AAPG Datapages/Search and Discovery Article #90235 © 2015 AAPG Asia Pacific Region, Geoscience Technology Workshop, Modern Depositional Systems as Analogues for Petroleum Reservoirs, April 21-22, 2015, Wellington, New Zealand

The Potential Impact of Evolving Basin Physiography and Tidal Dynamics on the Mangrove Biome and Hydrocarbon Charge System in the Tertiary South China Sea

Daniel S. Collins[1], Peter A. Allison[1], Howard D. Johnson[1], Alexandros Avdis[1], Jon Hill[2], and Matthew D. Piggott[1]

[1]Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London, SW7 2AZ UK (d.collins12@imperial.ac.uk)
[2]Environment Department, University of York, Heslington, York, YO10 5DD UK

Abstract

Tidal processes are a fundamental control on the lithospheric sequestration of carbon by mangroves. Tidal range controls the size and distribution of mangroves along tropical shorelines and the frequency, strength and direction of tidal flow transport controls the burial versus export of mangrove organic carbon. Increased supply of sediment also increases the capacity for mangrove carbon burial. 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

Mangroves are salt-tolerant, low-diversity, forests inhabiting the upper intertidal zones in tropical to subtropical regions. Whilst mangroves are limited globally by temperature (20°C winter surface seawater isotherm), the extent of mangroves on local and regional scales is predominantly a function of precipitation, tides, waves and river flow, all of which are a function of geological processes operative on various spatial and temporal. Mangroves are carbon-rich ecosystems containing an average of 937 tC/ha (Donato et al., 2011). High rates of carbon burial (174 gC/m² year; Fig. 1a) also reflect rapid rates of sediment accretion (c. 5 mm/year), which is facilitated by the attenuation of tidal flow around dense root networks (Fig. 1b). High sedimentation rates are ultimately controlled by the capacity of tidal flow to rework and transport sediment into mangroves. Despite only covering 0.5% of the total coastal ocean area, carbon burial in mangrove forests accounts for c. 14% of carbon sequestration by the global ocean (Fig. 1c-d; Alongi, 2012). Therefore, any increase in sediment accretion may substantially affect carbon sequestration in mangroves, the formation of coal and hydrocarbon source rocks, and even global climate.

In this study, we investigate: (1) the impact of tectonic-driven changes in basin physiography on the regional tidal system during the Oligo-Miocene evolution of the South China Sea (SCS); (2) the origin of preserved carbon-rich mangrove facies in the Baram Delta Province (BDP) of NW Borneo, in comparison to developing facies models for mangrove deposition along clastic shorelines; and (3) how the contemporaneous development of a number of major delta systems during the Miocene (e.g. Pearl River, Mekong and Baram Deltas) may have contributed to lithospheric sequestration of mangrove carbon.

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.

