fig. 21).
Higher magnetic susceptibility (χ) values occur in the uppermost parts of unit E (Fig. 21). Compared to GRAPE density peaks, χ seems to increase earlier. Mineral magnetic measurements, performed on material from χ peak positions of unit E, also show rapid changes within these parts, e.g. SIRM/χ peaks (chapter 4.4.2).

4.4.2 Mineral magnetic parameters

Magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM), SIRM/χ ratio, ARM/SIRM ratio and S-ratio show distinct changes in the uppermost sections of unit E. The data from core AB 242790-1 demonstrate these relationships quite clearly (see Fig. 22). The results of the other cores with respect to the parameters mentioned above are entailed in more details in Appendix A7-A10.

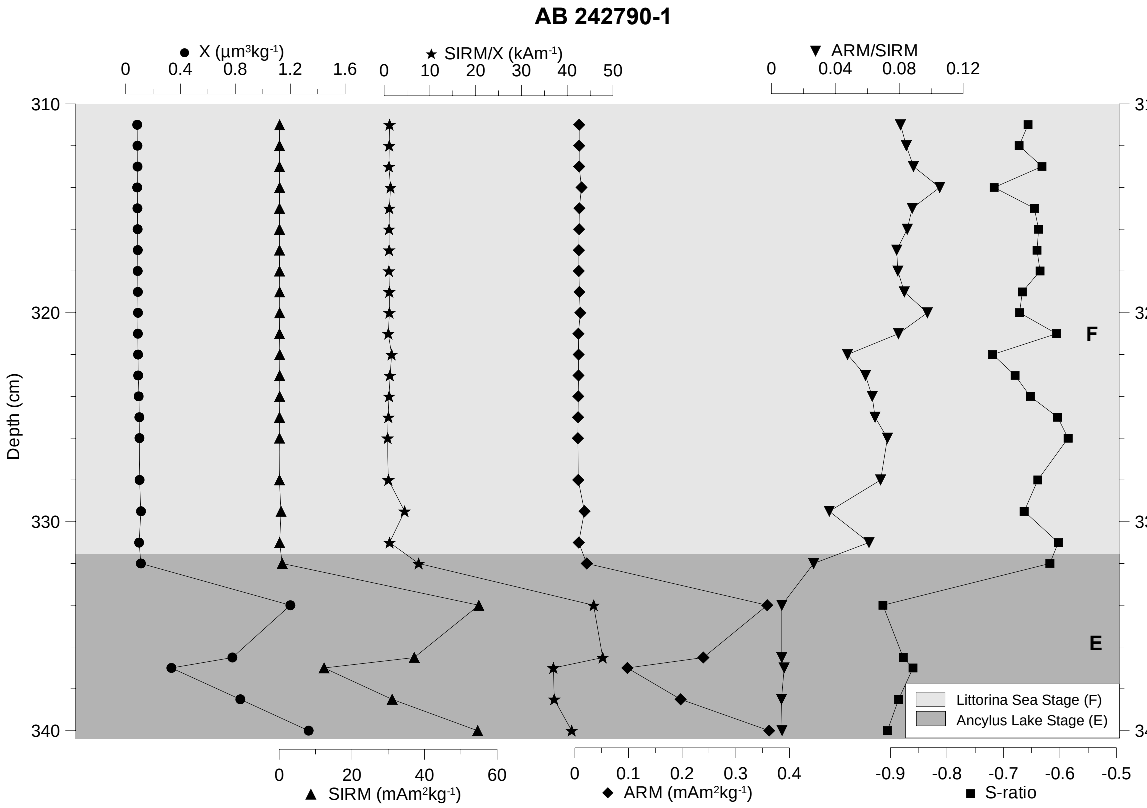


Fig. 22. Mineral magnetic parameters of the central core AB 242790-1 (magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM), SIRM/χ ratio, ARM/SIRM ratio and S-ratio). The transition from the lithostratigraphic unit E (Ancylus Lake Stage) to unit F (Littorina Sea stage) shows distinct changes. The boundary E/F refers to the onset in TOC increase.

Abb. 22. Mineralmagnetische Parameter des zentralen Kernes AB 242790-1 (magnetische Suszeptibilität (χ), anhysteretische remanente Magnetisierung (ARM), gesättigte isothermale remanente Magnetisierung (SIRM), SIRM/χ-Verhältnis, ARM/SIRM-Verhältnis und S-Verhältnis). Im Übergang von der lithostratigraphischen Einheit E (Ancylus See) zur Einheit F (Littorina Meer) treten deutliche Veränderungen auf. Die Grenze E/F bezieht sich auf den Anstieg im TOC-Gehalt.

Relatively high magnetic mineral concentrations, as reflected by χ and SIRM peaks, characterise the uppermost clayey Ancylus Lake sediments in unit E, while the overlaying sediment of unit F displays lower values in core AB 242790-1 (Fig. 22). These peaks are connected to increases in ARM, SIRM/χ value, and low ARM/SIRM and S-ratios in unit E.
ARM values and SIRM/χ ratio decrease rapidly at the boundary E/F and consist of low values in unit F. ARM/SIRM start to increase at the boundary E/F. An interpretation of the mineral magnetic results is given in chapter 5.

SIRM/χ ratio

SIRM/χ ratio can indicate both the mineralogical composition and the magnetic grain size of the sediments. With special focus on the transition from the lower Ancylus Lake to the upper Littorina Sea sediments the SIRM/χ ratios show that clear changes occurred in the investigated cores (Fig. 23).

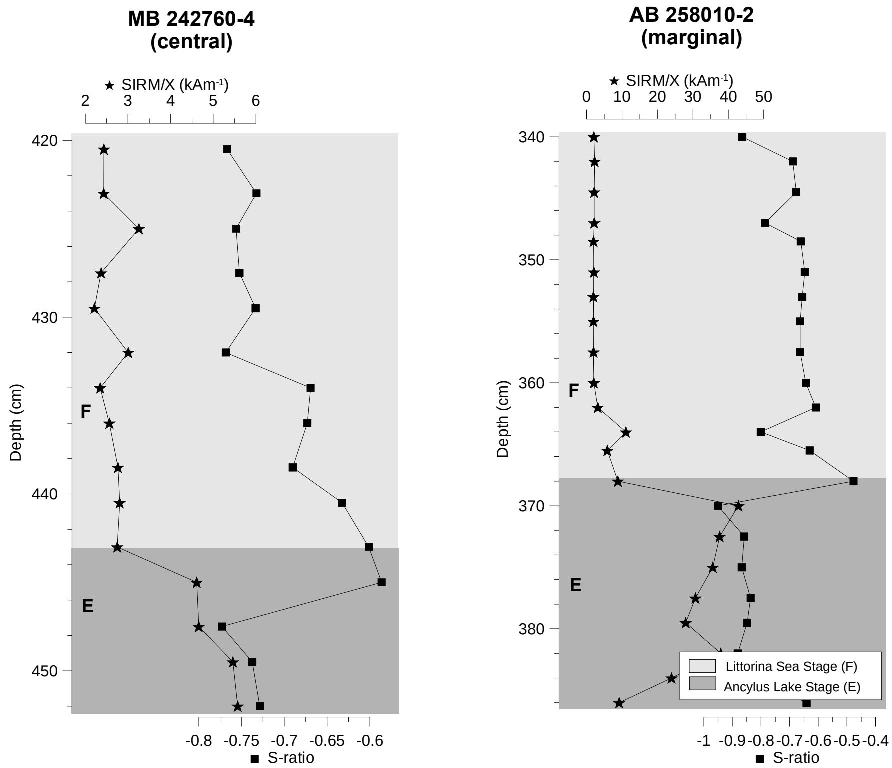


Fig. 23. SIRM/χ ratio and S-ratio for the Mecklenburg Bay and Arkona Basin, distinguishing between MB 242760-4 and AB 258010-2. The lithostratigraphic units E (Ancylus Lake Stage) and F (Littorina Sea stage) are included, demonstrating a drastic decrease in SIRM/χ ratio at the boundary E/F. S-ratios increase from unit E to unit F. The boundary E/F refers to the distinct TOC increase in the cores.

Abb. 23. SIRM/χ Verhältnisse und S-Verhältnisse aus der Mecklenburger Bucht (MB 242760-4) und dem Arkona Becken (AB 258010-2). Die lithostratigraphischen Einheiten E (Ancylus See) und F (Littorina Meer) zeigen eine drastische Abnahme im SIRM/χ-Verhältnis an der Grenze E/F an, währenddessen die S-ratios zum Hangenden ansteigen. Die Festlegung der Grenze E/F richtet sich nach dem markanten TOC-Anstieg.

SIRM/χ peaks (approximately up to 12 kAm^{-1} on average in the Mecklenburg Bay and around 6 kAm^{-1} in the central Arkona Basin) occur in the uppermost Ancylus Lake stage sediments (unit E).

They are accompanied by low S-ratios, ranging between -0.9 and -0.6. The relatively low S-ratios and high SIRM/χ ratios may imply the presence of greigite (Fe_3S_4; SOHLENIUS 1996, SNOWBALL 1991). Greigite displays high values of SIRM/χ, due to its high conductivity, which depresses χ values (SNOWBALL 1995). The results obtained from samples originating from both Mecklenburg Bay and Arkona Basin demonstrate sharp decreasing SIRM/χ values at the transition horizon E/F:

- on average from approximately 12 kAm^{-1} to 3 kAm^{-1} in the Mecklenburg Bay,
- from 42.9 kAm^{-1} to 8.8 kAm^{-1} in AB 258010-2,
- from 5.5 kAm^{-1} to 1.8 kAm^{-1} in AB 242800-1,
- and continuous low values (SIRM/χ < 4 kAm^{-1} on average) in unit F (Fig. 23).

4.5 Grain size distribution

The measurements take into account the distribution of grain size fractions > 63 µm (wt%), analysed at the Mecklenburg Bay and Arkona Basin cores. Thus the sieving residues present the content of sandy material. According to LEMKE (1998), MOROS (1998) and MOROS ET AL. (2002) the weight percentage of the grain size fraction > 63 µm is an important and sensitive parameter to mark the lithostratigraphic boundaries within sedimentary successions.

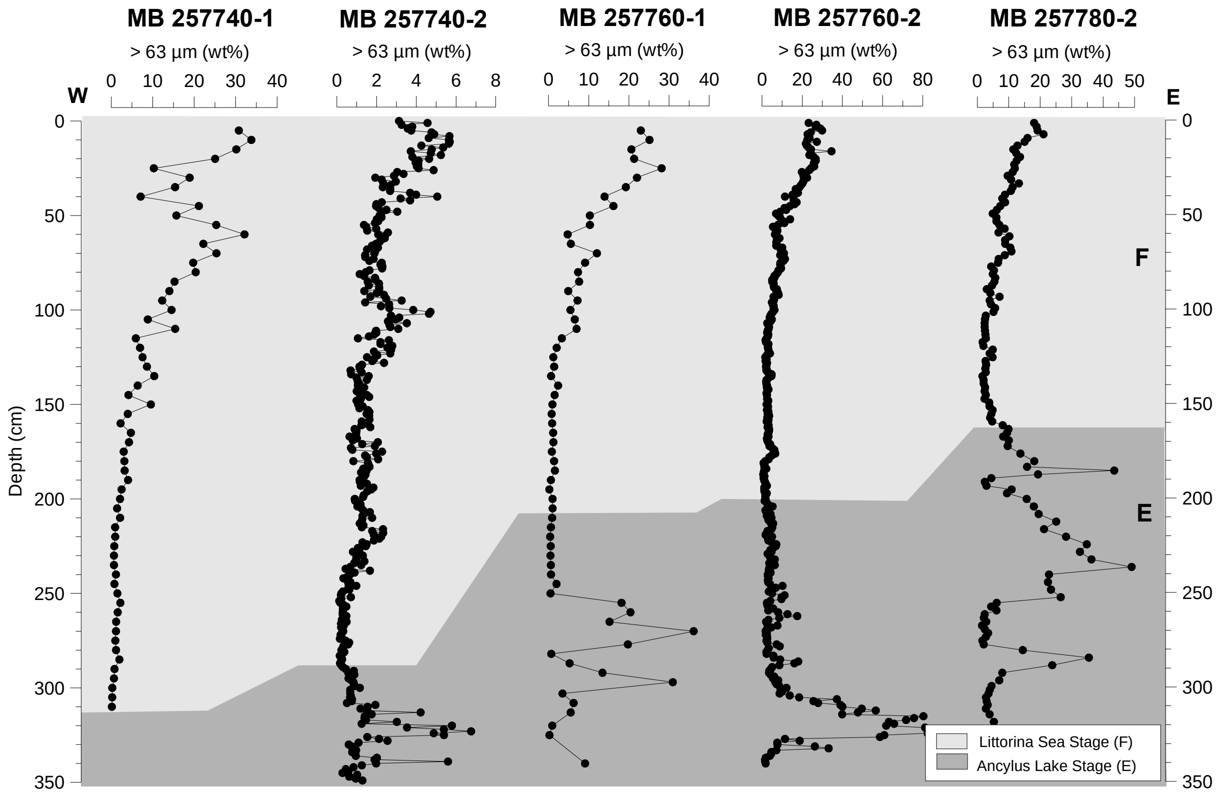


Fig. 24. Grain size distribution curves (> 63 µm) for core samples investigated in the marginal Mecklenburg Bay. Note, that the content of wt% > 63 µm does not change, considering the transition from unit E to F. Boundary E/F refers to the analysed TOC increase of the cores.

Abb. 24. Siebkurven zur Verteilung der Korngrößenfraktionen > 63 µm, gemessen an den marginalen Kernen der Mecklenburger Bucht. Die Siebwerte zeigen keine Veränderungen im Übergang von der Einheit E zu F an. Die Grenze E/F bezieht sich auf den ermittelten Anstieg im TOC-Gehalt.

The distribution of the grain size fraction > 63 µm of marginal Mecklenburg Bay cores are shown in Figure 24. The differentiation into the units E and F, i.e. the determination of the transgression onset, bases on the significant TOC increase in the lowermost deposits in unit F (see above). Sieving results from central cores are listed in Appendix 11. Similar to the physical sediment properties, no clear changes were observed in the sieving curves of the Mecklenburg Bay cores. The boundary between the Ancylus Lake and the Littorina Sea sediments is not visible in the content of wt% > 63 µm (Fig. 24, Appendix 11).

In contrast, the grain size content varies in the Arkona Basin. Sharp spikes in the wt% > 63 µm mark the lithostratigraphic boundary between the Ancylus Lake (unit E) and Littorina Sea deposits (unit F). In general, the sand content is low with < 5 wt% in those two lithostratigraphic units, but it increases clearly at the boundary between units E and F (Fig. 25). These peaks range between 3 and 16 wt% coinciding with the observed GRAPE density peaks in chapter 4.4.1 (around 1.5 g/cm^3 at the boundary E/F) and the clearly visible sediment colour change from dark greenish grey 5GY 4/1 (unit E) to olive grey 5Y 4/1 (unit F) described in chapter 4.2.2.

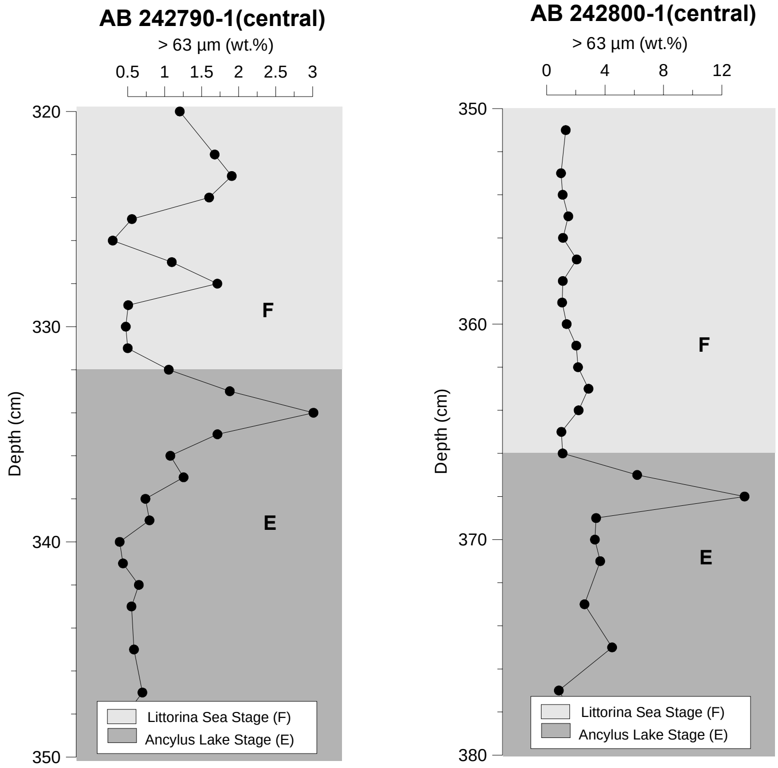


Fig. 25. Sharp peaks in distribution of the grain size fraction > 63 µm (wt%) mark the boundary E/F in the central Arkona Basin (AB 242790-1, AB 242800-1). The boundary E/F refers to the remarkable TOC increase of the cores.

Abb. 25. Deutliche Peaks der Korngrößenfraktion > 63 µm (wt%) charakterisieren die Grenze E/F im zentralen Arkona Becken (AB 242790-1, AB 242800-1). Die Grenze E/F bezieht sich auf den markanten Anstieg des TOC-Gehaltes der Kerne.

4.6 Palaeontology

4.6.1 Macrofossil assemblages

Plant and insect fragments as well as remains of *Bithynia tentaculata* (see Appendix A12-A14) were found in Ancylus Lake sediments, indicating terrestrial, telmatic or lacustrine environments. Those remains become less abundant in the uppermost Ancylus Lake sediments. They disappear almost completely in the transition horizon and Littorina Sea deposits. Shell remains of *Arctica islandica*, *Macoma baltica* and *Mytilus edulis* occur in Littorina Sea sediments referring to brackish-marine conditions (see Appendix A12-A14).

4.6.2 Microfossil assemblages

Foraminiferal assemblages

Foraminifers (Granuloreticulosea) are widely used as palaeo-environmental proxies. Due to their low abundance and low diversity in brackish waters just few works have reported about the foraminiferal distribution and ecology in the Baltic Sea, e.g. BRODNIEWICZ (1965), LUTZE (1965), HERMELIN (1987), and FRENZEL ET AL. (2005). These documentations are mainly based on deeper water associations. Foraminiferal assemblages provide information about general salinity and temperature trends, relative water depth, depth fluctuations of the halocline and habitat structures in the past (FRENZEL ET AL. 2005).
Owing to the (high) significant foraminiferal counts and widespread existence of ostracods in the carbonate-rich layers of the deep-water cores (e.g. MOROS 1998) suitable datable material for the determination and dating of the transgression horizon were analysed within the scope of this work. The quantitative analysis of the foraminiferal assemblages was not of (primary) interest.
The transition from Ancylus Lake (unit E) to Littorina Sea sediments (unit F) is clearly indicated by changes in the microfossil content. Individuals of Cladocera and Characeae, spores and seeds document the limnic facies of the clayey Ancylus Lake sediments (Appendix H). On approaching the transition horizon, the limnic findings decrease and abiotic components become predominant. The first foraminifers occur nearly immediately in the lowermost deposits of the Littorina Sea units (Tab. 6).

Tab.6. First occurrences and peaks of foraminifers, compared to the depth of the Littorina transgression (according to the TOC increase).

Tab.6. Vergleich von Teufen, in denen Foraminiferen erstmals auftauchen bzw. erste Lagen ausbilden mit der Basislage der Littorina Transgression (definiert anhand des markanten TOC-Anstieges).

Core	Littorina transgression according to TOC increase (cm)	Occurrence of first foraminifers (cm)	First foraminiferal peak (cm)
MB 242760-4	443	436-434	432-430 - ?
MB 242770-1	595	588-586	588-586 - 562-560
MB 257740-1	330	330	? (foil)
MB 257740-2	298	298	286-274
MB 257760-1	210	205	? (foil)
MB 257760-2	202	202	198-194
AB 242790-1	332	data not analysed	
AB 242800-1	366	362	360-352?
AB 258000-2	516	497	468-446
AB 258010-2	368	no foraminifers	

First foraminiferal associations are dominated by *Ammonia batavus*. It is a typical benthic foraminifer, nowadays living along the coastline of Mecklenburg-Vorpommern in the muddy, sandy and coarse sandy areas, even in the phytal up to 8 m water depth. The temperature tolerance ranges from cold-moderate, moderate to warm-moderate; i.e. -1.8 – 25 °C (LIPINSKI & WIEGANK 1969, WIEGANK 1972, FRENZEL 2003). A similar wide range is valid in terms of salinity, namely from oligohalin to polyhalin (4 - < 30‰ according to WIEGANK 1972). Besides *Ammonia batavus*, also *Ammonia beccarii*, *Cribroelphidium williamsoni,* and *Haynesina germanica* occurred in the first assemblages (Fig. 26).

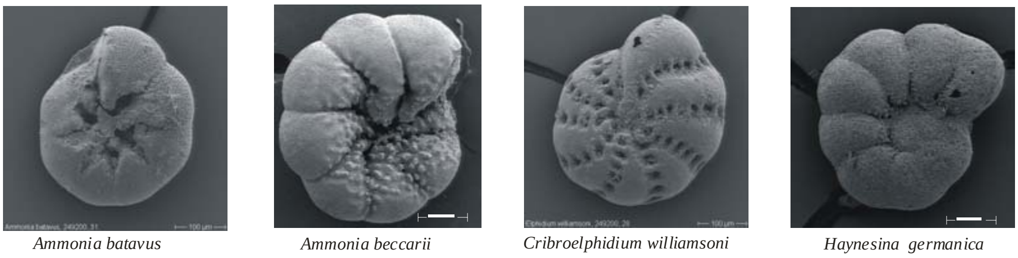


Fig. 26. Foraminiferal species observed in investigated MB and AB cores (pictures taken by P. Frenzel).

Abb. 26. Foraminiferarten, nachgewiesen in den untersuchten MB- und AB-Kernen (Fotos von P. Frenzel).

The first accumulations of foraminifers are restricted to a few peaks only. Comparing the calculated carbonate curve with the occurrence of the foraminifers it becomes obvious that carbonate peaks correlate with the peaks of foraminifers (Fig. 27). Thus the measured carbonate maximum corresponds to the accumulations of calcareous microfossils, mainly benthic foraminifers.

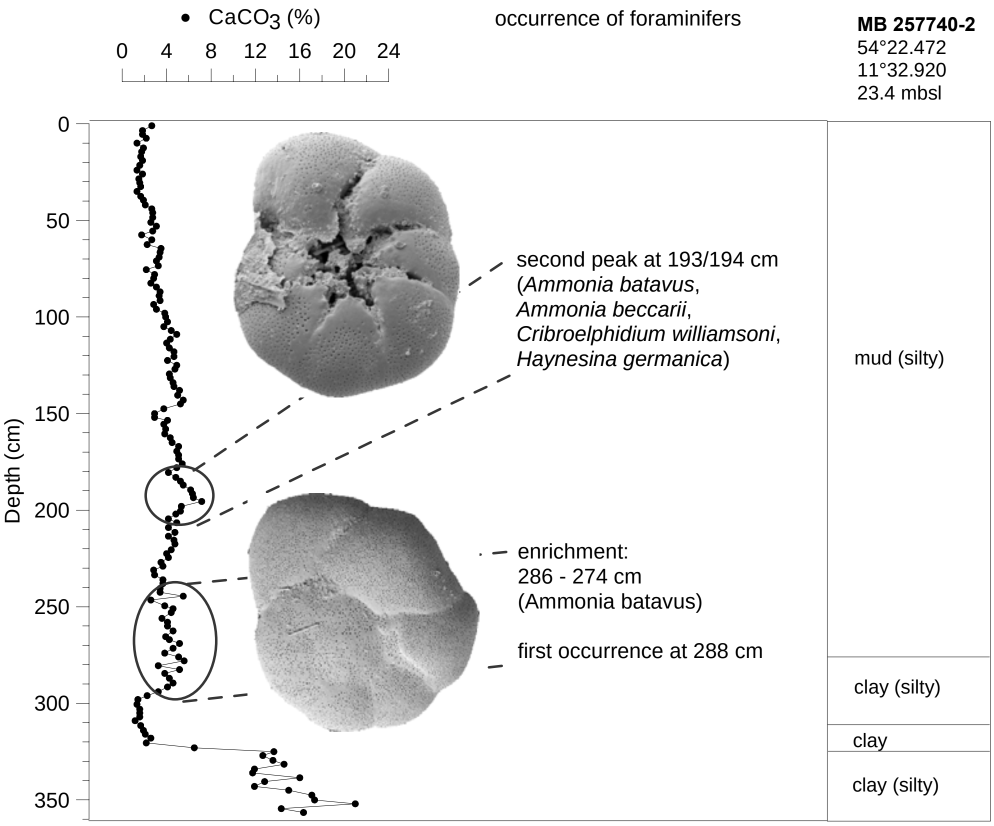


Fig. 27. Correlation of carbonate peaks ($CaCO_3$) with first occurrence of foraminiferal assemblages within the core MB 257740-2. Areas with accumulation of foraminifers are marked with grey circles.

Abb. 27. Korrelation der Karbonatpeaks ($CaCO_3$) mit den ersten (häufigen) Foraminiferen-Vorkommen (graue Kreise) des Kernes MB 257740-2.

Apart from the foraminiferal analyses described above, two cores from the Mecklenburg Bay, namely MB 257740-1 and MB 257760-1, were analysed semi-quantitatively by Dr. P. Frenzel, Dr. J. Bartholdy and O. Bennike. Related diagrams are shown in Appendix A12-A14, extended by ostracods, macrophytes and molluscs countings.

