Curr Clim Change Rep
DOI 10.1007/s40641-016-0038-6

Past, Present and Future Perspectives of Sediment Compaction as a Driver of Relative Sea Level and Coastal Change

Matthew J. Brain [1]

Abstract Compaction describes a range of natural syn- and post-depositional processes that reduce the volume of sediments deposited in low-lying coastal areas, causing land-level lowering and a distortion of stratigraphic sequences. Compaction affects our reconstructions and understanding of historic sea levels, influences how relative sea level changes in the future and can act as a catalyst for rapid, widespread changes in coastal geomorphology. Rates of compaction-induced relative sea-level rise vary across space and through time in response to a range of natural and anthropogenically accelerated processes and conditions. This paper provides a summary of our understanding of the causes and effects of compaction, considering findings from key palaeoenvironmental and stratigraphic studies, sea-level reconstructions and recent observational data. It then considers the implications of these findings for our ability to project compaction-induced relative sea-level and associated coastal changes into the future.

Keywords Compaction · Subsidence · Relative sea level · Coastal change

Introduction

Sea-level rise is arguably the most damaging and disruptive effect of climate change, with potentially widespread and significant impacts on coastal populations, infrastructure, landforms and ecosystems [1–7]. To plan for and mitigate these adverse effects, assessing and projecting future sea-level rise as accurately as possible is a key scientific goal [8–13]. This requires a thorough understanding of the many drivers of sea-level change through space and time. The relationship between global climatic, hydrologic, cryospheric and oceanographic processes and sea level is increasingly well constrained, as are regional deviations in sea level from the global mean (see recent reviews by Clark et al. [12], Dutton et al. [14], Kemp et al. [15], Khan et al. [16], Kopp et al. [17], Leuliette [18] and references therein). Global to regional sea levels are modified by vertical land-level changes, driving relative sea-level changes (here, defined simply as changes in the difference in elevation between land level and sea level; see Shennan [19] for further information and critique of definitions of relative sea level (RSL)) at a particular location and time. Regional land-level changes can result from glacio-, sedimentary- and hydro-isostatic adjustment [20–23] and tectonic processes [24, 25]. The focus of this review paper is on sediment compaction [26, 27•, 28, 29] which, in addition to changes in sediment supply [30–33], can result in land-level changes at the local scale.

Compaction describes a range of natural syn- and post-depositional processes that reduce the volume of sediments deposited in low-lying coastal areas [34, 35], causing land-level lowering (i.e. subsidence) [28]. This can occur as a result of stress- and time-dependent mechanical compression processes that reduce pore space and increase bulk density [36]. Compression processes include consolidation, which describes the expulsion of pore water from sediment interstices in response to burial by overburden sediments [37] or from self-weight [28] and creep, which describes ongoing viscous rearrangement of sediment particles [38••]. Predominantly organic sediments and peat deposits can also undergo florally

This article is part of the Topical Collection on *Sea Level Projections*

✉ Matthew J. Brain
matthew.brain@durham.ac.uk

[1] Department of Geography and Institute of Hazard Risk and Resilience, Durham University, South Road, Durham DH1 3LE, UK

and faunally mediated biochemical degradation, which can increase mass loss and can change the compressive strength of sediments [34, 39–42]. Compaction operates at various depths below ground level, and so a distinction is often made between near-surface (depths of ≤10 m or so below ground level) 'shallow subsidence' [43], typically occurring in deposits of Holocene age [44••, 45••, 46•] and deeper sediment compaction in pre-Holocene sediments [9, 47–49]. Compaction can be accelerated by anthropogenic activity [26, 50, 51], notably through land drainage [52–54] and exploitation of aquifers and hydrocarbon reserves [55, 56].

The contribution of sediment compaction to RSL rise is potentially highly significant at the local scale [38••, 44••], with some studies suggesting that compaction-induced subsidence can be equal to or greater than recent, current and projected rates of global sea-level rise [13, 57]. As such, there is a clear need to incorporate estimates of rates of compaction-driven land-level lowering into societally relevant and appropriate regional to local projections of RSL change to inform risk-management strategies [58, 59]. However, sediment compaction does not solely influence how RSL and coastlines may change in the future. It can also fundamentally affect the accuracy of reconstructions of historic sea level changes [35, 46•] which are crucial to our understanding of the controls on sea level and how these changed in the past; provide longer term context to current rates and patterns of sea-level change; and allow us to better constrain those that may occur in future [8, 14, 15, 60–63].

Past

Stratigraphic and Palaeoenvironmental Studies

Coastal stratigraphies and the palaeoenvironmental records contained within can be exploited to assess the magnitude and rate of compaction-induced subsidence over centennial to millennial timescales. In addition, coastal sedimentary archives can be used to obtain a broad understanding of the controls on compaction and some of the key effects on coastal landscapes.

