Deltaic subsidence due to compaction, isostasy and tectonics: Rates at syn-depositional time-scales (Holocene, Netherlands).

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Stratigraphical architecture and lithological variability of deltaic deposits are principally determined at syn-depositional time-scales. During delta aggradation, the properties of strata (thickness, consistency, depth, geometry) change rapidly, with strong feedbacks on successive sedimentation patterns. Simulation models that generate synthetic architectures operate on this time scale. They need their parameters specified based on field studies in order to realistically simulate deltaic build up and the auto- and allo-stratigraphic patterns therein. For parameters describing the rates of subsidence (whether due to compaction, tectonics or both) it is especially important to have these determined *at appropriate time-steps*. Here we present rates determined over time-steps of 10^2 to 10^3 years, as obtained for flood basins of the Rhine-Meuse delta in the Netherlands. The results come from combining field data and numerical modelling and unique full coverage of a sizable river-fed barrier-lagoon system.

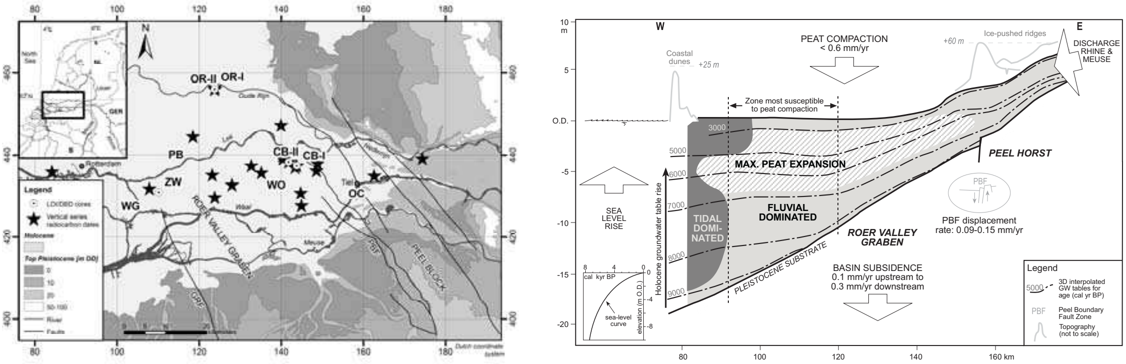

Fig. 1 *Study area location, high resolution accommodation and compaction reconstruction sites, cartoon longitudinal section through the coastal prism. Van Asselen (2010)*

The Rhine and Meuse rivers took the last 9 millennia to build up their joint deltaic wedge (coastal prism; Fig. 1). The overall geometry of the wedge can be understood in terms of external controls (sea-level rise, sediment supply), antecedent topography (buried valley slope, surrounding Pleistocene uplands) and tectonic setting (subsidence rates increasing downstream). On the inland side of the coastal plain, delta distributaries filled peaty lagoon accommodation space. On the seaward side, freshwater fluvio-tidal and lagoon environments alternated with brackish tidal inlet, mud flat and estuary environments. See the contribution of Stouthamer et al. (this conference) for an overview of delta evolution and alluvial architecture. Mapping and dating have documented the lithogenetic diversity and internal chronostratigraphy of the deltaic wedge in high detail, amongst others to allow the area to serve as an analogue for ancient reservoirs and a target case for simulation-modelling. To grow architectures in numerical models not only requires functions describing ‘sediment delivery’, ‘water level in the receiving basin’ and ‘sediment routing between apex and mouth’, but also requires functions describing subsidence variability in the deltaic area.

Subsidence sources, quantification: methods, materials, resulting rates

Subsidence in a delta comes from two principal sources: (1) compaction of fresh deltaic deposits (‘autocompaction’, ‘syn-sedimentary compaction’; e.g. Van Asselen et al., 2009) and (2) lowering of the delta substrate due to tectonics, isostasy and compaction of deeply buried deposits (e.g. Kooi et al., 1998). In the Rhine-Meuse delta, the vicinity to Scandinavian ice caps and the emerging/inundating southern North Sea add important glacio- and hydro-isostatic components to the latter source. Crevassing and avulsion cause locally different sediment-loading and floodbasin-filling histories and hence affect the degree of compaction that is regionally reached. Regional differences in compaction appear associated to the land-inward limit of tidal influence.

In the Rhine-Meuse delta, Holocene subsidence due to peat compaction is quantified at centennial to millennial timescales. Shorter time scales are not possible because of resolution limits of the ^{14}C dating method. The hind casting of compaction with our numerical models uses observations from the Cumberland Marshes (Canada), an inland-delta case of avulsion splay formation that is monitored over the last 135 years (river clastics burying peat). This allowed quantification on decadal to centennial scales needed to bridge the gap between reconstruction and modelling approaches (Van Asselen et al. 2009).

