GEOMORPHOLOGY

Survive or subside?

Deltas are among the most valuable coastal ecosystems, but they are very dynamic and the factors that influence their health are complex. The rate of compaction of underlying sediments might be a more significant factor than was thought.

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Faced with the pressures of human development and climate change, it is make-or-break time for many of the world's river deltas. But what exactly are the factors that determine whether a delta survives and prospers? On page 173 of this issue, Törnqvist *et al.*[1] go some way to providing an answer. They have developed a high-resolution model, based on empirical data, to assess why the Mississippi delta in the southern United States is losing wetlands at a particularly alarming rate. Their conclusion — that the largest part of the relative sea-level rise observed there results from the compaction of underlying organic-rich sediments — is likely to be valid for other similar deltas around the world, and should be taken into account for their successful management.

Delta preservation depends on a detailed understanding of how sediments are generated, transported and laid down, from source to sink[2] (Fig. 1). But our knowledge of the morphological and environmental behaviour of deltas remains primarily generic. We know that deltas act as filters, repositories and reactors for a range of materials, such as sediments, carbon, nutrients and pollutants, on their way from the continents to the oceans[3,4]. They are varied and extremely productive[5] ecosystems, and contain most of the world's coastal wetlands and coastal fisheries. Their high natural and agricultural productivity, coupled with the ease of getting around on their waterways, supports a significant proportion of the world's population.

We also know that deltas are naturally ephemeral systems: most current deltas are less than 6,000 years old. They form whenever oceans flood the continental shelf and sediment delivered by rivers fills the flooded space. Deltas are also naturally highly dynamic, maintained through a hierarchy of pulses of materials and energy. These include levee breaches, floods and the passage of hurricanes and lesser storms, and the timescales range from changes in river channels over hundreds to thousands of years to the daily comings and goings of the tide.

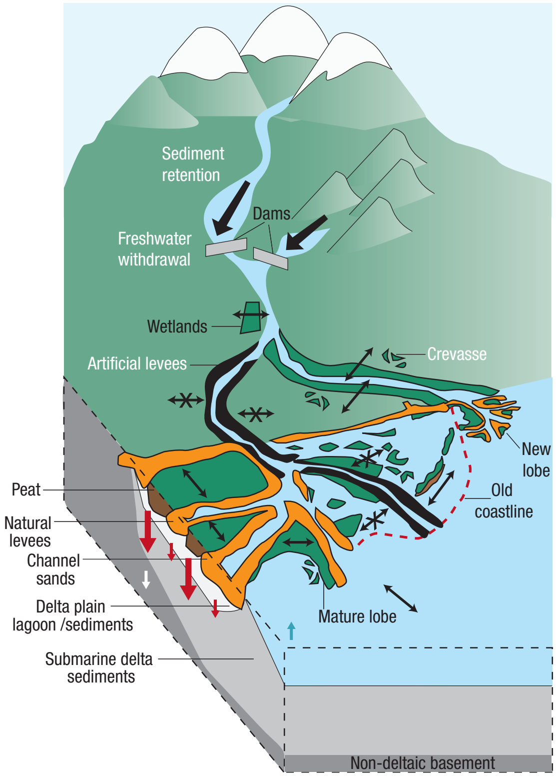

Figure 1 Sediment from source to sink. The impact of human activities on river deltas can only be viewed in the general context of sediment movements (black arrows) from continent to ocean. Deltas are highly dynamic systems that develop through strong interactions between river and sea, and are regulated by internal feedback mechanisms. The primary force leading to the formation and sustainability of deltas is river input. River channels change course over centuries, leading to the formation of new 'lobes' of land in the delta and the degradation of older delta plains and coastal fringes. Human impacts on a delta and in a river's watershed include sediment retention behind dams; freshwater extraction; the stabilization of river banks through artificial levees; the construction of new channels; and land reclamation. Crossed arrows indicate where these processes have reduced or eliminated sediment transport. Tectonic and isostatic subsidence (white arrow) and global sea-level rise (blue arrow) also have a part in delta survival, but, as Törnqvist and colleagues show[1], their effects may in some cases be subordinate to that of the varying rates of compaction of sediments underlying the delta (red arrows).