Compaction has been widely observed to distort Holocene coastal stratigraphies [34, 64, 65]. Törnqvist et al. [44••], for example, presented a stratigraphic cross section obtained along a sediment coring transect extending approximately 5 km normal to the Bayou Lafourche, Paincourtville, Louisiana, USA (Fig. 1). They documented the >2-m differences in elevation of a near isochronous (c. 1400 cal BP) peat layer which would have been effectively horizontal and uniform in elevation, covering extensive low-gradient coastal plains, at the time of formation. Subsequent deposition of thick (up to several metres), clastic overburden strata and differential compaction of underlying deposits distorted the peat stratum. Comparison of the in situ elevations of these intercalated samples with a reconstruction of the depositional altitude of the peat layer provided an estimate of the magnitude by which the peat layer has been lowered. This approach employs isochronous basal samples, which are situated directly on an incompressible surface and, hence, are unable to be lowered through compaction of underlying sediment. Törnqvist et al. [44••] noted post-depositional lowering (PDL) [46•] of the peat layer reached c. 6 m in some locations. In conjunction with the age of formation of the peat layer, Törnqvist et al. [44••] calculated averaged rates of compaction-induced subsidence of up to 5 mm year^{-1}. They also suggested that compaction could create land level lowering rates of up to 10 mm year^{-1} over shorter timescales, given the non-linear decline in the rate of compaction-induced lowering through time [38••].

Long et al. [45••] reported differences of up to c. 5.5 m in the elevation of the upper surface of a peat bed along a coring transect in the area surrounding Rye, East Sussex, Southeast England. They attributed these differences in elevation largely to the effects of differential sediment compaction. Palaeoenvironmental, chronological and sedimentological analysis of core sediments collected at West Winchelsea suggested that approximately 4.8 m of minerogenic sediment accumulated between c.1186 and 1460 CE, resulting from land-level lowering at an average rate of c. 18 mm year^{-1}. Long et al. [45] attributed this to a geomorphic response to coastal barrier breaching, which increased water depths and tidal energy, and caused loading of the peat layer by infilling of newly available accommodation space by minerogenic sediment. Enhanced drainage and consolidation of the peat layer were likely to have been caused by headward erosion of tidal creeks in response to the increase in tidal prism and energy conditions. In turn, the peat experienced rapid compaction, causing local RSL rise. This caused further positive feedback, notably in terms of further deposition of dense minerogenic overburden sediments and consequent rapid changes to the coastal landscape.

Relative Sea-Level Studies

Compaction-induced stratigraphic distortion of coastal sediment successions has an important secondary effect on the proxy reconstructions of RSL recorded therein. The requisite sea-level index points (SLIs) provide an estimate of position of RSL both in space and in time [19]. Compilations of SLIs permit construction of age–altitude plots to assess changes in RSL through time. Compaction-induced PDL of SLIs obtained from coastal sediment deposits lowers SLIs from their depositional altitudes [28]. Where sediments record a rising RSL trend, PDL of SLIs results in an overestimation of the magnitude and rate of RSL rise [35, 66, 67] (Fig. 2). In contrast, if sediments record falling RSL, compaction-induced lowering

