Tectonophysics 474 (2009) 643–656

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

An experimental investigation of gravity-driven shale tectonics in progradational delta

R. Mourgues [a,*], E. Lecomte [b], B. Vendeville [b], S. Raillard [c]

[a] UMR CNRS 6112, University of Maine, 72085 Le Mans cedex 09, France
[b] UMR CNRS 8157, University of Lille 1, 59655 Villeneuve d'Ascq, France
[c] Total, 64018 Pau cedex, France

ARTICLE INFO

Article history:
Received 9 December 2008
Received in revised form 4 May 2009
Accepted 8 May 2009
Available online 15 May 2009

Keywords:
Niger Delta
Shale tectonics
Gravity deformation
Fluid overpressure
Progradational delta
Analogue model

ABSTRACT

Many deltas exhibit gravitational deformation of their sedimentary cover. In these systems, the *décollement* layers do not always consist of rock salt but sometimes of overpressured shale. Unlike salt, the efficiency of detachment in shale depends on the magnitude of fluid overpressures and it varies through time and space, as rapid sedimentary burial progrades into deeper water. As a result, the gravity deformational domains are progressively translated seaward. Sandbox models involving high air pore pressures were used to simulate such gravity-driven shale tectonics in prograding deltas. Models were built with sand of various permeabilities and air was injected to simulate the mechanical effects of fluid overpressure. Our apparatus for the injection of air allowed us to control subsurface pressures in space and time during the experiments, and it was used to simulate the advance of the front of the overpressured domain during the sedimentary progradation. In our models, sand kept obeying a frictional behavior, for medium to high pore pressures, and the detachment appeared as very thin shear bands. Compressional belts that formed during the experiment were dominated by asymmetric basinward-verging fore-thrusts, as is often observed in deep-water, shale-detached foldbelts. Where the value of fluid pressures approached that of the lithostatic stress, sand was fluidized, resulting in ductile strains analogous to what occurs in highly overpressured mobile shale. During progradation, ancient buried thrustbelts were reactivated, thereby controlling later extension. During the experiments, sand volcanoes, analogous to mud volcanoes, formed in relation with tectonic structures. Some of them developed near normal faults but many of them formed directly above old buried thrusts.

1. Introduction

Many continental passive margins exhibit a gravitational deformation of the post-rift cover. This deformation often results from a combination of gravity gliding and gravity spreading (Schultz-Ela, 2001; Rowan et al., 2004), accommodated by proximal extension and distal shortening of the sediments. At the base of the sliding sediments, the *décollement* layer can consist of post-rift salt or shale that is overpressured. Detachments on salt occur in the Nile deep-sea fan (Gaullier et al., 2000; Loncke et al., 2006), the Atlantic margins of Mauritania, Angola (Brun and Fort, 2004; Fort et al., 2004) or the Mississippi fan and the northern Gulf of Mexico (Wu et al., 1990; Rowan, 1997; Rowan et al., 2004). In the Niger Delta (Weber and Daukoru, 1975; Morley and Guerin, 1996; Cohen and McClay, 1996; Hooper et al., 2002; Corredor et al., 2005; Briggs et al., 2006), the Amazon fan (Cobbold et al., 2004) or the Mexican ridges (Weimer and Buffler, 1992), the detachments stand in shale that is probably overpressured. By carrying part of the weight and so reducing the frictional resistance at the base of the sediments, the fluid overpressures allow the cover to glide on gentle delta slopes.

