Integrated Palaeogeographic Mapping and Tidal Modeling during the Oligo-Miocene, South China Sea

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Summary
Paralic source and reservoir rocks are a dominant component of Tertiary depositional systems in SE Asia. Reservoir architecture and heterogeneity within clastic coastal environments results from the complex interaction of tidal, fluvial and wave processes, which are, in turn, controlled by regional to local-scale basin physiography, shoreline geometry and the interaction between sediment supply and relative sea-level change. We simulate tidal range and bed shear stress in the South China Sea during the Oligo-Miocene and discuss (1) the impact of tectonic and physiographic changes on a regional decrease in shoreline tidal dynamics and (2) the impact of the regional-local tidal systems on shoreline geometry, depositional processes and preservation of organic carbon, with reference to the preserved ancient successions and modern depositional environments in the Baram Delta Province, NW Borneo.

Introduction

Predicting and recognising the relative influence of tide, fluvial and wave processes on ancient shoreline deposition is challenging, but can be mitigated by using numerical modelling approaches to compliment integrated sedimentological, stratigraphic and palaeogeographic studies (Ainsworth et al., 2011). Palaeotidal modelling of tidal range (Wells et al., 2005) and bed shear stress (Mitchell et al., 2011) has illustrated the control of basin- to regional-scale tectonics and physiography on ancient tide-influenced deposition. Rapid changes in basin setting, physiography and coastal rugosity during the Miocene evolution of the South China (SCS) are well documented (Hall, 2002), however the impact on the regional tidal system and shoreline facies deposition have not been previously investigated.

In this study, we investigate: (1) the key tectonic uncertainties in the reconstruction of the SCS; (2) the impact of tectonic-driven changes in basin physiography on the regional tidal system in the SCS during the Oligo-Miocene (3) the controls on early Miocene tide-influenced facies deposited along NW Borneo.

Methods

Fluidity is a finite element ocean model that uses flexible, unstructured, tetrahedral meshes to maximise accuracy and efficiency (Piggott et al., 2008). Fluidity has been extensively validated for tidal modelling (Wells et al., 2010). Multi-scale computational meshes were created using Gmsh (http://geuz.org/gmsh/) with shoreline geometries defined by a methodology derived from the open source Shingle Project (http://shingleproject.org/). Simulations were forced with full astronomical tidal forcing for 3 months simulation time and with a tidal bulge spin-up period of 5 days. Outputs are tidal range, the harmonic amplitude and phase for each tidal constituent and the maximum and average bed shear stress.

Global palaeoenvironment reconstructions for seven time slices (Chattian-Messinian) were provided by Getech *Globe* (http://www.getech.com/globe). Key issues that received focused attention during plate tectonic reconstructions were: (1) opening mechanism for the SCS (2) assembly of the Philippines, and (3) accretion history of NW Borneo. Sensitivity to highstand palaeogeographic interpretation has been investigated by comparing model runs for different SE Asia palaeogeographies. To assess bathymetric uncertainty, simulations were also performed for lower sea levels (-50 m and -100 m).

Results

Across the range of model scenarios, there is a general decrease in tidal range along palaeocoastlines of the developing SCS through the Oligo-Miocene (e.g. Fig. 1). In Chattian-Langhian times, coastal tidal range was regionally macro-mesotidal (>2 m) compared to microtidal (0-2 m) during Tortonian-Messinian times and diurnal tides dominated throughout. The key regional tectonic and physiographic controls on the evolving tidal system in the SCS during the Miocene were: (1) a lack of throughflow across the Sunda Platform; (2) the physiography of the Izu-Bonin Arc; (3) the decrease in width of the Luzon Strait as the Philippines migrated northwards, dissipating the amount of tidal energy entering the confined ocean basin; and (4) variations in shelf width and shoreline geometry and orientation relative to the incoming boundary tide from the Pacific, controlling shoaling and funnelling effects (Fig. 2). Amplification of the regional tide by funnelling effects in coastal embayments resulted in very high macrotidal (>7 m) conditions offshore NW Borneo and SE Vietnam during Burdigalian-Langhian and the developing Gulf of Thailand in the Serravallian (Fig. 2).

During the Miocene, there was also a modelled decrease in the maximum grade of sediment transported by coastal tidal currents (Fig. 2). In Burdigalian-Langhian times, macrotidal conditions in the western SCS were coincident with tidal currents capable of transporting fine to medium sand and locally fine gravel, with an average direction onshore. Maximum tidal flow modelled along the NW Borneo coastline was capable of transporting medium sand in the Tortonian, with bed shear stress decreasing north eastwards.