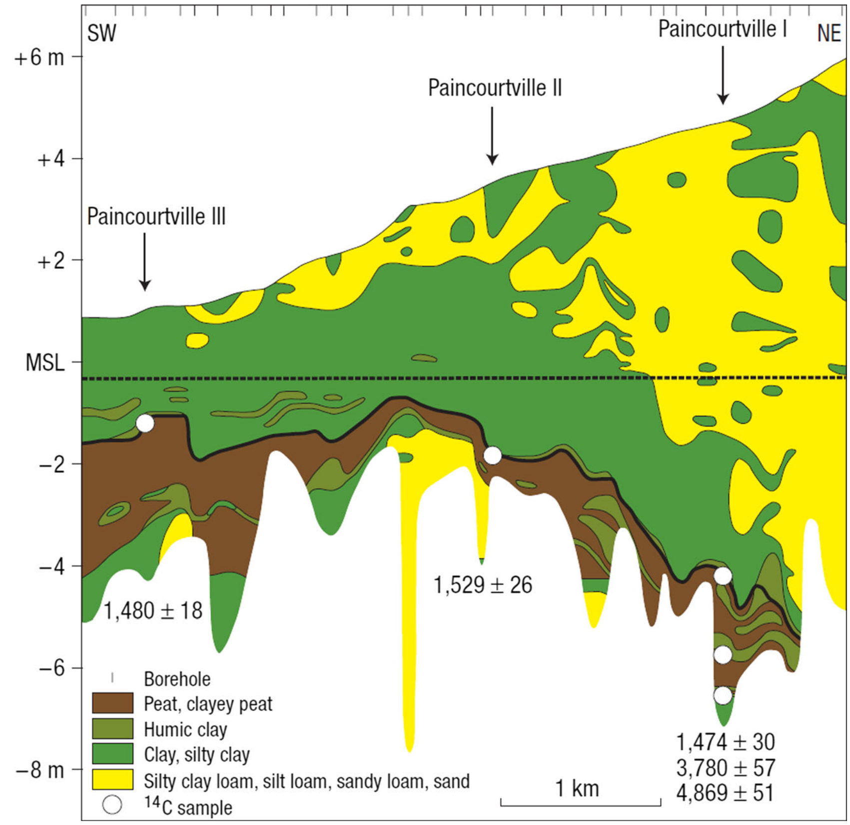

Fig. 1 Stratigraphic cross-section normal to Bayou Lafourche near Paincourtville, LA, USA, displaying distortion of an initially horizontal peat surface of uniform elevation. The *thick-dashed horizontal line* indicates the reconstructed initial elevation of the peat/swamp surface. The *thick solid line* indicates its position following compaction-induced lowering. Ages are in conventional radiocarbon years BP. MSL = contemporary mean sea level. For further details, view the original publication (ref. [44••]). Reprinted by permission from Macmillan Publishers Ltd: Nature Geoscience ([44••]; © 2008)

of SLIs causes an underestimate of the magnitude and rate of reconstructed RSL changes [35, 67] (Fig. 2).

Horton and Shennan [66] compiled a database of SLIs obtained from the Holocene coastal sediments of the eastern English coastline. They noted the considerable scatter in SLIs observed in regional sea-level curves of age against altitude. To assess the extent to which this scatter could be explained by sediment compaction and to estimate magnitudes and average rates thereof, Horton and Shennan [66] used a combination of basal SLIs and glacio-isostatic adjustment model results [68] to develop regionally specific compaction-free RSL records for the late Holocene. They noted that intercalated SLIs are located at elevations lower than their isochronous basal equivalents due to compaction-induced PDL. By considering the differences in elevation (i.e. the residuals) between compaction-prone (non-basal, intercalated) SLIs from and the modelled RSL curve, Horton and Shennan [66] calculated rates of calculated millennially averaged compaction-induced subsidence rates of 0.4 ± 0.3 mm year^{-1}. They noted considerable spatial variation between regions, notably in relation to macro-scale coastal geomorphology. For example, in the larger Humber Estuary, Horton and Shennan [66] found compaction-induced PDL rates of 0.6 ± 0.3 mm year^{-1}.

To study regional differences in compaction-controlled RSL changes further, Horton and Shennan [66] plotted the elevation residuals against three key stratigraphic variables: (1) the thickness of the sediment overlying each SLI; (2) the thickness of sediment beneath each SLI and the underlying incompressible basement; and (3) the full thickness of the Holocene sediment in which the SLI is situated. The results suggest that the magnitude of compaction-induced lowering of SLIs is generally positively related to the thickness of overlying sediment and the overall thickness of the sediment column but negatively related to the depth to the incompressible pre-Holocene basement (Fig. 3). However, the relationship between the thickness of sediment beneath each SLI and the underlying incompressible basement is often more variable and not statistically significant [27•] (Fig. 3). Greater thicknesses of overburden create greater compressive stresses, reducing the thickness of underlying strata, though samples located near to the base of a stratigraphic column experience a lower magnitude of PDL as the potential for cumulative compression of underlying sediments is limited. Edwards [65], Törnqvist et al. [44••] and Horton et al. [27•] not only reported similar results but also noted that the magnitudes and rates of compaction processes are functions of the lithology of overburden sediments and, hence, the specific nature and sequence of the stratigraphy at any location. Indeed, the effects of compaction have been observed to be greater in stratigraphic successions where denser minerogenic sediments are deposited on top of lower density and greater compressibility organogenic deposits [44••, 45••, 69].