Variation in the diatom assemblage of core AB 258000-1

Analysis of diatom assemblages has been emphasized as a complementary tool to reconstruct the palaeo-environment and the development of the salinity within the study area, which is limited to the Arkona Basin in this chapter.
Within the framework of a MSc-thesis at the University Greifswald, the core AB 258000-1 was investigated by STEYER (2004). The following results are related to this work focussing especially on the aspect of the Littorina transgression.
The first indications of a change in salinity conditions at the site occurred at a core depth of 445 cm (unit E) with the appearance of mesohalobous species (e.g. *Dimerogramma minor*, *Diploneis smithii*, *Grammatophora marina*). Nearly all freshwater diatoms disappeared from the record at a depth of 425 cm and thus marking drastically the transition to marine conditions there (boundary E/F; Fig. 28). The accumulations of *Diploneis smithii* (maximum at 425 cm), *Campylodiscus bicostratus* and *Campylodiscus clypeus* (maxima at 420 cm) indicate the transition to brackish-

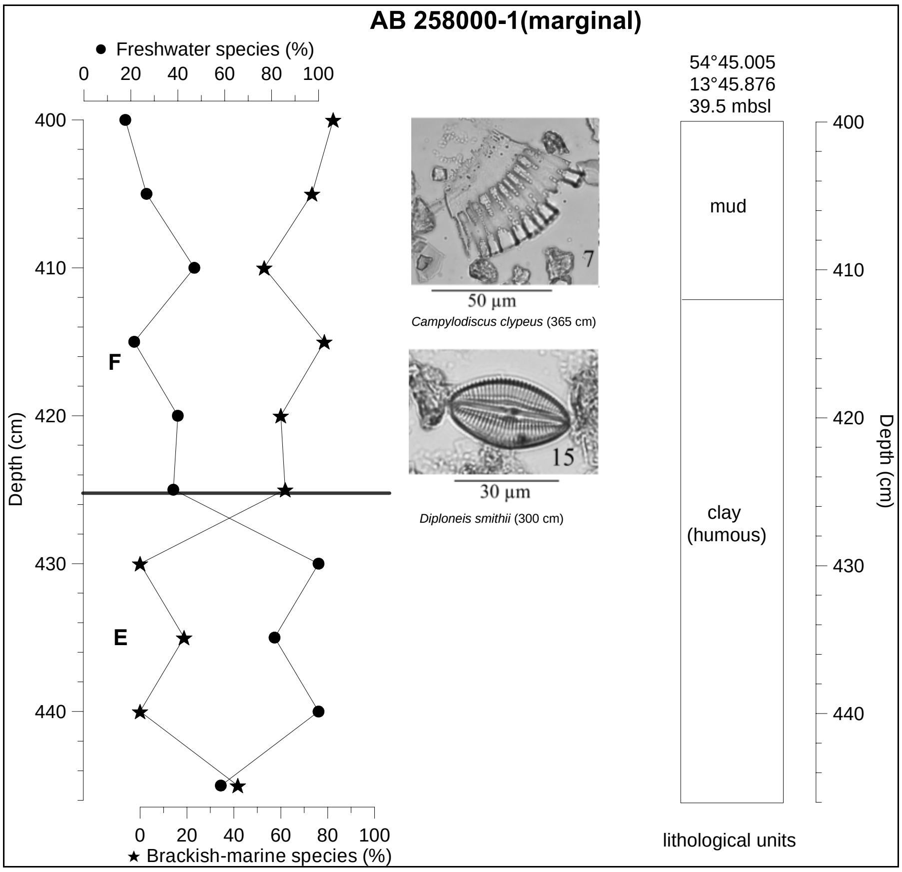


Fig. 28. Distribution of freshwater and brackish-marine diatom species in core AB 258000-1 (according to STEYER 2004). Note the diatom shift at 425 cm: brackish-marine diatom species appear and become dominant in unit F. The grey line corresponds to the boundary E/F referring to the diatom taxa.

Abb. 28. Verteilung der Süßwasser- und brackisch-marinen Diatomeenarten des Kernes AB 258000-1 (nach STEYER 2004). Es erfolgt ein Artenwechsel bei 425 cm: brackisch-marine Diatomeen treten auf und dominieren in der Einheit F. Die graue Linie markiert die Grenze E/F, bestimmt anhand des Diatomeenarten-Wechsels.

marine conditions at 425 cm sample depth (boundary E/F) as well. Furthermore, the occurrence of these brackish-marine diatoms coincides with an increase in planctonic diatoms (STEYER 2004), demonstrating the establishment of more stable marine conditions in unit F.

In summary, freshwater diatom species disappear rapidly in the uppermost centimetres of the Ancylus Lake sediments. Brackish-marine ones become abundant and dominant in the Littorina Sea deposits (unit F).

4.7 Dating of the Littorina transgression

An accurate correction for the reservoir age effect is still complicated and under discussion due to the complex structure of the Baltic Sea with its different basins and varying local evolutions (e.g. WINN ET AL. 1998, ERONEN ET AL. 1990). Ages are therefore given as uncorrected ^{14}C-ages without any calibration (^{14}C yr BP). Dateable material was taken close to the transgression horizon in order to date the first marine signal within the cores. Radiocarbon dates are listed in Table 7.
Various materials were dated to get dates describing the onset of the Littorina transgression as accurately as possible. Dates were obtained from:

(i) calcareous samples, i.e. mollusc remains and foraminifers (Fig. 29)
(ii) organic fractions, i.e. bulk samples which differ between humic acid residues and base residues.

These dates display considerable age differences within one sample as will be illustrated next.

Dating of different material from 588-586 cm core depth of the Mecklenburg Bay core MB 242770-1 delivered the following ages (Tab. 7):

(i) benthic foraminifers: 7265 ± 35 ^{14}C yr BP
(ii) mollusc shells: 7575 ± 35 ^{14}C yr BP
(iii) bulk sample, humic acid residues: 7975 ± 60 ^{14}C yr BP
(iv) bulk sample, base residues: 8205 ± 40 ^{14}C yr BP.

Ages derived from bulk sediment are considerably older (here almost 1000 yr) than those obtained from calcareous benthic foraminifers and shells. Two different organic fractions were dated on bulk sample KIA 28027, resulting in a 230 yr older base residues fraction compared to the humic acid residues one.
Generally, similar age results can be observed in the central Mecklenburg Bay core MB 242760-4 at 432-430 cm:

(i) benthic foraminifers: 7535 ± 45 ^{14}C yr BP
(ii) bulk sample, humic acid residues: 8155 ± 45 ^{14}C yr BP
(iii) bulk sample, base residues: 8530 ± 35 ^{14}C yr BP.

Mollusc shells occurring at depths between 436-434 cm yielded age up to 7460 ± 40 ^{14}C yr BP. The results of two different organic fractions, which were dated separately on bulk sample KIA 28345 show ^{14}C dating that reflect an older base residue age, i.e. 375 yr.
Another significant age difference between the bulk material fractions and the calcareous material can be observed in core AB 242800-1 from the central Arkona Basin. Dating of calcareous AB 242800-1 material yields:

(i) 6225 ± 30 ^{14}C yr BP for benthic foraminifers at 355 cm
(ii) 6495 ± 35 ^{14}C yr BP for *Artica islandica* at 359-360 cm
(iii) 6680 ± 50 ^{14}C yr BP for humic acid residues at 355 cm (bulk sample)
(iv) 7370 ± 45 ^{14}C yr BP for base residues at 355 cm (bulk sample).

Thus, the base residue date is 690 yr older than the humic acid residue date.

Tab. 7. Locations, coring device, water depth, their relation to the uppermost till surface, estimated position of the Littorina transgression, and uncorrected radiocarbon dates of the sites presented in this work. Bulk dates marked with * are derived from base residues or ** from humic acid residues.

Tab. 7. Kernstationen, Geräteeinsatz, Wassertiefe, Bezug zur Tiefenlage des obersten Geschiebemergels, Basislage der Littorina Transgression und unkorrigierte Radiokarbon-Datierungen der im Rahmen dieser Arbeit untersuchten Kerne. Bulk-Datierungen, gekennzeichnet mit * stammen von Laugen- bzw. mit ** von Säurerückständen der Bulk-Proben

Area	Core	Lat. N	Long. E	Coring device	Water depth (mbsl)	Location rel. to uppermost till surface	Base of transition (cm)	Sample (cm)	Dated material	delta ^{13}C (‰)	^{14}C-age BP (no reservoir correction)	Lab. Ref.
MB	242760-4	54°16.500	11°31.050	GC	23.0	central	443	432-430	benthic foraminifers	-2.74 ± 0.20	7535 ± 45	KIA 28346
MB	242760-4	54°16.500	11°31.050	GC	23.0	central	443	432-430	bulk sample**	-24.81 ± 0.13	8155 ± 55	KIA 28345
MB	242760-4	54°16.500	11°31.050	GC	23.0	central	443	432-430	bulk sample*	-23.86 ± 0.17	8530 ± 35	KIA 28345
MB	242760-4	54°16.500	11°31.050	GC	23.0	central	443	436-434	mollusc shells	2.68 ± 0.19	7460 ± 40	KIA 28347
MB	242770-1	54°16.530	11°25.550	GC	24.0	central	595	588-584	benthic foraminifers	-3.54 ± 0.30	7265 ± 35	KIA 27882
MB	242770-1	54°16.530	11°25.550	GC	24.0	central	595	588-586	mollusc shells	-2.71 ± 0.08	7575 ± 35	KIA 27881
MB	242770-1	54°16.530	11°25.550	GC	24.0	central	595	588-586	bulk sample**	-25.94 ± 0.19	7975 ± 60	KIA 28027
MB	242770-1	54°16.530	11°25.550	GC	24.0	central	595	588-586	bulk sample*	-26.90 ± 0.13	8205 ± 40	KIA 28027
MB	242770-1	54°16.530	11°25.550	GC	24.0	central	595	610-612	bulk sample**	-25.26 ± 0.10	8330 ± 40	KIA 28028
MB	242770-1	54°16.530	11°25.550	GC	24.0	central	595	610-612	bulk sample*	-25.22 ± 0.24	8340 ± 60	KIA 28028
MB	257740-1	54°22.472	11°32.920	VKG	23.4	marginal	330	320-310	*Mytilus edulis*	-0.95 ± 0.16	7455 ± 45	KIA 21670
MB	257740-1	54°22.472	11°32.920	VKG	23.4	marginal	330	330-320	*Mytilus edulis*	-0.3 ± 0.09	7405 ± 45	KIA 21671
MB	257740-1	54°22.472	11°32.920	VKG	23.4	marginal	330	340-330	*Macoma baltica*	-1.29 ± 0.16	7550 ± 45	KIA 21672
MB	257740-2	54°22.472	11°32.920	VKG	23.4	marginal	298	286-285	benthic foraminifers	-2.44 ± 0.21	6555 ± 40	KIA 27884
MB	257760-1	54°22.534	11°38.080	VKG	24.0	marginal	210	184	*Arctica islandica*	1.01 ± 0.05	6440 ± 35	KIA 21604
MB	257800-1	54°22.465	11°42.608	VKG	23.7	marginal	80	80	mollusc shells	1.20 ± 0.09	6440 ± 45	KIA 21607
AB	258010-1	54°55.180	13°09.077	VKG	42.4	marginal	350	350-340	*Mytilus edulis*	-1.9 ± 0.16	6585 ± 45	KIA 21681
AB	258010-2	54°55.177	13°09.080	VKG	42.4	marginal	368	345	bulk sample**	-26.38 ± 0.49	7675 ± 50	KIA 28025
AB	258010-2	54°55.177	13°09.080	VKG	42.4	marginal	368	345	bulk sample*	-26.68 ± 0.22	8125 ± 35	KIA 28025
AB	201310-1	54°57.960	13°40.020	GC	46.0	marginal	290	276-274	mollusc shells	0.47 ± 0.17	6490 ± 30	KIA 27883
AB	242800-1	54°56.000	13°50.030	GC	45.0	central	366	355	benthic foraminifers	-4.36 ± 0.17	6225 ± 30	KIA 27885
AB	242800-1	54°56.000	13°50.030	GC	45.0	central	366	355	bulk sample**	-27.98 ± 0.25	6680 ± 50	KIA 28029
AB	242800-1	54°56.000	13°50.030	GC	45.0	central	366	355	bulk sample*	-23.50 ± 0.08	7370 ± 45	KIA 28029
AB	242800-1	54°56.000	13°50.030	GC	45.0	central	366	360-359	*Arctica islandica*	1.47 ± 0.07	6495 ± 35	KIA 26267
AB	242800-1	54°56.000	13°50.030	GC	45.0	central	366	418	bulk sample**	-29.32 ± 0.10	9775 ± 50	KIA 28030
AB	242800-1	54°56.000	13°50.030	GC	45.0	central	366	418	bulk sample*	-26.15 ± 0.37	9950 ± 50	KIA 28030
AB	258000-2	54°45.004	13°45.874	VKG	39.5	marginal	491	462	bulk sample**	-24.81 ± 0.11	6985 ± 35	KIA 28026
AB	258000-2	54°45.004	13°45.874	VKG	39.5	marginal	491	462	bulk sample*	-22.61 ± 0.10	7395 ± 40	KIA 28026
AB	282080-1	54°50.717	13°55.509	VKG	44.0	marginal	268	248	*Mytilus edulis*	4.21 ± 0.05	6675 ± 35	KIA 26266
AB	282060-1	54°45.683	13°58.377	VKG	38.9	marginal	214	192	*Mytilus edulis*	2.84 ± 0.11	6570 ± 35	KIA 26270

MB Mecklenburg Bay; AB Arkona Basin

GC gravity corer; VKG vibrocorer

* base residues; ** humic acid residues

As shown for the Mecklenburg Bay, the age difference between the younger benthic foraminifers and the older bulk base residue date is more than 1100 yr. Hence, dating of organic fractions (bulk: base residues, humic acid residues) and calcareous material (benthic foraminifers, shells) of the same sample resulted in strongly varying ages (Tab. 7).

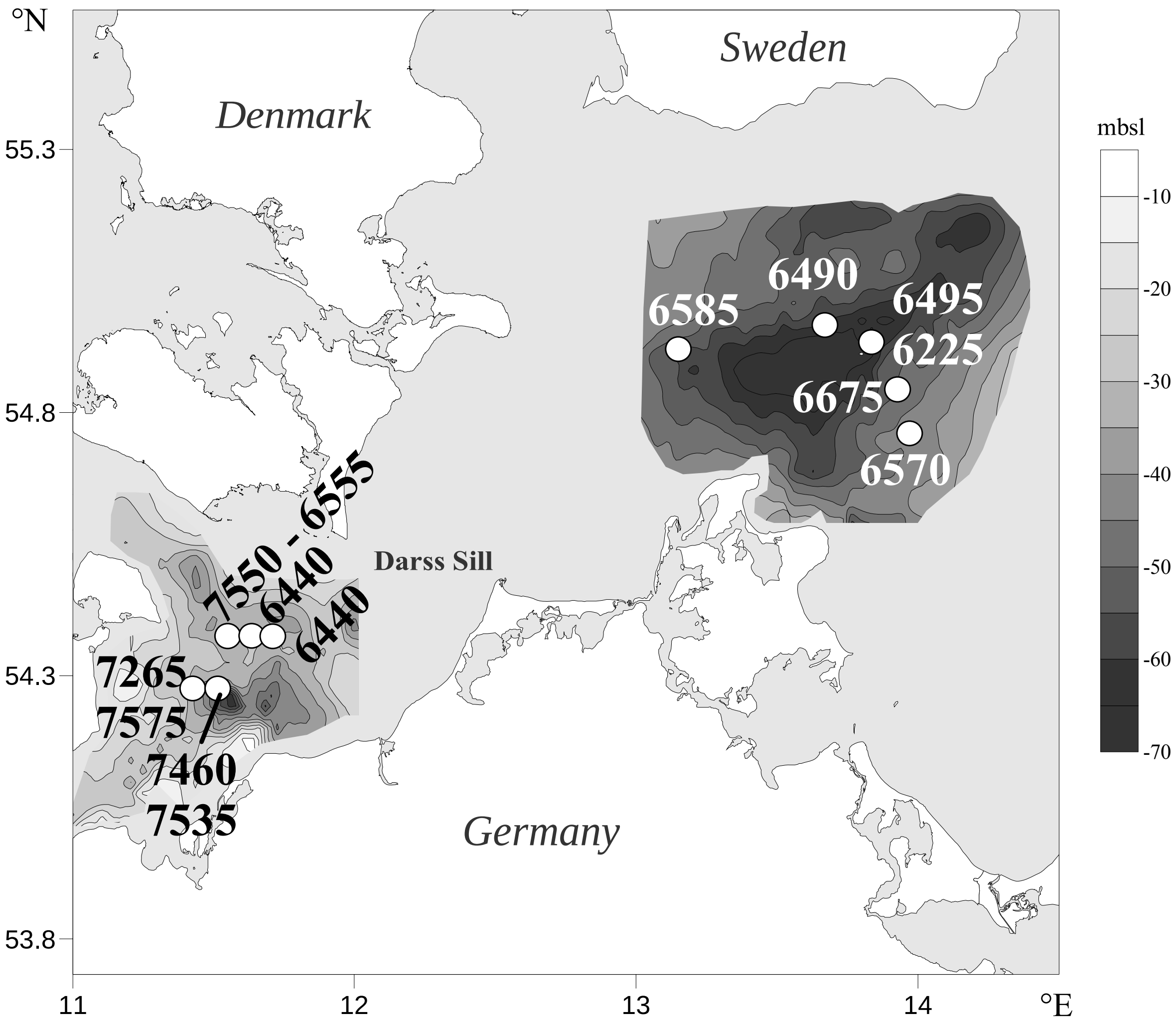


Fig 29. Uncalibrated AMS ^{14}C dates from the Mecklenburg Bay and the Arkona Basin in ^{14}C yr BP (no reservoir correction), derived from calcareous material (shell remains and benthic foraminifers). In general, Mecklenburg Bay data are older than Arkona Basin dates. Therefore, the determination of the occurrence of first marine signals, caused by the Littorina transgression, occurred in the Mecklenburg Bay at first. The depth of the uppermost till surface is included (isolines in mbsl; according to LEMKE 1998).

Abb. 29. Unkalibrierte AMS ^{14}C Daten von der Mecklenburger Bucht und aus dem Arkona Becken in ^{14}C a BP (keine Reservoirkorrektur), gemessen an kalkhaltigen Materialien (Molluskenreste und benthische Foraminiferen). Generell sind die Datierungen der Mecklenburger Bucht im Vergleich zum Arkona Becken älter. Folglich treten erste marine Signale, die durch die Littorina Transgression verursacht wurden, zuerst in der Mecklenburger Bucht auf. Die Tiefenlage des obersten Geschiebemergels ist ebenfalls in der Karte enthalten (Isolinien in mbsl; nach LEMKE 1998).

The two bulk fractions in core AB 258010-2 (marginal Arkona Basin) also showed a 450 yr older base residue date compared to humic acid residues dates. Radiocarbon dating results of organic fractions of core AB 258000-2 in the marginal Arkona Basin demonstrated similar data, i.e. an older base residue of about 410 years.

With respect to the bulk samples of the central cores MB 242770-1 and AB 242800-1 from the Ancylus Lake such a clear time difference was not obtained:

MB 242770-1

(i) 8330 ± 40 ^{14}C yr BP for humic acid residues at 610-612 cm

(ii) 8340 ± 60 ^{14}C yr BP for base residues at 610-612 cm

AB 242800-1

(i) 9775 ± 50 ^{14}C yr BP for humic acid residues at 418 cm

(ii) 9950 ± 50 ^{14}C yr BP for base residues at 418 cm.

Organic fraction dates (humic acid residues, base residues) derived from Ancylus Lake stage sediments display a much smaller age difference compared to the organic fraction dates of basal Littorina Sea stage sediments, which were taken nearest to the transgression horizon (Tab. 7).

In summary, dating of various material sampled close to the transgression base, displays a considerable age difference of up to 1100 yr between the youngest (calcareous material) and the oldest dates (base residue of bulk material). Calcareous materials deliver information of first dated brackish-marine signals within the basins (Fig. 29). Bulk material dating provides by far the oldest ages. Differences between the bulk dates of the two organic residues fractions were analysed with dates of the humic acid residues being generally younger than those of the base residues. Interestingly, there is a consistent 1000 yr age difference for the Littorina transgression horizon of the deeper Mecklenburg Bay and Arkona Basin, which is evident in all dated material, with the Arkona Basin dates displaying the younger ages.

5 Discussion

5.1 Discussion of proxy parameter

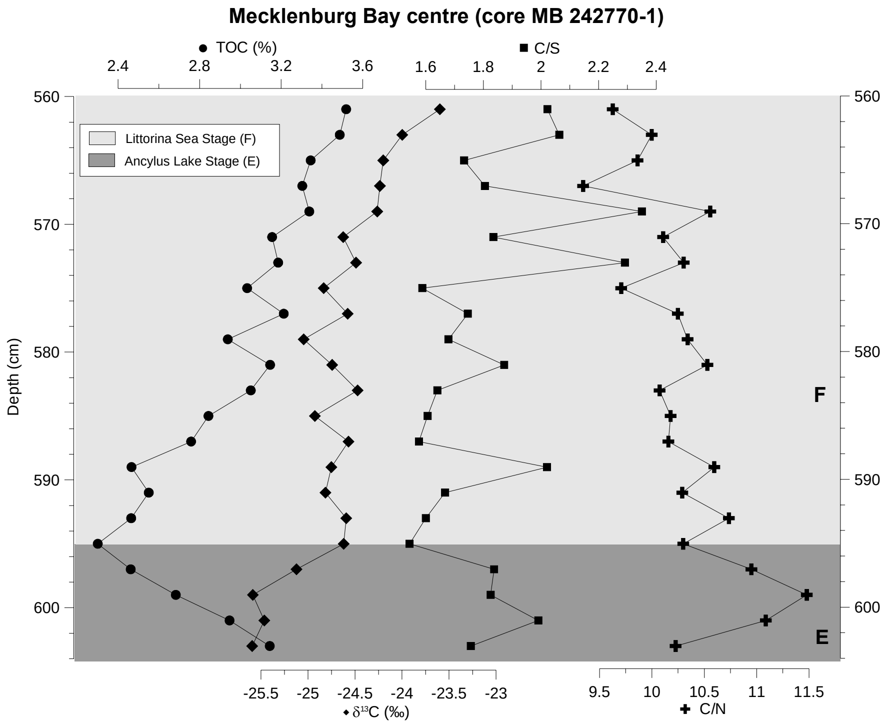
The transition from the Ancylus Lake to the Littorina Sea sediments is marked by changes in the measured parameters. After an evaluation of all results, only the most distinctly changing and most significant parameters are discussed in the following. These parameters are called proxy parameters and comprise (modified according to Tab. 3):

- GRAPE-density, magnetic susceptibility (χ) and grain size distribution > 63 µm, which are useful tools for the registration of erosion processes and current velocities (e.g. sandy layers),
- SIRM/χ ratio, indicating variation in the mineral magnetic composition (e.g. greigite formation),
- organic carbon (TOC), carbonate ($CaCO_3$), sulphur (S) contents and $\delta^{13}C$ isotopes, increasing at the transition base and reflecting palaeo-environmental shifts,
- occurrence of first foraminiferal and diatom assemblages/peaks, providing information about changes in salinity and productivity.

All these parameters (with the exception of $\delta^{13}C$ isotopes and diatom assemblages) were analysed in each core. They therefore guarantee and provide complete records and allow a correlation of these parameters within a core (Appendix A15-A18).
Changes in proxy parameters are best displayed in the central and deeper parts of the Mecklenburg Bay and the Arkona Basin with the clearest occurring in the Arkona Basin. The discussion therefore mainly refers to the central cores of the two basins.

5.1.1 Changes in surface water conditions at the transition from the Ancylus Lake to the Littorina Sea

Increasing organic carbon and sulphur contents, $\delta^{13}C$ values, C/S ratios as well as decreasing C/N ratios mark the transition from Ancylus Lake to Littorina Sea deposits in central/deeper Mecklenburg Bay and Arkona Basin cores (Fig. 30; see geochemical results 4.3). They deliver information regarding changes in surface water conditions caused by the Littorina transgression.
The rapid increase of TOC contents demonstrates the transition from the Ancylus Lake to the Littorina Sea phase sediments most clearly (Fig. 30). This increase is probably the result of an enhanced primary production, which is due to changes in surface water conditions (WINTERHALTER 1992). Such an increase in the primary production can be attributed to a stronger marine influence, warmer climate (post-glacial climatic optimum) and increased nutrient availability (STERNBECK ET AL. 1996). According to BIANCHI ET AL. (2000) inflowing marine waters may have altered limiting nutrients for primary production from phosphorous to nitrogen. X-ray fluorescence analyses (chapter 4.3.2) showed that the phosphorous content increases in the transition zone from the Ancylus Lake to the Littorina Sea sediments. Phosphorous is often bound in iron minerals under freshwater conditions (e.g. SOHLENIUS 1996). It was re-mobilized from these freshwater sediments due to the inflowing marine waters. Such inflowing saline waters consist of higher sulphate concentrations (EKMAN 1953). The formation of iron sulphide in marine sediments was limited by iron. Thus the iron, previously combined with phosphorous in freshwater Ancylus Lake sediments, is now bound in sulphide minerals of brackish-marine Littorina Sea deposits (CARACAO ET AL. 1990). This explains the shift from phosphorous to nitrogen-limited primary production very well. Nitrogen-fixing cyanobacteria took advantage of the change in nutrient supply best, resulting in the establishment of algae blooms in the early brackish-marine Littorina Sea (BIANCHI ET AL. 2000). Several previous studies (e.g. SOHLENIUS ET AL. 2001, ANDRÉN ET AL. 2000, SOHLENIUS & WESTMANN 1998, ABELMANN 1985) agree that cyanobacteria blooms could have caused the rapid increase in organic carbon content observed in the lowermost deposits of the early Littorina Sea.



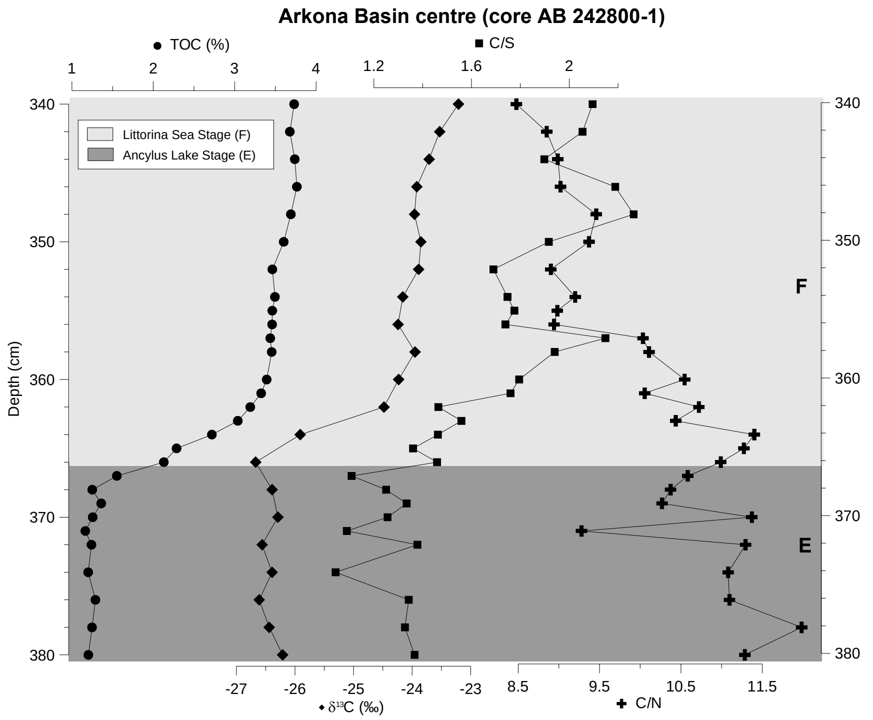


Fig. 30. Clear increases in TOC, $\delta^{13}C$ isotope values and C/S ratio and decreases in C/N ratio are displayed at the transition from Ancylus Lake to Littorina Sea deposits in both basins, the Mecklenburg Bay (MB 242770-1) and the Arkona Basin (AB 242800-1). Inflowing saline waters (Littorina transgression) caused changes in surface water conditions, expressed by increases/decreases of the proxy parameters. The boundary E/F corresponds to the remarkable TOC increase.

Abb. 30. Deutliche Anstiege im TOC-Gehalt, in den $\delta^{13}C$ Isotopen, im C/S-Verhältnis sowie eine Senkung im C/N-Verhältnis kennzeichnen den Übergang von den Ablagerungen des Ancylus See zum Littorina Meer in beiden Becken, der Mecklenburger Bucht (MB 242770-1) und dem Arkona Becken (AB 242800-1). Einströmende salinare Wasser (Littorina Transgression) lösten Veränderungen in den Oberflächenwasser-Bedingungen aus, die durch Anstiege bzw. Absenkungen der Proxy-Parameter wiedergegeben werden. Die Grenze E/F bezieht sich auf den markanten TOC-Anstieg.

