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The WASA core catalogue of Late Quaternary depositional sequences in the central Wadden Sea – A manual for the core repository

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Abstract

The reconstruction of submerged palaeolandscapes and detection of settling surfaces along coastal zones became a major research topic within the last two decades. In this context, the WASA project made use of a multidisciplinary approach for defining the extension and describing the characteristics of the Late Pleistocene to Holocene deposits in the central Wadden Sea region. In addition to sub-bottom transects, more than 140 sediment cores were taken in such an area for stratigraphic reconstruction, making use of multi-proxy analysis. To harmonize these data with the existing regional core database (LBEG archive) a new core catalogue was developed, that allows the identification of the local Late Quaternary sedimentary sequences and their characteristic facies. The WASA core catalogue has been successfully applied for reviewing the published data about the stratigraphic sequence of the Wadden Sea, for a better definition in terms of stratigraphic sequences and spatial extent of the Quaternary geological evolution of the region, and for a detailed reconstruction of the coastal palaeoenvironments.

1. Introduction

The WASA Project (The *WA*dden *S*ea as an *A*rchive of landscape evolution, climate change and settlement history: exploration – analysis – predictive modelling) was designed as a new approach for a detailed palaeolandscape reconstruction and detection of potential settling surfaces in the coastal zone of the central Wadden Sea. The multidisciplinary project, combining regional expertise in geosciences, archaeology, botany and marine biology, aimed for the reconstruction of the Late Quaternary sedimentary sequences using a multi-proxy analysis, i.e. by means of *in situ* techniques (sediment coring) and spatial surveys (hydroacoustic sub-bottom data). A large core archive (ca. 30,000 cores) for the same coastal zone already exists at the Geological Survey of Lower Saxony (NIBIS® Kartenserver, 2014. Thematic maps - Boreholes and profiles), which consists of data collected mainly during the 1960s and 1970s under different purposes and interests. As a consequence, the core descriptions and the related interpretations are not always consistent, and they are mostly limited to basic sedimentological information (e.g. sediment grain size, etc.), regardless of the facies, facies transitions or erosional contacts. As a consequence, the LBEG archive does not always provide comprehensive, comparable and consistent information, which can be used for a detailed landscape reconstruction of the region. To fill this gap, the specific focus of the WASA project is on sedimentary facies (indicators of biological and sedimentological processes) and depositional environments as descriptors of potential palaeoenvironments.

More than 140 cores were collected from the sub-, inter- and supratidal settings in the back barrier tidal flat and the offshore area of Norderney (East Frisian Islands), see Fig. 1. The WASA core descriptions and catalogue used for studying those cores are mostly based on the facies classifications made by Streif (1990) and have been already described in detail in Karle et al. (2017, 2021), and Schaumann et al. (2021). With respect to those works, the facies characteristics were reduced and simplified to the most important and distinctive descriptors, which can be easily used in the field to recognise the local stratigraphic sequence and its related facies. As a result, this manual offers a field proven and easy to use core catalogue of facies and depositional environments for the Late Pleistocene to Holocene of the central Wadden Sea.

The WASA core catalogue has been successfully applied for re-interpreting the LBEG cores and for integrating the information into multidisciplinary studies (e.g. Scheder et al., 2021; Schlütz et al., 2021). In such a sense, this manual serves as an introduction and reference for all the works, which have been published within the WASA project and made use of interpreted sedimentological facies for the description of the palaeoenvironments. Furthermore, it can be used for (i) supporting the harmonisation of existing core data sets; (ii) reviewing the scientific literature about the stratigraphic sequence of the Wadden Sea;