Horton and Shennan [66] determined that the inclusion of non-basal samples when calculating late Holocene rates of

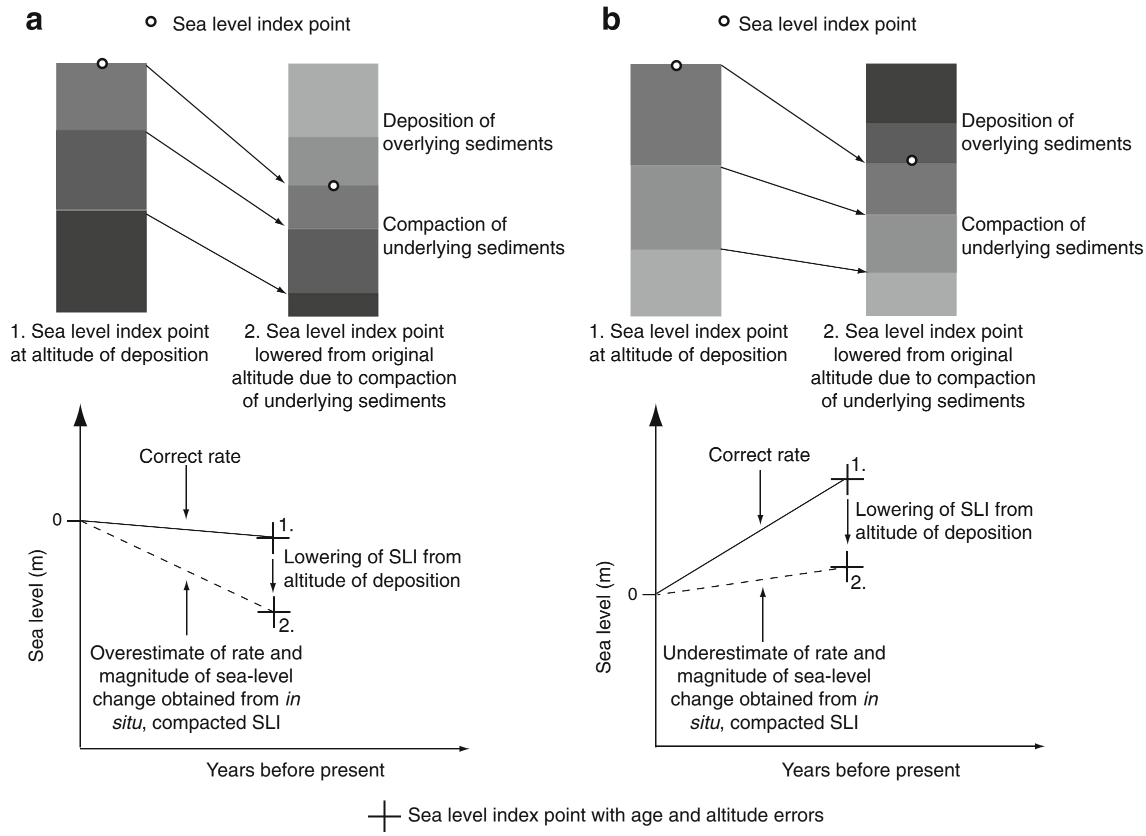

Fig. 2 Schematic depiction of the effects of sediment compaction on sea-level index points within low-energy intertidal stratigraphic successions and the subsequent effects on age-altitude reconstructions of sea level in **a** 'transgressive' (deepening upwards) and **b** 'regressive' (shallowing upwards) successions. Scales in **a** and **b** are indicative and are not directly comparable. Source: Brain (ref. [35]; In: Shennan, I., Long, A.J. and Horton, B.P. (eds), *Handbook of Sea-Level Research*). © 2015 Wiley, Ltd., reproduced with permission

RSL rise causes an overestimation of up to 0.4 mm year^{-1}. This is important because late Holocene rates of RSL change can provide an indication of directions, rates and patterns of land-level changes resulting from glacio-isostatic adjustment (GIA), assuming no or minimal meltwater inputs (see references in Engelhart et al. [70]). For this reason, regional compilations of SLIs favour the use of basal deposits to minimise the contribution of sediment compaction to reconstructed RSL