Compaction rates of up to 0.62 mm/yr, averaged over millennia, are measured in the delta. Higher rates of a few mm/yr occur over decades to centuries, shortly after loading. Averaged over millennia (~4000 - ~6000 years). Subsidence rates measured in the Cumberland Marshes: up to ~6 mm/yr. Averaged over ~135 years. Forward compaction modelling predicts compaction to occur most rapidly in the first decades after loading a peat sequence. Simulations for ranges of natural conditions yield subsidence rates successfully reproduce the above values, and predict values of up to 15 mm/yr (averaged over 50 years = time step in model) in 8-m-thick high-organic peat (LOI=0.8) in the most compaction prone areas of the fluvial delta. Absolute values of up to ~3 m subsidence are calculated for a 10-m-thick Holocene succession (Van Asselen, 2010; see also Fig. 2).

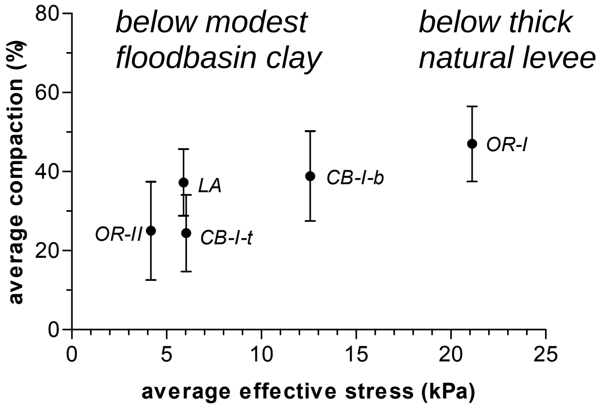

Fig. 2 Typical present compaction values of 6000-3000 yr old peats

Subsidence due to substrate lowering is quantified from groundwaterrise reconstructions. Similar to relative sea-level rise reconstructions, dates of begin of peat formation overlying pre-deltaic sandy strata (notably vertical series of dates collected along the flanks of isolated inland dunes; Fig. 3) provide index-points for past groundwater table rise. Many sites with vertical series of index-points exist, sufficient for geostatistical interpolation (3D universal block kriging; Cohen, 2005). The interpolation shows anomalies that match known neotectonic depocentre and faultzones. The depocentre (40 km^2 sank 0.05-0.10 mm/yr faster than downstream parts, and 0.10-0.15 mm/yr faster than upstream blocks, measured for the period 9000-3000 yr BP.

Interpolated stacks of palaeo-groundwater tables are used to break down accommodation into components ‘due to absolute sea level rise and regional tectonic dip’, ‘due to local subsidence’. It also identifies ‘overfilling of accommodation space’ as occurs in the upper part of a delta that aggrades and protrudes under increased sediment supply in the last 3000 years. Subsidence rates were higher in the period 20,000-6,000 than in the last 6000 yrs, in agreement with isostacy geophysical predictions, Scandinavian deglaciation and North Sea transgression history (e.g. Busschers et al., 2007; Hijma & Cohen, 2010).

