AAPG HEDBERG CONFERENCE
"DEEPWATER FOLD AND THRUST BELTS"
OCTOBER 4-9, 2009 – TIRRENIA, ITALY

Coupled Fluid-Mechanical Models of Large Scale Delta Instability

Steven J. Ings[1, 2] and Christopher Beaumont[1]

[1]Department of Oceanography, Dalhousie University, Halifax, NS, Canada, B3H 4J1
[2]Also at: Department of Earth Sciences, Memorial University, St. John's, NL, Canada, A1B 3X5

The structural evolution of many rifted continental margin sedimentary basins has been strongly affected by the presence of a weak and potentially mobile substrate. These weak sedimentary units are often laterally extensive and can deform and flow under the differential load of prograding sediments (i.e., gravity spreading). This process can be further subdivided into two categories depending on the nature of the substrate. Salt tectonics involves the flow of weak evaporites and associated overburden deformation and has significantly affected the evolution of regions such as the Gulf of Mexico, offshore west Africa, and offshore Brazil (e.g., Peel et al., 1995; Demercian et al., 1993). In contrast, shale tectonics involves the mobilization and flow of weak mudrocks ('shale'), and several studies indicate that shale mobilization is often associated with pore fluid pressures that significantly exceed hydrostatic levels (e.g., Wu and Bally, 2000). Regions affected by shale tectonics include the Niger Delta, Gulf of Guniea, the Amazon Fan, offshore Brazil, and the Baram Delta, offshore Brunei (e.g., Cohen and McClay, 1996; Cobbold et al., 1999, Van Rensbergen and Morley, 2003) (Figure 1).

Although gravity spreading above salt and shale can produce similar structures such as counter-regional faulted extensional basins, diapiric structures, and deep-water fold and thrust belts, there are significant observable differences. For example, regions affected by salt tectonics are often characterized by allochthonous salt sheets that have translated significant distances from their autochthonous position and have climbed to higher stratigraphic levels. In contrast, the bulk of the sediments in basins affected by shale tectonics typically remains autochthonous or parautochthonous (e.g., Van Rensbergen and Morley, 2003), implying that at the basin scale shale is generally much less mobile than salt.

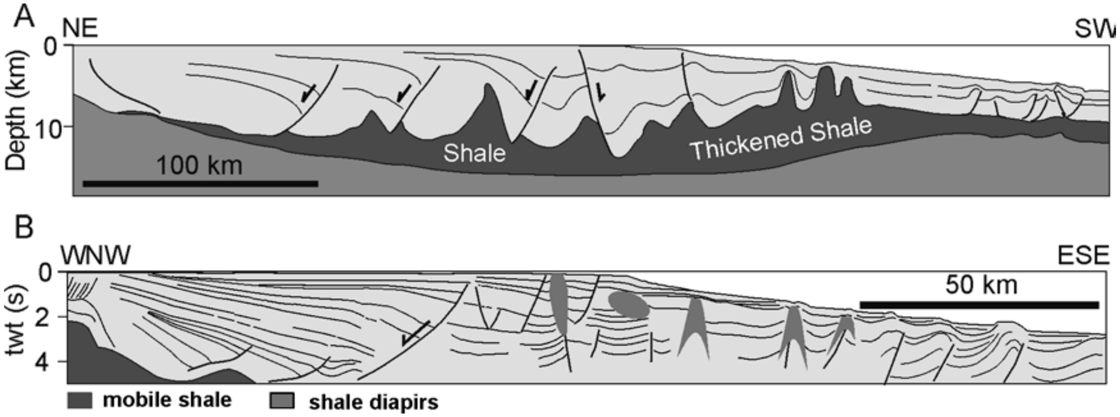

Figure 1. Schematic sections through A) the Niger Delta (compiled from Haack et al., 2000, Briggs et al., 2006, and Knox and Omatsola, 1987) and B) the Baram Delta, offshore Brunei (modified from Van Rensbergen and Morley, 2003).

Our present understanding of gravity-driven tectonics is dominated by studies of salt tectonics, including analogue modelling and numerical modelling which have greatly improved the understanding of the mechanics of salt tectonic systems. Shale tectonics, however, is a far less understood phenomenon and few studies have attempted to explain the mechanics and dynamics of these systems (e.g., Morgues and Cobbold, 2003; Albertz et al., *in press*). Shale tectonics is in many respects a more complex problem because consideration must be given to the dynamic relationship between sedimentation, fluid overpressure generation, shale mobilization and flow, and overburden deformation.