Measured higher organic carbon contents as well as the interpreted appearance of cyanobacteria blooms during the early Littorina Sea are also supported by the bulk $\delta^{13}C$ isotope values (Fig. 30, see chapter 4.3.3). The sharp increase of $\delta^{13}C$ isotope values from less than -26‰ (on average) in unit E to around -22.5‰ in unit F indicates a rapid change from the freshwater Ancylus Lake to the marine Littorina Sea environment. SCHELSKE & HODELL (1995) concluded that increases in $\delta^{13}C$ values of organic matter in sediments are an indication for greater primary productivity; higher biological productivity due to eutrophication causes depletion in dissolved inorganic carbon (DIC) in the biologically active layer at the sea surface. This depletion leads to ^{13}C-enriched biomass during photosynthesis. Consequently, the increase in $\delta^{13}C$ values of organic matter in sediments is an indication for greater primary productivity. SCHELSKE & HODELL (1991) explained the shift in $\delta^{13}C$ values being the result of higher primary production in the Littorina Sea. STRUCK ET AL. (2000) drew similar conclusions:

- Productivity was nitrate-based.
- Higher organic carbon concentrations and ^{13}C-enrichment are indications of enhanced productivity in early Littorina times.

According to RAU ET AL. (1989), WESTERHAUSEN ET AL. (1993) and STRUCK ET AL. (2000) carbon isotope values ranging from -19.00 to -24.00‰ are of marine origin. BICKERT (2000) reports a mean $\delta^{13}C$ value for terrigenous material of -27‰ (90% of land plants are C_3 plants) and -19‰ for marine-derived matter. DEGENS ET AL. (1968) and DEGENS (1969) proclaimed that the $\delta^{13}C$ values of marine phytoplankton range from 10‰ to -31‰; those for cyanobacteria are less than -27‰. In the Arkona Basin and Mecklenburg Bay cores $\delta^{13}C$ values are around -26‰ in Ancylus Lake deposits (Fig. 30), thus indicating material of terrigenous origin. Carbon isotope values of the Littorina Sea sediments range from -24.5‰ to -22.5‰, identifying marine organic matter, possibly derived from cyanobacteria blooms.

Furthermore, the decreasing C/N ratios in the cores (Fig. 30, see chapter 4.3.1) document an establishment of marine conditions in the beginning of the Littorina Sea stage/phase in the two basins as well. According to MEYERS (1994, 1997) C/N ratios can be classified as follows:

- C/N ratio consisting of phytoplankton and zooplankton is around 6,
- C/N ratio derived from freshly deposited marine organic matter is around 10,
- C/N ratio from terrigenous organic matter amounts 20 and more.

STEIN (1991) indicates C/N ratios between 6 and 15 to be marine organic material. This is in good agreement with the C/N ratios observed in the Mecklenburg Bay and the Arkona Basin cores, which generally drop within the transition zone (Fig. 30).

Results of the macroanalyses (chapter 4.6.1, Appendix A12-A14) support the observed C/N decrease. Plant and animal remains indicating terrestrial, telmatic or lacustrine environments become less abundant in the uppermost Ancylus Lake sediments. They disappear almost completely in the transition horizon and Littorina Sea deposits.

Fragments of insects, individuals of Cladocera and Characeae, spores and seeds document the limnic freshwater environment of the uppermost clayey-silty Ancylus Lake stage sediments (unit E). Similarly to the macrofossil analyses the content of limnic findings decreases dramatically at the transition from the Ancylus Lake (unit E) to the Littorina Sea deposits (unit F). HOFMANN & WINN (2000) investigated the Littorina transgression in the western Baltic Sea by the occurrence of subfossil Chironomidae and Cladocera. They observed high accumulations of Cladocera and Chironomidae below the Littorina transgression horizon, typical for freshwater habitats. Above the Littorina transgression horizon, however, Chyroids disappear and foraminifers occur (as shown below, chapter 5.1.2), demonstrating the marine influence. SARMAJA-KORJONEN & HYVÄRINEN (2002) also observed a dramatic fall in littoral Cladoceran diversity at the onset of the brackish Littorina transgression in their studied Finnish sediments. These results correspond well to the observed disappearance of limnic remains due to the inflowing marine waters of the Littorina transgression (see chapter 4.6.2).

Studying diatom assemblages is another useful tool for reconstructing the development and the position of the salinity changes within the surface waters of the Baltic Sea (e.g. WITKOWSKI 1994, WITKOWSKI ET AL. 2005). Investigated diatoms from the marginal Arkona Basin core AB 258000-1 were grouped into marine, brackish and freshwater species with regard to their water salinity preference. In the transgression horizon freshwater species disappear rapidly, whereas brackish-marine ones become abundant and dominant. MOROS ET AL. (2002) as well as KORTEKAAS (pers.

comm. 2005) report a sudden occurrence of brackish-marine diatom associations at the base of the transition horizon in the central Arkona Basin, too, indicating more saline surface waters. The change from oligohalobous to polyhalobous forms was also observed in other marginal Arkona Basin cores focussing on the transition E/F (LANGE & WULFF 1980, WITKOWSKI ET AL. 2005). Consequently due to inflowing marine waters (Littorina transgression) the surface water salinity increased. This resulted in a rapid shift to more brackish-marine diatom species in the beginning Littorina Sea (see chapter 4.6.2).
The transition to brackish-marine conditions is also expressed in increasing C/S ratios at the boundary E/F (Fig. 30, see chapter 4.3.1). According to BERNER & RAISWELL (1984) the C/S ratio can be used to interpret variations in past salinity. A mean C/S of 2.8 identifies marine conditions, which is explained by a correlation between sulphate concentrations and salinity leading to high iron sulphide content in marine sediments (RAISWELL & BERNER 1986). Thus, increasing C/S ratios in the early Littorina Sea stage are due to higher organic carbon and sulphate content, identifying the inflow of more saline waters.
According to EKMAN (1953) and SJÖBERG ET AL. (1984) the salinity was significantly higher in the Littorina Sea than at present. The slight increase in the Mg content in the lower Littorina Sea sediments (see XRF results 4.3.2 and Appendix A4) supports their observations of Mg increase due to a higher salinity. Even the slight increase in potassium was caused by the inflow of saline waters.

Besides the increased C/S ratios at the boundary E/F low C/S ratios occur in the uppermost Ancylus Lake deposits. Furthermore high iron and sulphur contents as well as high SIRM/χ ratios in the uppermost Ancylus Lake sediments correlate very well with the decreasing C/S and ARM/SIRM ratios (Fig. 31, Appendix A19-A20).

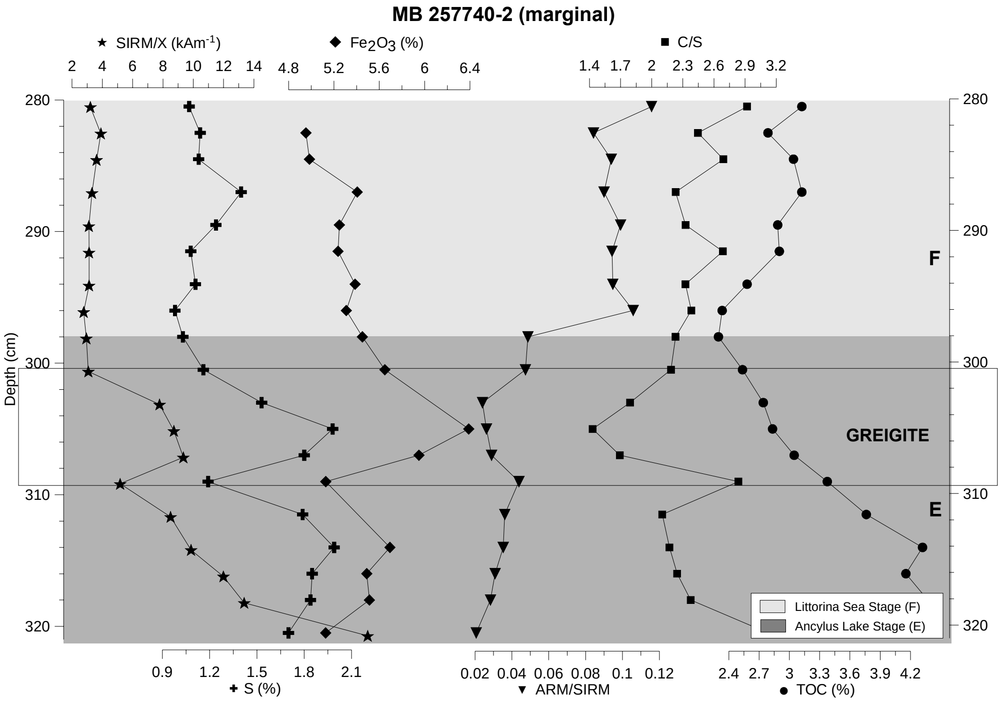


Fig. 31. ARM/SIRM, SIRM/χ and C/S ratios compared to the sulphur, iron and organic carbon contents investigated at the marginal cores MB 257740-2. Greigite (Fe_3S_4) is probably formed. Lithostratigraphic units E and F refer to the Ancylus Lake and Littorina Sea deposits. Boundary E/F refers to the increase in TOC.

Abb. 31. ARM/SIRM-, SIRM/χ- und C/S-Verhältnisse verglichen mit den Schwefel-, Eisen- und organischen Kohlenstoffwerten des marginalen Kernes MB 257740-2. Möglicherweise ist Greigit (Fe_3S_4) gebildet worden. Die lithostratigraphischen Einheiten E und F beziehen sich auf die Ablagerungen des Ancylus Sees und des Littorina Meeres mit der anhand der TOC-Messungen definierten Grenze E/F.

As described in several studies (e.g. BOESEN & POSTMA 1988, SOHLENIUS ET AL. 1996, STERNBECK & SOHLENIUS 1996 and LEPLAND ET AL. 1998), the formation of iron sulphide during the freshwater stage of the Ancylus Lake was limited by sulphate. It resulted in the formation of monosulphides. High sulphate concentration occurred in marine waters (BERNER 1971). So the formation of iron sulphide in marine sediments was limited by iron concentrations. Possibly, the excess of H_2S relative to Fe facilitated H_2S-downward diffusion to limnic Ancylus Lake sediments. There it reacted with iron minerals to form diagenetic greigite or pyrite (e.g. SOHLENIUS 1996, SNOWBALL pers. comm. 2004).
Greigite has low ARM/SIRM, similar to large magnetite grains. Large magnetite grains have low SIRM/χ. A combination of low ARM/SIRM and high SIRM/χ suggests the presence of greigite (SNOWBALL 1997).
Furthermore, low magnetic susceptibility and SIRM values at the boundary E/F (e.g. AB 258010-2) or in the lowermost deposits of unit F (e.g. AB 242800-1) may be effected by a higher content of organic carbon causing the dilution of the magnetic minerals content (SOHLENIUS 1996). According to SNOWBALL & THOMPSON (1988) rapid decreases in magnetic susceptibility could be connected with the dissolution of ferromagnetic minerals in brackish-marine water. They observed such dissolution in transgression periods, which led to an almost complete loss of magnetic grains and thus magnetic susceptibility. SANDGREN ET AL. (1990) as well described a dramatic decrease in magnetic susceptibility in brackish-marine Littorina Sea sediments as a result of the ingression of salt water in the area of eastern Sweden. However, it seems to be possible that the changes in the mineral magnetic contents were caused by the diagenetic formation of greigite.

5.1.2 Changes in bottom water conditions at the transition from the Ancylus Lake to the Littorina Sea

The bottom water conditions in the Mecklenburg Bay and Arkona Basin changed in a significant way during the Littorina transgression. Saline waters flew into the deeper basins first, initiating a rapid establishment of stable saline conditions at the bottom. One of the first organism groups being able to adapt quickly to the new habitat conditions were benthic foraminifers (e.g. MOROS 1998, LEMKE 1998, MOROS ET AL. 2002). This observation could be confirmed during the search for datable material under the binocular microscope. The first foraminifers appear close to the transgression boundary (see Tab. 6, chapter 4.6.2). Several individuals of *Ammonia batavus*, a benthic foraminifer, dominate the first findings. In an upward direction, *Ammonia batavus* become predominant, resulting in a first foraminiferal accumulation or peak. Besides *Ammonia batavus* few individuals of *Ammonia beccarii*, *Cribroelphidium williamsoni* and *Haynesina germanica* occur.
Furthermore, the benthic community depends on organic matter input from the surface (WEFER ET AL. 1999). Consequently, the significant TOC increase is linked to the changed bottom water conditions, i.e. the development of stable saline conditions at the bottom favoured the preservation of organic matter. Benthic foraminifers live on organic material falling to the bottom. Thus, their abundances should vary with food supply from above. Following, the accumulation rate of benthic foraminifers can be used to reconstruct productivity (HERGUERA & BERGER 1991, HERGUERA 1992).
As documented in chapter 4.6.2, the occurrence and accumulation of benthic foraminifers correlates well with the measured carbonate peaks. Consequently, these carbonate peaks consist of calcareous microfossils, e.g. benthic foraminifers or ostracods. The first occurrence of benthic foraminifers indicates the early Littorina transgression and their maximum accumulation possibly the culmination of the transgression, which coincides with the observed carbonate maximum.
According to MOROS (1998) the characteristic carbonate peak appears later, even with regard to the shift in TOC, in cores from marginal areas than in those from the central parts of the Arkona Basin. The central core AB 242800-1 is plotted together with Moros' Arkona Basin cores in Figure 32. Two lines mark the beginning of the significant TOC increase (black dashed line 1) and the maximum in carbonate (grey line 2). The difference between these lines is greater in marginal than in central cores. In the deeper (central) Arkona Basin the organic carbon and carbonate contents

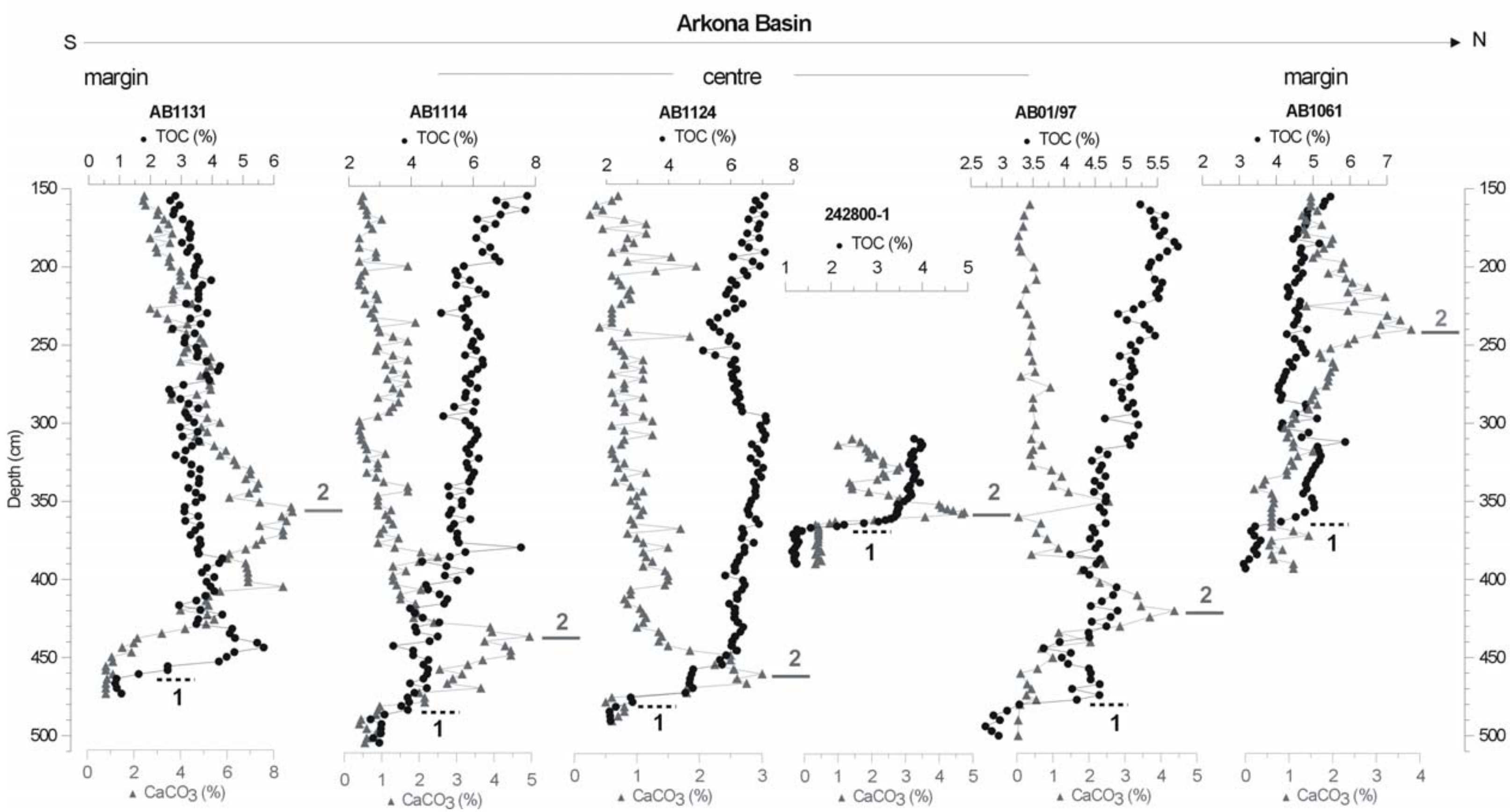


Fig. 32. Organic carbon content (TOC) and carbonate content ($CaCO_3$) of five studied cores from the Arkona Basin by Moros (1998) compared to core AB 242800-1. Dashed black lines (1) show beginning of significant increase in TOC. Grey lines (2) mark the first maximum in $CaCO_3$. The rapid increase in TOC indicates the beginning of the Littorina transgression and the maximum of $CaCO_3$ the transgression culmination. The terms „margin“ and „centre“ refer to the depth position of the uppermost till surface for site locations. Core sites are S-N oriented.

Abb. 32. Organischer Kohlenstoff- (TOC) und Karbonatgehalt ($CaCO_3$) von fünf untersuchten Kernen aus dem Arkona Becken (Moros 1998) verglichen mit dem Kern AB 242800-1. Die gestrichelten schwarzen Linien (1) zeigen den signifikanten Beginn des TOC-Anstieges. Die grauen Linien (2) markieren das erste $CaCO_3$-Maximum. Der schnelle TOC-Anstieg identifiziert den Beginn der Littorina Transgression und das $CaCO_3$-Maximum den Transgressions-Höhepunkt. Die Begriffe „Rand“ und „Zentrum“ beziehen sich auf die Tiefenlage des obersten Geschiebemergels. Die Kernstationen sind S-N orientiert.

start to increase nearly simultaneously and culminate in a first $CaCO_3$ peak accompanied by high TOC values. This carbonate peak marks the transgression culmination in deeper waters. Stable saline conditions have been established at the bottom (MOROS 1998). The rapid TOC increase characterises the beginning of brackish-marine conditions in surface waters (see chapter 5.1.2). The correlated organic carbon and carbonate contents of the central Mecklenburg Bay display weaker shifts at the transgression base, too (Fig. 33).
Several Authors (e.g. SOHLENIUS 1996, ANDRÉN 1999) describe a transition phase from the Ancylus Lake stage to the Littorina Sea stage, the so-called Mastogloia stage and Initial Littorina Sea. As mentioned before, a clear transition phase like the Mastogloia Sea stage is only found and described in coastal areas (MILLER & ROBERTSSON 1979). The term Initial Littorina Sea is related to deeper basins explaining the occurrence of a slightly brackish transition with low diatom accumulations there (e.g. ANDRÉN 1999, ANDRÉN ET AL. 2000). Compared to the data presented here, a transition phase, like the Initial Littorina Sea, has not been observed in the deeper basins of the Mecklenburg Bay and Arkona Basin.
In marginal Arkona Basin areas the carbonate maximum appears later (Fig. 32). A transition phase probably developed in marginal areas first until saline waters created marine stable bottom water conditions there. The observed transitional phase seems to reflect the yet sparsely recorded Mastogloia stage.

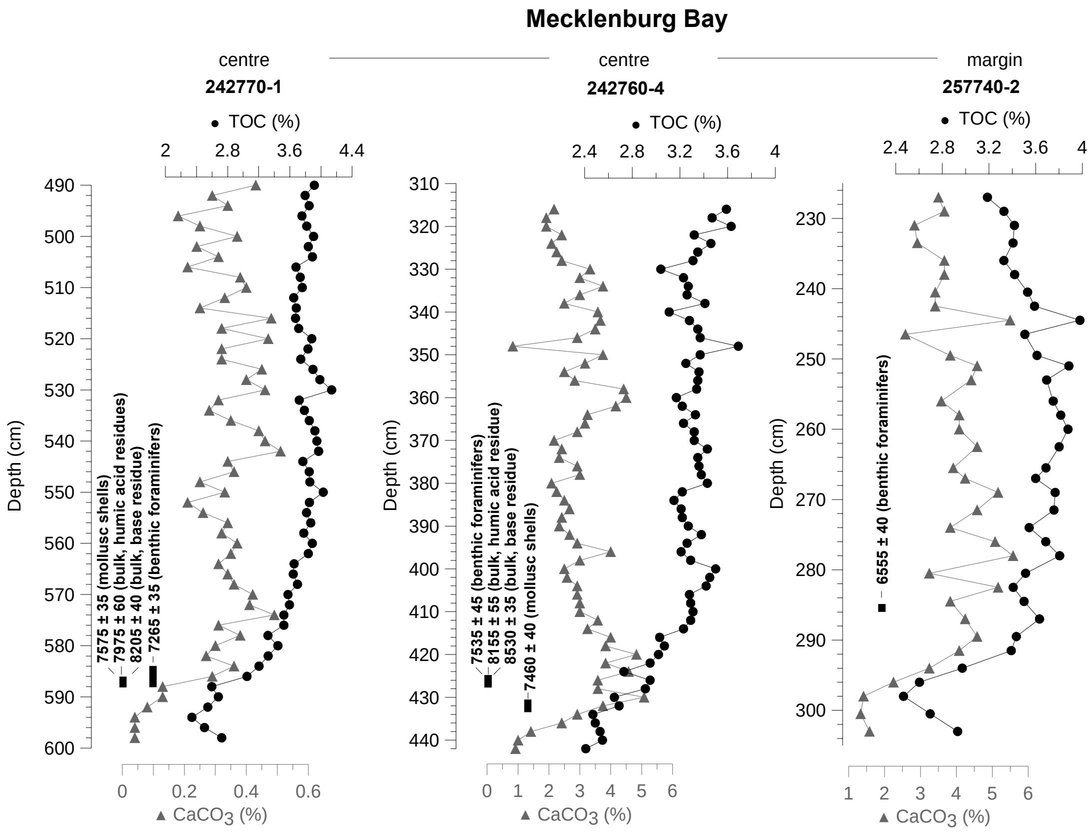


Fig. 33. Organic carbon content (TOC) and carbonate content are shown ($CaCO_3$) of three studied cores from the Mecklenburg Bay. Uncorrected AMS ^{14}C dating performed on marine benthic foraminifers, mollusc shells and bulk (different fractions) are included. TOC and $CaCO_3$ display weaker increases (compared to AB results, see Fig. 33). Black boxes for AMS ^{14}C dating indicate sample depths. Their lengths correspond to the sampling interval. The terms "margin" and "centre" refer to the depth position of the uppermost till surface for site locations.

Abb. 33. Organische Kohlenstoff- (TOC) und Karbonatgehalte ($CaCO_3$) von drei Kernen aus der Mecklenburger Bucht, ergänzt durch unkorrigierte AMS ^{14}C Datierungen mariner benthischer Foraminiferen, von Molluskenreste und von Bulkfraktionen. TOC und $CaCO_3$ steigen schwach an (im Vergleich zum Arkona Becken, siehe Abb. 32). Die Länge der schwarze Kästen entspricht dem Teufenintervall der entnommenen AMS ^{14}C Proben. Die Begriffe „Rand" und „Zentrum" beziehen sich auf die Tiefenlage des obersten Geschiebemergels.

Apart from benthic foraminifers and ostracodes, shell remains of *Arctica islandica*, *Macoma baltica* and *Mytilus edulis* were found close to the transgression base in both basins. They also indicate a distinct change from a fresh- to a brackish-marine bottom water environment.

5.1.3 Comparison of the Mecklenburg Bay with the Arkona Basin

The sediments of the central Arkona Basin display clearer signals of changing parameters than those of the central Mecklenburg Bay. For example, the geochemical proxy records of the Mecklenburg Bay do not show those rapid shifts from a terrestrial/lacustrine to a marine environment. This can be due to the general shallower depth and smaller area of the Mecklenburg Bay. Here, intensive reworking of Ancylus-time peat gyttjas during the Littorina transgression seems to play an important role. Inflowing marine waters most likely eroded the Ancylus-time sediments and flooded former terrestrial areas. This may have caused a mixing of older Ancylus Lake and younger Littorina Sea material resulting in the only slight (e.g. $CaCO_3$ content) and sometimes stepwise (e.g. $\delta^{13}C$) variations in the investigated Mecklenburg Bay parameters (Fig. 34). This mixing influenced also the age composition of the Mecklenburg Bay deposits (see chapter 5.2).

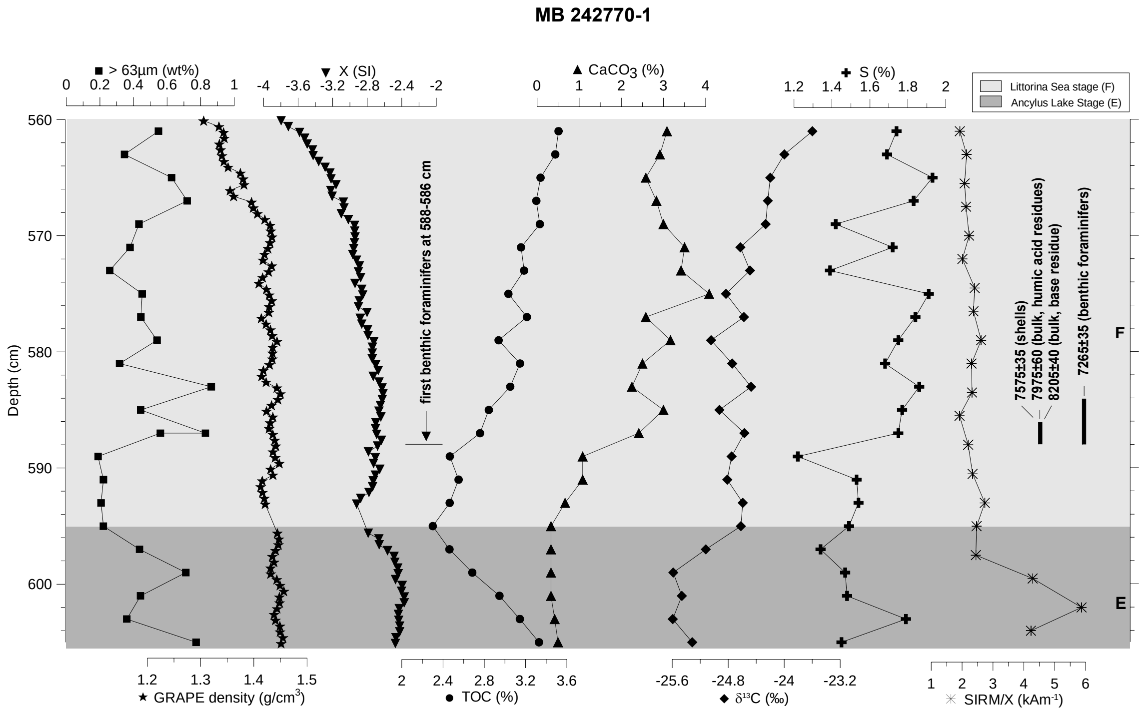


Fig. 34. Proxy parameters from the central core MB 242770-1 combined with uncalibrated AMS ^{14}C dates. Lengths of black boxes for AMS ^{14}C dating correspond to sampling interval. Parameters start to increase at the transition from unit E to F.