Rowan et al. (2004) showed that the structural style of the contractional fold belts depends largely on the nature of the *décollement* layer. Salt is often considered as a viscous material having a very low strength. Consequently, it starts to deform very soon after its deposition. It leads to symmetric detachment folds, shortened salt diapirs and/or inflated and thickened salt massifs and nappes (Rowan et al., 2004; Fort and Brun, 2005). In the case of shale, contractional thrust and fold belts are dominated by asymmetric, basinward-verging thrust imbricates and multiple detachment levels (Briggs et al., 2006). The main difference between salt and shale comes from their rheology. Salt rheology does not change with temperature, depth of burial or strain. Its rheological behavior does not vary much through time and space. On the contrary, shale is a plastic material and its strength greatly depends on the magnitude of the pore fluid overpressure. If shale is highly overpressured and undercompacted, it becomes mobile and deforms under low stresses, rising by hydrofracturing the overburden and producing diapirs and mud volcanoes (Morley and Guerin, 1996; VanRensbergen and Morley, 2000; VanRensbergen and Morley, 2003; Deville et al., 2006). If shale is moderately overpressured or more compacted, it becomes more

* Corresponding author.
E-mail address: Regis.Mourgues@univ-lemans.fr (R. Mourgues).

0040-1951/$ – see front matter
doi:10.1016/j.tecto.2009.05.003

rigid and frictional and the detachments take the appearance of thin shear zones or faults (sharp detachment)(Morley and Guerin, 1996; Briggs et al., 2006).

In a sedimentary basin, fluid overpressure can result from several mechanisms (Osborne and Swarbrick, 1997; Swarbrick et al., 2002) that are mainly controlled by the depth of burial. Fluid overpressures may result from a reduction in the pore space, caused by diagenesis or compaction during burial or horizontal compression of tectonic origin. They also result from an increase in the volume of pore fluid resulting from thermal dilation, mineralogical transformation (smectite to illite) and hydrocarbon generation (for example, production of thermogenic gas at depths of over 5 km) (Barker, 1990; Cobbold et al., 2004). As soon as the generating mechanism stops, abnormal pressures tend to dissipate because the rocks are permeable (Neuzil, 1986). As a result, overpressures occur at depth; they are likely to be transitory and they may vary in space and time.

At basin scale, the front of the overpressured domain may advance basinward as sediments prograde seaward. As a result, the gravity deformational domains progressively migrate into deeper water (Fig. 1). The basinward limit of this deformation may not only be controlled by the sedimentary wedge (McClay et al., 1998; Vendeville, 2005) but also by the boundary between overpressured and normally pressured shale, because of the increasing resistance to sliding.

For the last two decades, salt and shale tectonics have been invariably studied with sandbox modeling by using silicone putty as a *décollement* layer (Cobbold and Szatmari, 1991; Vendeville and Jackson, 1992; Koyi, 1996; Ge et al., 1997a,b; McClay et al., 1998; Gaullier et al., 2000; Brun and Fort, 2004; Fort et al., 2004; Gaullier and Vendeville, 2005; Vendeville, 2005). Such viscous analogue material is probably well suited for salt whose rheology remains constant through time, but it appears inadequate to simulate the deformations of shale that is highly space and time-dependent.

For several years, a new analogue technique involving pore fluid has begun to prove itself. This new technique consists of injecting compressed air in sandbox models to reduce effective strength of materials and produce efficient detachments. The first tests were carried out by Cobbold and Castro (1999) and Cobbold et al. (2001) performed the first compressional experiments. Mourgues and Cobbold (2003) have also used such models for demonstrating the significance of seepage forces in tectonics. More recently, the technique was improved by Cobbold et al. (2004), Mourgues and Cobbold (2006a,b) and was successfully applied to verify some of the theoretical predictions for thrust wedges containing fluid overpressures (Cobbold et al., 2009) and for gravitational spreading and gliding above overpressured *décollements*. Mourgues and Cobbold (2006a) used an apparatus which allowed them to control the distribution of fluid pressure in the models and thus, gravitational instabilities of any desired shape could be triggered.

In this paper, we further explore the potential of this method by applying it to the complexity of shale tectonics and particularly to the gravitational instabilities in prograding deltas. We start by briefly describing the thin-skinned deformation resulting from slope instabilities in the Niger Delta where overpressured shale provides the necessary basal detachment. Then, we discuss the scaling of models involving pore fluid and we introduce a new apparatus that allows us to control the pore fluid pressures in space and time in basin scaled models. Several experiments of prograding deltas are presented and are used for discussing some aspects of shale tectonics and the advantages versus the limits of this analogue technique.