What is new is that direct human intervention, coupled with the indirect effects of climate change, is now beginning to change deltas on timescales of decades, which is relevant for human management concerns. Direct pressures include the reduced delivery of sediment owing to the trapping of the sediment and freshwater supply behind river dams upstream[6], and hydrological alterations and reclamation, such as the construction of levees that block river input to the delta plain[7]. If we are to manage deltas for the better, it is imperative to understand clearly how they form, how we have modified them, and what our realistic expectations for sustaining them should be.

Törnqvist and colleagues' contribution is to analyse deposits from more than 100 shallow boreholes in the Mississippi plain just over 100 kilometres to the west of New Orleans. These sediments show a clear transition, dated to around 1,500 years ago, from older wood-peat deposits to younger fluvial deposits. At that time, the area must have been a coastal swamp lying at, or just above, high-tide level.

By assessing the deformation of this transition line in relation to the thickness of the deposits above, the authors were able to assess the rate of compaction of the underlying peat in the time since the fluvial deposits began to be laid down. They could thus isolate the contribution of this compaction to the overall change of sea level relative to the land. The rates they establish — some 5 mm per year — suggest that the compaction of underlying peat is indeed highly significant, providing space to accommodate large quantities of fluvial sediment.

A central element of schemes to restore the Mississippi delta and others like it worldwide is the reintroduction, on various scales, of river water onto the delta plain. If Törnqvist and colleagues' estimation of the rate of compaction in the Mississippi delta is right — and, as they point out[1], there are reasons to believe that it is a conservative estimate — then any effective diversions will need to involve large amounts of fluvial sediments, similar to the quantities moved in natural processes such as the breaching of river banks (creating 'crevasses') and large floods. Because compaction is highly variable in space and time, depending on the underlying strata, the effectiveness of such diversions depends on a detailed understanding of sedimentary architecture underneath. A similar variability applies to other processes crucial to the preservation of deltas, such as sediment and water delivery, wetland development and maintenance, and the redistribution of coastal sediments. Future research should therefore focus on how this heterogeneity affects large-scale delta dynamics.

The effects of climate change — accelerated and possibly erratic sea-level rise, probably stronger and more frequent hurricanes, and alterations in the hydrological cycle affecting freshwater input into deltas — will also have to be taken into account when developing delta-management strategies. Against a backdrop of rising energy prices, restoration strategies should not depend on energy-intensive techniques such as the dredging and pumping of sediments over long distances for beach nourishment and marsh building. Rather, ecotechnological approaches that depend mainly on natural energies such as tides, waves and natural currents to disperse freshwater and sediments should be favoured[8]. The kind of detailed knowledge supplied by work such as that of Törnqvist *et al.* can only help us in making informed decisions.

References

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GEODYNAMICS

Layer cake or plum pudding?

Whether convection in the Earth's mantle extends through its entire depth or if the mantle is layered has long been debated. Recent research suggests that spatially and temporally intermittent or partial layering is the most likely solution.

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Since the late 1960s, when plate tectonics and slow, creeping convection of the rocky mantle became accepted, geoscientists have been debating whether convection extends from the surface to the core–mantle boundary, or whether the mantle is compositionally and dynamically layered. Geochemical observations appeared to support layering, whereas geophysical observations tended to support whole-mantle convection. The potential compositional boundary was typically put at 660 km depth, corresponding to the major seismic discontinuity that marks the boundary between the upper mantle and lower mantle. A range of possible reconciliations have been proposed, including leaky layering at 660 km, layering deeper in the mantle, or ubiquitous compositional heterogeneity like a 'plum pudding'. This debate continues, and was the focus of a special Union session "Whole or Layered Mantle Convection" at the AGU Fall Meeting held in December in San Francisco[1].

There are two geochemical observations that suggest there are distinct reservoirs in the Earth's mantle — a concept that is, at first sight, incompatible with whole-mantle mixing. First, the upper mantle is depleted in incompatible trace elements compared with what is expected from primitive planet-building material that the Earth should, on average, be composed of. The findings from the upper mantle therefore require there to be complementary enriched material somewhere else. Second, several isotopically distinct components can be traced in volcanic rocks, so these must exist in the mantle[2]. By contrast, geophysical observations, in particular from seismology, indicate that some subducted oceanic plates, known as slabs, sink all the way into the lower mantle (Fig. 1). This seems to rule out complete layering at 660 km.

In light of this controversy, geochemical observations have been interpreted to support different conceptual models: while some geochemists argue for 'leaky' layered convection (C. J. Allegre, Institut de Physique du Globe, Paris, France), others argue that