Fig. 34. Proxy Parameter des zentralen Kernes MB 242770-1 ergänzt mit den unkalibrierten AMS ^{14}C Datierungen. Die Länge der schwarzen Boxen entsprechen dem Teufenbereich der Datierungsproben. Die Parameter verändern sich am Übergang von der Einheit E zu F.

Organic carbon or carbonate values rise nearly simultaneously in the central Arkona Basin and are accompanied by a first strong $CaCO_3$ peak. Peaks in wt% > 63 µm coinciding with GRAPE density spikes and higher magnetic susceptibilities characterise the transgression base in the deeper Arkona Basin core (Fig. 35) and are accompanied by a macroscopically distinct sediment colour change (chapter 4.2.2). It seems that the transgressive influence was more pronounced in the Arkona Basin than in the Mecklenburg Bay (see chapters 4.2 - 4.6).

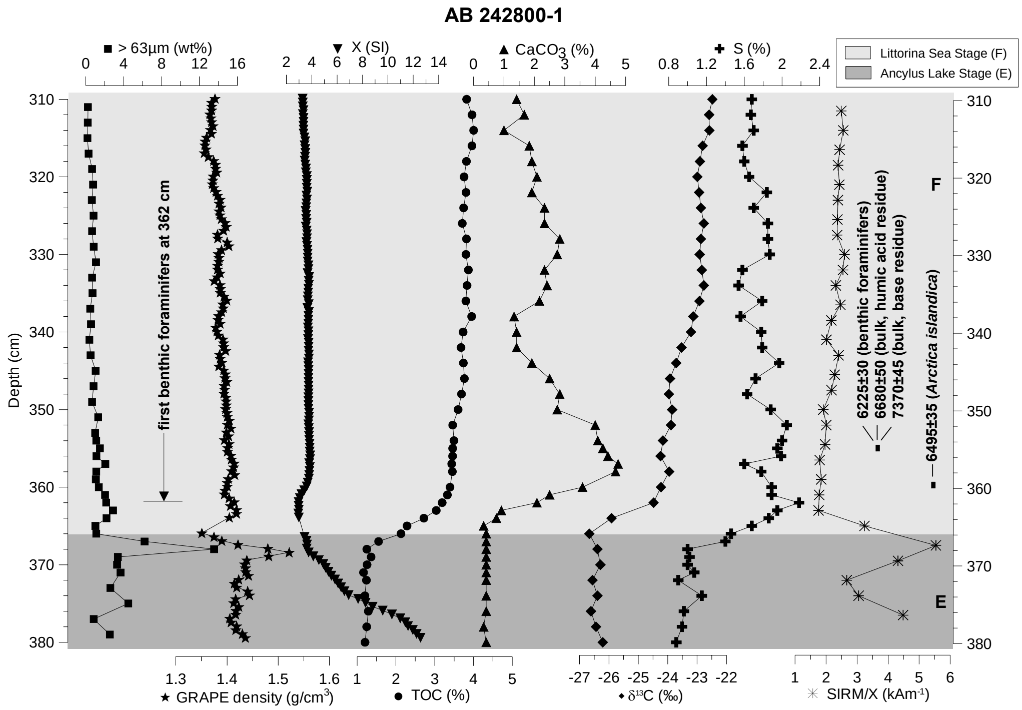


Fig. 35. Proxy parameters from the central core AB 242800-1 combined with uncalibrated AMS ^{14}C dates. Lengths of black boxes for AMS ^{14}C dating correspond to sampling interval. The proxy parameters analysed in the Arkona Basin show clearer changes at the trangression base than the Mecklenburg Bay ones (Fig. 34).

Fig. 35. Proxy Parameter sowie unkalibrierte AMS ^{14}C Datierungen des zentralen Kernes AB 242800-1. Die Länge der schwarzen Boxen entsprechen dem Probenintervall der Datierungsproben. Die Proxy Parameter zeigen deutlicherere Veränderungen im Arkona Becken gegenüber der Mecklenburger Bucht (Abb. 34) an.

5.2 Timing of the Littorina transgression and possible marine pathway

The precise determination of the onset of the Littorina transgression in the western Baltic Sea was anticipated using radiocarbon dating. According to the proxy parameter the transgression base was defined for each core (see results and Appendix A15-A18). Therefore, all datable material was selected closest to the transgression base in order to date the first marine signal within the Mecklenburg Bay and Arkona Basin cores. As described in chapter 4.7, dates were derived from:

(i) calcareous samples, i.e. mollusc remains and benthic foraminifers,
(ii) organic fractions, i.e. bulk samples being divided into humic acid residues and base residues.

The dates display considerable age differences (see chapter 4.7 and Tab. 7):

(i) within the same sample by comparing calcareous and bulk dates,
(ii) within the same sample by comparing the two organic bulk fractions, i.e. humic acid and base residues,
(iii) between the Mecklenburg Bay and Arkona Basin (see Fig. 36).

Generally, all dates give ages younger than 8,000 ^{14}C yr BP for the transgressive event. Only few samples are older consisting of two bulk samples from the Mecklenburg Bay, one bulk sample from the Arkona Basin and two older Ancylus Lake samples (see Tab. 7). Ages are much younger than expected based on former publications (e.g. KLIEWE & JANKE 1982, 1991, JANKE & LAMPE 2000). In the following, the discussion focuses on the dating results of the central cores from the deeper basins, as the transgression is probably recorded more precisely there.

To demonstrate again the striking age discrepancies in dating different material at the same core depth (transgression horizon), the oldest or second oldest calcareous remains of the deeper Mecklenburg Bay and deeper Arkona Basin, respectively, as well as their bulk fractions were corrected and calibrated. They are presented in Tab. 8. The dates have been corrected for a marine seawater reservoir effect subtracting 400 years. This number corresponds to the standard seawater reservoir age in the eastern North Atlantic (KROG & TAUBER 1974) and is very often used in published calibrated datasets (e.g. KÖNIGSSON & POSSNERT 1988, BENNIKE & JENSEN 1998, LEMKE 1998).

Tab. 8. Radiocarbon dates from two central cores of the Mecklenburg Bay and the Arkona Basin. The ages have been corrected (-400 yr reservoir correction according to Bennike & Jensen 1998) and calibrated by using calibration software Calib 5.0.1. (STUIVER ET AL. 2005).

Tab. 8. Radiocarbon-Datierungen zwei zentraler Kernes der Mecklenburger Bucht und des Arkona Beckens. Die Alter wurden korrigiert (-400 a Reservoirkorrektur gemäß nach Bennike & Jensen 1998) und kalibriert mit der Software Calib 5.0.1. (STUIVER ET AL. 2005).

Core	Depth below core top (cm)	Dated material	^{14}C-age BP (no reservoir correction)	Corr. and calib. age BP (1σ)	Laboratory Reference-number	Calibration curve / Calib 5.0.1
MB 242770-1	588-586	mollusc shells	7575 ± 35	7633	KIA 27881	Marine04
MB 242770-1	588-586	humic acid residues	7975 ± 60	8877	KIA 28027	IntCal04
MB 242770-1	588-586	base residue	8205 ± 40	9165	KIA 28027	IntCal04
AB 242800-1	355	benthic foraminifers	6225 ± 30	6244	KIA 27885	Marine04
AB 242800-1	355	humic acid residues	6680 ± 50	7548	KIA 28029	IntCal04
AB 242800-1	355	base residues	7370 ± 45	8258	KIA 28029	IntCal04

At the same depth, the calcareous age of the mussel in MB 242770-1, for example, is approximately 1,200 and 1,500 years younger than the calibrated ages of the humic acid residues and the base residue samples, respectively. Calibrated dates of the central Arkona Basin core AB 242800-1 show a similar result; the age difference between the benthic foraminifers and the bulk sample fraction dates differ approximately 1,300 and 2,000 years, respectively.
It is obvious that bulk samples give too old ages and that calcareous-dated material provides the more precise dates. Interpreting bulk dates, mixing of terrestrial and marine material in the sediment matrix has to be considered. Several authors like SOHLENIUS (1996), BENNIKE & JENSEN (1998) as well as USCINOWICZ (2003) report that small fragments of amber, coal, reworked, probably interglacial charred and non-charred wood fragments are abundant in most sediment types of the Baltic Sea and thus explain the presence of “old” carbon in the bulk samples. Another uncertainty of bulk dating can be attributed to the hard water effect. It can also lead to too high bulk ages as e.g. plant species incorporate some carbon from the water (BENNIKE & JENSEN 1998). Reworked plant remains have also been recognised with the binocular microscope during the investigations of the sieving remains.
Interestingly, the ages of the two different bulk fractions, the base and the humic acid residues, also differ significantly (apart from those two older Ancylus Lake bulk samples). Mixing with older, reworked material (e.g. Ancylus time material) and hard water effect may cause older base residues. Final explanations for younger humic acid residue ages are still unclear and subject of

discussions. The younger ages are probably derived from plants, which were growing at the time when marine waters (Littorina transgression) flooded the areas (GROOTES pers. comm. 2005).
Dates of humic acid residues are closer to the dates of calcareous macrofossils. However, in many published studies only base residues were dated. There is too little data from the Mecklenburg Bay and the Arkona Basin to discuss the age differences of the different bulk fractions properly.
The generally older bulk ages in the Mecklenburg Bay may partly be due to a stronger mixing impact, shallower water depths and the smaller area. Reworked terrestrial older Ancylus-time material may have been eroded or transported by incoming Littorina transgression water. This is supported by the observed higher C/N ratios (C/N peaks > 10) at the transgression boundary in marginal Mecklenburg Bay cores. Also the only stepwise increase of $\delta^{13}C$ values in the Mecklenburg Bay center supports hints of a strong input of terrestrial material during the early Littorina phase (Fig. 34). Terrestrial organic material is characterized by very light $\delta^{13}C$-values but material from enhanced primary production by heavier values. Hence, the only slight increase of $\delta^{13}C$-values in the Littorina transgression horizon may have been caused by a mixing of reworked Ancylus-time gyttja material and organic matter from enhanced primary production during the early Littorina phase.
According to the present dates, the transgression within the central Arkona Basin occurred approximately 1,000 years later than in the deeper Mecklenburg Bay . This is evident from all the dated material (Tab. 7). After the final drainage of the Ancylus Lake the Darss Sill became a land area with local lakes (e.g. BENNIKE & JENSEN 1998). Agreeing with LEMKE (1998) and WITKOWSKI ET AL. (2005) the Darss Sill with its threshold depth of 24 mbsl (e.g. LEMKE & KUIJPERS 1995) seems to act as a barrier for the incoming marine waters. This barrier behaviour may explain the different regional development east and west of the Darss Sill area, namely in the Mecklenburg Bay and the Arkona Basin (Fig. 36).
Published ages for the onset of the Littorina transgression were mainly derived from bulk material (e.g. ANDRÉN & ANDRÉN 2001, SOHLENIUS & WESTMAN 1996, WINN ET AL. 1986). Dates of calcareous material are rarely described in the literature. Radiocarbon dates of this work referring to the onset of the Littorina transgression in the central Mecklenburg Bay range between 8500 ^{14}C yr BP (bulk dates) and 7500 (7200) ^{14}C yr BP (calcareous material). It seems that the bulk ages from the Mecklenburg Bay agree with the published bulk ages, whereas the calcareous fossil dates reveal considerably younger ages. ERONEN ET AL. (1990) set the onset of the Littorina transgression in the Mecklenburg Bay between 8,500-8,000 ^{14}C yr BP (bulk samples). On the other hand BENNIKE & JENSEN (1998) dated their oldest marine mollusc remain from the Mecklenburg Bay to 7,220 ± 90 ^{14}C yr BP, which corresponds well to the calcareous dates obtained during this work. These dates come close to the observations of a first marine ingression in the Great Belt at 8,100 ^{14}C yr BP, which were also based on the dating of marine calcareous fossils (JENSEN ET AL. 1997, 2005, BENNIKE ET AL. 2004). WINN ET AL. (1998) dated the beginning of the transgression in the Great Belt around 8320 ^{14}C yr BP (bulk material).
In the central Arkona Basin materials yield calcareous fossil ages younger than 7,000 ^{14}C yr BP (excluding bulk samples, Fig. 36), displaying considerably younger ages compared to reported marine ages from Blekinge with 8,900 ^{14}C yr BP, describing the beginning of the Littorina transgression by brackish diatom flora, and 7,750 ^{14}C yr BP, marking the establishment of full marine conditions (BERGLUND ET AL. 2001, 2005). The first inflow of marine waters into the Bornholm Basin was dated to 8,900 ^{14}C yr BP (ANDRÉN ET AL. 2000) and into the Gotland Basin with 8,000 ^{14}C yr BP (SOHLENIUS ET AL. 1996).
Comparing dates with published relative (RSL) and eustatic (ESL) sea level curves of e.g. KÖSTER (1961), KROG (1979), DUPHORN (1979), KLIEWE & JANKE (1982) and KOLP (1986) for the southern Baltic Sea, the clear age discrepancy also occurs between the onset of the Littorina transgression (new data) and a rapid sea level rise before 8,000 ^{14}C yr BP (RSL and ESL curves; Fig. 37). Dates of this work indicate the onset of the Littorina transgression after 8,000 ^{14}C yr BP in the Mecklenburg Bay and the Arkona Basin (Fig. 36, 37, Tab. 7). In the central Mecklenburg Bay dated samples are older than in the deeper Arkona Basin. This favours a transgression pathway via the Belts into the Mecklenburg Bay (Fig. 36). Dates from the Arkona Basin are younger indicating a later onset of the Littorina transgression there.
These results contradict Swedish data published by BERGLUND ET AL. (2005), YU (2003) and BJÖRCK (1995), who describe a first marine transgression via the Öresund (area around Blekinge)

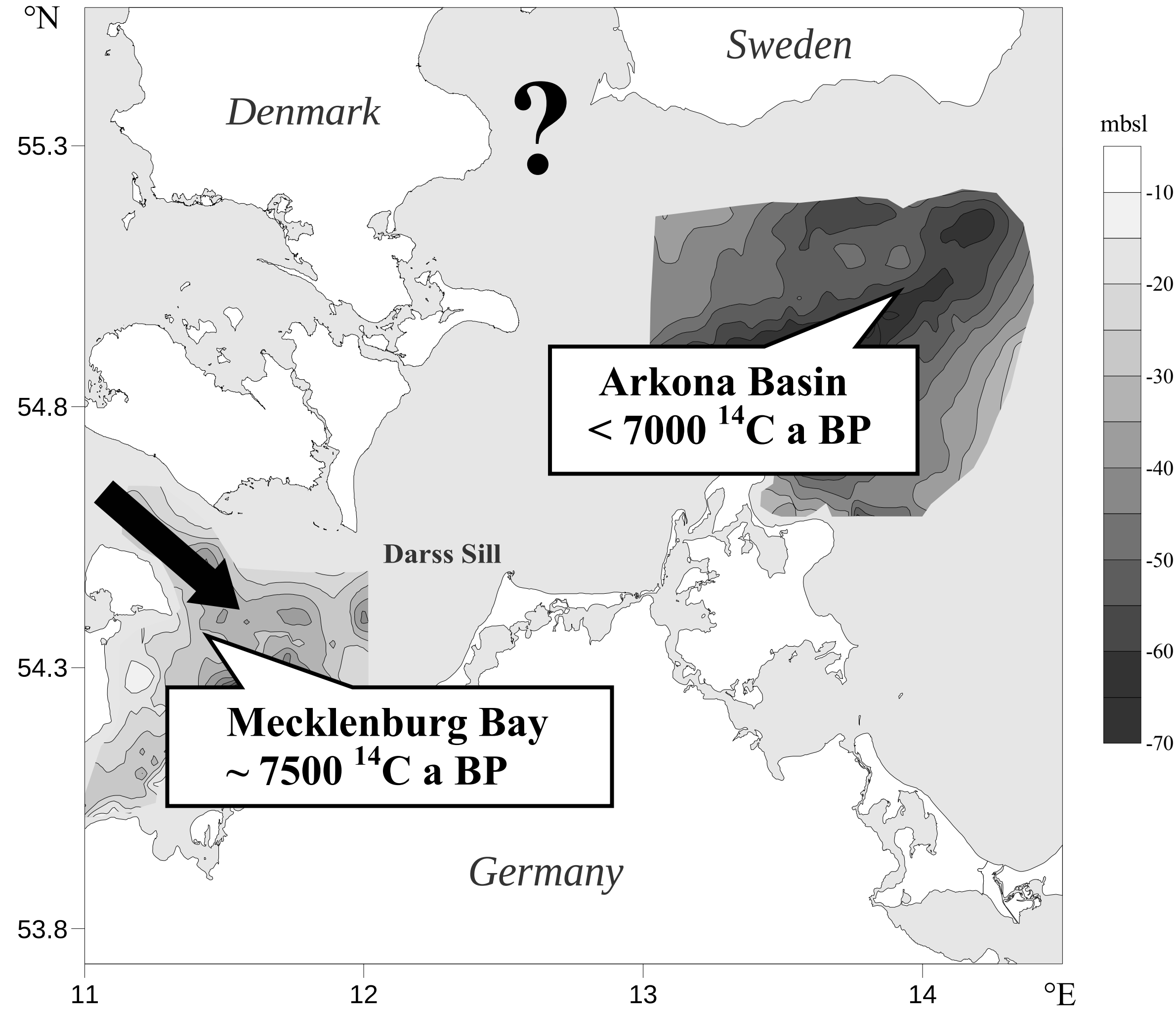


Fig. 36. The onset of the Littorina transgression in the western Baltic Sea derived and summarised from uncalibrated AMS ^{14}C dates from the Mecklenburg Bay and the Arkona Basin. The Mecklenburg Bay records older marine ages than the Arkona Basin. This favours a transgression pathway via the Belts into the Mecklenburg Bay (black arrow). The depth of the uppermost till surface (in mbsl) is included (according to LEMKE 1998).

Abb. 36. Der Beginn der Littorina Transgression in der westlichen Ostsee, bestimmt und zusammengefasst anhand unkalibrierter AMS ^{14}C Datierungen aus der Mecklenburger Bucht und aus dem Arkona Becken. Die Mecklenburger Bucht weist im Vergleich zum Arkona Becken ältere marine Radiokarbonalter auf. Dies favorisiert einen Transgressionspfad über die Belte in die Mecklenburger Bucht (schwarzer Pfeil). Die Tiefenlage des obersten Geschiebemergels wird ebenfalls gezeigt (in mbsl; nach LEMKE 1998).

at around 8,200 ^{14}C yr BP. The actual depth of the critical bedrock threshold at Drogden Sill (7 m b.s.l.) is much less than sill depths found in the Belts (c. 24 m b.s.l.). Even when considering differential isostatic uplift in both threshold areas this difference is too large to allow for an initial transgression via Öresund without additional assumptions, e.g. neotectonic movements in the Öresund region. In this context, SANDGREN ET AL. (1999) proved high late glacial uplift rates at Kullen Peninsula (north of Öresund) compared to the surrounding area. CHRISTENSEN (1995) reported from striking differences between local shore-line displacement curves in northern Sjælland and Barsebäck in SW-Skåne as well as between eastern and western Sjælland. Vertical block movements of up to 20 m occurred within only about two thousand years during the last deglaciation of the south-eastern Kattegat, as shown by JENSEN ET AL. (2002). JANKE & LAMPE (2000) point to neotectonic activity in the entire Western Pomeranian coastal region. All these reports demonstrate that the region is part of an active major European fault zone, the Tornquist-Teisseyre-Zone (as mentioned in the beginning, see chapter 2.2).

Further investigations are therefore necessary to overcome the existing contradictions, regarding the different onsets for the Littorina transgression in the areas of the Öresund and the western Baltic area and to assess the possible occurrence of neo-tectonic block movements during the Holocene in a better way.

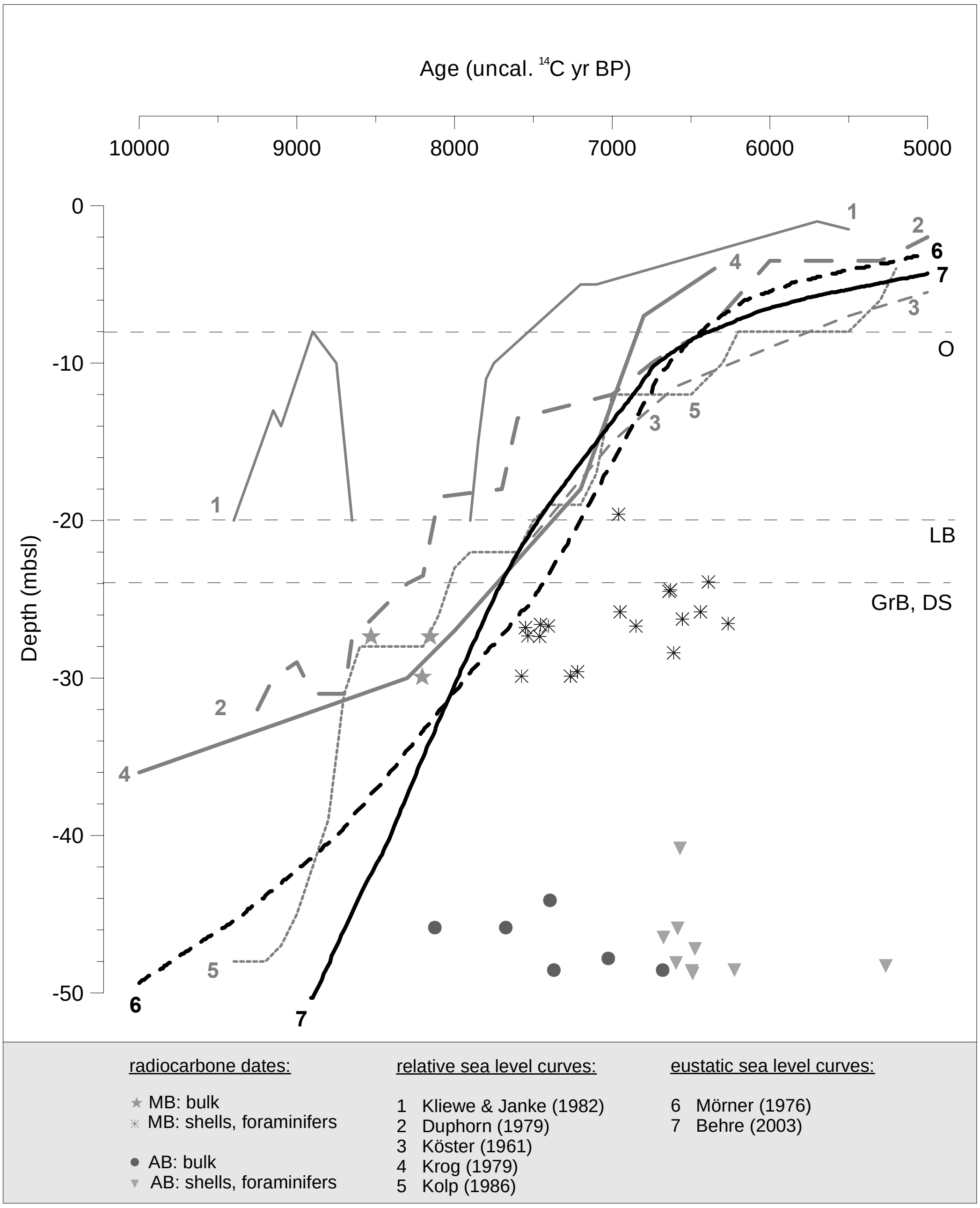


Fig. 37. Published relative and eustatic sea level curves from the south-western Baltic Sea compared with dated first marine signals in the Mecklenburg Bay (MB) and Arkona Basin (AB). Note the differentiation between bulk and calcareous-dated materials (AMS ^{14}C dates). Calcareous materials display younger ages than bulk ones. Mecklenburg Bay dates record older marine ages than the Arkona Basin. Long vertical dashed lines show depths of thresholds in mbsl: Little Belt -20, Great Belt -24, Darss Sill -24, Öresund -8 (LEMKE 1998).

Abb. 37. Veröffentlichte relative und eustatische Meeresspiegelkurven der südwestlichen Ostsee im Vergleich mit den ersten marin-datierten Signalen der Mecklenburger Bucht (MB) und des Arkona Beckens (AB). Auffallend ist der Altersunterschied zwischen Bulk- und kalkhaltigen Materialien, wobei kalkhaltige Proben die immer jüngeren Alter wiedergeben. Datierungen aus der Mecklenburger Bucht belegen gegenüber dem Arkona Becken ältere marine Radiokarbonalter. Die gestrichelten Linien zeigen die Tiefen der Schwellen in mbsl an: Kleiner Belt -20, Großer Belt -24, Darßer Schwelle -24, Öresund -8 (LEMKE 1998).

Summary

The Littorina transgression has caused one of the most pronounced environmental changes that occurred during the post-glacial history of the Baltic Sea. Marine waters entered the Danish Straits and flooded the Baltic Basin as a result of a global eustatic sea level rise and glacio-isostatic subsidence. The inflow of saline waters, i.e. the Littorina transgression, caused a transformation of the entire Baltic Basin's hydrography from the freshwater Ancylus Lake into the brackish-marine basin of the Littorina Sea. The general picture of this development is known. However, many details regarding the sediment proxies that are indicative of this event, the precise determination of the onset of the Littorina transgression as well as the chronological order in which the thresholds of the Belts and Öresund where flooded remain open.

In order to reconstruct the Littorina transgression in the western Baltic Sea two different approaches were implemented, namely the characterisation of the initial main transgressive phase by a multi-proxy-methodical work programme (physical, sedimentological, geochemical, and palaeontological investigations) and the precision of the onset of the Littorina transgression using radiocarbon dating.

17 cores were investigated covering the two basinal areas west and east of the Darss Sill, which are the Mecklenburg Bay and the Arkona Basin. Proxy parameters indicating the most significant changes by the Littorina transgression were defined and include the organic carbon, sulphur and carbonate contents, $\delta^{13}C$ isotopes, the first appearance of foraminiferal and diatom assemblages as well as the weight percentage of material > 63 µm, GRAPE-density, magnetic susceptibility and SIRM/χ ratio.

Changing proxy parameters are best displayed in the central and deeper parts of the Mecklenburg Bay and the Arkona Basin. The most distinct changes occur in the Arkona Basin. The first occurrence of benthic foraminifers (*Ammmonia batavus*) indicates changing bottom water conditions at the transition from the Ancylus Lake to the Littorina Sea stage. Their maximum represents the culmination of the Littorina transgression and coincides with the observed carbonate maximum. Besides benthic foraminifers, ostracodes and shell remains of *Arctica islandica*, *Macoma baltica* and *Mytilus edulis* were found close to the transgression horizon in both basins. They also indicate clearly the change from a fresh to a brackish-marine bottom water environment. Increasing organic carbon and sulphur contents, $\delta^{13}C$ values, C/S ratios as well as decreasing C/N ratios deliver information regarding changes in surface water conditions that were caused by the Littorina transgression. The rapid increase of TOC contents demonstrates the transition from Ancylus Lake to Littorina Sea phase sediments best. This increase is probably due to an enhanced primary production mainly. The shift in $\delta^{13}C$ values is interpreted to be a result of higher primary production in the surface waters of the beginning Littorina Sea, too. The range of carbon isotopes identifies marine organic matter, which is possibly derived from cyanobacteria blooms. Furthermore, the decreasing C/N ratios also support the establishment of marine conditions in the two basins. The disappearance of terrestrial, telmatic or lacustrine plants and animals at the transition base also contributed to the observed drop in the C/N ratio. The sudden appearance of brackish-marine diatom assemblages reflects the change to higher salinity surface water conditions. The inflowing, more saline waters led to higher sulphate contents and thus to a rise in C/S ratios in the early Littorina Sea. Apart from the increased C/S ratios at the boundary E/F, low C/S ratios occur in the uppermost Ancylus Lake deposits. It coincides with the observed high iron and sulphur contents as well as with the high SIRM/χ and low ARM/SIRM ratios, which are interpreted to demonstrate the diagenetic formation of greigite (Fe_3S_4) in the upper Ancylus Lake sediments.