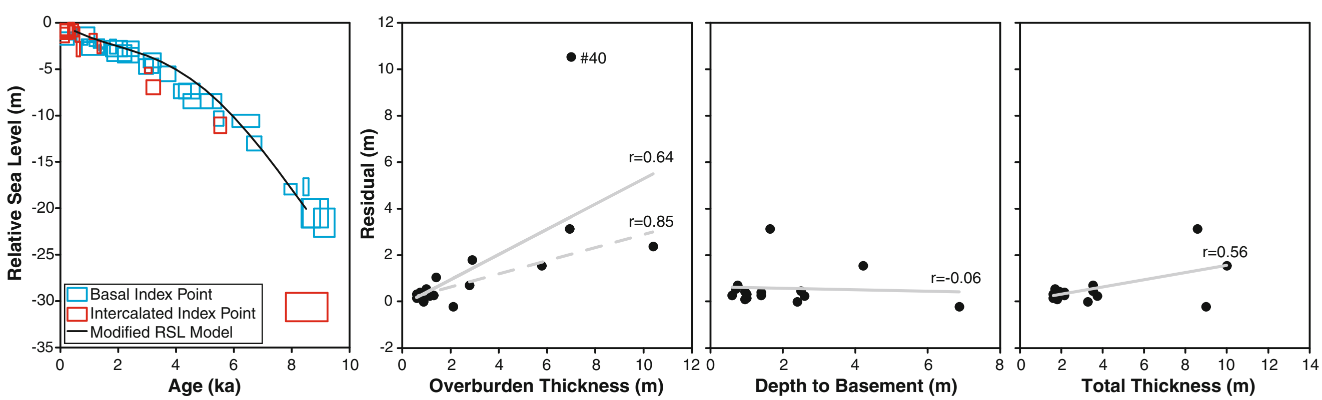

Fig. 3 From *left* to *right*: Holocene sea-level index points and modelled relative sea-level curve for New Jersey, USA. Sea-level index points are classed as either compaction-free basal samples or compaction-prone intercalated samples; overburden, depth to basement and total thickness of sediment versus residual for intercalated index points. 'Residual' is the difference between the fitted RSL curve and the centre point of each intercalated index point. In the second left graph (residual vs. overburden thickness), index point #40 formed at c. 8.5 ka and is located 10 m below same age basal index points. The solid regression line (where $r = 0.64$) includes index point #40; the *dashed* regression line (where $r = 0.85$) excludes it. This removal is justified by Horton et al. [27•] on the basis of significant anthropogenic disturbance at the site. Source: Horton et al. [27•]. © 2013 Wiley, Ltd., reproduced with permission

change and in determining background rates of GIA-controlled RSL [70–72]. Similarly, the use of compaction-free basal SLIs is preferable when reconstructing RSL over multi-decadal to centennial timescales, where greater temporal resolution is required to permit comparison with climatic, oceanographic and cryospheric datasets [8, 61, 73]. However, basal peats are not ubiquitous through time and space [71] and very few studies have used them to assess sub-millennial variability in RSL [60, 74].

Where basal peats are not present or suitable at a particular location, geotechnical modelling provides a means of correcting post-depositionally lowered SLIs for the effects of compaction [37, 39, 75, 76]. This approach is based on theories and models developed in geotechnical engineering and soil mechanics that have subsequently been refined to suit the specific geotechnical properties of intertidal sediments that result from the unique lithologies and hydrogeological and early-stage diagenetic conditions encountered in intertidal settings [36, 46•]. Geotechnical modelling requires considerable empirical input to quantify the strength properties of the contemporary and core sediments of interest but permits samples at all depths within a single core of sediment to be 'decompacted' and returned to their depositional altitude, even in the absence of basal SLIs [35]. Such models are able to accurately reproduce the depth-specific values of bulk density measured in sediment cores [35, 67••] and replicate the broad patterns of compaction effects seen in stratigraphic field investigations noted above, such as greater contributions of compaction to PDL in deeper, transgressive sequences [46•].

Recently, geotechnical modelling studies have better constrained the influence of compaction on reconstructed RSL over the last 200 or so year, during which global sea-level rise accelerated in response to increases in global temperature [8, 77]. Reconstructions of absolute sea level from salt-marsh deposits in the northern [60, 61, 73, 74, 78–83] and southern [63, 84] hemispheres have revealed an inflection that varies spatially in terms of the timing, abruptness and magnitude of acceleration [77]. Brain et al. [46•] numerically demonstrated that compaction can contribute up to 0.4 mm year^{-1} of local sea-level rise to reconstructions of RSL obtained from salt-marsh sediments in successions ≤3-m thick. As such, they demonstrated that the order-of-magnitude increases in the rate of sea level recorded in salt-marsh sediments resulted from increases in absolute sea level, and cannot be explained solely as an increase in local RSL resulting from sediment compaction [85]. However, spatial differences in compaction-driven PDL are of the same order of magnitude and range as those resulting from other processes that control RSL [10, 86–89]. Therefore, if not corrected for, compaction could influence our interpretations of the processes causing spatial variability in RSL. To this end, further geotechnical modelling is required at a greater range of sites to ascertain spatial variability in compaction-induced subsidence.

Brain et al. [67••] applied the geotechnical modelling approach to a core of salt-marsh sediment from North Carolina, USA, to determine the degree to which it has been affected by compaction-induced PDL. The North Carolina sea-level record has been used as a pseudo-global sea-level reconstruction and has been used to calibrate semi-empirical models of climate-related sea-level variability and project future global sea-level changes in response to temperature changes [61]. If the observed historical relationship between global temperature and sea level is incorrect as a result of PDL effects in the North Carolina record, future projections of climate-controlled sea level would overestimate the rate and magnitude of future sea-level rise. Brain et al. [67••] determined that the key features of the North Carolina sea-level record were not an artefact of sediment compaction, though minor PDL of up to 2.5 cm was observed in the core (Fig. 4). This finding improves confidence in the relationship between modelled global sea level and temperature and, hence, future projections of sea-level rise [10, 11].