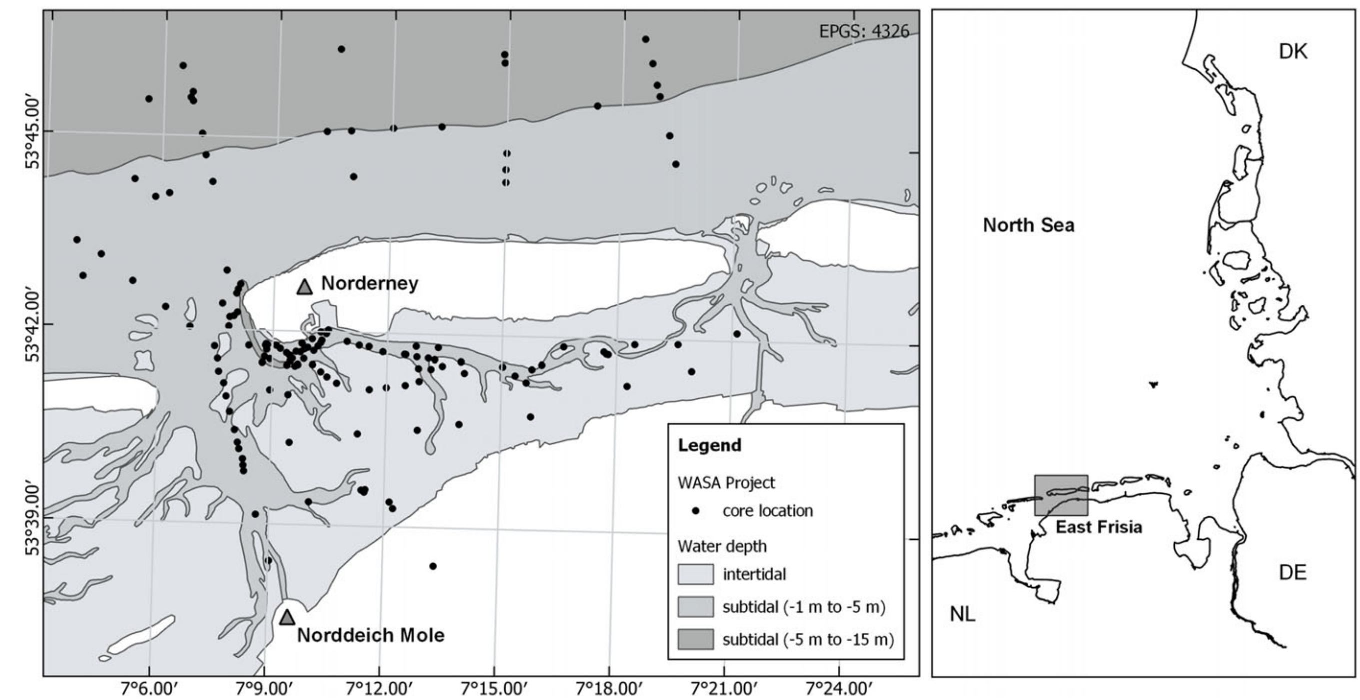

Fig. 1. Position of cores in the central Wadden Sea (Norderney backbarrier and offshore) taken by the WASA project.

(iii) a detailed reconstruction of the regional palaeoenvironments; (iv) a better definition in terms of stratigraphic sequences and spatial extent of the Quaternary geological evolution of the area; (v) refining the existing local Holocene sea-level curves by improving the definition of sea-level index points, and (vi) defining the preserved palaeosurfaces, where human settlements were potentially possible.

2. Middle to Late Quaternary geological evolution of the study area

The youngest geological history of the North Sea Basin is characterised by glacial and interglacial periods, which resulted – for the present-day central Wadden Sea region – in the deposition of a thick sedimentary successions including a variety of glacial, periglacial, aeolian, fluvial, and marine deposits.

