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NUMERIC DE-COMPACTION OF HOLOCENE SEDIMENTS

Nico SCHMEDEMANN[1], M.-Th. SCHAFMEISTER[2], Gösta HOFFMANN[3]

Abstract. Sea-level development is often determined by the interpretation of Holocene sediments. To do this, sea-level curves are fixed by dating organic enriched sediments and measuring their depositional heights. Organic enriched sediments like organic mud or peat which are usually well dateable are also susceptible to compaction. To correct the layers for initial sediment thickness and consequently the depositional heights for dated sediments, it is necessary to de-compact the sediment sequence for the dated point. By this the correct paleo-surface at the time of deposition can be reconstructed. The software “DeLos” (Dekompaktion von Lockersedimenten) is written to perform the time consuming calculations in a fast way. The software assumes that sediments are composed of an incompactable solid part and compactable pore space.

DeLos shows that the surface displacement could easily reach magnitudes of 50% within high compactable sediments. Especially such layers with large thicknesses of several meters are often used to get vertical profiles for time-depth correlation (Brown, 1975). Due to compaction processes the dated samples are remarkably displaced.

Key words: peat, mud, sediment, compaction, de-compaction, modelling, Holocene.

INTRODUCTION AND AIMS

Sea level changes are usually plotted in depth-time diagrams. For absolute datings in the Holocene, the radiocarbon method is often applied, which uses organic samples commonly. While these deposits are highly prone to compaction, the bedding depth observed in the field therefore differs from the one that would be obtained from initial thicknesses by the amount of compaction. During diagenesis compaction processes are common within sediments. Grain stress increases and consequently porosity decreases with depth, due to the weight of overlying sediments. For an advanced sea-level change curve, which is important for the reconstruction of relative sea-level changes in the Holocene, the knowledge of compaction is of great importance. The question of compaction within organic enriched sediments is not only raised in the area of the southern Baltic Sea (e.g. Hoffmann, 2004) but also at the coastal wetland in southeast England (Long *et al*., 2005) and southwest England (Allen, 1998). It seems that very young compaction processes (e.g. Holocene) are of great concern wherever flat coastal ranges are influenced by regression and transgression events. Compaction processes which take place well beyond those depths documented by the Holocene are simulated by already existing mathematical models for numeric simulation of compaction (e.g. Springer, 1993). By using an existing model (Gustavs, 1992) and adapted sediment parameters it is possible to numerically de-compact even thin layers of Holocene sediments. Therefore we developed a software solution – named DeLos. If the specific parameters are known, the software can be applied to all kinds of unconsolidated sediments. DeLos computes initial thicknesses of all layers and their compaction in case of coverage by sediments deposited later, from a given Profile. For this study four cross-sections located at the coastal range of Mecklenburg–Vorpommern/Germany (Fig. 1) where analysed. Two of them (Recknitz valley and Lobber Lake-lowland) are visualized later in this paper.

The need for an advanced sea-level curve with high resolution in space and time is given to understand which processes took place on a coast under transgressive circumstances. Since late Pleistocene the sea level in range of the area mentioned, is rising at different rates and with phases of

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[1] Freie Universität Berlin, Fachrichtung Planetologie und Fernerkundung, Malteserstr. 74-100, D-12249 Berlin, Germany; e-mail: nico.schmedemann@fu-berlin.de
[2] Institut für Geography and Geology Ernst-Moritz-Arndt-University of Greifswald, Friedrich-Ludwig-Jahnstr. 17A, 17487 Griefswald, Germany; e-mail: schaf@uni-greifswald.de
[3] Neotectonics and Natural Hazards, RWTH Aachen University, Lochnerstr. 4-20, 52056 Aachen, Germany; e-mail: g.hoffmann@nug.rwth-aachen.de

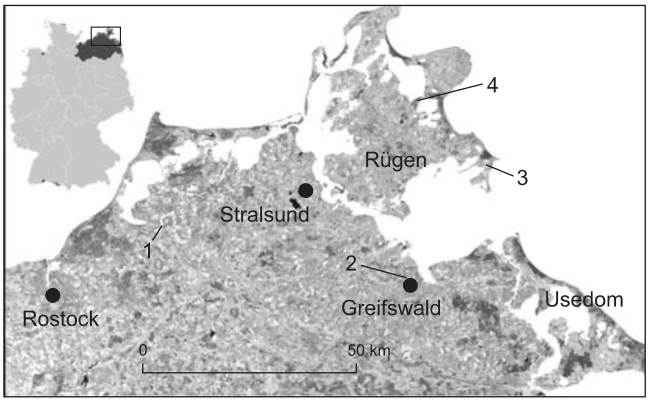

Fig. 1. Location map of cross-sections

1 – Recknitz valley, 2 – museum port/Greifswald, 3 – Lobber Lake lowland, 4 – Augustenhof