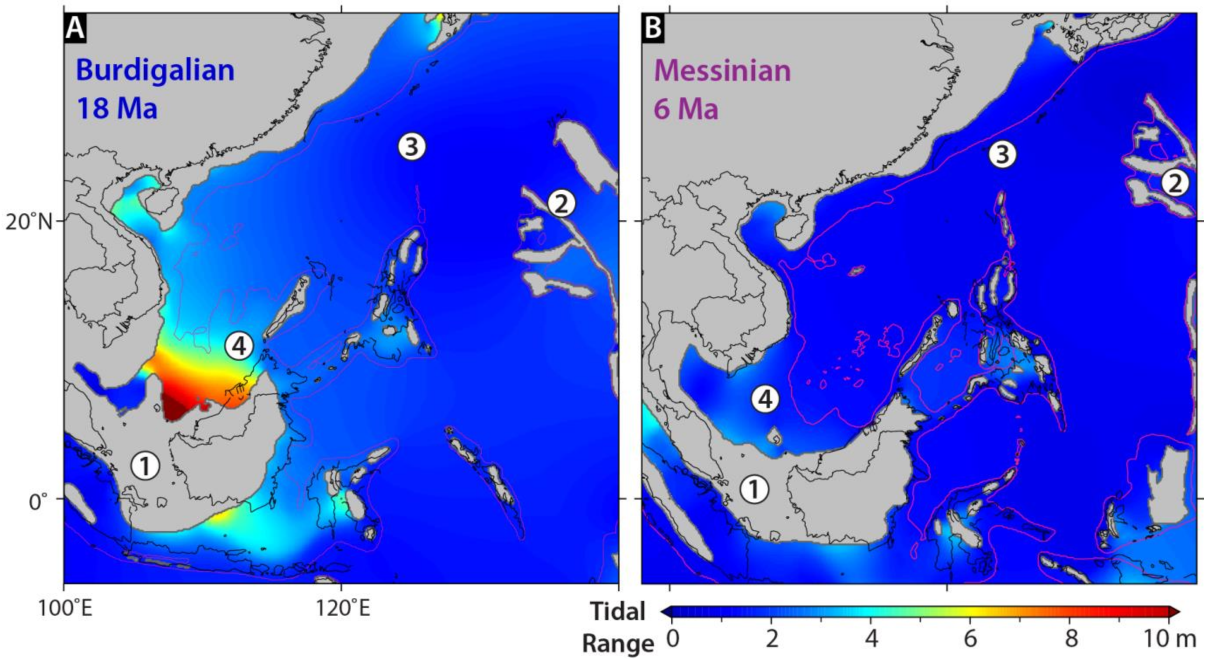

Fig. 4. Modelled tidal range in the South China Sea for the Burdigalian (A) and Messinian (B).