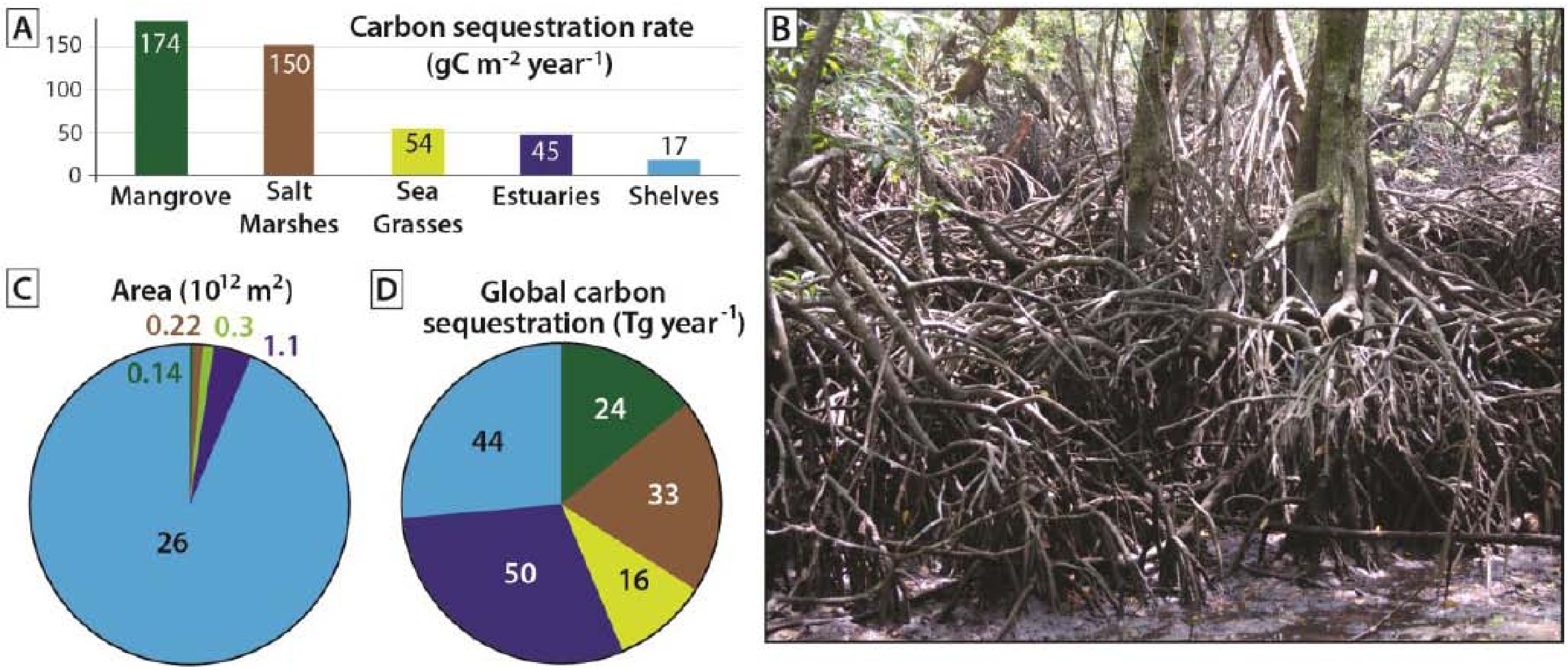

Fig. 1. Organic carbon burial in mangrove systems. A. Carbon sequestration rate of mangroves and other coastal habitats. B. Example mangrove forest in Selerong, Brunei. C. Comparison of global area of mangroves and other coastal habitats. D. Comparison of global carbon sequestration in mangroves and other coastal habitats. After Donato et al. (2011) and Alongi (2012).

Global palaeoenvironment reconstructions for seven timeslices (Chattian-Messinian) were provided by Getech Globe (http://www.getech.com/globe). Sensitivity to highstand palaeogeographic interpretation has been investigated by comparing model runs for different SE Asia palaeogeographies. To assess bathymetric uncertainty, simulations were 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. 2). 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 dominate 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 funneling effects (Fig. 2). Amplification of the regional tide by funneling 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 is also a modelled decrease in the maximum grade of sediment transported by coastal tidal currents. 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 in the western BDP was capable of transporting medium sand in the Tortonian and fine sand in the Messinian, with mud transport only possible in the eastern BDP.

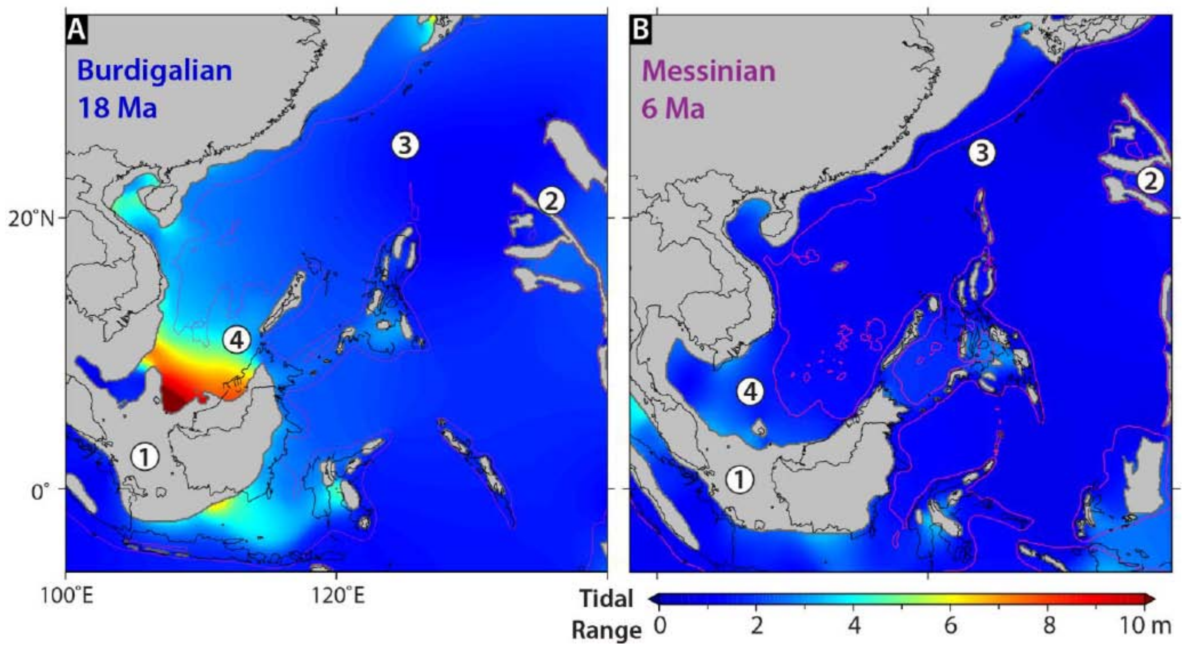

Fig. 2. Modelled tidal range in the South China Sea for the Burdigalian (A) and Messinian (B).