Peaks in wt% > 63 µm, GRAPE density and magnetic susceptibilities coincide with macroscopically distinct sediment colour changes at the transgression base in the deeper Arkona Basin cores. Changes in these proxy parameters are more clearly established at the transition from Ancylus Lake to Littorina Sea sediments in the deeper Arkona Basin than in the central Mecklenburg Bay.

Low magnetic susceptibility and SIRM values at the transgression base (E/F) and/or in the lower Littorina Sea deposits are probably caused by diagenetic processes.

Various datable materials, i.e. calcareous remains (mollusc debris and benthic foraminifers) as well as bulk samples (two organic fractions: humic acid and base residues), were selected closest to the transgression base in order to date the first marine signals within the Mecklenburg Bay and Arkona

Basin cores. Generally, all data give ages younger than 8,000 ^{14}C yr BP for the onset of the Littorina transgression. However, the dates display considerable age differences within one sample comparing calcareous and bulk dates. Clearly, bulk samples give too old ages and calcareous dated material provides the more precise dates. Mixing with older reworked carbon material influences the bulk samples and causes their older ages. Following, the observed older bulk ages in the Mecklenburg Bay might be due to the mixing with reworked older Ancylus-time material. Interestingly, the ages of the two different bulk fractions, the base and the humic acid residues, also differ significantly within one sample. Due to too little data a final explanation cannot be given here.

The onset of the Littorina transgression in the central Mecklenburg Bay is dated between 8,500 (bulk dates) and 7,200 (calcareous material) ^{14}C yr BP. The transgression within the central Arkona Basin happened approximately 1,000 years later than in the deeper Mecklenburg Bay. Investigated dates from the deeper Arkona Basin are younger than 7,000 ^{14}C yr BP (excluding bulk samples). This is evident from all the respective dated material. The Darss Sill area with its threshold depth of about c. 24 mbsl seems to have acted as a barrier, which explains the separate regional development west and east of the Darss Sill area in the Mecklenburg Bay and the Arkona Basin. Regarding these new dates, the Littorina transgression favoured a pathway via the Belts into the Mecklenburg Bay. Dated materials refer to younger ages indicating the first marine signals in the Arkona Basin.

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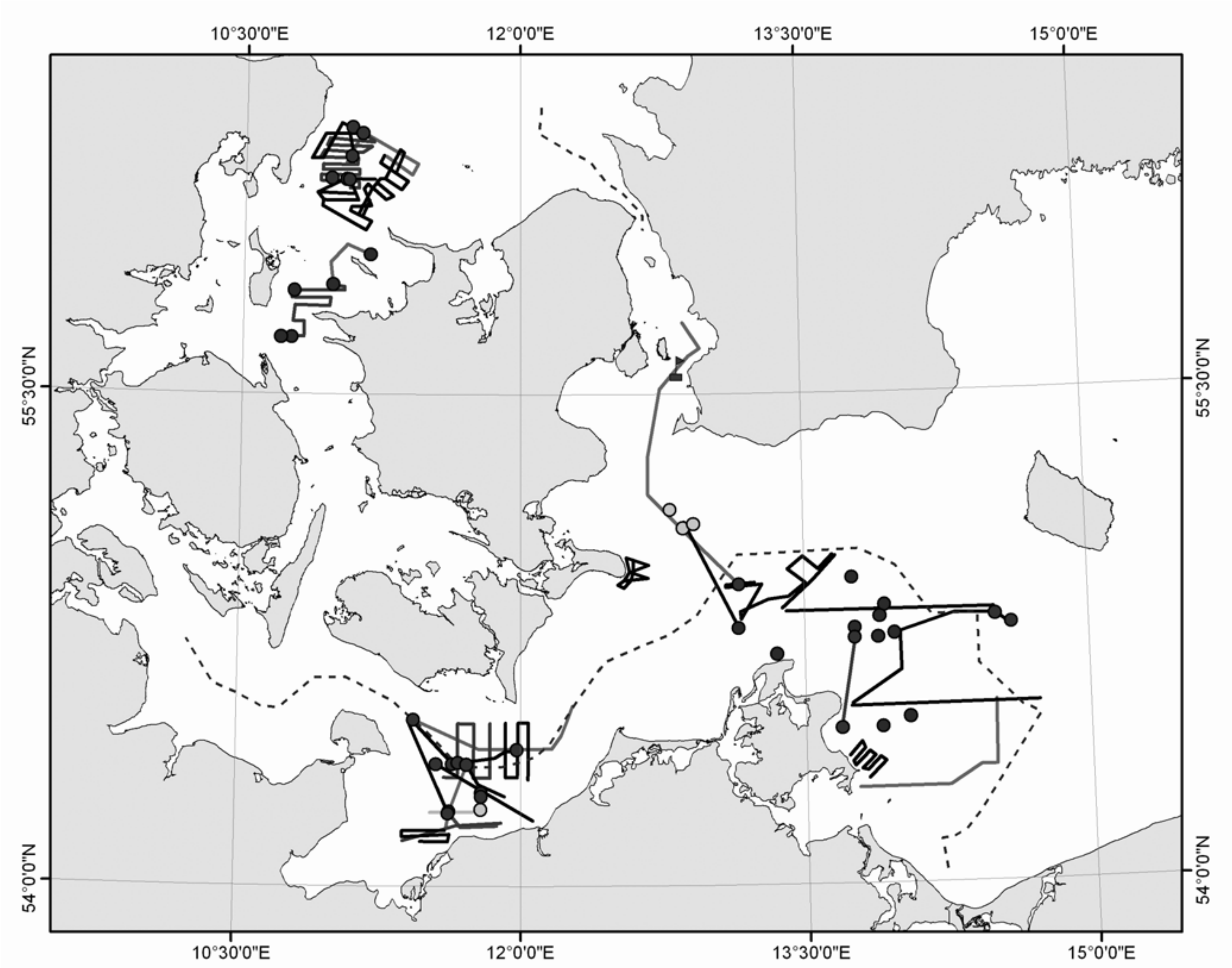
Appendix

Anhang



A1: Example for profile tracks and core sites during various expeditions in 2003 and 2004 within the framework of the SINCOS-project. Areas of interest cover the Arkona Basin, the Mecklenburg Bay and the Kattegat.

T1: Core descriptions

Core	Upper border (cm)	Lower border (cm)	Sediment type	Sediment colour (after Munsell-Rock-colour-Chart)	Carbonate content	Remarks
MB 257740-1	0	320	mud	olive gray 5 Y 4/1	-	H_2S scent, shells of Arctica at top, 175 - 180 cm; small intact mussels and snails at 272 cm; shell debris (Mytilus) at 303 cm and 311 cm; fish remains at 40, 70, and 72 cm; continuous downward transition
MB 257740-1	320	367	clay (silty)	olive gray 5 Y 4/1	-	transition to olive black 5Y 2/1; indistinct lower boundary
MB 257740-1	367	410	clay (silty)	olive gray 5 Y 4/1	+	soft, slightly lighter laminae (light olive gray 5Y 5/2) at 395 and 404 cm; sharp lower boundary
MB 257740-1	410	432	peat gyttja	brownish black 5 Y 2/1	-	finely laminated, fine lighter carbonate bearing laminae; sharp lower boundary
MB 257740-1	432	442	calcareous gyttja	light olive gray 5 Y 6/1	++	sharp uneven lower boundary
MB 257740-1	442	443	fine sand - medium sand	medium gray N 5	(+)	from 274 cm onwards with coarse wood and reed remains; indistinct lower boundary
MB 257740-1	443	573	clay	olive gray 5 Y 4/1	++	soft plastic, sticky, indistinctly laminated
MB 257740-2	0	275	mud	olive gray 5 Y 4/1	-	some small shell remains (snails: 193 cm, 200 cm, 245 cm; mussels: 110 cm, 113 cm), indistinct lower boundary
MB 257740-2	275	310	clay (silty)	light olive gray 5 Y 5/2	+	indistinct laminated, indistinct lower boundary
MB 257740-2	310	324	clay	olive gray 5 Y 4/1	-	indistinct lower boundary
MB 257740-2	324	377	clay (silty)	olive gray 5 Y 4/1	+	*Bithynia tentaculata* in lower part, plant remains, sharp lower boundary
MB 257740-2	377	404	peat gyttja	brownish black 5 YR 2/1	-	laminated, sharp lower boundary
MB 257740-2	404	412.5	clay	light olive gray 5 Y 6/1	++	some shell remains; fine sand/medium sand layers at 411.5 cm and at 412.5 cm (0.5 - 2 mm in diameter), sharp lower boundary
MB 257740-2	412.5	563.5	clay	light olive gray 5 Y 5/2	++	laminated; interbedding of light olive gray 5Y 5/2 and light olive gray 5Y 6/1 distinct laminae; some dark yellowish brown 10YR 4/2 laminae between 552 cm - 554 cm
MB 257760-1	0	210	mud	olive gray 5 Y 3/2	-	mussel shells of Arctica and Mytilus at 173-195 cm; continuous downward transition
MB 257760-1	210	257	clay (humous)	olive gray 5 Y 4/1	-	fine plant fibres; indistinct lower boundary
MB 257760-1	257	269	clay (silty)	light olive gray 5 Y 5/2	+	small amount of few fine plant fibres; distinct lower boundary
MB 257760-1	269	279	silt (clayey)	olive gray 5 Y 4/1	+	fine plant and snail remains; sharp lower boundary
MB 257760-1	279	300	clay	dark greenish gray 5 GY 4/1	(+)	clay -> silty clay, downward decreasing carbonate content, slightly lighter layer at 287 cm, layer of plant remains at 290 cm; distinct lower boundary
MB 257760-1	300	316	clay	brownish gray 5 YR 4/1	-	many fine plant fibres, few lighter lenses; indistinct lower boundary
MB 257760-1	316	339	peat gyttja	dusky brown 5 YR 2/2	-	fine silty laminae; sharp lower boundary
MB 257760-1	339	342	silt	brownish gray 5 YR 4/1	+	sharp lower boundary
MB 257760-1	342	344	interbedding	medium dark gray N 4	(+)	interbedding of two layers of clay and medium sand with sharp internal boundaries; sharp lower boundary
MB 257760-1	344	553	clay	olive gray 5 Y 4/1	++	homogeneous, plastic
MB 257760-2	0	187	mud	olive gray 5 Y 3/2	-	sharp lower boundary
MB 257760-2	187	220	mud (silty)	olive gray 5 Y 4/1	-	indistinct lower boundary
MB 257760-2	220	290	clay (silty)	olive gray 5 Y 4/1	++	some *Bithynia tentaculata*; sharp lower boundary
MB 257760-2	290	309	silt (clayey)	olive gray 5 Y 4/1	-	indistinct lower boundary

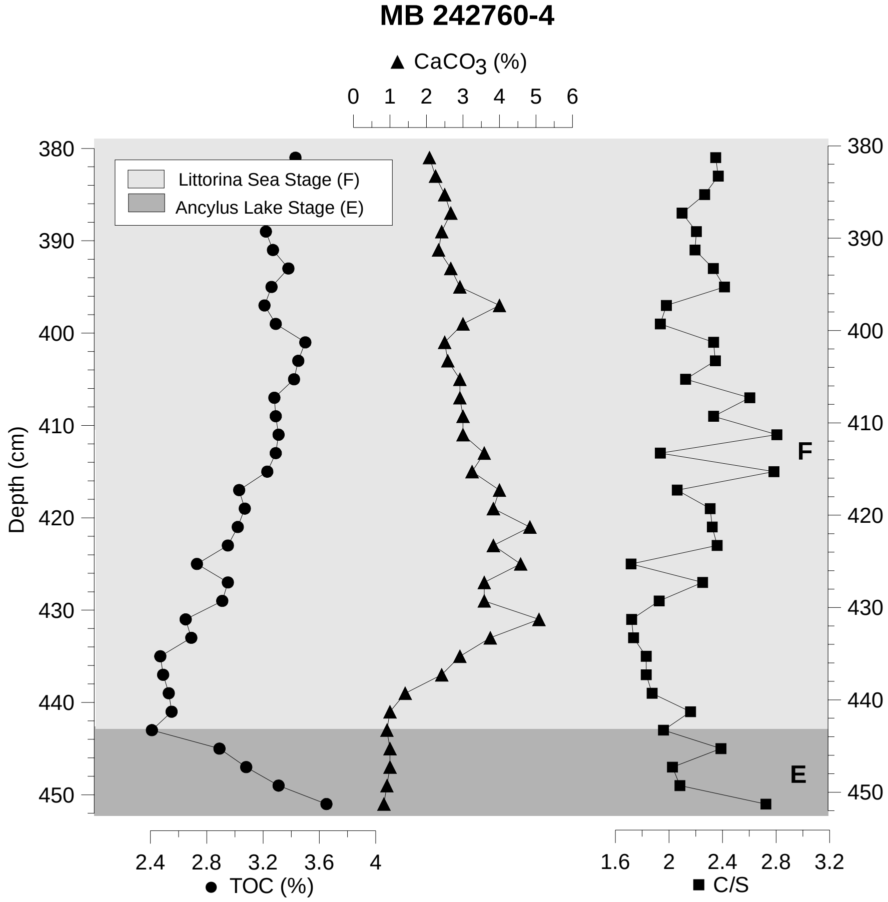
MB 257760-2	309	330	peat gyttja	brownish black 5 YR 2/1	-	sharp lower boundary
MB 257760-2	330	334	silt (clayey)	olive gray 5 Y 4/1	++	at 330 cm and 330.5 cm: sharp layers of fine sand (2-3 mm thick), light olive gray 5Y 5/2, carbonate bearing; sharp lower boundary
MB 257760-2	334	335.5	fine sand - medium sand	light olive gray 5 Y 5/2	+	sharp lower boundary
MB 257760-2	335.5	551.5	clay	olive gray 5 Y 4/1	+	homogeneous;at 396.5 cm: distinct change in colour to dark yellowish brown 10YR 4/2, high carbonate bearing, indistinctly laminated
MB 257780-2	0	164	mud (sandy)	olive gray 5 Y 3/2	-	shell rest at 92.5 cm and 130 cm (Arctica islandica); sharp lower boundary (change in colours!)
MB 257780-2	164	194	clay (sandy)	olive gray 5 Y 4/1	++	fine sand at the lower part; indistinct lower boundary
MB 257780-2	194	254	fine sand	olive gray 5 Y 4/1	++	mica bearing (biotit), remains of wood (< 1 mm), *Bithynia tentaculata*; indistinct lower boundary
MB 257780-2	254	285	silt (fine sandy)	light olive gray 5 Y 5/2	++	interbedding of fine sandy and medium sandy layers in the lower part, mica bearing (biotite), *Bithynia tentaculata*; continuous downward transition
MB 257780-2	285	340	silt	olive gray 5 Y 3/2	-	partly interbedding of fine sand and silt; continuous downward transition
MB 257780-2	340	383.3	peat gyttja	brownish black 5 YR 2/1	-	interbedding with clayey layers at the lower part; sharp lower boundary
MB 257780-2	383.3	383.5	medium sand - coarse sand	dark greenish gray 5 G 4/1	-	sharp layer; distinct lower boundary
MB 257780-2	383.5	550	clay	light olive gray 5 Y 6/1	++	at 425 cm colour change to dark yellowish brown 10 YR 4/2, layered
MB 257800-1	0	80	mud	olive gray 5 Y 4/1	-	homogeneous, few shell remains, small intact mussel shell at the base; distinct regular boundary
MB 257800-1	80	308	interbedding	different colours	(+)	interbedding of silty clay, clayey silt and silt, light olive gray 5 Y 3/2, olive gray 5 Y 4/1, downward decreasing carbonate content, mica bearing, fine shell debris, many humous particles, partly enriched in thin layers, plant remains; distinct oblique lower boundary
MB 257800-1	308	330	peat gyttja	dusky brown 5 YR 2/2	-	silty layers of up to 2 cm thickness in upper part; continuous downward transition
MB 257800-1	330	336	clay (silty)	olive gray 5 Y 4/1	++	fine humous laminae in upper part; sharp lower boundary
MB 257800-1	336	336.5	clay (silty)	medium dark gray N 4	++	some small stones; sharp lower boundary
MB 257800-1	336.5	348	clay	olive gray 5 Y 4/1	++	plastic; sharp lower boundary
MB 257800-1	348	349	medium sand	medium dark gray N 4	(+)	sharp lower boundary
MB 257800-1	349	552	clay	olive gray 5 Y 4/1	++	homogeneous
MB 242760-4	0	414	mud	olive gray 5 Y 3/2	-	uppermost 2 cm olive black 5 Y 2/1, 53-56 cm mussel remains (Macoma?); continuous downward transition
MB 242760-4	414	454	clay	olive gray 5 Y 4/1	-	laminated; indistinct lower boundary
MB 242760-4	454	???	peat gyttja	dusky yellowish brown 10 YR 2/2	-	
MB 242770-1	0	552	mud (silty)	dark greenish gray 5 GY 4/1	-	H2S scent, greenish black 5 GY 2/1 in uppermost centimetres, indistinct lamination beginning at 218 cm (2 mm thin laminae), two Arctica islandica at 8 cm, mussels at 28 cm, 380.5 cm and 451 cm; continuous downward transition
MB 242770-1	552	607	clay (silty)	olive gray 5 Y 4/1	-	at 586 cm mussel remains; unsharp lower boundary
MB 242770-1	607	651	clay (silty)	dark greenish gray 5 G 4/1	+	continuous downward transition
MB 242770-1	651	670.5	peat gyttja	dusky yellowish brown 10 YR 2/2	-	distinct lower boundary
MB 242770-1	670.5	673.5	clay	light olive gray 5 Y 6/1	++	sharp lower boundary
MB 242770-1	637.5	674.5	fine sand - medium sand	light olive gray 5 Y 5/2	++	sharp lower boundary
MB 242770-1	674.5	692.5	clay	light olive gray 5 Y 6/1	++	sandy lense at 679 cm (1 cm in diameter)
AB 258010-1	0	65	mud	black N 1	-	H2S scent; continuous downward transition
AB 258010-1	65	350	mud	olive gray 5 Y 3/2	-	H2S scent, small amount of mussel shells in upper part; continuous downward transition

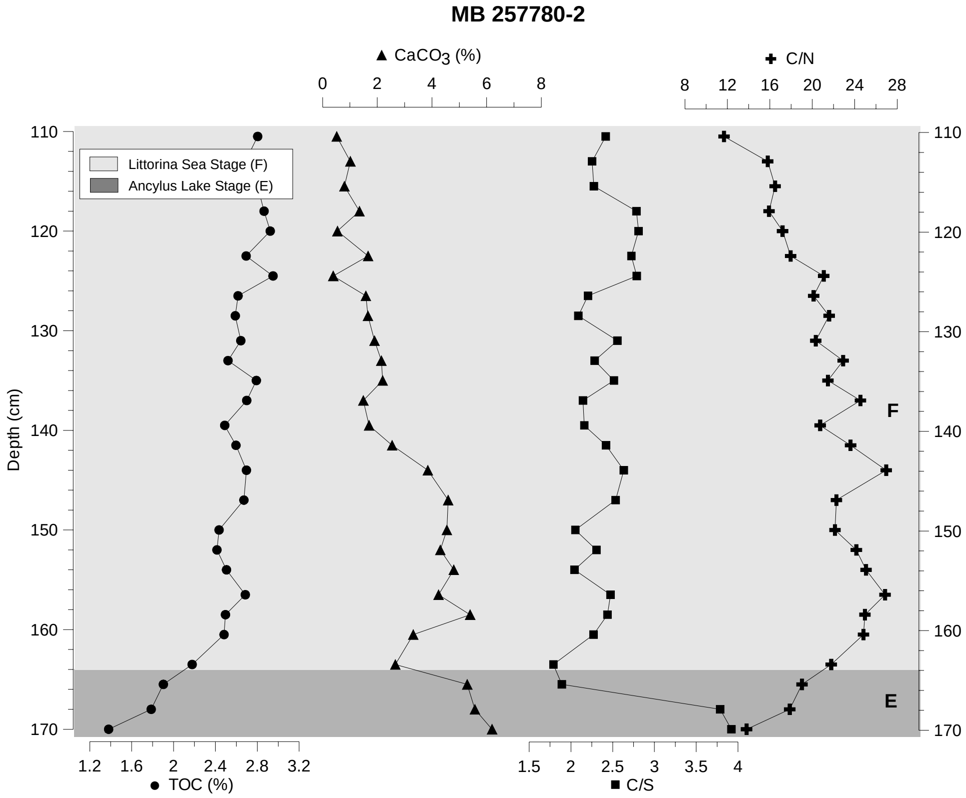
AB 258010-1	350	381	clay	olive gray 5 Y 4/1	-	indistinctly fine laminated; distinct lower boundary
AB 258010-1	381	420	clay	different colours	-	dark greenish gray 5 GY 4/1 -> greenish black 5 GY 2/1, slightly more clayey than unit above, downward increasing number of darker layers, especially from 412 cm on; continuous downward transition
AB 258010-1	420	542	clay	black N 1	-	some slightly lighter layers, some traces of plant remains
AB 258010-2	0	362	mud	olive gray 5 Y 3/2	-	H2S scent, homogeneous; indistinctly lower boundary
AB 258010-2	362	367	fine sand (silty)	olive gray 5 Y 3/2	-	mixing of clayey, silty ,and sandy parts, fine sand layer in the transition horizon at the end of core section 2 to the beginning of core section 3; indistinctl lower boundary
AB 258010-2	367	405	clay	dark greenish gray 5 GY 4/1	-	at 385 cm lense of peat gyttja (6 cm x 1 cm); continuous downward transition
AB 258010-2	405	568	clay	dark greenish gray 5 GY 4/1	-	increase of laminated layers to the end, black laminae (grayish black N 2): < 5 mm thick, distinctly fine laminated
AB 201310-1	0	290?	mud	olive gray 5 Y 3/2	-	H2S scent, shell remains; continuous downward transition
AB 201310-1	290?	???	clay	olive gray 5 Y 4/1	-	some sulfidic aggragates (< 2 mm)
AB 242790-1	0	324	mud	olive gray 5 Y 3/2	-	H2S scent, few shell debris, 0-35 cm olive black 5 Y 2/1 (homogeneous black), 35-58 cm olive gray 5 Y 3/2 (black laminae), 58-88 cm olive gray 5 Y 3/2 (no laminae), black rest sulfidic marks (< 3 mm in diameter); continuous downward transition
AB 242790-1	324	428	clay (silty)	olive gray 5 Y 4/1	-	increase in organic-rich layers at 358 cm (plant remains?), at 392 cm colour change to medium dark gray N 4, sulfidic aggregates at 358 cm
AB 242800-1	0	360	mud (silty)	olive gray 5 Y 4/1	-	H2S scent, black colour in uppermost top, indistinct laminated at 64 cm, sediment colour change to olive gray 5 Y 3/2 at 97 cm (end of lamination), foraminifers?, mussel remains at 8 cm, 86 cm, 92 cm and 324 cm (Arctica islandica); continuous downward transition
AB 242800-1	360	368	clay	dark greenish gray 5 GY 4/1	-	sharp uneven oblique lower boundary
AB 242800-1	368	416	clay	dark greenish gray 5 GY 4/1	-	black laminae (< 1 mm length, organic remains), indistitinct laminated at the bottom; sharp lower boundary
AB 242800-1	416	420	clay	olive gray 5 Y 4/1	-	indistinct lower boundary
AB 242800-1	420	???	clay	dark greenish gray 5 GY 4/1	-	increasing organic remains (black mottled)
AB 258000-1	0	65	mud	olive gray 5 Y 3/2	-	H2S scent, very indistinctly layered, some shell debris, intact Macoma at 36 cm; distinct lower boundary
AB 258000-1	65	412	mud	olive gray 5 Y 4/1	-	homogeneous, some fine shell debris, continuous downward transition
AB 258000-1	412	449	clay (humous)	dark greenish gray 5 GY 4/1	-	humous particles in thin laminae, downward increase in number and thickness, thin sandy layer at 445 cm; distinct lower boundary
AB 258000-1	449	463	clay (silty)	light olive gray 5 Y 5/2	-	more silty at 452-457 cm, fine silty layer at the basis; distinct lower boundary
AB 258000-1	463	473	clay (humous)	olive black 5 Y 2/1	-	silty humous clay, fine laminated, fine plant remains; distinct lower boundary
AB 258000-1	473	475	fine sand - medium sand	medium gray N 5	-	few plant remains; sharp lower boundary
AB 258000-1	475	570	clay (silty)	dark greenish gray 5 GY 4/1	-	plastic
AB 258000-2	0	491	mud (silty)	olive gray 5 Y 3/2	-	H2S scent, some shell debris; continuous downward transition
AB 258000-2	491	524	silt	olive gray 5 Y 4/1	-	laminated; sharp lower boundary
AB 258000-2	524	527	fine sand (silty)	dark greenish gray 5 G 4/1	-	sharp lower boundary
AB 258000-2	527	533	silt	dark greenish gray 5 G 4/1	-	continuous downward transition
AB 258000-2	533	543	silt	olive gray 5 Y 4/1	-	laminated; sharp lower boundary
AB 258000-2	543	554	coarse sand	light olive gray 5 Y 6/1	-	silty lenses (up to 1 cm in diameter), at 549.5 cm small shell debris (mussel?, Gastropods?) REMARK: in the core catcher coarse peat gyttja with Phragmites remains below the clay; followed by layer of clayey medium sand
AB 282060-1	0	214	mud	olive gray 5 Y 3/2	-	indistinctly mottled, soft, some few shell debris, pieces of a bigger shell at 193 cm; first 20 to 30 cm had to be removed while extracting the core out of the tube; sharp lower boundary
AB 282060-1	214	217	fine sand - medium sand	olive gray 5 Y 4/1	-	sharp lower boundary
AB 282060-1	217	428	clay (silty)	olive gray 5 Y 4/1	++	colour change to dark yellowish brown 10 YR 4/2, plastic, thin silty/sandy layers at 338 cm, 357 cm, 403 cm (light olive gray 5 Y 6/1); indistinct lower boundary

AB 282060-1	428	482	till	medium light gray N 6	++	compact, many pebbles; sharp lower boundary
AB 282060-1	482	490	medium sand - coarse sand	light olive gray 5 Y 6/1	++	small stones; sharp lower boundary
AB 282060-1	490	601	till	olive gray 5 Y 4/1	++	compact, many pebbles; more sandy in upper part
AB 282080-1	0	268	mud	olive gray 5 Y 3/2	-	a little darker in upper part, soft, remains of Astarte at 112 cm, Mytilus remains at 246 cm, fish bones at 238 cm; sharp lower boundary
AB 282080-1	268	271	fine sand - medium sand	medium gray N 5	-	sharp lower boundary
AB 282080-1	271	572	clay (silty)	light olive gray 5 Y 5/2	++	colour change to dark yellowish brown 10 YR 4/2, plastic --> downward increasingly compact, few thin silt layers