Two Elsterian ice advances have been recorded in Northern Germany, producing up to 400 m deep tunnel valleys (Lutz et al., 2009; Stackebrand, 2009; Murton & Murton, 2012). The Elsterian glaciation was followed by the Holsteinian Interglacial; during its maximum, the coastline in the East Frisian area was situated ca. 10 km north of its present-day position (Linke et al., 1985; Streif, 1990; Schaumann, 2018). In fact, Holsteinian marine deposits have not been described so far in the study area. During the Saalian glaciation, only the first (namely the 'Main Drenthe') of three ice advances reached the East Frisian region (Rappol et al. 1989; Meyer, 2005; Litt et al., 2007; Graham et al., 2011) as documented by initially outwash sediments and, later on, moraine-deposits (see core N14, PANGAEA-WASA). In the study area, the Saalian moraine is directly overlain by Eemian (compare core N14, PANGAEA-WASA), Weichselian or even Holocene sediments. During the Eemian Interglacial, the coastline reached up to 5 km south of the present-day coastline (Caspers et al., 2002; Streif, 2004; Schaumann, 2018). Dechend & Sindowski (1956) describe the Eemian shallow marine environment as a sandy tidal flat system for the East Frisian region (see core N14, PANGAEA-WASA). Schaumann et al. (2021) even differentiate between a mixed- and sandy-tidal flat for the Eemian. Climatic cooling marked the following onset of the Weichselian glaciation when the ice extent did not reach the study area. The periglacial sands deposited during this period have been referred to as 'brown sands' in the literature and are related to fluvial and aeolian deposition (e.g. Streif, 1990; Sindowski, 1973; see Fig. 2 (core VVC17) and core N11, PANGAEA-WASA). During the maximum of the Weichselian glaciation, sea level dropped to 110-130 m below the present-day level (Streif, 2004). The subsequent climate warming during the Holocene resulted in sea-level rise. Finally, the characteristic landscape elements of the recent Lower Saxony coastal region with its barrier islands, mudflats and salt marshes, were formed in the course of the last 8500 years under the influence of ongoing sea-level rise (e.g. Davis, 1994). The so-called Geest landscape, consisting of the deposits of the last glaciations and interglaciations, was flooded, partially reshaped and disconformably covered in varying thicknesses of up to 25 m Holocene coastal deposits, which show multiple cycles of peat formation, flooding, and marine transgression over time (Fig. 2 – core VVC17). Fossil soil horizons (mostly podzols) can be occasionally found in the upper part or on top of the Pleistocene sequence (Fig. 2 – core VVC17). The presence of such horizons indicates the preservation of palaeosurfaces that have not been subject to deep erosion and, therefore, may represent surfaces which could have been potentially used for human settlement. The peatlands mostly developed as fen peat, whereas bog peat was documented only at few locations of the study area (Schlütz et al., 2021). In most of the WASA cores, the peat beds are erosively overlain by intertidal (i.e. tidal flat) or subtidal (i.e. channel) deposits (Fig. 2 – intercalated peat in core VVC17); some cores show a slow and continuous transition from