regression. To understand the processes in the past enables us to predict the coast development in the future where sea-level rise is expected due to global warming (Mauz, Bungenstock, 2005). In course of the Littorina-Transgression the coast in the SW-Baltic was shaped (e.g. Hoffmann, Barnasch, 2005). Starting at transition between Boreal and Atlantic a basal peat which is very common in the SW-Baltic indicates a moderate rising sea- level, because peat has a maximum level of grow rate. During the early middle Atlantic the sea-level rise speeds up that peat couldn't match that rising rate. The basal peat was covered by marine sediments. At that time an archipelago developed in the area of the modern islands of Rügen and Usedom. The islands of the ancient archipelago are Pleistocene highs. Due to erosion these islands delivered Material which accumulates on lee side of the islands to form beach ridges and wind flats since the late Atlantic when sea-level rise slows down significantly. Since that time prograding of beach ridges closes lagoons from the sea and peat develops on the wind flats. To narrow down in which height the Littorina transgression flooded the basal peat it is of great concern to de-compact the significantly compacted basal peat.

MATHEMATICAL MODEL

For describing the computation of paleo-thicknesses from present thicknesses, the term de-compaction is used. The pore fluids have no impact to compaction as long as the pore space is not closed and the fluids are able to draw aside the grain stress. Sediments are made up of an incompactable solid part and a pore space which is compactable. The recent porosity is the result of compaction related to the strength of the compaction constant, the initial porosity and depth. The compaction constant shows the compaction rate with increasing grain stress which is related to the buried depth. Eq. (1) (e.g. Springer, 1993) describes the dependencies between those units by neglecting the influences of different rock densities.

$$\varphi(z) = \varphi_0 e^{-bz} \qquad (1)$$

φ – recent porosity
φ_0 – initial porosity
b – compaction constant
z – depth

An overview of initial porosities and compaction constants for typical Holocene sediments in the area of the southern Baltic Sea is given in Table 1. Porosity-depth curves of those sediments are shown in Figure 2. The validity of the values used for porosity-depth curves is given only for buried depths less than 20 m.

Table 1

Initial porosity (φ_0) and compaction constant (b) of common Holocene sediments

Sediment	φ_0 [%]	b [1/km]	Source
Lodgement till	10	0.01*	Landslide conference (Nationalparkamt Ruegen April 19, 2005)
Clay	82	25.00	Dietrich, 1989
Silt	56	0.39	Gustavs, 1992
Sand	49	0.27	Gustavs, 1992
Organic mud	82	40.00	Gustavs, 1996
Peat	90**	50.00**	Succow, Joosten, 2001

* consequence calculation technique
** assumption due to differential compaction of peat

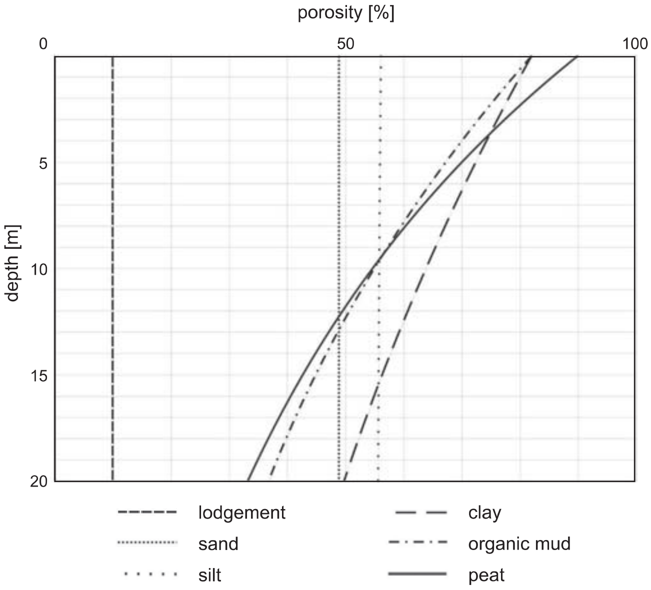

Fig. 2. Porosity – depth curves of common Holocene sediments; based on Table 1

SEDIMENT CHARACTERISTICS

Lodgement Till. The lodgement tills are formations which are related to the last glaciations. Due to the extra load of overlying ice sheets they are precompacted. Later deposited sediments are not thick enough to reproduce such stresses. That's why it is assumed that no compaction occurs within lodgement tills during the Holocene.