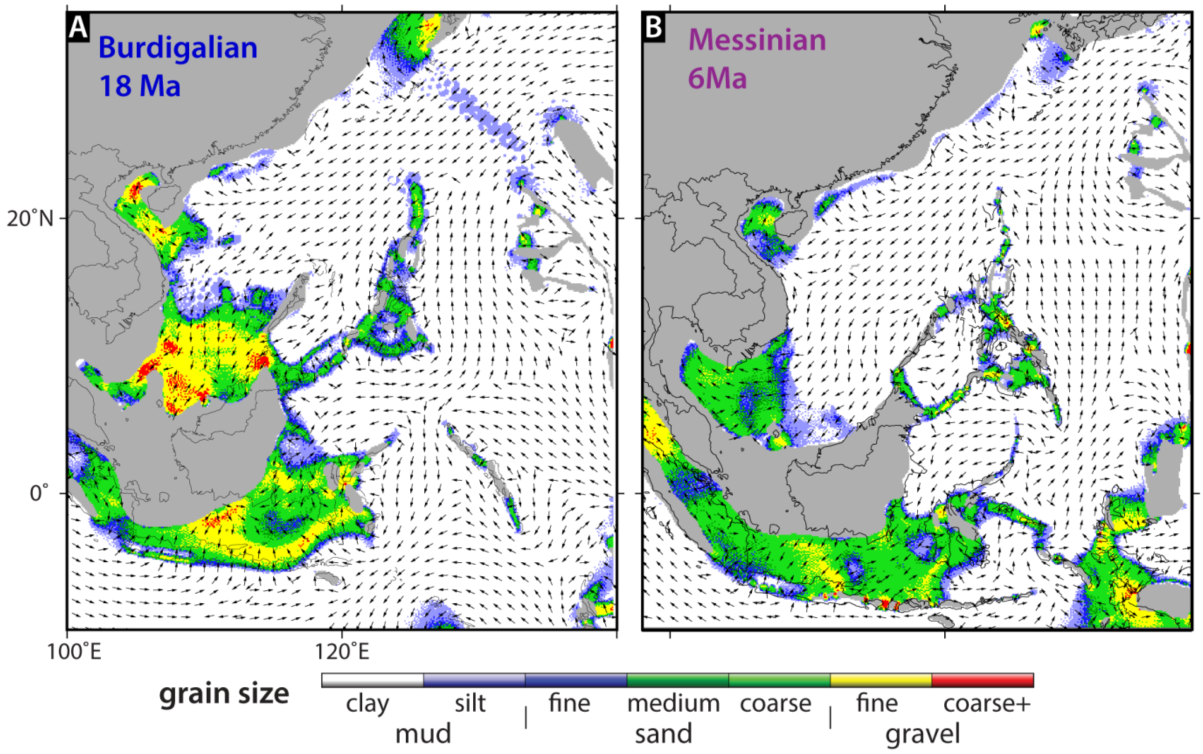

Fig. 5. Modelled maximum bed shear stress in the South China Sea for the Burdigalian (A) and (B) Messinian.

Discussion

We demonstrate the significant impact of tectonic-driven changes in basin morphology on tidal processes within the SCS during the Miocene. Tidal magnitude along a given coastline is the integrated effect of both regional (>100 km) and local-scale (c. 1-100 km) changes. Major controls on the relative power of tides, for instance compared to waves, in the SCS are: (1) the distribution of landmasses controlling both the magnitude of tidal inflow and outflow into a basin; and (2) coastal rugosity and the orientation of coastal embayments relative to the incoming boundary tide. Variations in tidal magnitudes in relation to changes in shelf width are difficult to deconvolve from relatively regional-scale changes, especially at finer time-scales.

A review of published data shows similarities in the distribution between Oligo-Miocene outcrop-reservoir tidal facies and modeled tidal bed shear stress. In the Early to Late Miocene, tide-influenced paralic reservoirs have been interpreted for the Cuu Long and Nam Con Son Basins, offshore South Vietnam (Lee et al., 2001) and the Malay Basin in the Gulf of Thailand (Shoup et al., 2013). In the Middle Miocene, mangrove-related facies have been interpreted for the Malay Basin (Shoup et al., 2013) and the Sabah Basin of eastern Borneo ((Noad and Harbury, 1997). Corroboration of time-integrated tidal model results and long-term tidal influence on deposition indicates the capacity for palaeotidal modeling to provide indicative insight for predictive models of coastal-shelf sedimentary processes and facies architecture (Ainsworth et al., 2011).

Furthermore, integration of model results with detailed facies analysis for a given location can provide important constraints on regional versus local controls on shoreline processes. The Early Miocene of the Balingian Province of Central Sarawak (termed the Nyalau Formation in onshore outcrops and Cycle II in the subsurface and offshore) comprises up to c. 500 m of clastic coastal plain to coastal-deltaic deposits with widespread evidence of tidal influence. The modelled time slices encompass the same gross stratigraphic interval. The succession comprises numerous small-scale (c. 10’s m thick), coastal-coastal plain parasequences, displaying abundant facies evidence of tidal influence, which are often capped by mangrove coals and/or mangrove root horizons (Amir Hassan et al., 2013). The vertical stacking of tide-influenced coastal-coastal plain deposits (maintained for at least c. 5Myr) indicates relatively long-lived conditions that favoured the development of strong tidal processes. Foremost among these, as informed by the tidal modelling work, was probably the basin physiography: (1) narrow, elongate basin shape, (2) ‘blind’ geometry at the south-west end of the funnel-shaped South China Sea, and (3) an open connection to the Pacific Ocean to the north-east. This compares favourably with the postulated development of other Miocene tide-dominated basins around the world, including the palaeo-Mediterranean-Atlantic margin (e.g. Martin et al., 2009), the Molasse marine basins of western Europe (e.g. Reynaud et al., 2013), the Amazonian embayment (e.g. Räsänen et al., 1995), the Eastern Venezuela Basin (Buatois et al., 2012) and the Pearl River Mouth Basin, China (Zheng and Deng, 2012).

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