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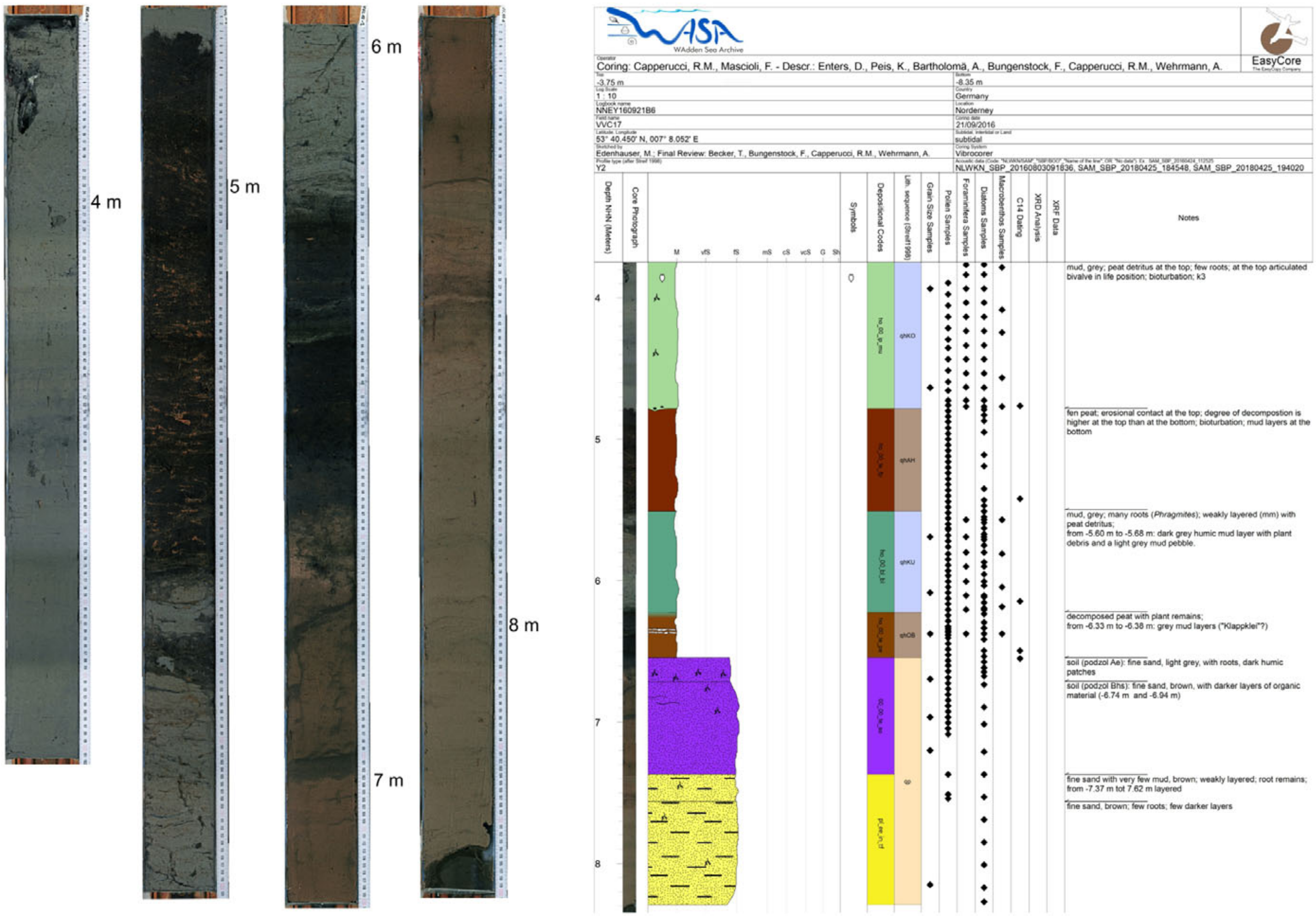

Fig. 2. Example of the transfer of core description, analysis, interpretation and stratigraphical classification and subsequent sampling of the core halves of VVC17 (left) into the EasyCore template (right). The latter will be available in the PANGAEA data publisher (PANGAEA-WASA).

peat to salt marsh and/or brackish-lagoonal and, finally, to tidal flat depositional environments (compare Fig. 2 – core VVC17 and core N11, PANGAEA-WASA).

3. Methods and application

3.1. Coring

Three coring systems were deployed in the field in order to cover the range from subtidal to supratidal settings. The coring locations were planned based on geological maps, existing core data (LBEG) and preliminary evidence showed by the hydroacoustic subbottom data.

For the subtidal setting (mostly offshore of Norderney, the Riffgat channel (i.e., the tidal inlet), and the ferry route from Norddeich to Norderney), a modified version of the vibrocorer VKG6 (medconsultant GmbH) was used from aboard the research vessels *FK SENCKENBERG* (Senckenberg am Meer, SaM, Wilhelmshaven) and *BURCHANA* (Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, NLWKN, Norderney). The vibrocorer was deployed in full-weight load mode (1.1 t gravity weight) and was equipped with PVC liners of 5000 mm length and 100 mm diameter.