Present

Present-day observations of rates of compaction-induced subsidence in coastal environments have been made at a variety of scales [55, 90•, 91, 92, 93]. Cahoon et al. [43], for example, reported point measurements of subsidence resulting from compaction of near-surface salt-marsh stratigraphies in Louisiana, Florida and North Carolina, Southeastern, USA. Over a 2-year monitoring period, Cahoon et al. [43] recorded shallow subsidence of 0.45 to 4.50 cm, equivalent to annually averaged rates of 2.3 to 22.5 mm year^{-1}. Anthropogenic activity can accelerate compaction and associated subsidence significantly, as was documented during the drainage of Whittlesey Mere which, prior to drainage, was a 400–500 ha, c. 1-m deep lake [54] in the East Anglian Fenlands, UK. Drainage of the Mere and groundwater table lowering caused consolidation and wastage of an extensive peat layer, resulting in subsidence of 3.91 m over c. 128 years (1850–1978 CE), equivalent to an average rate of 30.5 mm year^{-1} [54]. Maximum subsidence rates during the early stages of drainage were observed to reach 220 mm year^{-1} [54], demonstrating the potential significance of compaction processes in driving RSL changes.

Point estimates cannot, however, provide sufficient spatial coverage to appropriately constrain variability in subsidence-induced compaction over coastal landscapes, particularly the widespread subsidence observed over large river delta systems [51]. To this end, remote sensing techniques, notably Interferometric Synthetic Aperture Radar (InSAR), can be used to accurately and precisely (i.e. with millimetre scale resolution) measure vertical changes in land level through

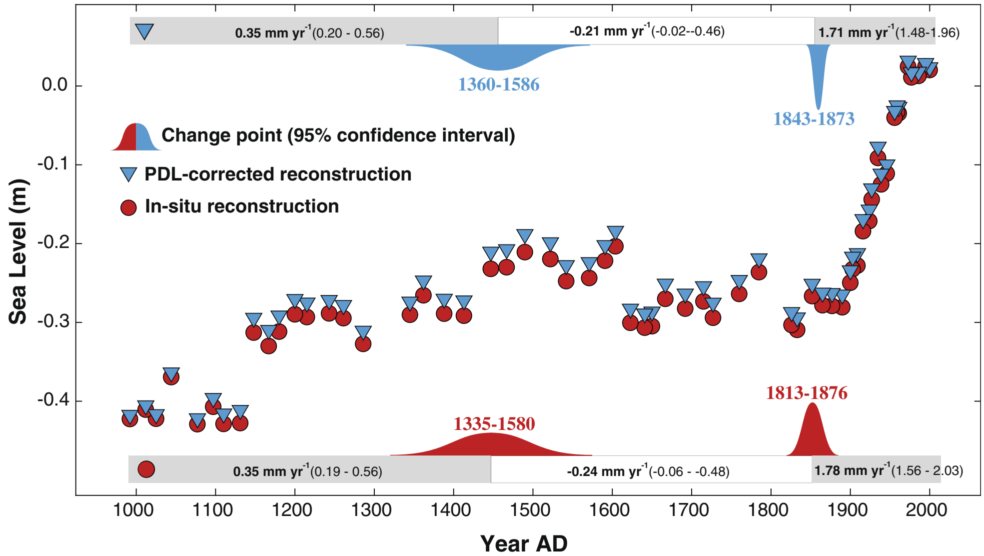

Fig. 4 Reconstructed sea-level changes at Tump Point, NC, USA following correction for land-level change resulting from glacio-isostatic adjustment (0.9 mm year^{-1}). A statistical model identified persistent sea-level trends for the in situ (*red circles*) and decompacted (*blue triangles*) reconstructions. For clarity, reconstructions are presented as estimate midpoints without vertical or temporal uncertainties (see ref. [61] for further details of errors). Reprinted from Brain et al. [67••]. © 2014, with permission from University of Washington/Elsevier Inc

time, particularly where fixed location ground reflectors ('permanent scatterers') can be exploited [94–97].

Higgins et al. [98••] used InSAR to determine rates of compaction-induced subsidence in the Ganges–Brahmaputra delta, Bangladesh, noting average annual rates of up to 18 mm year^{-1} over a c. 4-year period (2007–2011 CE). The InSAR results demonstrated good agreement with direct point measurements of subsidence but provided a considerably more detailed assessment of spatial patterns of subsidence and the variability therein (Fig. 5), as also noted in many studies employing a range of techniques [92, 99, 100]. In turn, this permitted Higgins et al. [98••] to consider the causes of subsidence. Comparison with regional geology maps revealed a strong sub-surface lithological control on subsidence rates, the lowest of which were observed in areas where stiffer Pleistocene clays outcropped [98••]. In contrast, the highest rates of subsidence were noted where surface deposits were composed of softer organic Holocene muds. Similar high rates (≤15 mm year^{-1}) of subsidence in Holocene sediments (depths of 30–40 m below ground level) have been reported in the Po Delta, Northeastern Italy by Teatini et al. [101] on the basis of an 8-year (1992–2000 CE) interferometric monitoring dataset.