Clay. At the moment of sedimentation, awkwardly shaped clay particles create a large but fragile pore space. So the ability for compaction is high. By an empiric approach the values for initial porosity and compaction constant displayed in Table 1 were found by Dietrich (1989). It should be mentioned that these values are wide spreading, not only in dependence of the kind of clay minerals but also in dependence of depth. This means in this case the compaction constant is not really constant on large depth intervals.

Sand and Silt. Sand and silt consist of a high percentage of quartz grains which show a remarkably resistance to compaction. For the low grain stresses which occur at the depths mentioned above, quartz grains only reorder their packaging geometry particularly. However, no major reduction in pore space results from that reorientation at these shallow depths.

Organic Mud. Organic enriched sands and silts are much more susceptible to compaction. An attempt to calculate the initial porosity for organic mud is Eq. (2) (Gustavs, 1996). According to this equation the initial porosity depends on organic enrichment, mean grain size, sorting and grain stress.

$$\varphi = (0.868 + 0.0121 \times C_{org} - 0.00599 \times \text{mean} + 0.00453 \times \text{sort}) \times e^{(-0.000072 \times p)} \qquad (2)$$

C_{org} – organic carbon [%]
mean – mean grain size [µm]
sort – sorting [µm] (standard deviation of grain size)
p – grain stress [Pa]
φ – porosity [%]

It seems to bee more practical to use generalized values for initial porosity and compaction constant, due to lateral variations for example of organic content.

Peat. Depending on its genetic environment peat shows a wide diversity of behaviour. Peat shows no compaction at all as long as it is saturated with water, with respect to its sedentary growth. If peat falls dry, due to the absence of ascending force it compacts and for the most part does not refit by later hydrating. Additionally there occurs a decomposing of dead peat plants. Up to 100 kg × km^{-2} × a^{-1} of organic material is led away, according to Succow and Joosten (2001). The mineral content increases by decomposing. Inorganic material shows more resistance to compaction, while organic material compacts clearly. Peat shows almost no compaction as long as it is not covered by any other sediment. But auto compaction occurs for example due to increasing mineralization and other processes mentioned. If peat is covered by clastic sediments it compacts conspicuously. Peat is often used as indicator for the water level in the surrounding area.

IMPLEMENTATION OF DE-COMPACTION INTO AN APPLICATION PROGRAM

The recently programmed de-compaction algorithm "DeLos" (Dekompaktion von Lockersedimenten) is based on an older program called "deltaPhi" (Gustavs, 1992). DeLos was created using Microsofts development environment Visual Basic 6 with service pack 6. While running on Windows platforms (Windows 98 or higher) and its text file based Input/Output abilities, DeLos' data files are highly compatible throughout many of Windows applications and are easily editable. For time efficient computing of the de-compaction calculations, it is beneficial to reverse sedimentary history. This means eliminating the top layer of a given vertical sedimentary profile. Then the de-compaction algorithm cuts the profile into thin parts. The thickness of the slices depends on the compactability of the material, e.g. peat slices are discretized far thinner than sand slices. By default peat slices are as thick as half a mm, while sand slices range on the order of dm. Different slice thicknesses are used because of far less compaction of sand compared to peat. In this way errors made by generalizing the value of porosity throughout the whole slice are comparable and we achieve nearly the same accuracy throughout the whole profile. In addition the different downward porosity gradient demands more processing time on highly compactable profile parts. Within the de-compacted profile the buried depth of the current slice is lower. With the higher porosity the de-compacted slice thickness will be calculated. By adding together all de-compacted successional slices of the same sediment type, the whole de-compacted layer is calculated. If this is done for all residual layers, the active top layer is eliminated and the new residual profile is going to be de-compacted. This goes on until the bottom layer is the only one left. The result of all calculations is a triangular matrix of layer thicknesses. To the very left appears the uncovered bottom layer and to the very right the given profile. On a Pentium 4 class computer with an AMD Athlon XP Barton 3200+ CPU (core speed 2200 MHz) and 1024 MB RAM running at a Front-Side-Bus of 200 MHz a 16.82 m tall 18 layer profile made up of organic mud is de-compacted within 1.9 seconds with an error in layer thicknesses (sum of errors in Table 2) less then 2 cm. An AMD Orion CPU with 650 MHz core speed and 896 MB RAM at 100 MHz Front-Side-Bus needs for the same task 9.1 seconds. Table 2 gives an overview of user defined accuracy level, the resulting processing time and the reached accuracy (cf. Table 3). The reached accuracy is the sum of all differences within the triangle matrix compared to a triangle matrix calculated with very high accuracy (level of accuracy = 10000000).