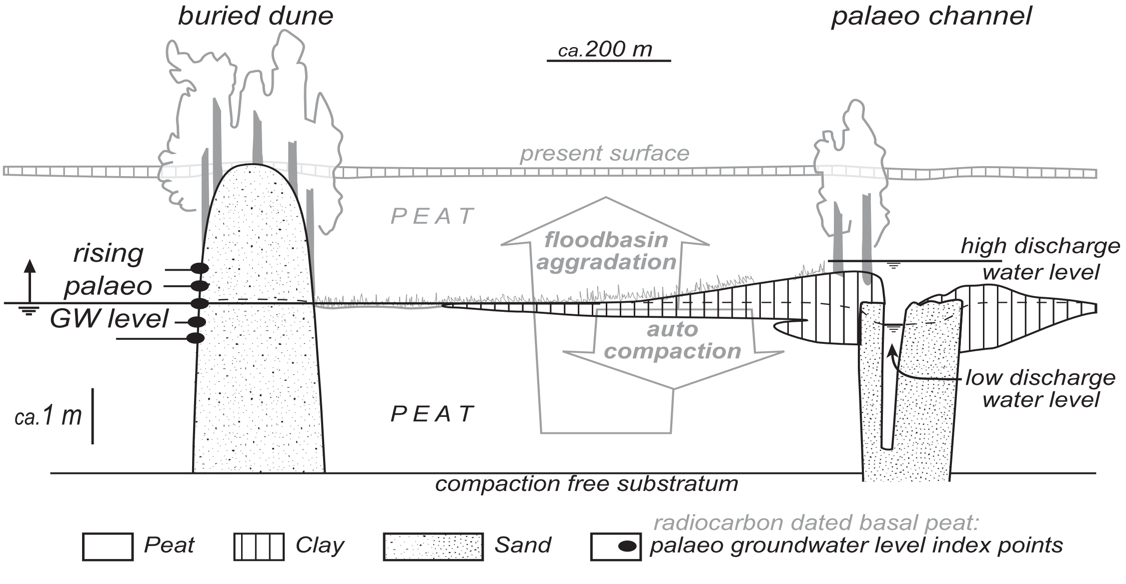

Fig. 3 Interrelations between compaction, the creation of accommodation space, groundwater rise reconstruction and fluvial sedimentation in the study area (Cohen, 2005)

Regional differences in compaction of basal strata: a role for tides?

A marked difference exist between the state of compaction of the basal peats in the west of the delta (preserved under freshwater tidal-fluvial and brackish tidal-lagoon clastics, e.g. Hijma & Cohen, 2010) and more inland basal peats buried under lagoonal and fluvial deposits (e.g. Cohen, 2005). There is a contrast in state of compaction and not a gradual transition. This suggests that it is not just differences in mean age and thickness of overlying Holocene sequence that determine the degree of compaction of basal organic strata. The tidal ranges in the lagoon varied in space and altered in time, especially in the first millennia following transgression of the basal peat. In contrast, in the inland fluvialdominated part of the delta floodbasins were flooded occasionally only and averaged over the year experienced rather stable water levels that steadily rose due to sea-level rise at the river mouth and lowering of the substrate. From geomechanical theory and numerical modelling it follows that greater natural water level variations cause higher sedimentation rates and stronger syn-sedimentary compaction.

Compaction: creating or recreating accommodation space

There are two ways to look at accommodation space on syn-depositional time-scales. Depending on the view point, compaction contributes to accommodation space creation or compaction allows storing sediments in earlier-created accommodation space. This difference is trivial when repeated delta formation over hundred thousands to millions of years is considered and one deltaic wedge with all its internal autocompaction completed marks a single time-step. It is not trivial when modelling internal alluvial architecture of deltaic wedges at time-steps of 50, 100 or 1000 years. Either way, the quantifications of 'compaction subsidence' and 'substrate-lowering subsidence' can be compared to the total amount of accommodation space created and filled during the transgression and high stand forming modern deltas such as the Rhine delta.

In the Rhine-Meuse backbarrier delta, subsidence due to peat compaction has (re)created 40% of the available Holocene accommodation space for aggradation (Van Asselen, 2010). At the present river mouth, substrate subsidence in the last 9000 years has created at least 3 meters (12.5%) of 24 meters of total vertical accommodation (22%). In the inland part of the delta (neotectonic depocentre), 20% (1 meter) of total vertical accommodation is due to substrate subsidence (last 7000 years) and the remainder due to sea-level rise at the river mouth and the backwater effect that this has in the floodbasins and channels (Cohen, 2005).

The most important implications of accommodation space (re)created by compaction and local subsidence centres are: (1) at system scale: increases sediment trapping efficiency in deltas, stalling progradation and thickening clastic overbank facies units, (2) at a local scale: where and while crevassing occurs and avulsions initiate, thickened natural levees and crevasse splay deposits with feedback on avulsion potential, (3) at the scale of regions within the delta: control on channel belt width/thickness and dominant direction, echoing through in alluvial architecture parameterizations (net-to-gross, connectedness).

Selected references

Busschers, F.S et al. (2007) Late Pleistocene evolution of the Rhine in the southern North-Sea Basin: imprints of climate change, sea-level oscillations and glacio-isostacy. Quat. Sc. Rev.26, 3216-3248

Cohen, K.M. (2005) 3D Geostatistical interpolation and geological interpretation of paleo–groundwater rise in the Holocene coastal prism in the Netherlands. Ch. 14 in River Deltas—Concepts, Models, and Examples. SEPM spec. publication 83, 341-364.

Hijma, M.P. & Cohen, K.M. (2010) Timing and magnitude of the sea-level jump preluding the 8200 yr event. Geology, 38, 275-278.

Kooi, H., et al. (1998), Geological causes of recent (~100 yr) vertical land movement in the Netherlands. Tectonophysics 299, pp. 297-316.

Van Asselen, S. (2010) Peat compaction in deltas. Implications for Holocene delta evolution. Published PhD thesis Utrecht University (pending defense, 16 june 2010). Netherlands Geographical Studies XXX.

Van Asselen, S., et al. (2009). Effects of peat compaction on delta evolution: a review on processes, responses, measuring and modeling. Earth Science Reviews 92, 35–51.