InSAR has also been used to assess the spatial pattern of rates of subsidence associated with consolidation of porous strata as a result of groundwater abstraction over large (of the order 10^3 km^2) areas. Erban et al. [102], for example, reported rates of c. 10–40 mm year^{-1} in the Mekong Delta, Vietnam, between 2006 and 2010 CE. These rates correlated well with calculations of compaction-induced subsidence based on changes in hydraulic head measured in groundwater monitoring wells, demonstrating the utility of predictive models where the compaction process is sufficiently isolated and understood (see also [103–106]). However, assigning a cause for observed subsidence is not always straightforward and often requires careful critique and comparison of monitoring techniques, datasets and modelling approaches [49, 55, 91].

Future

Our understanding of compaction processes and effects has contributed greatly to our ability to constrain the many controls on RSL, such that local to regional scale projections thereof grow increasingly robust. For example, use of basal peat-derived RSL data and geotechnical modelling of compaction-induced PDL has improved the accuracy of long-term estimates of GIA [66, 71, 86] and improved confidence in our projections of climate-related global sea-level variability [46•, 67••].

Compaction is, and will continue to be, a significant driver of RSL rise in some locations in future [26, 57]. Global mean sea level between 1901 and 1990 rose at a rate of 1.2 ± 0.2 mm year^{-1}, as determined from probabilistic (re-)analysis of tide gauge records and inputs from physics-based numerical models [107]. Examination of satellite altimetry records (namely those obtained by the TOPEX/Poseidon and Jason missions) indicated that the average rate of global sea-level rise between 1993 and 2009 was 3.4 ± 0.4 mm year^{-1}

