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

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Why time scales matter and what we offer...

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. Subsidence comes from two principal sources: compaction of fresh deposits (‘autocompaction’, syn-sedimentary compaction) and (2) substrate lowering due to tectonics, isostasy and compaction of deeply buried deposits. 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, that match time-scales at which creation of accommodation space is considered.

We determined rates over time-steps of 102 to 103 years, for flood basins of the Rhine-Meuse delta in the Netherlands. These results come from combining field data and numerical modelling, facilitated by unique datasets that fully cover the sizable river-fed barrier-lagoon system that is the Rhine-Meuse delta in the Netherlands. The poster presents the outcomes and the implications for accommodation space.

Subsidence due to strain accommodation is quantified from groundwater rise 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 (figs. above) 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). The interpolation shows anomalies that match known neotectonic depocentre and faultzones. The depocentre (40 km²) 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 9000-3300 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 isostatical geophysical predictions, Scandinavian deglaciation and North Sea transgression history.

Crevassing and avulsion cause sediment-loading and floodbasin-filling histories to differ per location and affect the degree of compaction in delta subregions. The effect of autocompaction, i.e. compaction due to loading of peaty strata, is quantified at 15 sites in the central delta. We compared actual depth of peats of known age with the palaeo-groundwater table heights at their time of formation (figs. above). Data on bulk-density, peat composition and organic matter content was also gathered, and used to hindcast compaction at the 15 sites. These two methods reproduced each other and resolve compaction-driven subsidence at centennial to millennial timescales. Shorter timescales are not possible because of resolution limits of the 13C-dating method.

To bridge the gap between reconstruction and modelling approaches, additional measurement and quantification of natural load-induced peat compaction on decadal to centennial scales was needed. Such data was collected in the Cumberland Marshes (Canada), an inland-delta that developed over the last 135 years, where river clastics buried peats of similar composition as in the Rhine delta in the Middle Holocene. Parameters calibrated on Canadian peats were used to simulate local natural compaction histories for synthetic delta successions.
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SAMPLING FRESH PEAT
Cumberland marshes, Canada

ACCOMMODATION AND SYN-SEDIMENTARY TIME

There are two ways to look at accommodation space on syn-depositional time-scales. Depending on the viewpoint, compaction contributes to accommodation space creation or compaction allows storing sediments in earlier-created accommodation space (e.g. figure below). This difference is not trivial when modelling internal alluvial architecture of deltaic wedges at time-steps of 50, 100 or 1000 years. It is insightful to intercompare quantifications of ‘compaction subsidence’ and ‘substrate-lowering subsidence’ with the total amount of 1000 years. It is insightful to intercompare quantifications of ‘compaction subsidence’ and ‘substrate-lowering subsidence’ with the total amount of accommodation space created and filled during Holocene transgression and high stand, i.e. the not-eustasy-driven part of delta accommodation.

Subsidence due to peat compaction has locally (re)created up to 40% of the Rhine delta’s accommodation space, in inner parts of the delta. In transgressive tidal floodbasin areas this may have been even more (more work needed!). Substrate subsidence in the last 9000 years has created at least 3 meters (12.5%) of a total 5 meters in the last 7000 years over the inland tectonic depocentre.

Autocompacted floodbasin sites in the Rhine delta show peat surfaces to have locally lowered up to ~3 meters within 10-m-thick successions. The associated compaction rates were up to 0.62 mm/yr, averaged over multiple millennia (figs. above). Higher rates of a few mm/yr occurred over decades to centuries, shortly after loading. Subsidence rates measured in the Cumberland Marshes: up to ~6 mm/yr, averaged over ~135 years.

Forward modelling predicts compaction to occur most rapidly in the first decades after loading a peat sequence. Simulations for ranges of natural conditions yield rates up to 15 mm/yr (averaged over 50 years = time step in model) in 8-m-thick high-organic peat (LOI=0.8), representative for the most compaction prone areas in the delta.

COMPACATION MODELLING: BACKWARD, FORWARD

Field data
Synthetic Sequence

Auto compacted floodbasin sites in the Rhine delta show peat surfaces to have locally lowered up to ~3 meters within 10-m-thick successions. The associated compaction rates were up to 0.62 mm/yr, averaged over multiple millennia (figs. above). Higher rates of a few mm/yr occurred over decades to centuries, shortly after loading. Subsidence rates measured in the Cumberland Marshes: up to ~6 mm/yr, averaged over ~135 years.

Forward 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 that successfully reproduce field observations. They predict rates up to 15 mm/yr (averaged over 50 years = time step in model) in 8-m-thick high-organic peat (LOI=0.8), representative for the most compactation prone areas in the delta.