Table 2

Processing time in dependence of accuracy and CPU clock speed for AMD-CPUs

Level of accuracy	Sum of errors [m]	Calculation time [s]				
		AMD Athlon		AMD Athlon XP		
		Orion (650 MHz)	Thunderbird (1009 MHz)	mobile Thoroughbred 1400+ (1100 MHz)	Barton 2500+ (1840 MHz)	Barton 3200+ (2200 MHz)
2	4.76E+00	0.065	0.031	0.024	0.017	0.014
4	4.54E+00	0.067	0.032	0.026	0.017	0.015
8	4.46E+00	0.066	0.032	0.026	0.017	0.015
16	3.07E+00	0.067	0.033	0.026	0.017	0.015
32	1.95E+00	0.070	0.035	0.028	0.018	0.015
64	1.04E+00	0.080	0.040	0.032	0.020	0.019
128	5.82E-01	0.107	0.068	0.044	0.027	0.023
256	2.89E-01	0.196	0.109	0.077	0.045	0.040
512	1.46E-01	0.355	0.199	0.157	0.089	0.077
1024	7.78E-02	0.767	0.449	0.338	0.188	0.168
2048	4.36E-02	1.765	1.028	0.750	0.425	0.373
4096	2.67E-02	4.036	2.348	1.755	0.957	0.866
8192	1.84E-02	9.088	5.223	3.870	2.163	1.868
16384	1.43E-02	19.912	11.736	8.722	4.861	4.215
32768	1.22E-02	44.059	26.037	19.223	10.619	9.388
65536	1.12E-02	96.695	57.176	42.195	23.451	20.427
131072	1.07E-02	218.066	125.972	92.878	52.304	45.851
262144	1.05E-02	466.076	274.288	202.666	112.531	99.143

Table 3

Processing time in dependence of accuracy and CPU clock speed for Intel-CPUs

Level of accuracy	Sum of errors [m]	Calculation time [s]					
		Intel Pentium					Intel Celeron
		P4 Northwood 3200 MHz	P4 Northwood 2600 MHz	P4 Willamette 1800 MHz	P3 Coppermine 866 MHz	P3 Coppermine 800 MHz	Mendocino 551 MHz
2	4.76E+00	0.010	0.018	0.047	0.027	0.040	0.043
4	4.54E+00	0.010	0.018	0.032	0.029	0.025	0.044
8	4.46E+00	0.010	0.018	0.032	0.029	0.025	0.044
16	3.07E+00	0.010	0.022	0.032	0.029	0.025	0.045
32	1.95E+00	0.011	0.021	0.034	0.034	0.027	0.051
64	1.04E+00	0.014	0.024	0.041	0.040	0.035	0.066
128	5.82E-01	0.022	0.035	0.060	0.059	0.052	0.101
256	2.89E-01	0.042	0.064	0.103	0.113	0.124	0.205
512	1.46E-01	0.120	0.133	0.209	0.282	0.215	0.448
1024	7.78E-02	0.210	0.300	0.515	0.547	0.501	1.082
2048	4.36E-02	0.483	0.695	1.095	1.298	1.152	2.512
4096	2.67E-02	1.127	1.584	2.469	2.996	2.678	5.696
8192	1.84E-02	2.582	3.587	5.666	6.791	6.047	13.395
16384	1.43E-02	5.729	8.088	12.882	15.284	13.534	31.276
32768	1.22E-02	12.631	17.760	27.952	33.576	29.811	64.072
65536	1.12E-02	28.621	39.326	61.806	74.058	66.097	144.577
131072	1.07E-02	61.339	85.598	135.546	160.816	143.180	310.307
262144	1.05E-02	133.475	185.070	294.191	349.475	311.292	682.850

RESULTS

Model profile. A time-dependent development of an interbedding of sand and organic mud is shown in Figure 3. The layer thicknesses are plotted versus time in this diagram. Every layer has a thickness of 1 m, on the very right side within the diagram, at the present time. The bottom layer of organic mud is most affected by compaction. It lost nearly half of its initial thickness, actually its thickness decreases from 1.97 m to 1 m. Because of reduced extra loads of overlying sediments, shallower layers of organic mud are less affected by compaction. No noticeable compaction occurs within the sand layers. Table 4 shows all de-compaction data for the model profile.