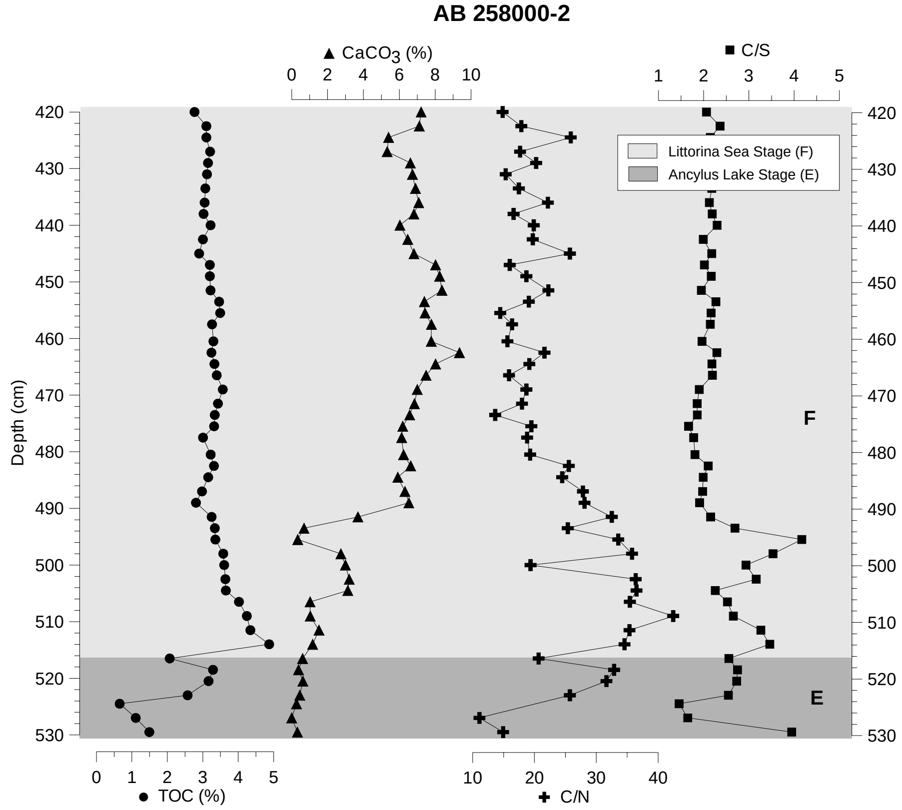
carbonate content:

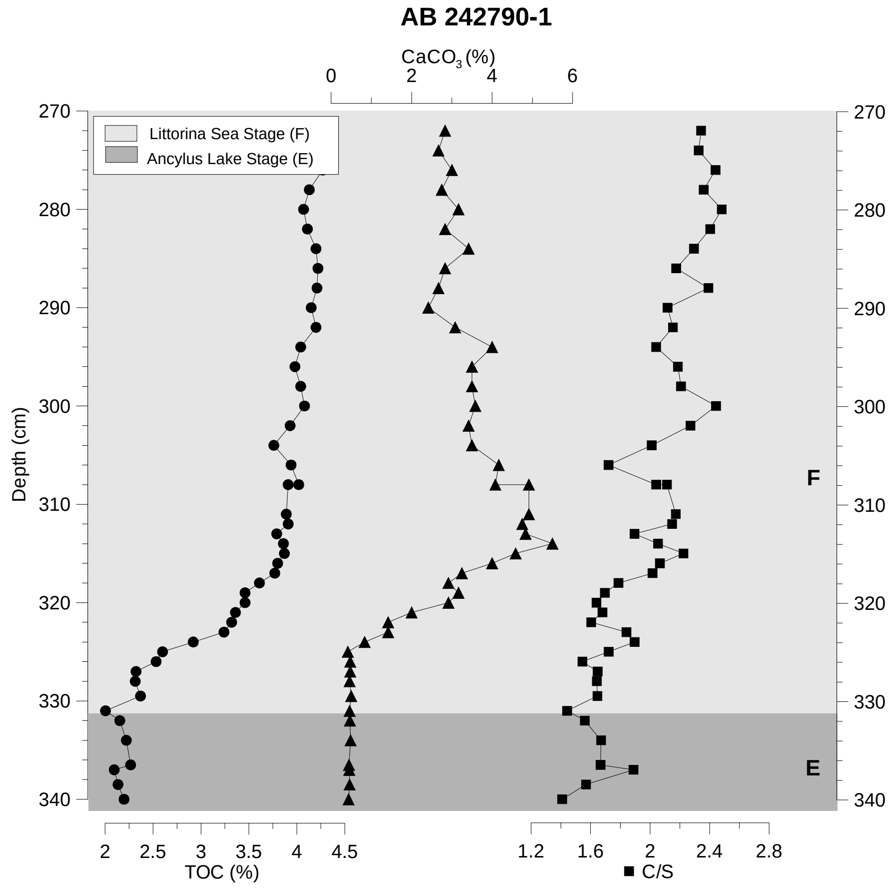
- \- no carbonate bearing
- \+ carbonate bearing
- ++ high carbonate content



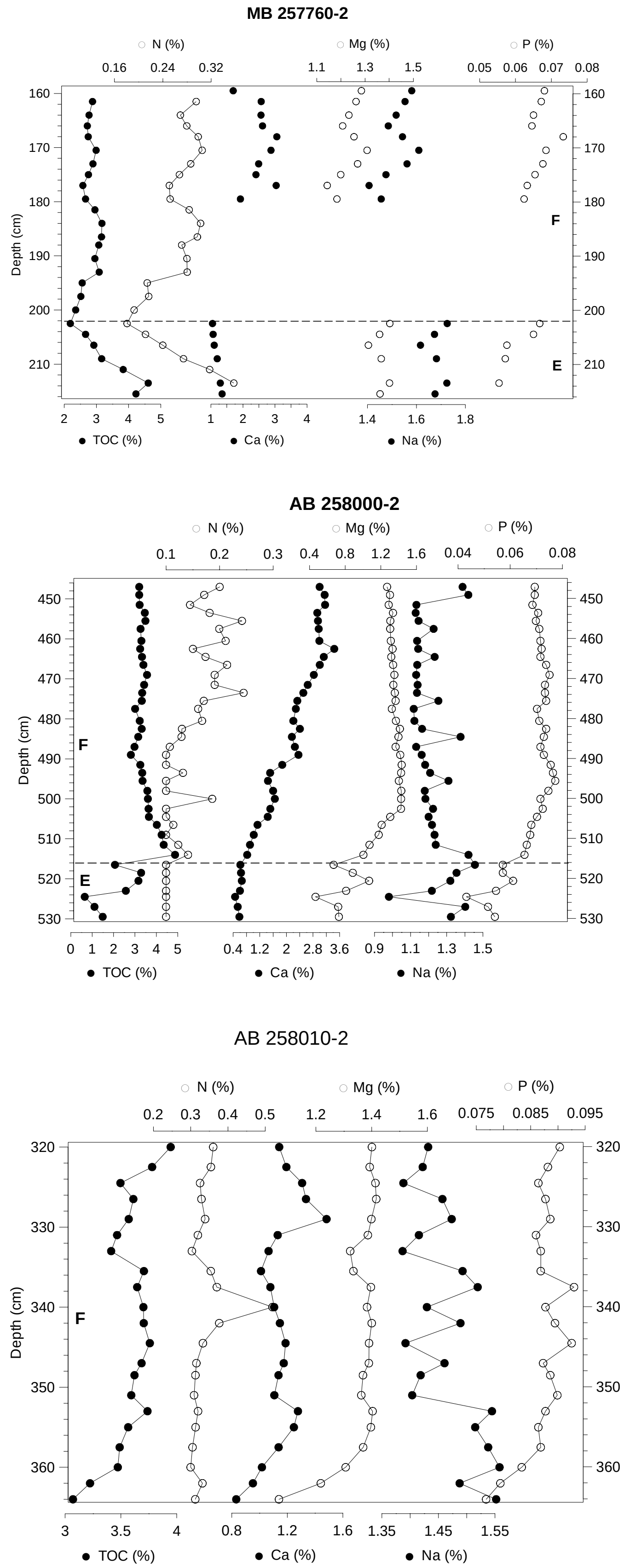


A2: Increases in TOC and $CaCO_3$ contents and C/S ratios at the transition from the Ancylus Lake to the Littorina Sea deposits in MB 242760-4 and MB 257780-2. C/N ratio in core MB 257780-2 displays high values, which can be attributed to the mixing with old reworked organic material. The boundary E/F corresponds to the remarkable TOC increase.

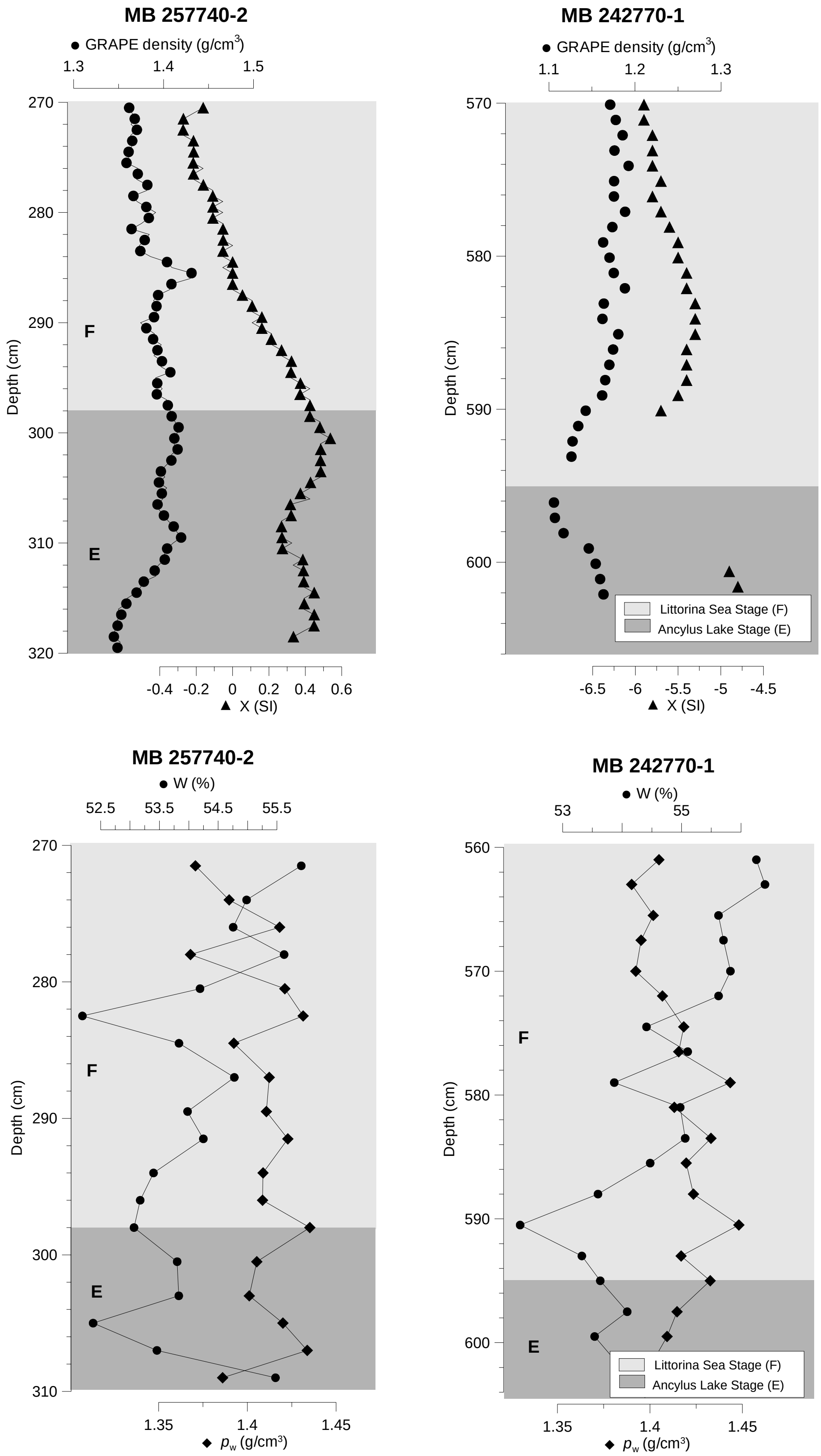




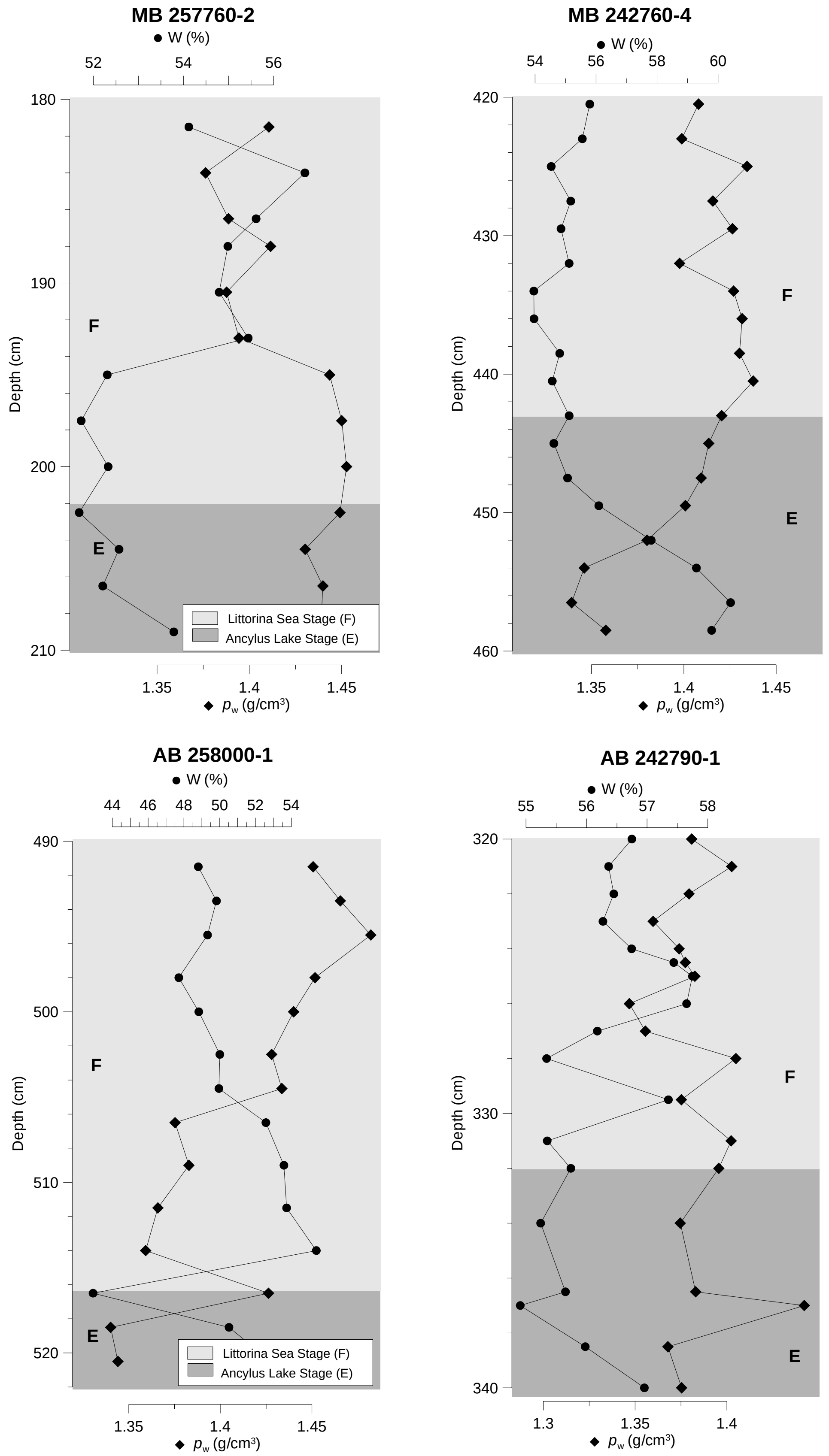
A3: Distinct increases in TOC and $CaCO_3$ contents and C/S ratios at the boundary E/F in cores AB 258000-2 and AB 242790-1. C/N ratio in core AB 258000-2 displays high values at the transgression base, which decrease in the upper Littorina Sea deposits. The boundary E/F refers to the onset in TOC increase.



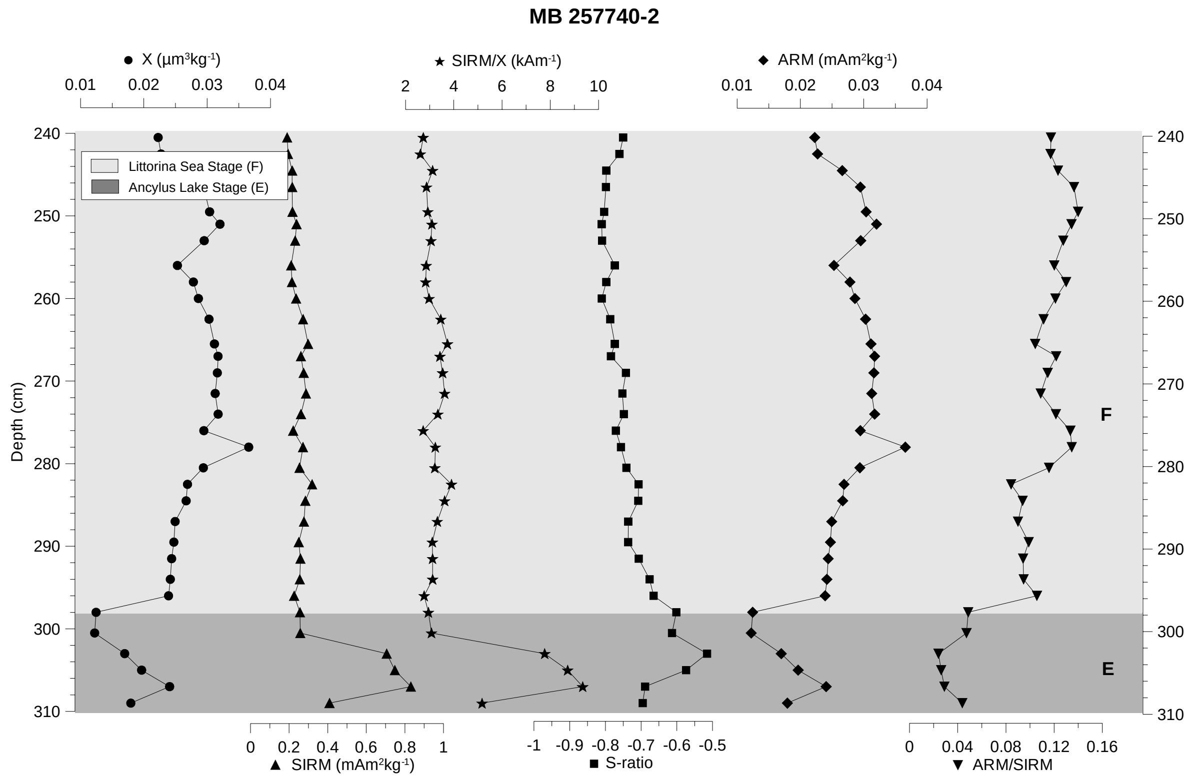
A4: Ca, Mg, Na and P contents compared to TOC and TN values, which were recorded in the marginal cores MB 257760-2, AB 258000-2 and AB 258010-2. The dashed line separates Ancylus Lake (E) and Littorina Sea (F) deposits. It is related to the onset in TOC increase. Generally, all parameters increase from unit E to unit F, probably caused by the inflowing saline waters.

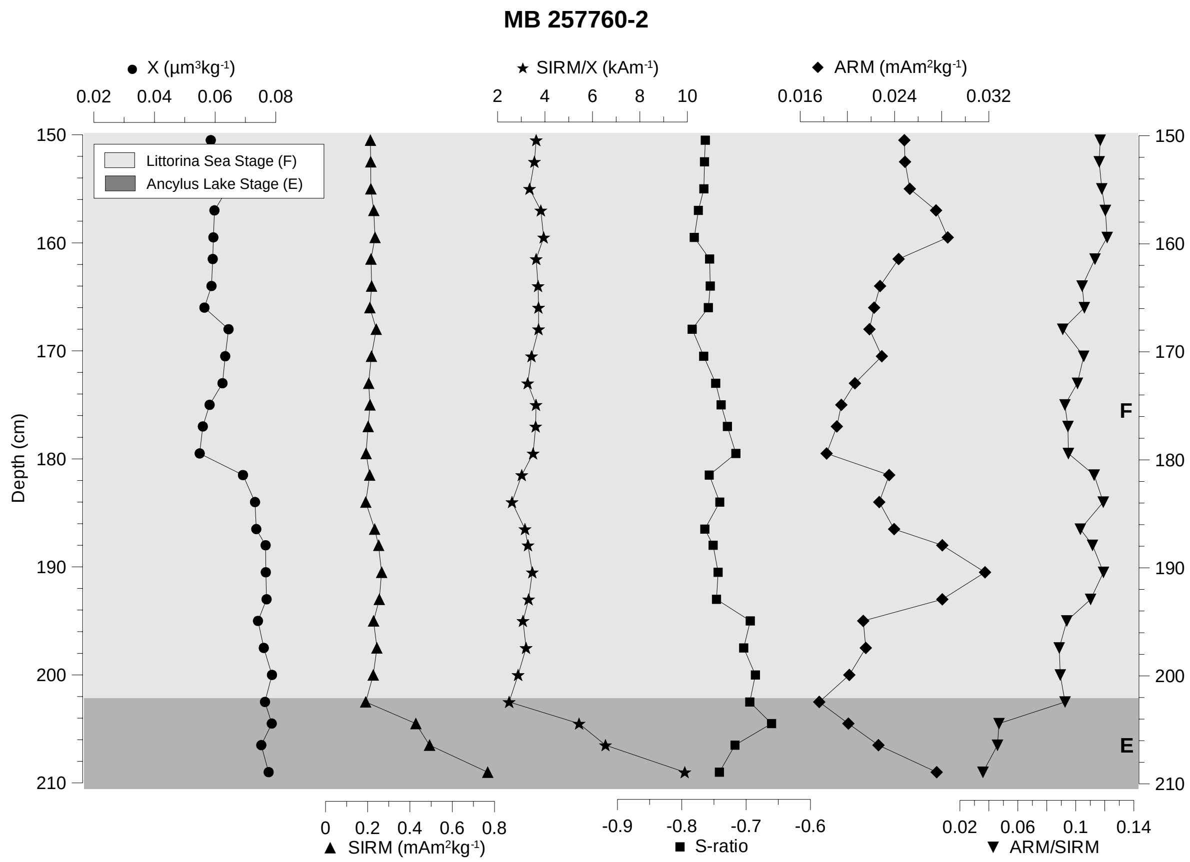


A5: GRAPE density, magnetic susceptibility (χ), water content (W) and bulk density (ρ_w) measured at the Mecklenburg Bay cores MB 257740-2 and MB 242770-1. The parameters show no distinct changes at the transition from the Ancylus Lake (unit E) to the Littorina Sea (unit F) deposits. The boundary E/F refers to the onset in the TOC increase.

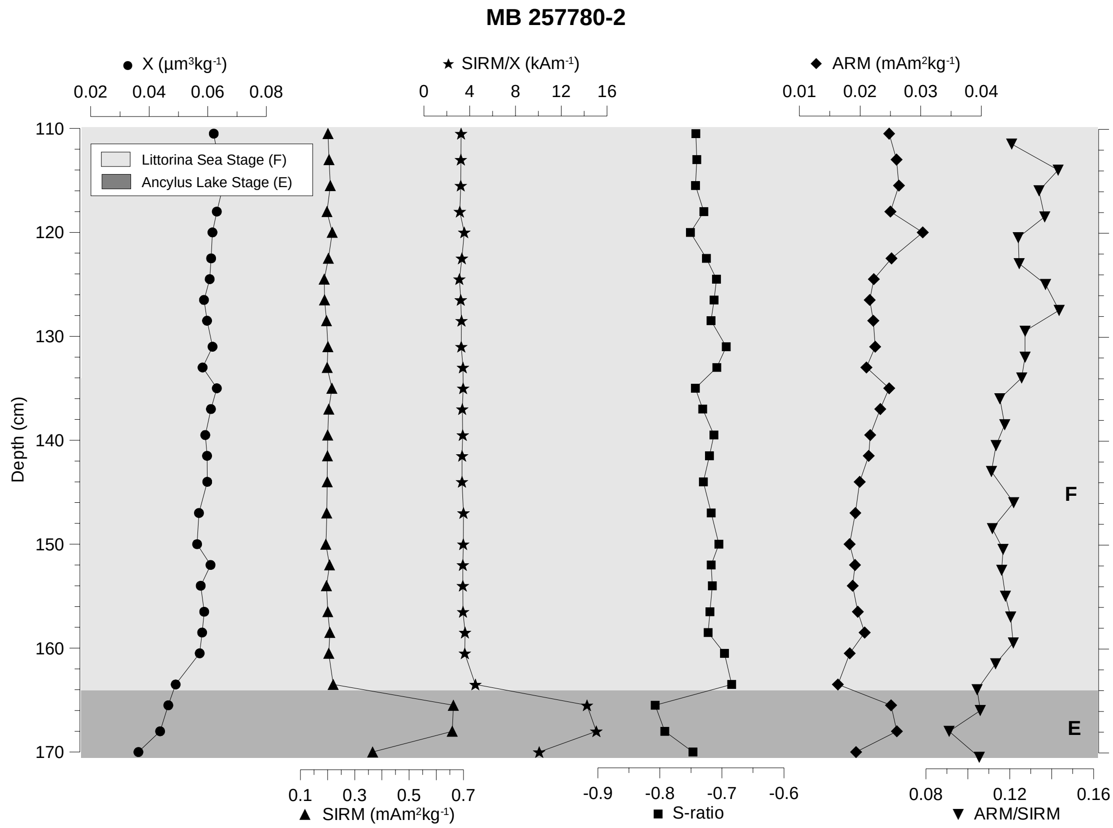


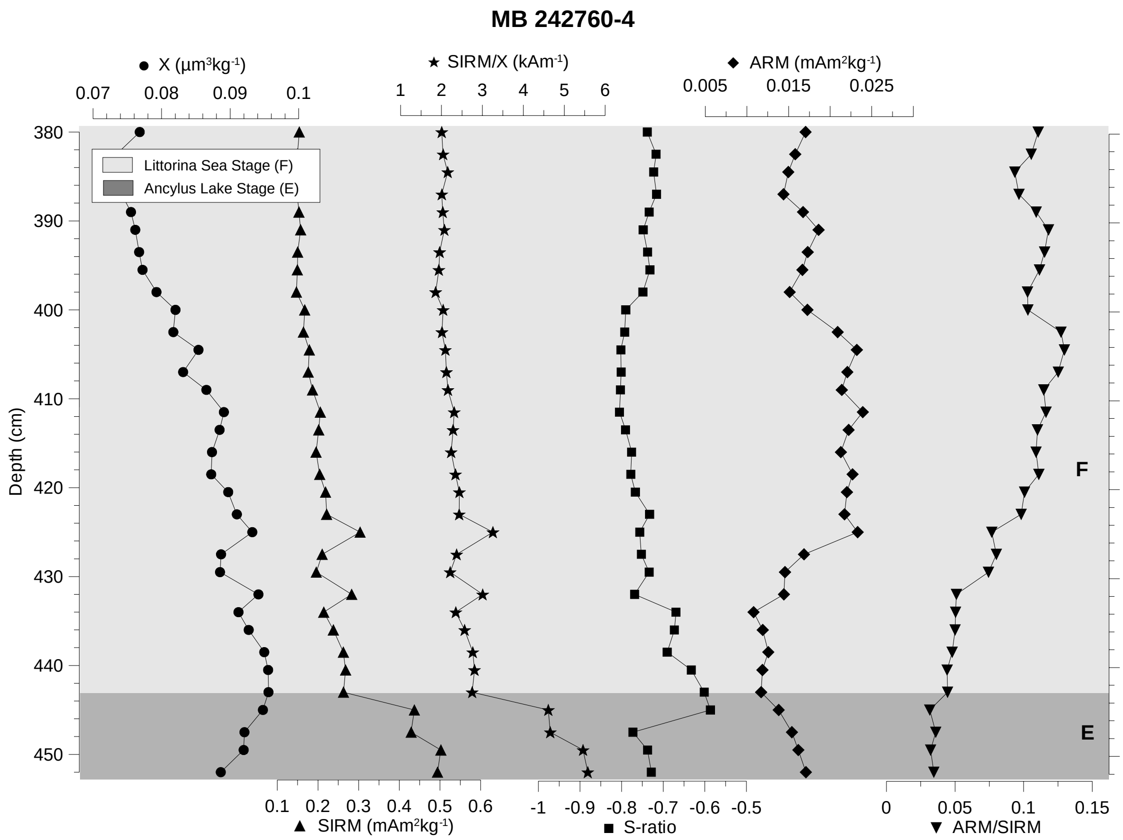
A6: Water content (W) and bulk density (ρ_w) of MB 257760-2, MB 242760-4, AB 258000-1 and AB 242790-1. Opposite to the Mecklenburg Bay, parameters show clear changes (decrease in W and increase in ρ_w values) in the Arkona Basin. The boundary E/F refers to the onset in the TOC increase.