The tidal flat cores were collected using a portable vibrocorer (Wacker Neuson generator with an IE high-frequency vibrator head of 20 kg) and 6000 mm long aluminium liners with a diameter of 80 mm. A hand-driven pulley-chain system, coupled with a telescopic tripod, was used for recovering the cores.

South of the dike line, on land, a Jackhammer auger corer (weight: 50 kg) was preferred, as it allows the coring of coherent but unconsolidated sediments in undrained environments. The liner in the coring extractor had a diameter of 50 mm and a length of 1000 mm.

The cores were cut into sections if necessary, sealed, labelled and moved to the lab for further processing.

3.2. Positioning and levelling

All positions for the intertidal and supratidal cores were recorded by means of a DGPS RTK-corrected system, providing a horizontal precision of 0.01–0.02 m and a vertical precision of 0.02–0.03 m. The elevation data are referred to the German standard elevation zero (Normalhöhennull, NHN).

The horizontal position of the subtidal cores was achieved using a SeaPath System (Kongsberg Maritime) with RTK corrections (SAPOS-Service). For the elevation, the cores were positioned on a multibeam-derived DTM (from 2016) kindly provided by the NLWKN with a horizontal precision of < 0.40 m and a vertical precision of 0.15–0.30 m depending on the absolute water depth (Francesco Mascioli, personal communication).

Table 1. The WASA core catalogue displays the Late Pleistocene to Holocene coastal palaeoenvironments of the central Wadden Sea and their sedimentary facies. The depositional codes derived from the prior four columns and include series/epoch, stage/age, the depositional environment and the subenvironment/facies with 00 indicating 'not defined'. The EasyCore template as shown in Fig. 2 is based on the depositional and colour codes of the core catalogue.

Series/Epoch	Stage/Age	Depositional Environment	Subenvironment/Facies	Depositional Code	RGB colour code
HOLOCENE	Not defined	Subtidal	Lower shoreface	ho_00_su_ls	54, 93, 156
			Upper shoreface	ho_00_su_us	
			Channel lag	ho_00_su_cl	85, 142, 213
			Channel fill	ho_00_su_cf	
		Intertidal unprotected	Beach/foreshore	ho_00_iu_be	183, 221, 232
		Intertidal protected	Sand flat	ho_00_ip_sa	166, 218, 152
			Mixed flat	ho_00_ip_mi	
			Mud flat	ho_00_ip_mu	
		Brackish-lagoonal	Brackish-lagoonal	ho_00_bl_bl	90, 165, 134
		Salt marsh	Salt marsh ('Groden')	ho_00_sm_sm	102, 102, 51
		Terrestrial	Peat, not defined	ho_00_te_pe	132, 68, 10
			Bog peat (*Sphagnum*)	ho_00_te_bp	89, 50, 0
			Fen peat (*Phragmites*)	ho_00_te_fp	126, 40, 0
PLEISTOCENE	Weichselian	Periglacial plain	Eolian/fluvial	pl_we_pp_ef	255, 203, 12
	Eemian	Intertidal	Tidal flat (sand/mixed flat)	pl_ee_in_tf	255, 228, 47
	Saalian (Drenthe)	Glacial	Moraine	pl_sa_gl_mo	255, 255, 145
		Periglacial plain	Eolian/fluvial	pl_sa_pp_ef	
	pre-Drenthe	Lacustrine/deltaic	Lacustrine/deltaic	pl_pd_ld_ld	255, 255, 215
		Terrestrial	Soil – potential settlement	00_00_te_so	151, 47, 255