Recknitz valley cross- section. Figure 4 shows a de-compacted cross-section, whereas the recent state is depicted in Figure 5. For the Recknitz valley in the centre of the cross--section ^{14}C datings are available. It is located at the valley of the river "Recknitz" about 2.5 km south east to the city of Ribnitz-Dammgarten near the coast of Mecklenburg-Vorpom mern, Germany. There is a significant compaction visible within the peat 1. The top of this peat layer dropped from

Table 4

De-compaction data for the model profile

Sediment	Surface [m] at time step									
	1	2	3	4	5	6	7	8	9	10
Mud										0
Sand									–0.7	–1
Mud								–1.34	–1.7	–2
Sand							–2.26	–2.62	–2.82	–3
Mud						–2.92	–3.26	–3.62	–3.82	–4
Sand					–4.09	–4.46	–4.61	–4.79	–4.90	–5
Mud				–4.78	–5.09	–5.46	–5.61	–5.80	–5.90	–6
Sand			–6.25	–6.55	–6.64	–6.78	–6.84	–6.91	–6.96	–7
Mud		–7.03	–7.26	–7.55	–7.65	–7.78	–7.84	–7.91	–7.96	–8
Sand	–9	–9.00	–9.00	–9.00	–9.00	–9.00	–9.00	–9.00	–9.00	–9

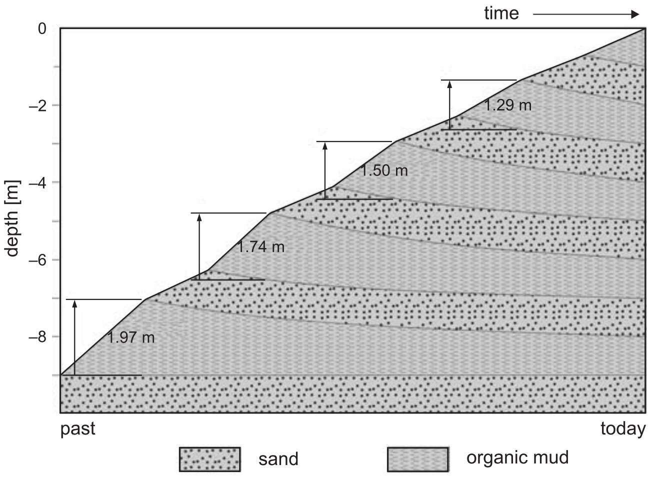

Fig. 3. Time dependent development of an interlayered bedding of sand and organic mud

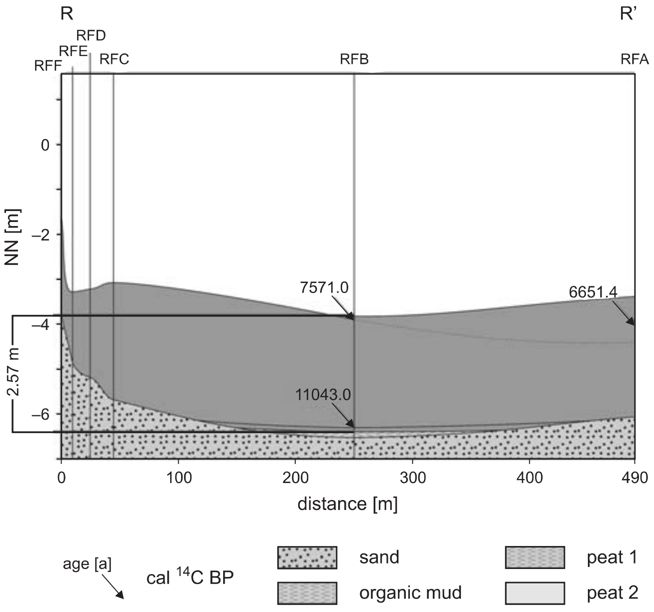

Fig. 4. De-compacted cross-section, after deposition of the peat 1; location: valley of river Recknitz (Germany)