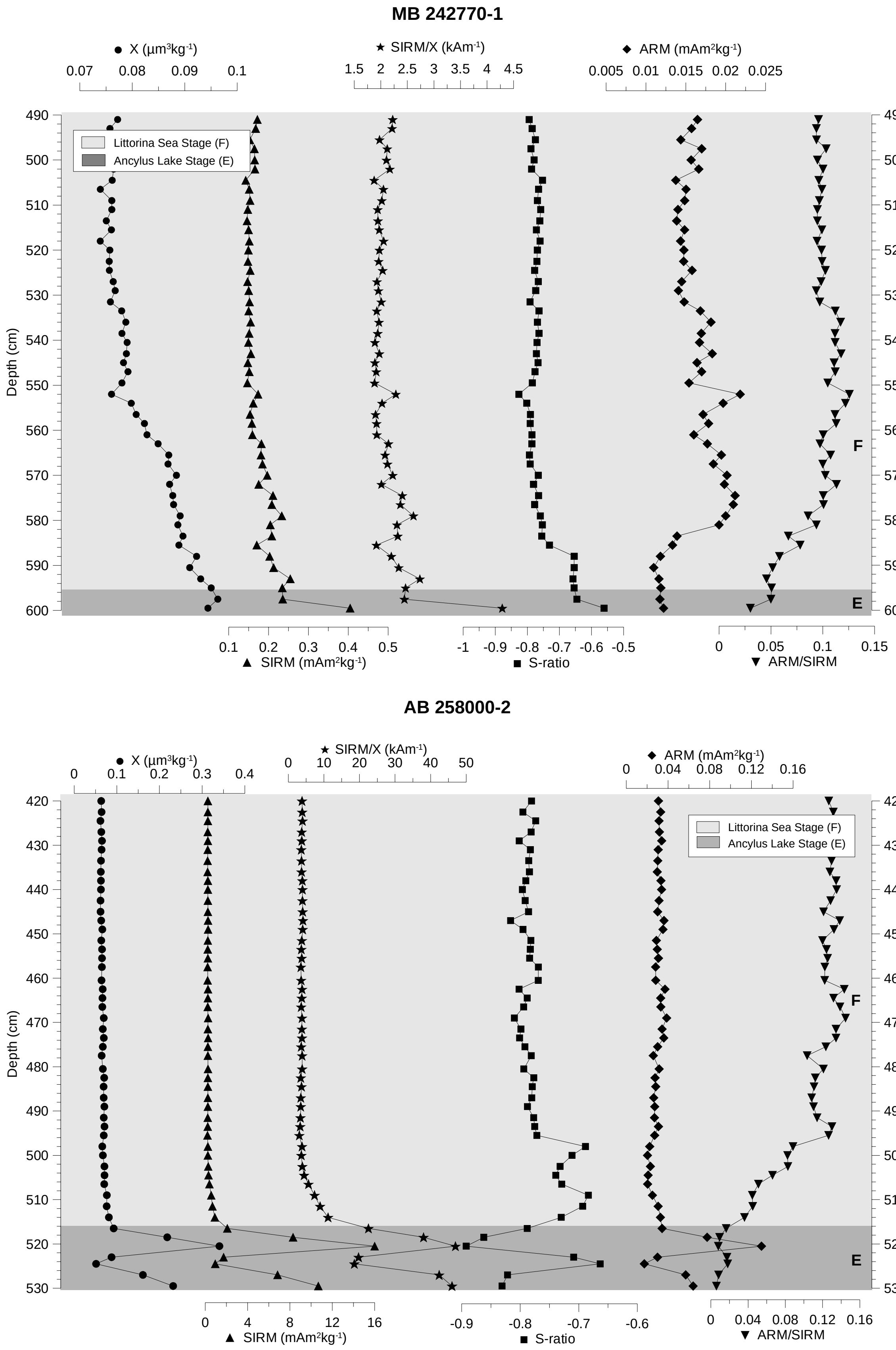


A7: Mineral magnetic parameters (magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM) saturation isothermal remanent magnetization (SIRM), SIRM/χ-, ARM/SIRM- and S-ratio) analyzed in MB 257740-2 and MB 257760-2. The transition from the lithostratigraphic unit E (Ancylus Lake Stage) to unit F (Littorina Sea stage) shows distinct changes. The boundary E/F refers to the onset in TOC increase.

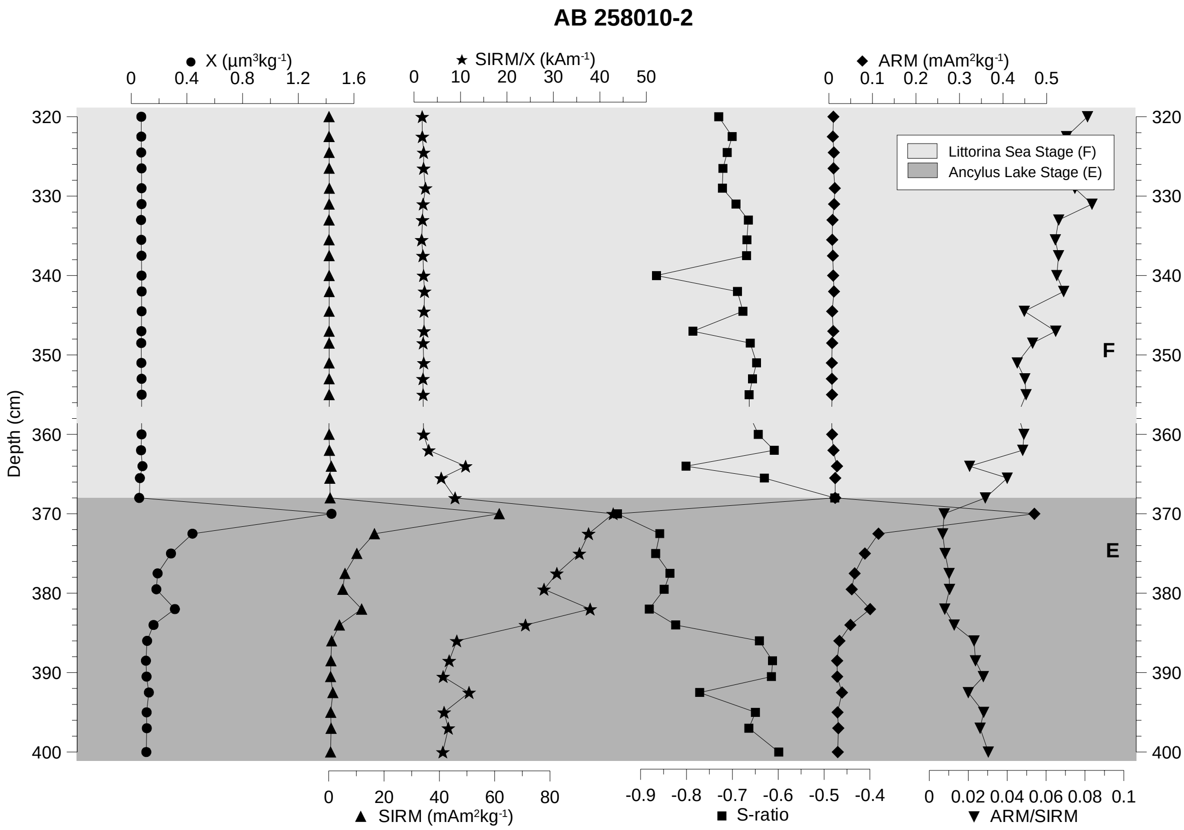


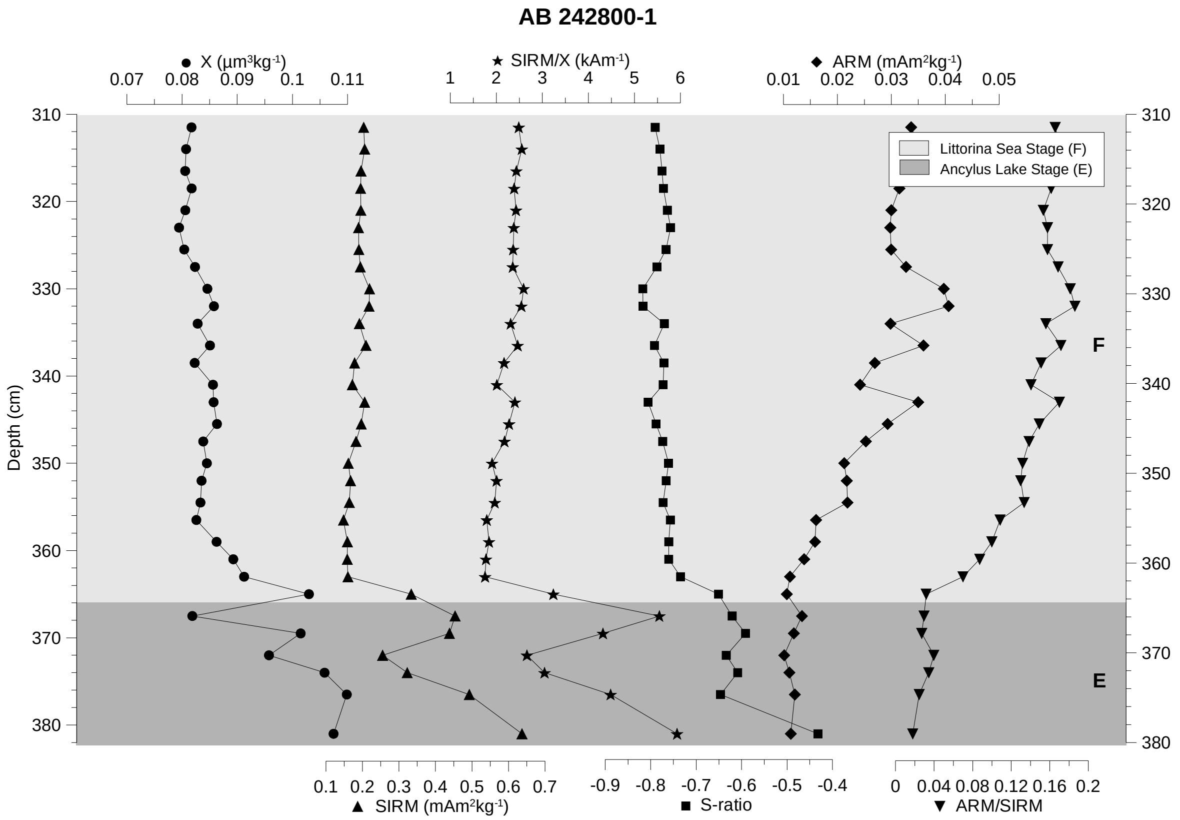


A8: Mineral magnetic parameters (magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM) saturation isothermal remanent magnetization (SIRM), SIRM/χ-, ARM/SIRM- and S-ratio) from MB 257780-2 and MB 242760-4. The transition from the lithostratigraphic unit E (Ancylus Lake Stage) to unit F (Littorina Sea stage) is marked by clear changes. The boundary E/F refers to the onset in TOC increase.

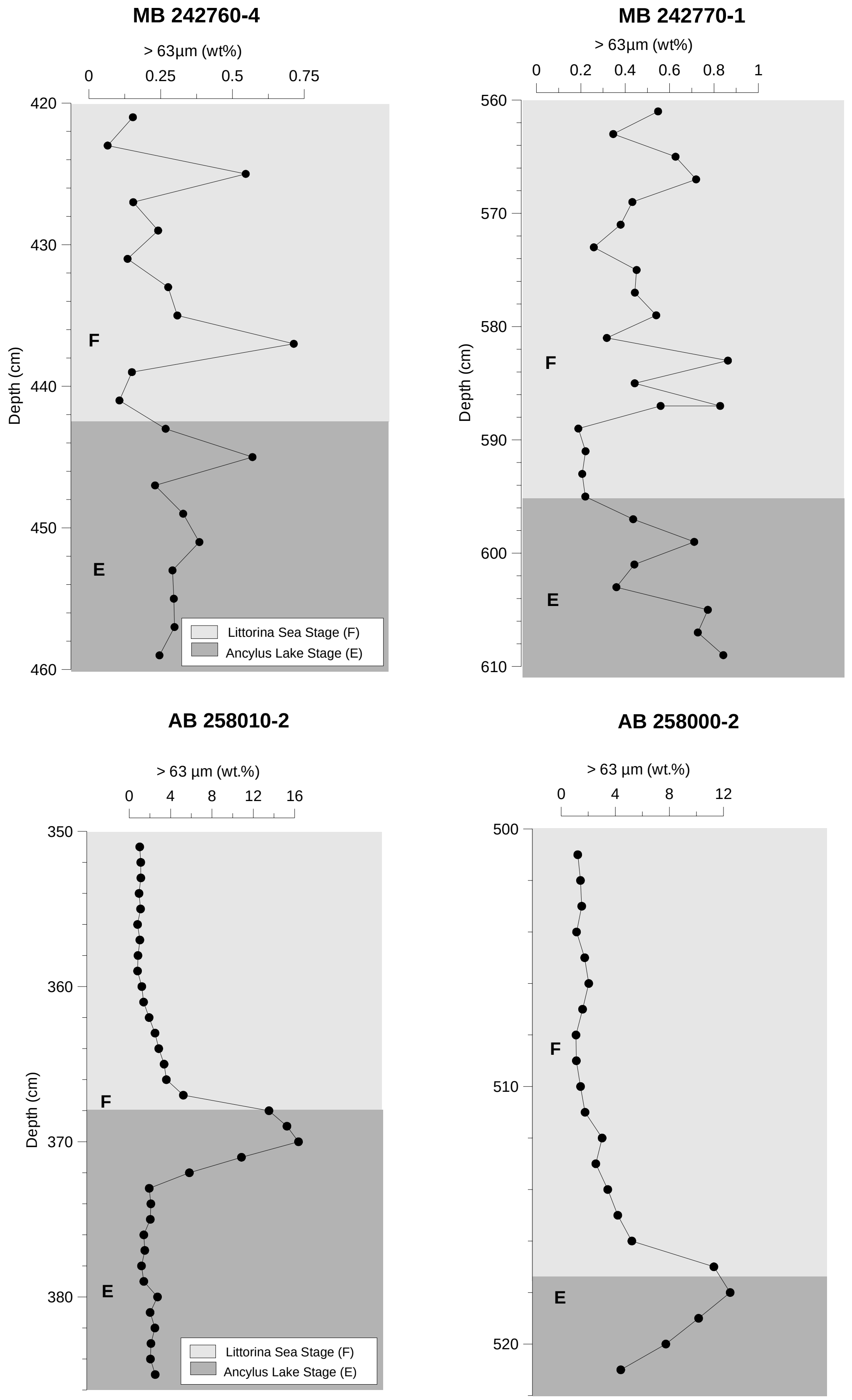


A9: Mineral magnetic parameters (magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM) saturation isothermal remanent magnetization (SIRM), SIRM/χ-, ARM/SIRM- and S-ratio) from MB 242770-1 and AB 258000-2. Distinct changes mark the transition from unit E (Ancylus Lake Stage) to unit F (Littorina Sea stage). The boundary E/F refers to the onset in the TOC increase.





A10: The mineral magnetic values from AB 258010-2 and AB 242800-1 (magnetic susceptibility (χ), anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM), SIRM/χ ratio, ARM/SIRM ratio and S-ratio) display clear changes regarding to the transition from the Ancylus Lake (unit E) to the Littorina Sea (unit F) deposits. The boundary E/F refers to the onset in TOC increase.



A11: Grain size distribution > 63 µm investigated in the Mecklenburg Bay and the Arkona Basin. The boundary E/F refers to the onset in the TOC increase. The content of wt% > 63 µm does not change in MB 242760-4 and MB 242770-1, whereas sharp peaks mark the boundary E/F in AB 258000-2 and AB 258010-2.

			Lithology				Fauna																						Flora				
sediment depth	volume [ml]	sediment	pebbles	gypsum cristals	quartz sand	pyritized root tubes?	*Ammodiscus*	*Ammonia*	*Cribroelphidium*	*Eggerella scabra*	*Haynesina*	*Nodulina dentaliniformis*	*Subrheophax aduncus*	*Mytilus*	Ostracoda (marin-brackish)	Ostracoda (freshwater)	bristles of polychaetes	nereid polychaetes	Cladocera (cuticula)	Cladocera (ephippia)	chironomids	egg capsules (?) of invertebrates	cuticules of worms?	oribatide mites	insect fragments	*Bithynia tentaculata*	*Pisidium*	plant fragments	oospores of characeans	large diatoms (Centrales)	habitat	salinity
15	60	grey clay								3			2					1										2	1		brackish water below halocline	17-29
35	80	grey clay								3			2	1	1										1			1	1		brackish water below halocline	17-29
55	90	grey clay								3			2												2			1	1		brackish water below halocline	17-29
75	19	grey clay			2					2												1	1						1		brackish water below halocline	17-29
95	63	grey clay		1	2			1		2				3								1	3					1	1		brackish water below halocline	17-29
105	21	grey clay		1	2			2		2		1		1								1	1					1		2	brackish water below halocline	17-29
125	20	grey clay			1		2	1		2		1		1								1						1		3	brackish water below halocline; estuarine influence?	17-29
145	29	grey clay						2		2				2								2						1	1	3	brackish water below halocline	17-29
165	51	grey clay		1	1			1		2		2		3								1	1	1				2	1		brackish water below halocline	17-29
185	50	grey clay		1	1			2						1								1						2	1	2	brackish water above halocline	12-21
205	19	grey clay					1	1						3								1			1			1	1	2	brackish water above halocline; estuarine influence?	12-21
225	19	grey clay		2			1	1						1								1						1	1	2	brackish water above halocline; estuarine influence?	12-21
245	30	grey clay		2			1	2	1			1		2	1							2		1	2			1	1		brackish water above halocline; estuarine influence?	12-21
265	16	grey clay		3				2			1			2							1	1		1				1			brackish water above halocline; estuarine influence?	12-21
285	22	grey clay		3			2	1						1								1						1	1		brackish water above halocline; estuarine influence?	12-21
300	34	grey clay					1													1	1							2	2		brackish water above halocline; estuarine influence?	12-21
310	36	grey clay												2			2		1			2			1			1	1	2	brackish water; increasing water depth?	12-21
320	29	grey clay		1				1	2		2			2					1										1		shallow brackish water, calm	12-21
330	23	grey clay						2						1														2	1		shallow brackish water, turbulent	12-21
340	21	grey clay																	1			1						1			small freshwater body? or reworked sediment?	
350	20	grey clay																	3	1	1	2				2		2	2	1	small freshwater body, shallow; cooling?	fresh
360	21	grey clay																	3	1	1	2				2		2	2	3	small freshwater body, shallow	fresh
370	21	grey clay																	3	1	1	2				2		2	2	3	small freshwater body, shallow	fresh
380	27	grey clay																	3	1	1	2		1		2			2	3	small freshwater body, shallow	fresh
394	35	grey clay																	3		1	2		1		2			2	3	small freshwater body, shallow; warming	fresh
405	27	grey clay																	3		1	2		1		2			2		small freshwater body, shallow; warming	fresh
420	25	grey clay																	3			1						3			silting up?	fresh
438	22	grey clay	1													3			3		1						1				freshwater lake, cold	fresh
450	15	grey clay		2	1	2																									periglacial basin?	
500	12	grey clay		2	1	2																									periglacial basin?	

legend: 1 = a few 2 = common 3 = very abundant fresh = freshwater by P. Frenzel

Littorina Sea stage
Ancylus Lake stage

A12: Macrofossil and microfossil findings investigated in core MB 257740-1. The numbers refer to countings of the findings. Clearly, a transition from limnic to brackish-marine conditions is shown by the disapperance of e.g. Cladodera and the occurrence of benthic foraminifers. The yellow and blue coloured fields refer to the AncylusLake and Littorina Sea stages.

	terrestrial			telmatic								lacustrine																	fluvial	marine	
Depth (cm)	*Betula* sect. *Albae* sp.	*Pinus sylvestris*	*Populus tremula*	*Alnus glutinosa*	*Phragmites australis*	*Scirpus lacustris*	*Scirpus maritimus*	*Carex* spp.	*Urtica dioeca*	*Lycopus europaeus*	Radicells	Characeae indet.	Amblystegiaceae indet.	*Menyanthes trifoliata*	*Potamogeton perfoliatus*	*P. filiformis*	*Zannichellia palustris*	Spongillidae indet.	*Erpobdella* sp.	*Piscicola geometra*	Cladocera indet.	*Orthotricia* sp.	Chironomidae indet.	Oribatida indet.	*Bithynia tentaculata* lids	*Cristatella mucedo*	Pisces indet.	*Perca fluviatilis*	*Hydropsyche* sp.	*Ammonia beccari*	*Elphidium* sp.
200-210	2											r		1							r				5					c	r
210-220	1											r								3	a		r	r		5					
220-230	2				4	1		1				r									a		r	r		8		r			
230-240	1			1	2							c							1	15	a		r	r		11					
240-257					2					1		c								5	a		r	r		20	r				
257-269	8	r										c								10	a		r	r	10	45	r				
269-279	4						1					a					1			20	a		r	r		35	r				
279-289	4											c							1	7	a	1	r	r	11	18					
289-300	4											a			1				1	20	a		r	r	30	80	1		1		
300-316	1		1					1				r	c			1					a		r	r		5					
316-326											a		c								a		r								
326-339								1	2												a		r	r							
339-342																		r			a		r	r							

r = rare c = common a = abundant by O. Bennike

Littorina Sea stage
Ancylus Lake stage

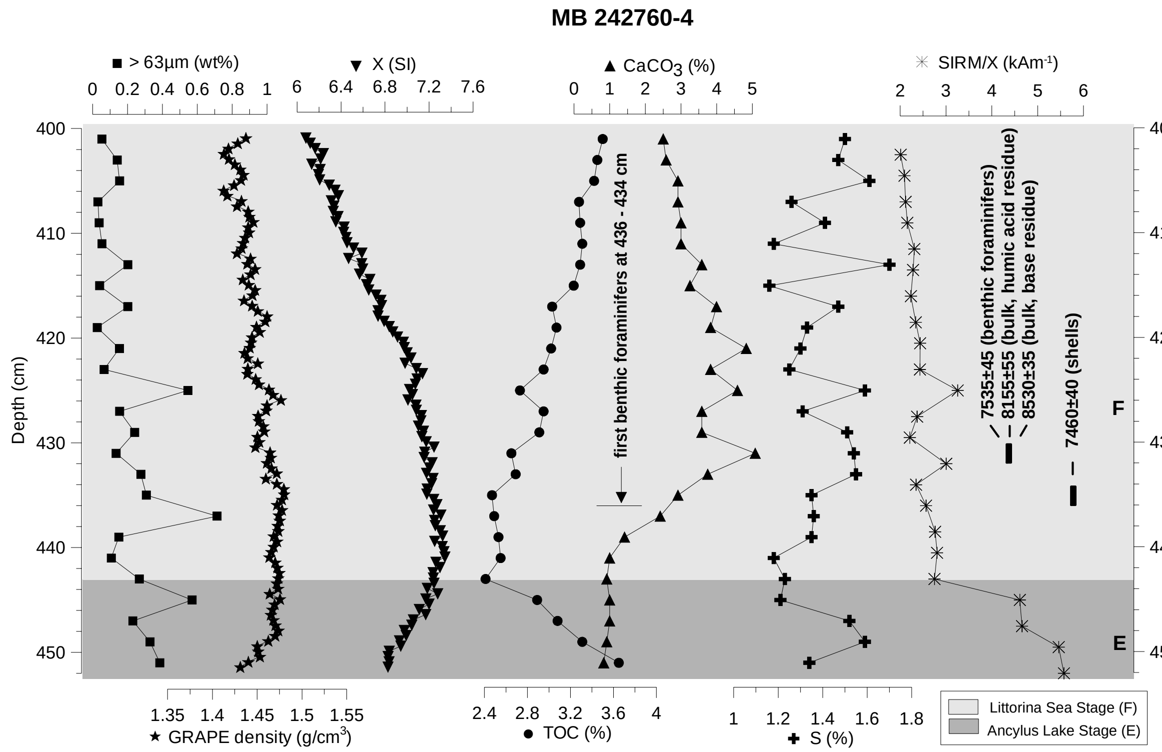
A13: Macrofossil and microfossil findings investigated in core MB 257760-1. The numbers refer to countings of the findings. The transition from limnic to brackish-marine conditions is shown by the disappearance of e.g. Cladodera and Characeae and the occurrence of benthic foraminifers. The yellow and blue coloured fields refer to the AncylusLake and Littorina Sea stages.