3.3. Profile types

The Holocene sedimentary succession in the coastal zone of the Central Wadden Sea is characterised by the alternation of clastic sediments and intercalated peat layers, representing the cycles of landward and seaward coastline shifts that occurred during the sea-level rise. The peat deposits are dominant on the landward side, while clastic deposits are typical in the tidal flat areas on the seaward side. These sediment sequences are determined following the lithological classification principle according to Barckhausen et al. (1977), Streif (1979, 1998) and Hoselmann & Streif (2004). The Holocene sediments are subdivided based on the vertical succession and lateral interfingering of siliciclastic sediments and peat deposits. Thus, this classification system reflects the depositional history of the Holocene coastal plain deposits in terms of (local) progradational and retrogradational phases and provide basic information to map former palaeogeographies as shown by Karle et al. (2021). For example, profile type x1 corresponds to solely siliciclastic deposits: in landward areas with generally thicker peat sequences, it would indicate the presence of clastic channel fill deposits.

The profile type and the related lithological sequences are provided for each of the WASA cores (see the template, Fig. 2), in order to include a relevant information, which can be used together with coring data derived from other sources or projects. For cores not reaching the Pleistocene and therefore not covering the preserved Holocene sequence, the profile type for the documented sediment sequence is given.

3.4. The WASA core *catalogue: Core description, analysis, interpretation and stratigraphic classification*

The cores were cut lengthwise in the lab and high-resolution digital images were taken under constant light conditions.

In a second step, the cores were macroscopically described and subdivided into depositional units, which presented significant differences from the intervals above and below. Based on its characteristics and its relative vertical stratigraphic position (i.e. in relation to specific intervals, for example, peat or moraine deposits), each of those units was assigned to a distinct depositional environment, sedimentary facies and time stage (e.g. Holocene, Weichselian, Eemian, etc., Table 1).

The macroscopic description (Supplementary material Table 1) includes the main sediment attributes (e.g. grain size, colour, presence of specific minerals, e.g. mica), texture (sorting, clast/matrix support, grading), stratigraphic features (e.g. lamination, cross-bedding, lenses), post-depositional structures (reworking, cryoturbation, bioturbation, erosional contacts, boreholes), macrofauna definition (presence of single shells, articulated bivalves, etc.), and presence and nature of plant organic matter (e.g. roots, peat layers, reworked peat fragments and organically enriched sediments). The sediments were tested with diluted (10%) hydrochloric acid for carbonate content, and its amount was scored on a 6-steps scale from K0 (no reaction, 0% content of $CaCO_3$) to K5 (violent reaction, very high content of $CaCO_3$ – Preuß et al., 1991). The abundance of shells, shell fragments and shell debris was flagged using a similar scale (from S0 to S5). For

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specific intervals, a first assessment about the presence of environment-related organisms/remains (e.g. marine diatoms for the Pleistocene sediments, or sponge spiculae for marine deposits) was carried out.

After the macroscopic description, one core half was sampled for in-depth analysis with regard to the specific disciplines involved in the project. Samples were taken at both regular and irregular intervals, depending on the specific research questions or approaches for each discipline, namely for grain size analysis (for method see Elschner et al., 2021), gravel component analysis (for method see Schaumann et al., 2021), C/N and TOC (Elschner et al., 2021), ^{14}C-datings (Enters et al., 2021; Scheder et al., 2021; Schlütz et al., 2021), palynology (Schlütz et al., 2021), diatoms (Bulian et al., 2019), foraminifers and ostracods (Scheder et al., 2019, 2021; Haynert et al., 2020), and taphonomy. Additionally, down core scanning was applied on most of the intact core halves for magnetic susceptibility, and XRF (for methods see Lee et al., 2021). Based on the above listed analysis, some of the macroscopic core descriptions could be specified or corrected (Elschner et al., 2021; Scheder et al., 2021).

It has to be noted that some of the aforementioned macroscopic-derived characteristics can be found in more than one depositional environment, and therefore they could not be used as standalone indicators for appointing specific facies. Thus, the coring location (e.g. offshore, in a tidal inlet or in the tidal flat nearby the present dike line) played an important role in the definition of the depositional environment, especially for recent sediments.