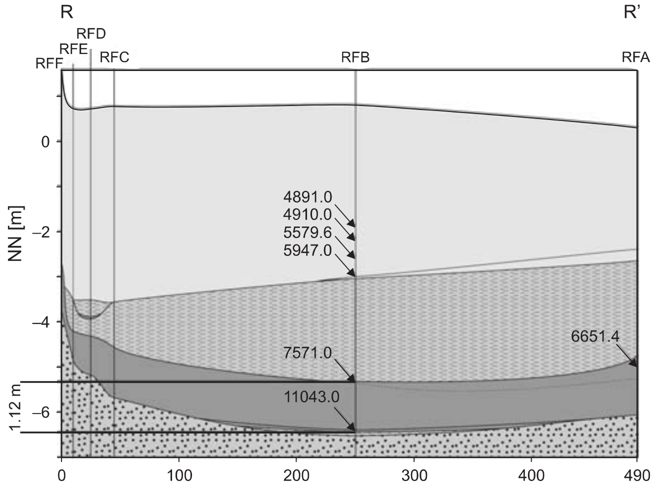

Fig. 5. Present cross-section; location: valley of river Recknitz (Germany)

For explanations see Figure 4

Table 5

De-compaction data for drill site RFB;
location: valley of river Recknitz

Sediment	Surface [m] at time step										
	1	2	3	4	5	6	7	8	9	10	11
Peat											0.80
Peat										–0.55	–1.90
Peat									–0.79	–1.14	–2.20
Peat								–1.16	–1.59	–1.80	–2.60
Peat							–1.61	–2.00	–2.25	–2.40	–3.00
Mud						–1.67	–1.73	–2.09	–2.33	–2.47	–3.05
Peat					–3.83	–4.91	–4.92	–5.02	–5.10	–5.14	–5.33
Peat				–3.87	–3.91	–4.94	–4.96	–5.06	–5.13	–5.17	–5.35
Peat			–6.17	–6.31	–6.31	–6.37	–6.37	–6.37	–6.38	–6.38	–6.40
Mud		–6.34	–6.34	–6.40	–6.40	–6.43	–6.43	–6.44	–6.44	–6.44	–6.45
Sand	–6.55	–6.55	–6.55	–6.55	–6.55	–6.55	–6.55	–6.55	–6.55	–6.55	–6.55

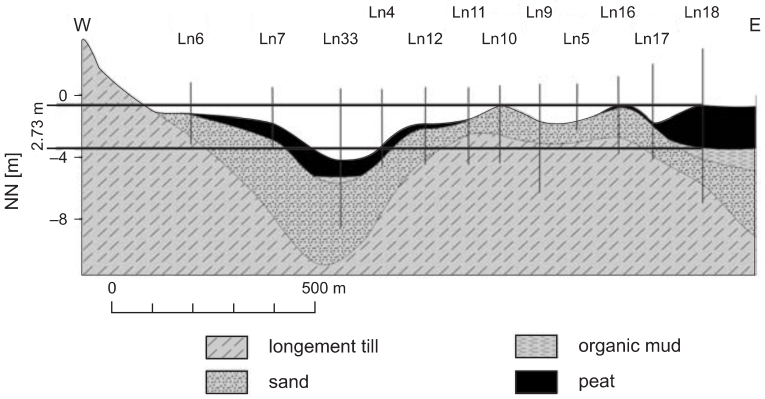

Fig. 6. De-compacted cross-section, after deposition of peat layer; location: Lobber Lake-lowland

3.83 m to 5.33 m below sea level, at drill site RFB. From this layer border a sample was dated by ^{14}C-dating. By assuming that this peat shows the sea level at the dated time, there occurs a difference of 1.5 m between non de-compacted and de-compacted depth for this point in the sea-level curve. As mentioned within the graphics the thickness of peat 1 decreases from 2.57 m to 1.12 m. Table 5 shows all de-compaction data for drill site RFB.

Cross-section Lobber Lake-lowland. Figure 6 shows a de-compacted cross-section which can be compared to the recent state (Fig. 7). The Lobber Lake-lowland cross-section is located at the south-east of the island of Ruegen about 1 km south to the city of Goehren (Germany). The peat is clearly affected by compaction. At drill site LN18, it's thickness decreases from 2.73 m to 1.35 m. Due to compaction of the underlying mud the descent of the peat surface is a bit larger then the difference between non-compacted and compacted peat. The top of the peat layer dropped from 0.68 m to 2.25 m below sea level, at the drill site mentioned above. In nearly the same way as in the Recknitz valley cross-section, the dislocation of the peat surface reaches amounts of 1.57 m.