In this study we use a coupled fluid-mechanical model (Morency et al., 2007) to investigate generic shale tectonic systems. This model includes compaction driven Darcy fluid flow calculated dynamically throughout the model evolution. This evolving fluid pressure field is coupled to skeleton deformation through the effective pressure and, therefore, the strength of sediments in the model is determined in part by the level of the pore fluid pressures. Here shale is modelled as a Bingham visco-plastic material, as described by Albertz et al. (*in press*). The Bingham shale has finite frictional plastic strength but upon yielding flows viscously. We use this model to investigate the relationship between pore fluid pressure generation in a prograding sedimentary delta, the destabilization of the delta when fluid pressures reach a critical value, and the subsequent structural evolution of the delta during gravity spreading.

Figure 2 shows the result of a numerical model designed to approximate progradation of a clastic delta at a rifted continental margin. The delta is composed of a sand lithology (shades of gray) deposited on the shelf with time-equivalent shale deposited on the slope and abyssal plain (light and dark gray layers). For simplicity no syn-rift sediments are included in the model and the prograding wedge directly overlies crust. Note that although only a small sliver of crust is shown in the plots, the model includes a complete crustal model as a basal boundary condition.

As the delta progrades across the model, pore fluid pressure builds until it reaches a value large enough that it puts the material at the base of the wedge on yield (Fig. 2; t = 30 Ma). At this time, the pore fluid pressure are >90% of the lithostatic pressure (Fig. 2 B). Beyond this point in the model evolution, the delta is unstable and gravity spreading leads to the formation of a proximal extensional domain, characterized by landward dipping (counter-regional) normal faults, and a compensating distal fold and thrust belt. The extensional basins form diachronously (seaward younging) as shale is squeezed out from beneath them. A domain of thickened shale develops beneath the continental slope.

Structural styles similar to those developed in the numerical model (Fig. 2) can be observed in the schematic sections from the Niger Delta and the Baram Delta shown in Figure 1. In particular, counter-regional extensional basins and distal fold and thrust belts can be observed in both sections and a thickened shale domain comparable to that developed in the numerical model can be observed in Figure 1A. Additional results will be presented that illustrate the relationship between sedimentation, margin destabilization, and the development of particular structural styles comparable with those observed in nature. The model results will also be used to show how the development of the distal fold and thrust belt is a dynamic part of the entire unstable delta system and as such its evolution is partly controlled by the nature of landward extension.