In comparison to the Holocene sediments, the Pleistocene deposits showed a general enrichment in mica content, due to the depletion of metamorphic rocks during the glacial and periglacial stages, lately reworked during the interglacial phases (Schaumann et al., 2021).

With regard to the Pleistocene sediments, the $CaCO_3$ content and the presence/abundance of diatoms are an important function for the characterisation of the marine deposits and for distinguishing them from similar recent sediments. In fact, the Pleistocene deposits generally show content of $CaCO_3 = K0$. The finding of marine diatoms within the fine fraction (mud) layer of the Pleistocene intervals, together with the sedimentological characteristics, supported the definition of proper intertidal facies related to the Eemian interglacial (Eemian tidal flat). Where the diatoms were not found or where no investigations were carried out, the transition to the Weichselian remains uncertain.

For moraine deposits, a specific analysis of the fine gravel fraction of cores N70, N20, N22 and Nney02 confirmed its attribution to the Main Drenthe Saalian ice advance (Schaumann et al., 2021).

The definition of the ages, the depositional environments and the related facies were translated into a graphical representation (colour and texture) and a unique coding, to be used for sketching the cores in EasyCore (Supplementary material Table 1). At each depositional environment (e.g. subtidal unprotected, subtidal protected, etc.) corresponds a unique colour, defined in its RGB values (so that the same colour-code could potentially be used consistently from external sources and by means of different software). The unique coding (“Depositional Code” in Table 1) is made of 8 digits, separated by underscores: ss_aa_dd_ff, where ss: Series/Epoch (e.g. ho for Holocene); aa: Age/Stage (e.g. we: Weichselian); dd: depositional environment (e.g. ip for intertidal protected) and ff: Facies (e.g. ef for eolian/fluvial). 00 stands for ‘not defined’.

3.5. Dating samples

Datings samples were collected and analysed by the WASA working groups using different calibration programs and correction factors. The results have been already published in several studies (see here in after for the details) with regard to specific cores. In order to offer a comprehensive and consistent overview of the dating outcomes, they have been harmonised using age data and the respective calibration procedures. For this manual, the datings relative to two cores (N11 and VVC17, Fig. 2 and Table 2) are presented. The remaining datings will be made available to the public on PANGAEA data publisher (PANGAEA-WASA).

The ^{14}C age determination was performed at the Poznań Radiocarbon Laboratory (Poland) by means of accelerator mass spectrometry (AMS, see in Elschner et al., 2021 for details). The results were originally calibrated with the software CALIB (Version 7.1), using the calibration curves IntCal13 and Marine13 (Reimer et al., 2013). According to the measurements of Enters et al. (2021), the ΔR value for reservoir correction of ages originating from *in situ* shell material was presumed 74 ± 16 ^{14}C years. During the proofreading of the latter, the ‘new’ ΔR value was recalculated to -85 ± 17 ^{14}C years (note the negative sign) when the most recent marine calibration curve, i.e. Marine20 (Heaton et al., 2020) was published.

The chronological framework in Scheder et al. (2021) is based on AMS-^{14}C dating of peat (see also Bulian et al., 2019), *in situ* bivalves and foraminifera tests. ^{14}C dating was performed at the Poznań Radiocarbon Laboratory (Poland) and the Beta Analytic Inc (USA). Calibration and age-depth modelling were accomplished using the R software (rbacon, v. 2.3.9.1, Blaauw & Christen, 2019), calibration curves IntCal13 and Marine13 (Reimer et al., 2013) of CALIB 7.1 with the respective reservoir correction (74 ± 16 ^{14}C years) after Enters et al. (2021). The available age data were used by R to interpolate an age model up until the sediment surface, where necessary layer boundaries were integrated into the modelling process to account for different possible sedimentation rates.