As visible within the two compared cross-sections, the amount of dislocation is not only a manner of buried depth but also of thickness of the compacted layer. For example the peat thickness at drill site LN12 is about 15 cm at the present state. According to the DeLos software the initial thickness was 30 cm. The relative dislocations at both drill sites, LN18 and LN12, are nearly 50% but in dependence of layer thicknesses the actual dislocation is clearly different. The Tables 6 and 7 give an overview of all de-compaction data of the drillings LN18 and LN12.

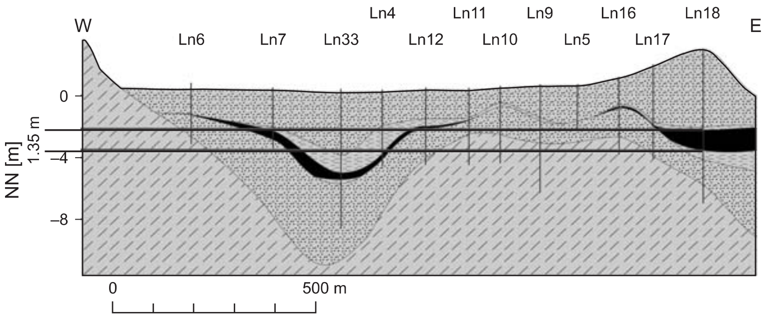

Fig. 7. Present cross-section; location: Lobber Lake-lowland

For explanations see Figure 6

Table 6

De-compaction data for drill site LN12; location: Lobber Lake-lowland

Sediment	Surface [m] at time step				
	1	2	3	4	5
Sand					0.50
Mud				–1.32	–1.55
Peat			–1.85	–1.91	–2.00
Silt		–2.15	–2.15	–2.15	–2.15
Lodgement till	–4.10	–4.10	–4.10	–4.10	–4.10

Table 7

De-compaction data for drill site LN18; location: Lobber Lake-lowland

Sediment	Surface [m] at time step					
	1	2	3	4	5	6
Sand						3.00
Mud					–0.56	–2.10
Peat				–0.68	–0.83	–2.25
Mud			–3.11	–3.32	–3.42	–3.60
Sand		–4.15	–4.15	–4.15	–4.15	–4.15
Lodgement till	–5.80	–5.80	–5.80	–5.80	–5.80	–5.80

DISCUSSION

It may be simplistic to calculate porosity without regard to densities of overlying sediments. But errors at relative sea-level curves could be much greater then those made by neglecting sediment densities, if no de-compaction is applied to dated sediments. Preconditioned that all Holocene sediments are water saturated, their densities range between c. 1.8 g/cm^3 for sand and c. 1 g/cm^3 for peat. While sand is nearly incompactable under mentioned conditions and peat is not compacted due to ascending forces, we can make an assumption that the weight of 1.8 m of peat is the same as 1 m of sand. For an assessment for the difference between the compaction of 4 m mud imagine two models. Within model 1, 1.8 m of peat covers the 4 m thick mud layer. In model 2 the mud is covered by 1 m of sand as substitution for the peat from model 1. In this configuration extra load on the mud should be the same within both models. Figure 8 shows the two models. On the right side (#2) occurs the 4 m thick covered mud and to the left (#1) the de-compacted mud. The difference of de-compacted mud thickness of the two models is 29 cm. The difference of ignoring compaction and consideration of compaction is at least 39 cm. Due to the fact that for this comparison the densest (sand) and the least dense (peat) sediment type from Holocene were chosen, all other combinations should show fewer differences. This shows, that the error of neglecting compaction at all, is greater then the error of neglecting different sediment densities. Nevertheless this work is just the beginning. In its continuation, not only the calculating with respect to sediment densities will be improved. Other improvements on the roadmap for DeLos 2.0 are 2- and 3-dimensional de-compaction algorithms and direct determination of pore space by measuring water content within water saturated sediments. This should lead to a better resembling of sedimentary history at specific drill sites.