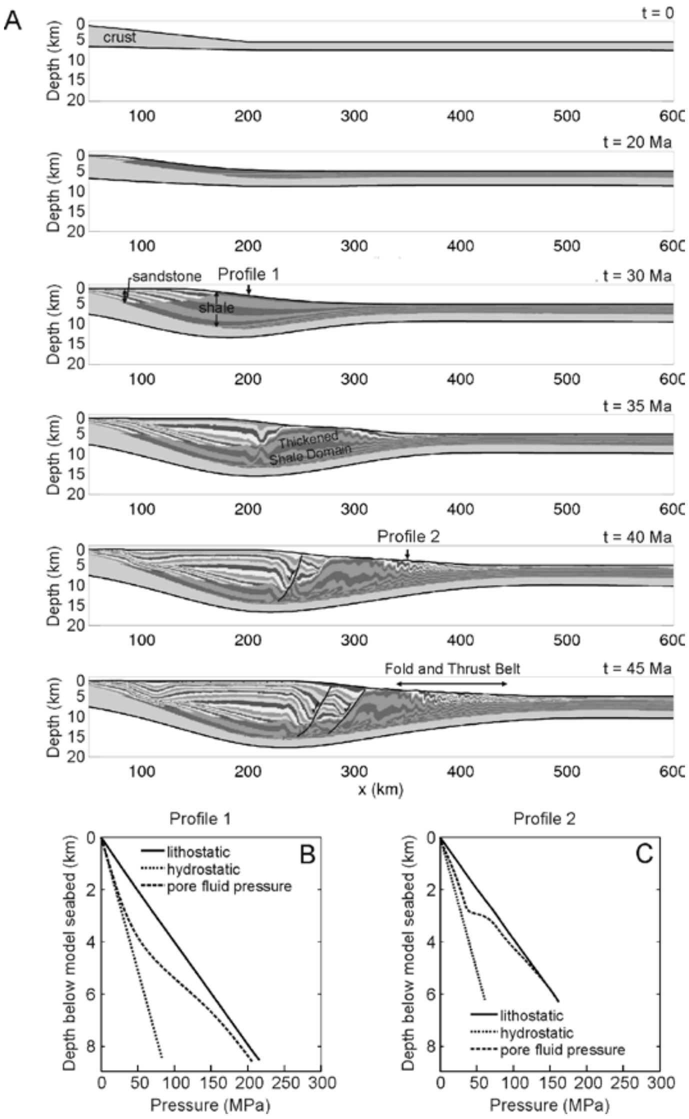

Figure 2. A) Numerical model evolution of a prograding clastic wedge of shale (light and dark gray) and sandstone (shades of gray). B) Pressure profile 1 (t = 30 Ma; x = 200 km). C) Pressure profile 2 (t = 40 Ma; x = 350 km).

REFERENCES

Albertz, M., C. Beaumont, and S. J. Ings, *In Press*, Geodynamic modeling of sedimentation Induced overpressure, gravitational spreading and deformation of passive margin mobile shale basins. AAPG Hedberg volume on shale tectonics.

Briggs, S. E., R. J. Davies, J.A. Cartwright, and R. Morgan, 2006, Multiple detachment levels and their control on fold styles in the compressional domain of the deepwater west Niger Delta: Basin Research, v. 18, p. 435–450.

Cobbold, P. R., R. Mourgues,and K. Boyd, 2004, Mechanism of thin-skinned detachment in the Amazon Fan: assessing the importance of fluid overpressure and hydrocarbon generation: Marine and Petroleum Geology, v. 21, p. 1013-1025.

Cohen, H. A., and K. McClay, 1996, Sedimentation and shale tectonics of the northwestern Niger Delta front: Marine and Petroleum Geology, v. 13, no. 3, p. 313-328.

Demercian, S., P. Szatmari, and P. R. Cobbold, 1993, Style and pattern of salt diapirs due to thin-skinned graviational gliding, Campos and Santos basins, offshore Brazil: Tectonophysics, v. 228, p. 393-433.

Haack, R. C., P. Sundararaman, J. O. Diedjomahor, K. Xiao, N. J. Gant, N.J.E. D. May, and K. Kelsch, 2000, Niger Delta petroleum systems, Nigeria: *in* M. R. Melloand B. J. Katz, eds., Petroleum Systems of South Atlantic Margins: AAPG Memoir 65, p. 213-231.

Knox, G. J., and E. M. Omatsola, 1989, Development of the Cenozoic Niger Delta in terms of the ‘Escalator Regression’ Model and impact on hydrocarbon distribution. Proceedings KNGMG Symposium ‘Coastal Lowlands, Geology and Geotechnology’, pp. 181-202. Kluwer Academic Publishers, Dordrecht.

Morency, C., R. S. Huismans, C. Beaumont, and P. Fullsack, 2007, A numerical model for coupled fluid flow and matrix deformation with applications to disequilibrium compaction and delta stability, Journal of Geophysical Research: 112, B10407, doi: 10.1029/2006JB004701.

Mourgues, R. and P. R. Cobbold, 2003, Some tectonic consequences of fluid overpressures and seepage forces as demonstrated by sandbox modelling: Tectonophysics, v. 376, p. 75-97.

Peel, F. J., C. J. Travis, and J. R. Hossack, 1995, Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: A preliminary analysis: *in* M.P.A. Jackson, D.G Roberts and S. Snelson, eds., Salt tectonics: a global perspective: AAPG Memoir 65, p. 153-175.

Van Rensbergen, P., and C. K. Morley, 2003, Re-evaluation of mobile shale occurrences on seismic sections of the Champion and Baram deltas, offshore Brunei, in Subsurface Sediment Mobilization, edited by Van Rensbergen, P., Hillis, R.R., Maltmann, A.J., and Morley, C.K., p. 395-409, Geological Society of London Special Publication 216, p. 395-409.

Wu, S., and A.W. Bally, 2000, Slope tectonics – comparisons and contrasts of structural styles of salt and shale tectonics of the Northern Gulf of Mexico with shale tectonics of offshore Nigeria in Gulf of Guinea, in Atlantic Rifts and Continental Margins, edited by Mohriak, W., and Talwani, M., AGU Geophysical Monograph 115, p. 151-172.