Discussion

We predict that both the productivity and preservation of mangrove organic carbon will have increased in response to the increased tidal prism and tidal flow strengths along shorelines in the South China Sea in the early-mid Miocene. The degree of biological and sedimentary change in shoreline systems will vary locally as a function of changes in balance of tide, wave and fluvial processes. Assuming an increase in tidal power over wave and fluvial processes, increased development of longer, deeper and intricately branched tidal channels will have increased the area of marine-influenced coastal plain. Coupled with increased tidal bed shear stress, enhanced sediment and material transport within channels would permit wider development and increased diversity of mangroves. Increased wave power in the early-mid Miocene may have also occurred in response to the regional tectonic changes and in turn contributed sediment to shoreline mangrove systems. Furthermore, sedimentation rates within mangrove systems may have been further increased and sustained along coastlines with increased delivery of fluvial sediment, increasing the potential sediment volume reworked by tide and wave processes. Increased sedimentation rates contribute to increasing productivity of mangroves by accreting and maintaining an increased area of coastal plain within the upper intertidal zone.

Ancient mid- to late-Miocene successions in the BDP record deposition in variably storm-wave dominated shoreface and fluvio-tide deltaic environments. Carbonaceous-rich, mudstone dominated facies predominantly occur in association with interpreted fluvio-tidal channels. We interpret abrupt vertical changes from sandier facies to bioturbated mudstones within these channels to reflect rapid autogenic changes in local sediment supply and fluvial abandonment. If the number and geometry of fluvio-tidal channels increased during the Miocene, there would therefore have been an increased capacity for shoreline sequestration of mangrove carbon in this facies association. Preservation of fluvial-tidal facies associations and mangrove-related carbonaceous facies is more abundant in the Lambir Formation (western BDP) relative to the Belait Formation (eastern BDP). Model results show increased tidal range and bed shear stress in the western BDP during Langhian-Messinian times, consistent with increased abundance and preservation of tidal depositional elements in the eastern BDP. There is, however, a distinct lack of preserved coastal plain facies in ancient successions across the BDP. We attribute this preservational bias to the continued uplift of the Crocker Range hinterland, with concomitant uplift of a wider coastal plain. Erosion of coastal plain facies will have also occurred during regressive phases of higher-frequency transgressive-regressive cycles, especially on the uplifted footwalls of normal faults.

On a sub-basin scale, we expect increased preservation of mangrove-facies related to basin physiography and shoreline geometry changes during transgressive-regressive cycles. Using the present day Brunei Bay and the Holocene evolution of the Baram Delta (Caline and Huong, 1992) as analogues, increased coastal rugosity during transgression will favour the amplification of tides and attenuation of waves and thus the increased abundance of tidal channels and mangroves along the embayed shoreline. In the Belait Formation, tide- and wave-dominated facies association are vertically compartmentalised on a >10 m scale by key stratal surfaces, which we therefore interpret to reflect changes in coastline geometry and local process dominance within the Berakas Syncline, Brunei.

Taking an average estimate of 0.5% TOC and 7 km thickness (7-12 km; Hall and Nichols, 2002) for stratigraphic successions of the mid- to late-Miocene Champion Delta, annual carbon burial for the delta was c. 1 GtC/yr, which is equivalent to c. 0.7 ppm CO_2 per year. However, the Champion Delta (c. 140,000 km^3) only comprises c. 4% maximum of the estimated total Neogene sediment volume in Borneo basins, in which coastal to shallow marine sediments form a major component (Hall and Nichols, 2002). Furthermore, a number of major mid- to late-

Miocene delta systems developed during post-rift basin phases in the South China Sea, including the present day Mekong, Red River and Pearl River Deltas (Doust and Sumner, 2007). Our modelling results suggest that these deltaic systems were all influenced by higher tidal energies. The combined magnitude of carbon burial associated with increased mangrove productivity and fluvio-tidal deposition in these coastal systems may have been significant for hydrocarbon source-rock formation and global climate.

References Cited

Alongi, D. M., 2012, Carbon sequestration in mangrove forests: Carbon Management, v. 3, no. 3, p. 313-322.

Caline, B., and Huong, J., 1992, New insight into the recent evolution of the Baram Delta from satellite imagery: Geological Society of Malaysia Bulletin, v. 32, pp. 1-13.

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., and Kanninen, M., 2011, Mangroves among the most carbon-rich forests in the tropics: Nature Geoscience, v. 4, no. 5, pp. 293-297.

Doust, H., and Sumner, H. S., 2007, Petroleum systems in rift basins – a collective approach in Southeast Asian basins: Petroleum Geoscience, v. 13, no. 2, pp. 127-144.

Hall, R., and Nichols, G., 2002, Cenozoic sedimentation and tectonics in Borneo: climatic influences on orogenesis: Geological Society, London, Special Publications, v. 191, no. 1, pp. 5-22.

Piggott, M. D., Gorman, G. J., Pain, C. C., Allison, P. A., Candy, A. S., Martin, B. T., and Wells, M. R., 2008, A new computational framework for multi-scale ocean modelling based on adapting unstructured meshes: International Journal for Numerical Methods in Fluids, v. 56, no. 8, pp. 1003-1015.

Wells, M. R., Allison, P. A., Piggott, M. D., Hampson, G. J., Pain, C. C., and Gorman, G. J., 2010, Tidal modeling of an ancient tide-dominated seaway, part 1: model validation and application to global Early Cretaceous (Aptian) tides: Journal of Sedimentary Research, v. 80, no. 5, pp. 393-410.