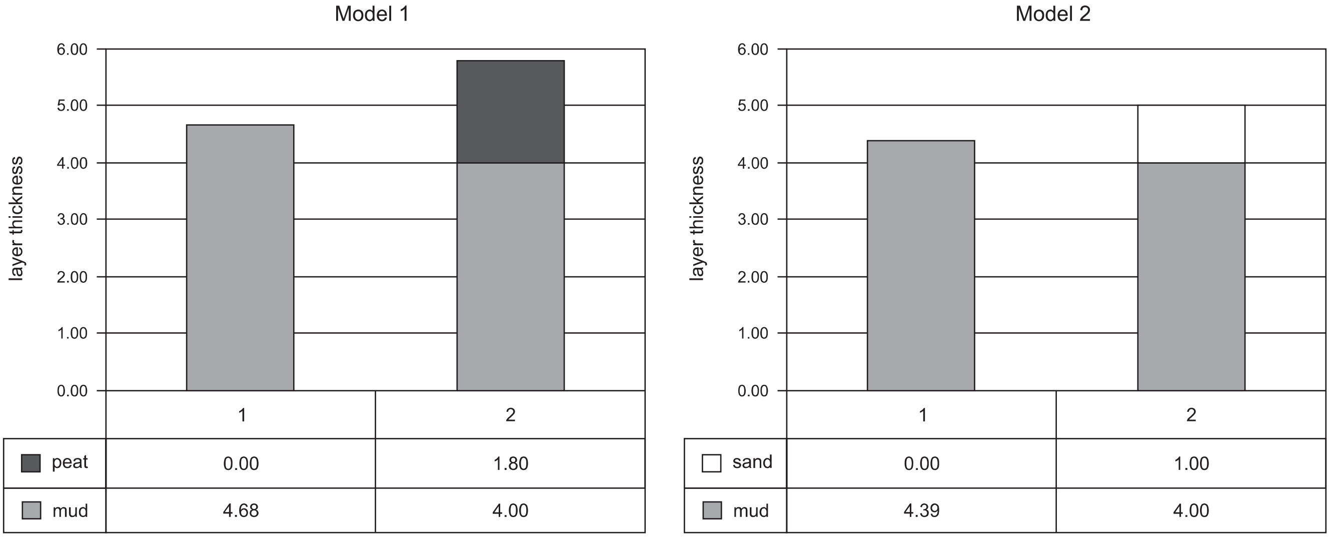

Fig. 8. Comparison of two de-compaction results with different cover sediments but equal extra loads, in consideration of different sediment densities of overlying layer

REFERENCES

ALLEN J.R., 1998 — Geological impacts on coastal wetland landscapes: some general effects of sediment autocompaction in the Holocene of northwest Europe. *The Holocene*. 1999, **9**, 1: 1–12.

BROWN R.H., 1975 — C-14 Age Profiles for Ancient Sediments and Peat Bogs. *Origins*.1975, **2**, 1: 6–18.

DIETRICH H., 1989 — Die Bedeutung von sedimentärer Fazies und Diagenese für die Beckenanalyse. PhD-thesis. Ernst-Moritz--Arndt-Universität Greifswald.

GUSTAVS I., 1992 — Rechnergestützte Inversion und Modellierung des Kompaktionsprozesses von Sedimenten. Thesis. Ernst-Moritz-Arndt-Universität Greifswald.

GUSTAVS I., 1996 — Sedimentological control parameters and compaction - a complex model of porosity distribution in Holocene muds of the Arkona Basin. Computerized Modeling of Sedimentary Systems – Program and Abstracts. international symposium in Güstrow/Germany. 08–11.10.1996. Güstrow/ Germany.

HOFFMANN G., 2004 — Rekonstruktion und Modellierung der Küstenevolution im Bereich der Pommerschen Bucht in Abhängigkeit von holozänen Meeresspiegelschwankungen. PhD-thesis. Ernst-Moritz-Arndt-Universität Greifswald.

HOFFMANN, G., BARNASCH J., 2005 — Late Glacial to Holocene coastal changes of SE Rügen Island (Baltic Sea, NE Germany). *Aquatic Sci. – Res. Across Boundaries*, **67**, 2: 132–141.

LONG A.J., WALLER M.P., STUPPLES P., 2005 — Driving mechanisms of coastal change: Peat compaction and the destruction of late Holocene coastal wetlands. Abstract: 33. Abstract Book – Dunkerque 2005 – A joint INQUA – IGCP 495 Meeting.

MAUZ B., BUNGENSTOCK F., 2005 — Towards a chronology of Holocene sea-level changes: A new approach using optical dating of clastic sediments. Abstract: 38. Abstract Book – Dunkerque 2005 – A joint INQUA – IGCP 495 Meeting.

SPRINGER J., 1993 — De-compaction and Backstripping with Regard to Erosion, Salt Movement, and interlayered bedding. *Computers & Geosciences*. **19**, 8: 1115–1125.

SUCCOW M., JOOSTEN H., 2001 — Landschaftsökologische Moorkunde, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.