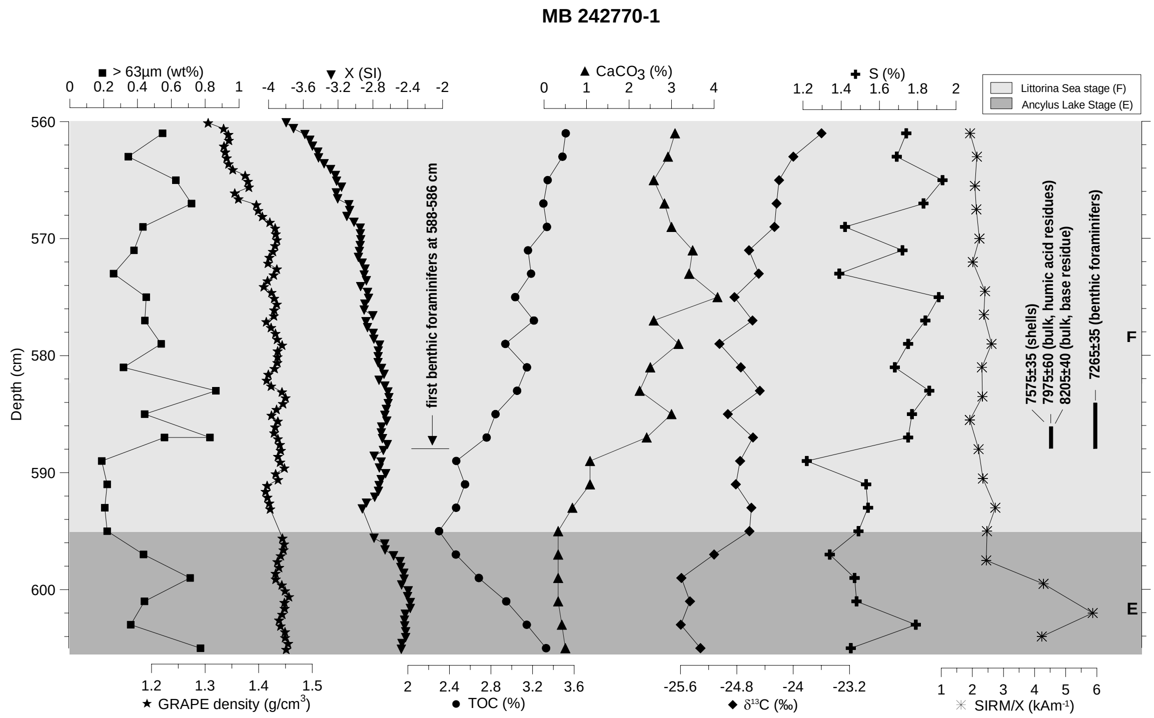
	Depth (cm)	340-350	360-370	381-390	400-410	420-430	440-450	460-470	480-490	500-510	520-530
marine	Bryozoa indet.	r									
	Arctica islandica	3									
	Cerastoderma sp.	2									
	Mytilus edulis	r									
	Cytheromorpha fuscata	c									
	Hydroidea indet.	r									
	Ammonia beccari	r									
lacustrine	Pisces indet.					r					
	Cristatella mucedo			2	1						
	Chironomidae indet.	r	r	r	r	r	r	r	r		r
	Orthotrichia sp.			1							
	Cladocera indet.	c	c	c	c	a	a	a	a	c	c
	Nymphaea sp.		1								
	Amblystegiaceae indet.			r							
	Characeae indet.		r		r		r				
telmatic	Radicells									c	c
	Carex spp.										1
	Phragmites australis	1		r			r				
terrestrial	*Betula* sect. *Albae* sp.			1	1	2					

r = rare c = common a = abundant by O. Bennike

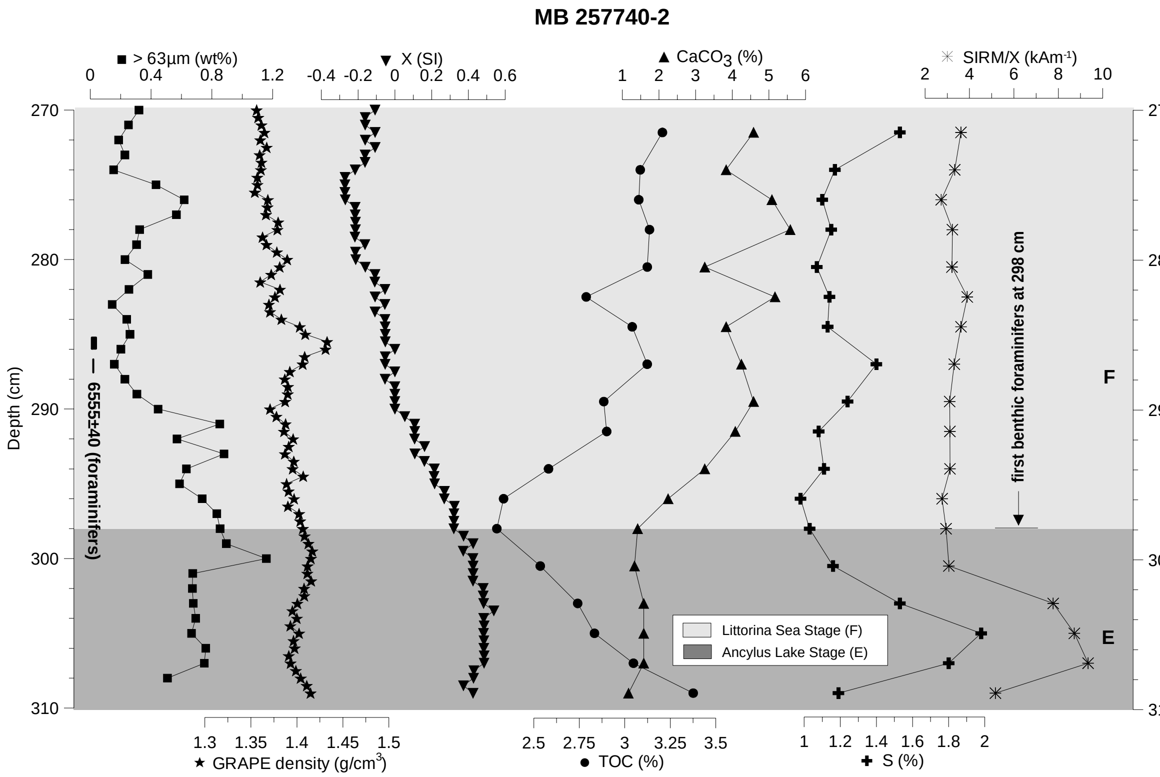
Littorina Sea stage
Ancylus Lake stage

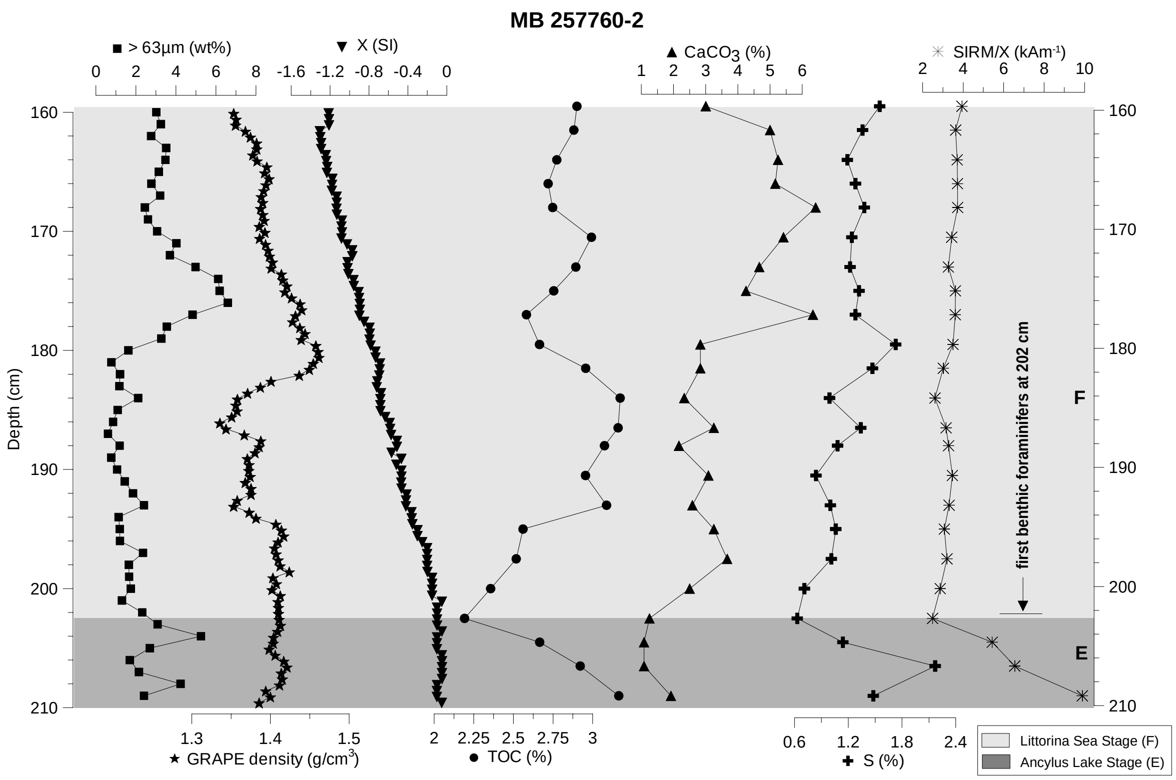
A14: Macrofossil and microfossil findings investigated in core AB 258010-1. The numbers refer to the count of the material. The transition from limnic to brackish-marine conditions is shown by the disappearance of e.g. Chironomidae and Characeae and the occurrence of benthic foraminifers. The yellow and blue coloured fields refer to the Ancylus Lake and Littorina Sea stages.



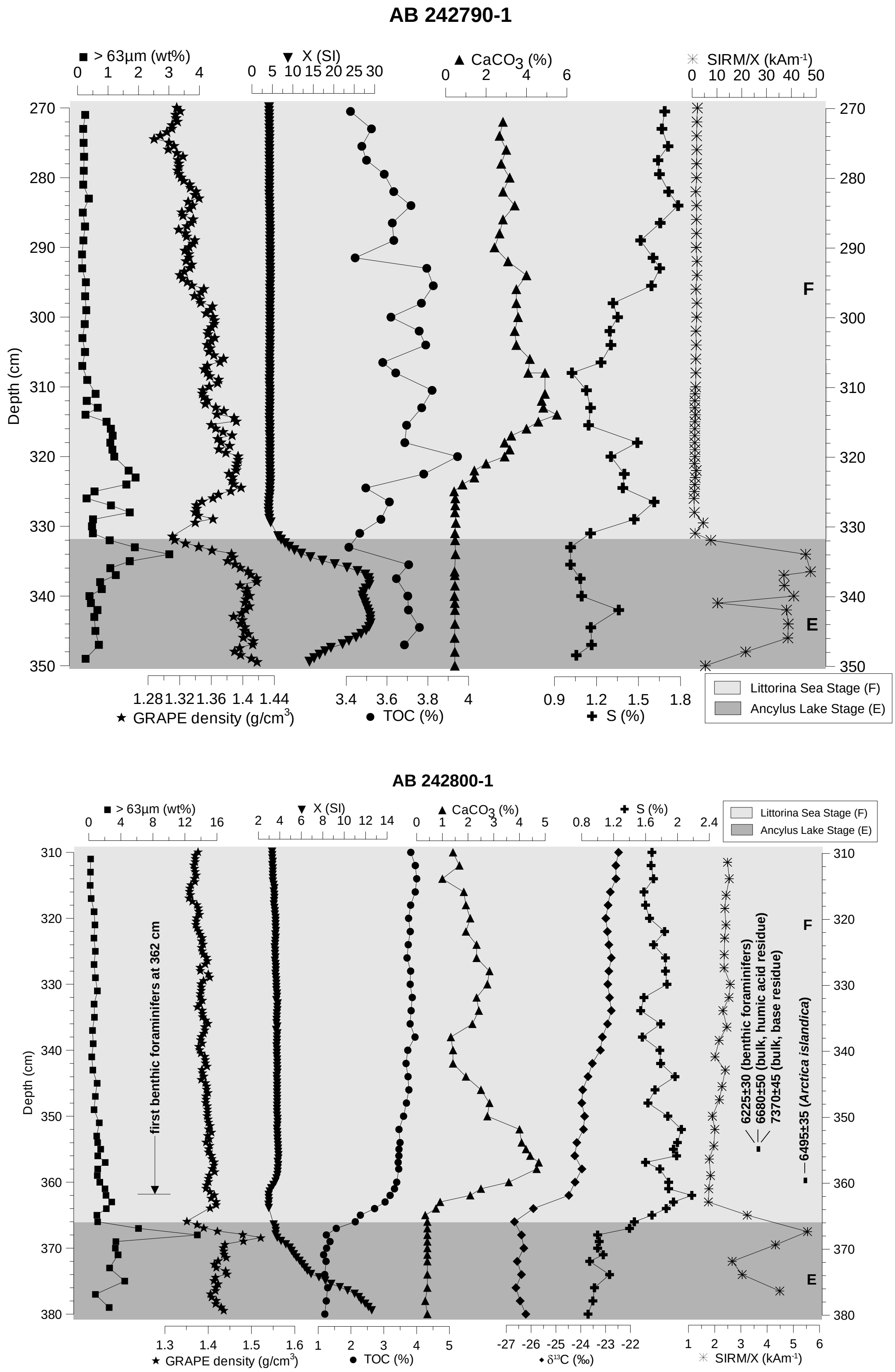


A15: Proxy parameters from MB 242760-4 and MB 242770-1 combined with uncorrected AMS ^{14}C dates. The lengths of the AMS ^{14}C boxes correspond to the sampling interval and the units E and F to the Ancylus Lake and Littorina Sea stages. Note that geochemical parameters (TOC, $CaCO_3$ and S contents) start to increase at the boundary E/F whereas sediment physical ones (wt% > 63 µm, GRAPE density and magnetic susceptibility (χ)) reflect no significant changes. The SIRM/X ratio decreases rapidly at the transgression base, i.e. at the boundary E/F (related to the TOC increase).

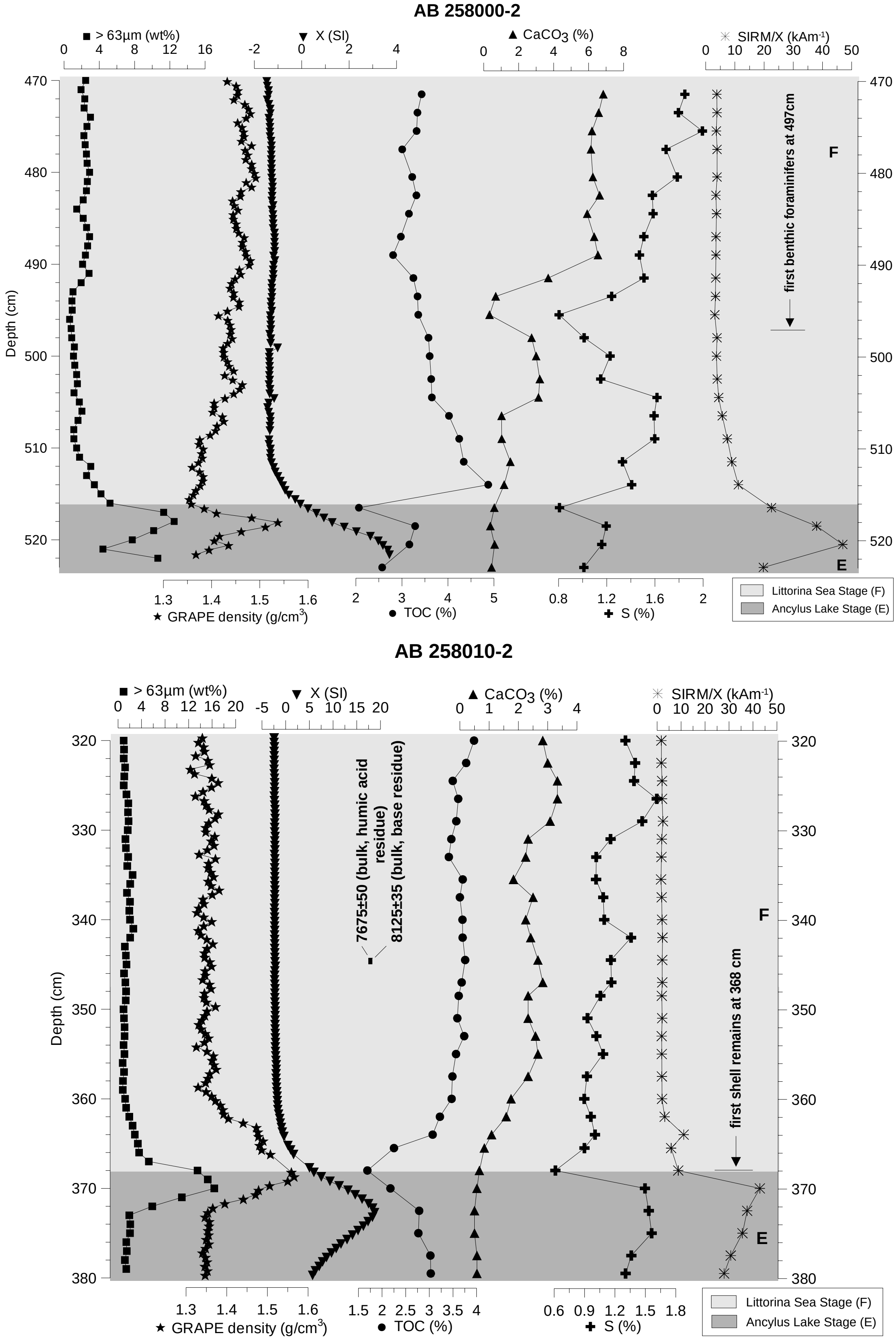




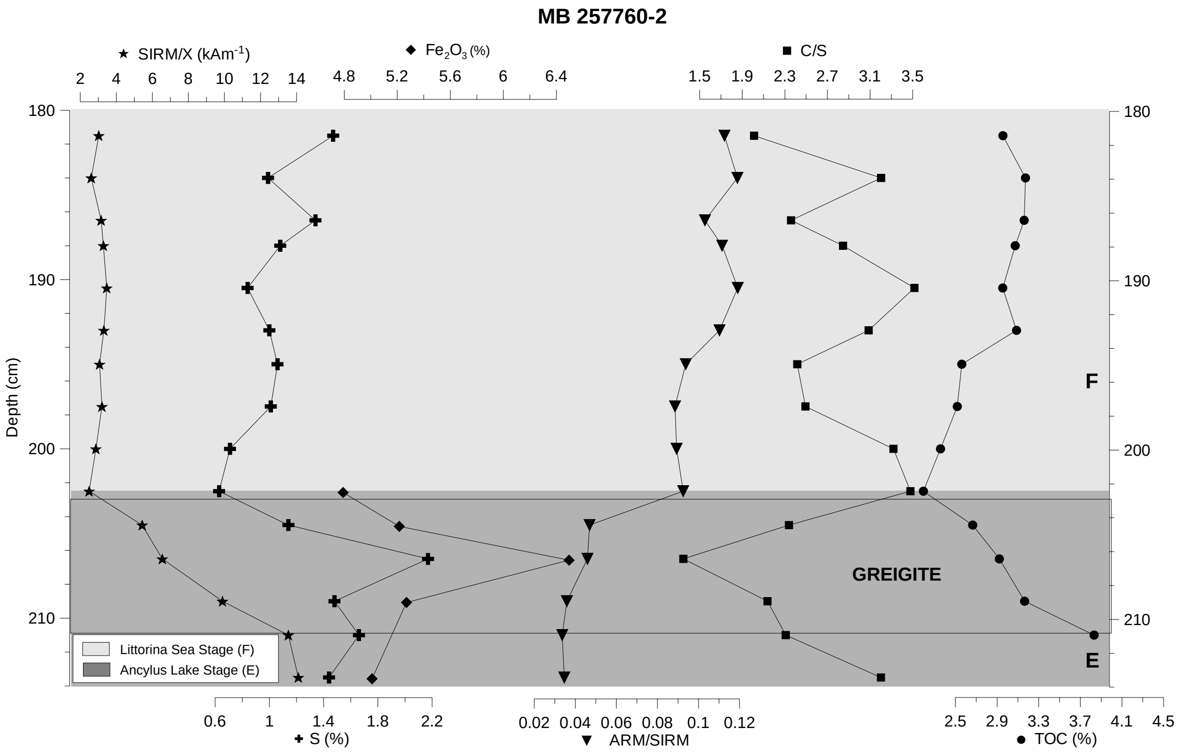
A16: Geochemical proxy parameters (TOC, $CaCO_3$ and S contents) increase and SIRM/X ratio decrease remarkable at the boundary E/F from MB 257740-2 and MB 257760-2. Physical sediment properties (wt% > 63 µm, GRAPE density and magnetic susceptibility (χ)) show no changes. Uncorrected AMS ^{14}C dates were determined. The lengths of the AMS ^{14}C boxes correspond to the sampling interval and the boundary E/F to the TOC increase.

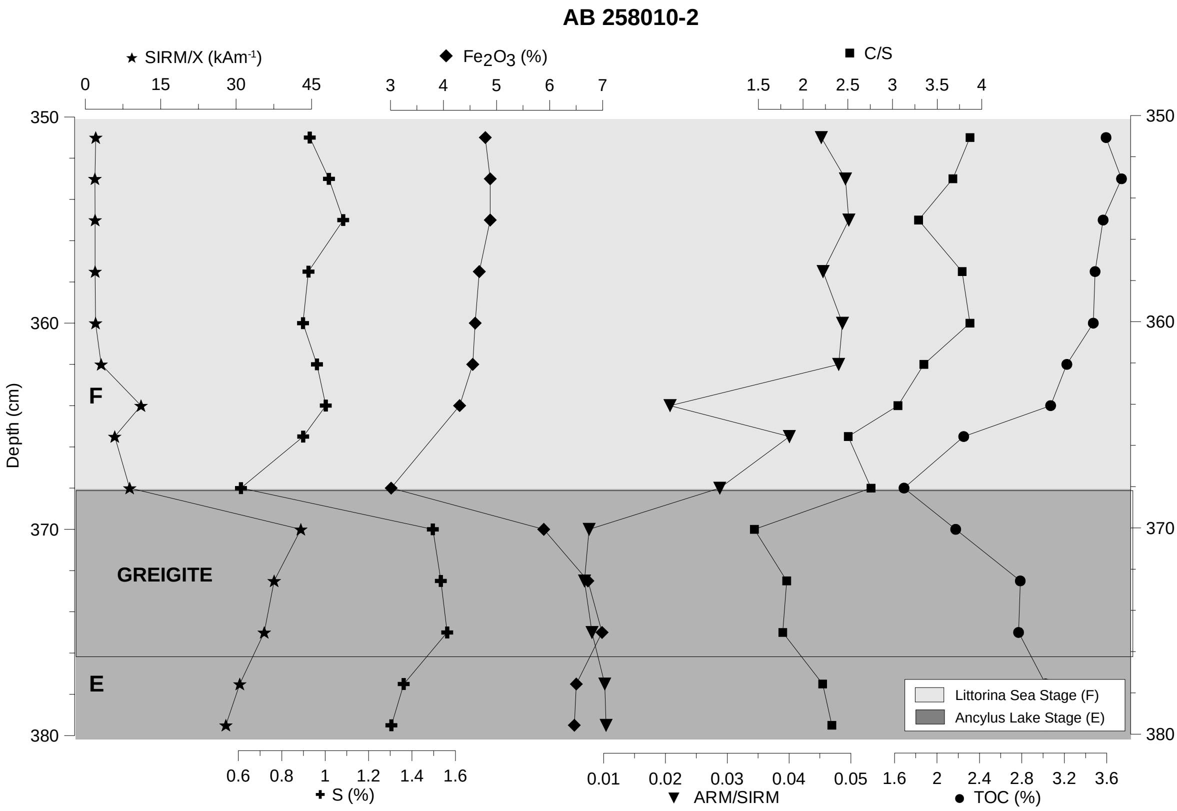


A17: Distinct changes in all proxy parameters (wt% > 63 µm, GRAPE density, magnetic susceptibility (χ), TOC, $CaCO_3$ and S contents and SIRM/X ratio) characterise the onset of the Littorina transgression in AB 242790-1 and AB 242800-1. The lengths of the black AMS ^{14}C boxes correspond to the sampling interval and the boundary E/F to the onset in the TOC increase. Units E and F refer to the Ancylus Lake and Littorina Sea stage, respectively.

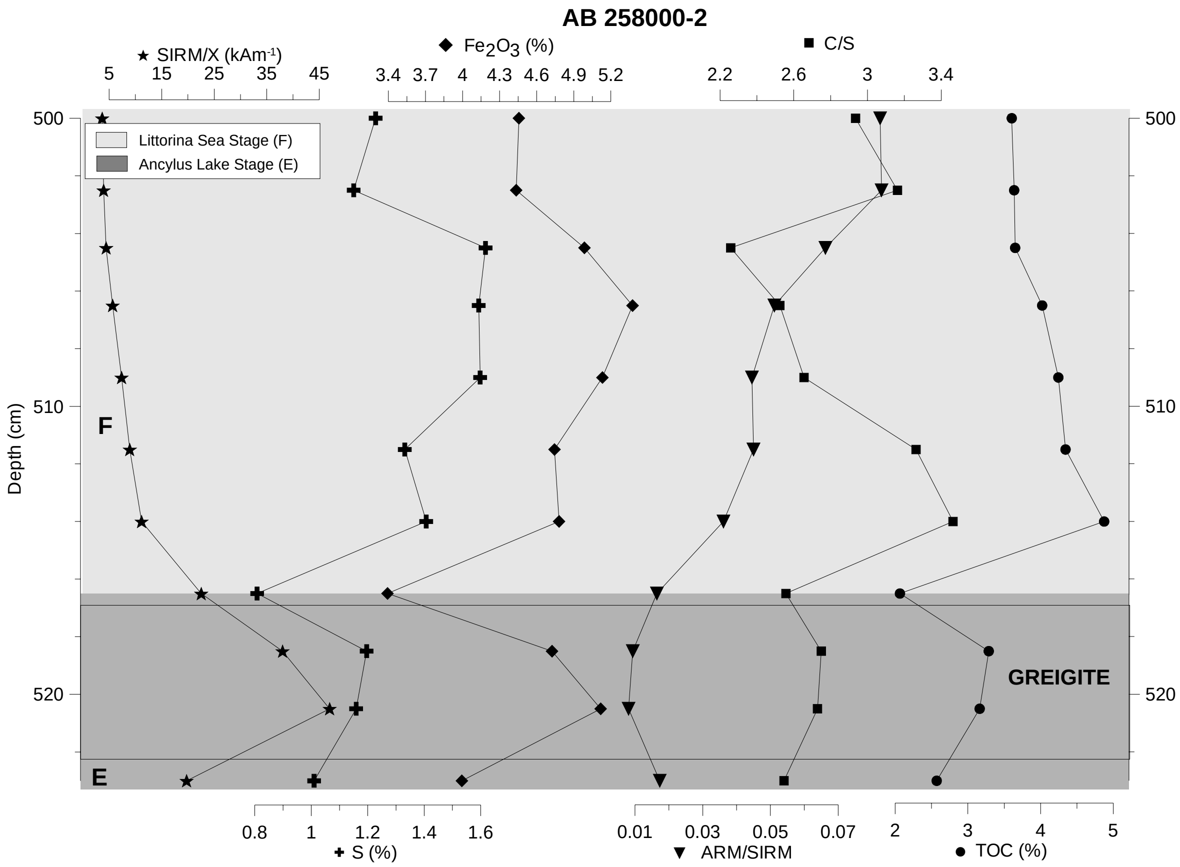


A18: The proxy parameters from AB 258000-2 and AB 258010-2 show clear changes at the transgression base. Peaks in wt% > 63 µm, GRAPE density, magnetic susceptibility (χ), increases in TOC, $CaCO_3$ and S contents and a decrease in SIRM/X ratio mark the boundary E/F. The units E and F are related to the Ancylus Lake and Littorina Sea stage and the boundary E/F to the onset in the TOC increase.





A19: ARM/SIRM, SIRM/χ and C/S ratios are compared to the sulphur, iron and organic carbon contents in cores MB 257760-2 and AB 258010-2. The peaks in SIRM/X ratios, sulphur and iron contents and the decreases in TOC content, ARM/SIRM and C/S ratio refer to greigite formation (Fe_3S_4). Units E and F are related to the Ancylus Lake and Littorina Sea deposits and boundary E/F to the onset in the TOC increase.



A20: ARM/SIRM, SIRM/χ and C/S ratios and sulphur, iron and organic carbon contents are shown analyzed in core AB 258000-2. The peaks in SIRM/X ratios, sulphur and iron contents and the decreases in TOC content, ARM/SIRM and C/S ratio refer to greigite formation (Fe_3S_4). Units E and F are related to the Ancylus Lake and Littorina Sea deposits and boundary E/F to the onset in the TOC increase.

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