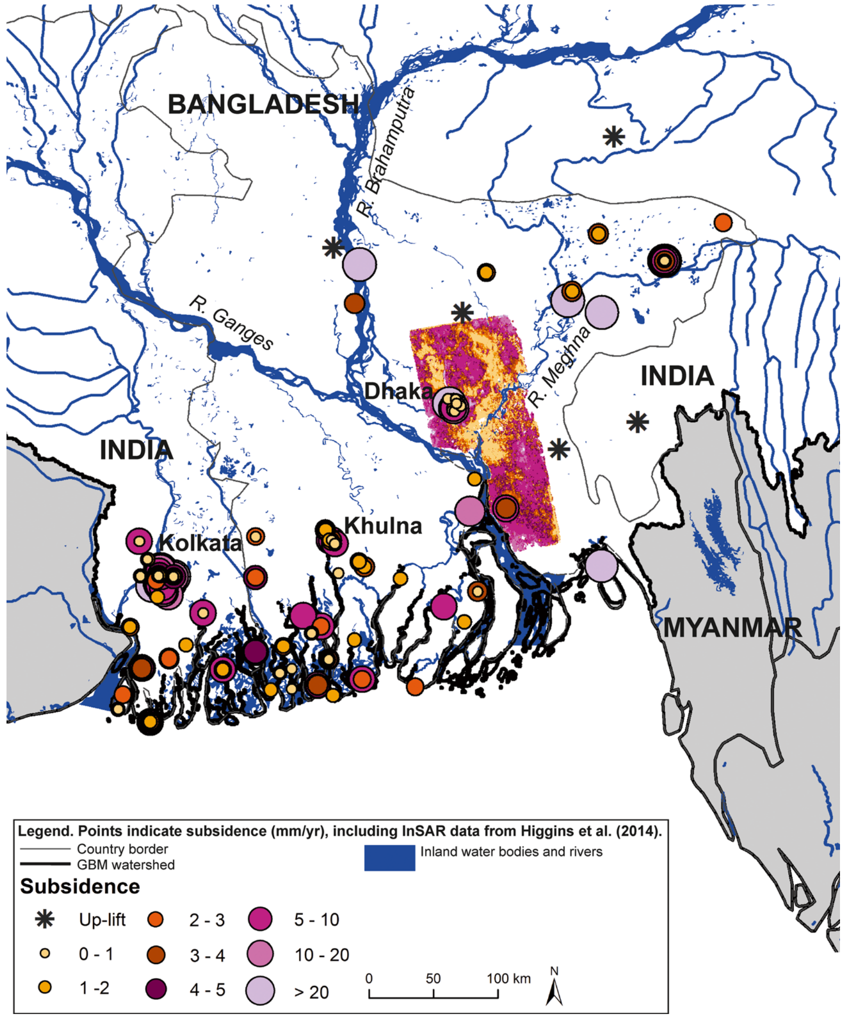

Fig. 5 Rates of subsidence recorded for the Ganges–Brahmaputra–Meghna delta and surrounding areas, demonstrating the resolution of coverage provided by InSAR methods (data are from ref. [98••]) relative to point-based estimates. Source: Brown and Nicholls [90•], 10.1016/j.scitotenv.2015.04.124, reproduced under Creative Commons Attribution-NonCommercial-NoDerivatives (CC BY NC ND) 4.0 International Public License http://creativecommons.org/licenses/by-nc-nd/4.0/ and with permission from S. Brown. See original publications for discussion of the sources and accuracy of individual data points

[108]. Future accelerations are deemed to be highly likely, primarily in response to thermal expansion of ocean waters and enhanced melting of ice caps and glaciers [13]. The highest emissions and temperature rise scenario considered by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) project rates of rise of between 8 and 16 mm year^{-1} (Representative Concentration Pathway (RCP) 8.5) during the period 2081 to 2100 [13]. In some locations, reported rates of compaction-induced subsidence can equal or even greatly exceed the highest rates of projected global sea-level rise.

Projecting rates of compaction-induced subsidence into the future is not a trivial task. The stratigraphic record provides considerable insight into the sub-surface controls on compaction and adds longer term context to contemporary observations of subsidence rates. However, reported rates of compaction-induced subsidence vary considerably in terms of the measurement method employed; causal mechanism; spatial location, coverage and resolution; duration of the observation period; and in terms of the quality and accuracy of the data reported [90]. Extrapolation of observed rates may be appropriate over short (sub-decadal) timescales, but subsidence rates can change extremely rapidly (i.e. over annual to monthly timescales) in some circumstances, particularly where anthropogenic activities provide the causal mechanism [92, 97] or where geomorphic thresholds are exceeded [45••].

Put simply, compaction operates at the local scale over a variety of timescales; as such, assessment and projection of compaction-induced land-level lowering require local scale, site-specific studies to identify the causes of compaction and the depths at which they operate. Encouragingly, as outlined here, identifying such controls on compaction can be achieved through a combination of contemporary observations and stratigraphic studies. In turn, such processes can then be modelled where our understanding of process permits, allowing increasingly robust projections of compaction-induced subsidence. Recent modelling work [38••, 76] has demonstrated how accurate and robust assessment of compaction can be achieved with an appropriate geotechnical model, permitting local to regional scale assessment of land-level lowering in complex stratigraphies and unique lithologies over short- to medium-term timescales.

It is also critical that future assessment of compaction-induced RSL rise in coastal environments does not focus solely on changes in elevation. Compaction is one of many geomorphic processes operating in coastal environments, and is intricately linked to marine, fluvio-estuarine and coastal sedimentary processes [26, 32, 39, 45••]. Hence, the potential for compaction to cause rapid and widespread coastal change should not be neglected; incorporating the effects of compaction into conceptual models and numerical simulations of coastal wetland behaviour is an important ongoing consideration [5, 39, 109].

Conclusions

My key conclusions are as follows:

1. Sediment compaction is an important process in coastal stratigraphic successions. Compaction reduces the volume of coastal sediment deposits. The resultant land-level lowering creates a local relative sea-level rise.
2. Stratigraphic studies and observational data have revealed that rates of compaction are variable both spatially and temporally but can be greater than current and projected increases in absolute sea level.
3. Compaction influences our interpretations of reconstructions of relative sea-level change obtained from compaction-prone coastal stratigraphies. Without correction, this affects the accuracy of estimates of long-term rates and spatial patterns of glacio-isostatic adjustment and can affect our understanding of the sensitivity of global sea level to past and projected temperature changes.
4. Our ability to project rates of compaction-induced coastal subsidence into the future depends on accurate assessment of causal compaction processes and the spatial and temporal timescales over which they operate and subsequent robust numerical modelling of resultant land-level changes and subsequent changes in coastal geomorphology.

Acknowledgments This paper is a contribution to the Paleo-Constraints on Sea Level Rise 2 (PALSEA2) working group and IGCP Project 639 'Sea Level Change from Minutes to Millennia'. MB thanks two anonymous reviewers for their helpful comments and Sally Brown, Stephanie Higgins, Ben Horton and Tor Törnqvist for permitting the use of their figures and data in this paper.

Compliance with Ethical Standards

Conflict of Interest The corresponding author states that there is no conflict of interest.

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•• Of major importance

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