Dating of the peat samples (Schlütz et al., 2021) was also carried out at the Poznań Radiocarbon Laboratory (Goslar & Czernik, 2000). Calibration was done with OxCal v.4.3 (Bronk Ramsey, 2009) including deposition models (Bronk Ramsey, 2008; Bronk Ramsey & Lee, 2013). Data in the text refer to mean ages with 2σ intervals (Bronk Ramsey, 2009).

3.6. The EasyCore template

One of the major duties listed in the proposal of the WASA Project was the transfer of the sediment core information into an open access data repository (PANGAEA-WASA) for making them available to future research in earth and environmental science. A specific WASA template was therefore designed using the software package EasyCore, which offers in a single page all the relevant information for each core, such as the core metadata (e.g. core name, position, etc.), a core photo, a lithological sketch (colour- and texture-based for each of the facies), a graphical overview of all the samples taken for different purposes (e.g. grain size, pollen, etc.), and the macroscopic description of each sedimentary unit.

Metadata are noted in the header and includes the core operators (collectors and descriptors), the elevation of the top and bottom of the core (NHN referred), the logbook name (which

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Table 2. ^{14}C data for cores N11 (PANGAEA-WASA) and VVC17 (Fig. 2). All data have been calibrated with the Intcal20 and Marine20 (Reimer et al. 2020; Heaton et al. 2020) by Oxcal (Bronk Ramsey, 2009). If already published, the respective reference is given in the last column. Note that previously published age data are eventually calibrated with a former calibration curve and a different delta R value for marine samples.

									OxCal IntCal20		
Core	Lab. no.	^{14}C age	^{14}C std	$\delta\ ^{13}C$ (permil)	Bottom m NHN	Top m NHN	Sampled layer	Taxa	2 Sigma cal BP	2 Sigma cal BP	reference
N 11	Poz-106656	6360	35	−24.4	−10.14	−10.12	Top basal peat	*Mentha arvensis/aquatica*	7420	7167	
N 11	Poz-115128	6940	40	−28.5	−10.37	−10.33	Top Pleistocene (soil)	Fine bulk	7917	7678	
N 11	Poz-106487	6460	40	−29.2	−10.39	−10.37	Top Pleistocene (soil)	*Alnus*	7429	7280	
N 11	Poz-106619	6960	40	−29.0	−10.39	−10.37	Top Pleistocene (soil)	Fine bulk (non-marine)	7922	7688	
VVC 17	Poz-95124	4780	40	−27.3	−4.84	−4.82	Top intercalated peat	Fine bulk	5593	5331	Scheder et al. (2021)
VVC 17	Poz-94535	4690	40	−27.6	−4.84	−4.82	Top intercalated peat	*Cladium mariscus, Carex flava-type, Carex* spec.	5573	5317	Scheder et al. (2021)
VVC 17	Poz-95026	5100	40	−29.6	−5.47	−5.45	Bottom intercalated peat	Fine bulk	5927	5743	Scheder et al. (2021)
VVC 17	Poz-94532	5320	40	−32.4	−6.26	−6.24	Top basal peat	*Cladium mariscus*	6268	5951	Scheder et al. (2021)
VVC 17	Poz-94533	6050	40	−26.4	−6.55	−6.53	Bottom basal peat	Fine bulk	7150	6786	Scheder et al. (2021)
VVC 17	Poz-94534	6710	40	−32.1	−6.60	−6.58	Bottom basal peat	Fine bulk	7667	7505	Scheder et al. (2021)

provides information about the location, coring date and station; Fig. 2), the core name (field name), the coring date (day/month/year), the geographic coordinates, the tidal setting (sub-, inter, supratidal), the core sketching team, the coring system, the profile type, and the list of hydroacustic subbottom transects corresponding to the coring location (where present).

All data generated, processed and published in the frame of WASA will successively be stored in the open access data repository PANGAEA under the project title WASA (PANGAEA-WASA). This will assure access to these data for further research initiatives, organisations and public. For this manual, a first batch (cores N11, N14 and VVC17) of the WASA cores is presented (see the supplementary material).

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/njg.2022.1

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