2. Gravity shale tectonics: example from the Niger Delta

The Niger Delta is a good example of a regional gravity shale-tectonics system and is one of the most prolific hydrocarbon provinces. The delta is located in the Gulf of Guinea (central West Africa) and it is one of the largest modern delta-systems in the world (Weber and Daukoru, 1975; Cohen and McClay, 1996; Hooper et al., 2002; Briggs et al., 2006). It sits at the southern end of the Benue trough formed during the Cretaceous opening of the South Atlantic. During Cretaceous, the Benue trough progressively filled with Albian and younger post-rift deposits and by the late Eocene, a delta began to prograde over the continental margin (Doust and Omatsola, 1989) The delta now consists of a broadly arcuate sedimentary prism some 12 km thick and covering 140,000 km^2 (Hooper et al., 2002). At the base of the Tertiary section of the Niger Delta is the Akata Formation which is of marine origin. It is composed of thick shale sequences that are believed to contain source rocks, ranging in thickness from 2000 m at the distal part of the delta to 7000 m beneath the continental shelf. This unit exhibits anomalously low P-wave seismic velocities that may reflect regional fluid overpressures (Corredor et al., 2005) and it provides a good detachment horizon for large gravity tectonics.

The Niger Delta is divided in two main lobes separated by the Charcot Fracture Zone, a prominent ridge of oceanic basement. Deformation in the delta has resulted from gravitational thin-skinned instabilities that formed various structural zones (Fig. 2a,e) (Damuth, 1994; Corredor et al., 2005). An extensional province, on land and in shallow water, is characterized by both basinward dipping and counter-regional listric normal growth faults. Basinward of the extension zone is a diapir zone that exhibits passive, active and reactive mud diapirs that form mud volcanoes at the seafloor (Graue,

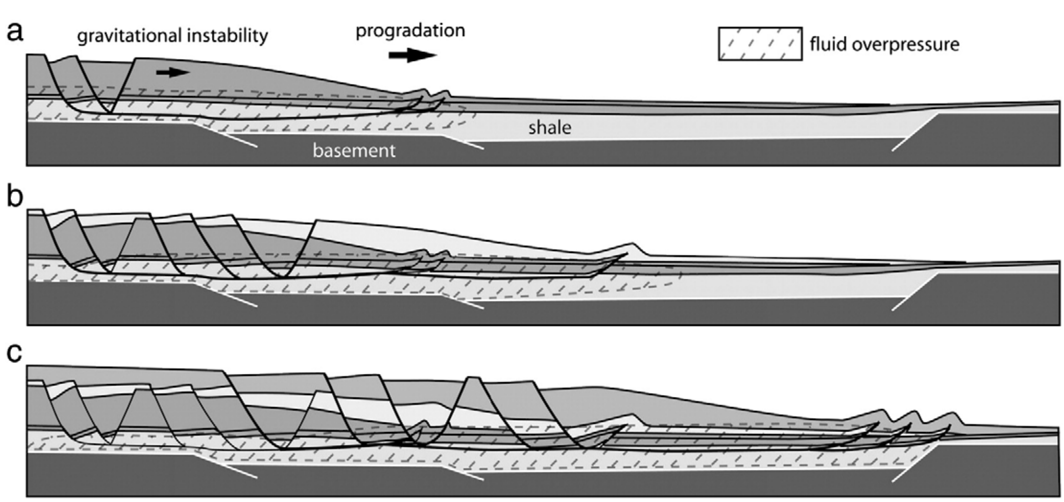

Fig. 1. Evolutionary model of fluid overpressure and gravitational deformation in a prograding delta. Whatever the generating mechanism may be (compaction or hydrocarbon generation), the front of the overpressured domain may advance basinward as sediments prograde seaward.