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High-resolution record of tectonic and sedimentary processes in growth strata

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ABSTRACT

Growth strata are used to determine the kinematics of synsedimentary structures such as faults. Classical methods of analysis such as thickness versus throw plot consider that the available space created by fault slip in the hanging wall of faults is instantaneously filled up by sediments. This has lead many previous works to identify a cyclic activity for growth faults. Here we perform a careful analysis of the variation of strata thicknesses on each side of a very well documented normal growth fault in the Niger delta. We show that these thickness variations are induced by the alternation of sedimentary processes during continuous fault slip. Suspended-load processes induce either uniform or slightly variable thickness of a large majority of mudstone layers. Bedload processes result in a preferential thickening of sand layers in the hanging wall. These high quality data thus provide strong grounds for doubting the polycyclic growth diagnosed for some faults at the scale of sedimentary cycles and supports the notion that fault displacement rates can be very well behaved. Our study emphasizes the important conclusion that stable fault growth, and related displacement rates, can appear to be punctuated when viewed at the scale of sedimentary cycles. It follows that care should be taken when attempting to derive displacement rates on temporal scales equivalent to those of alternating sedimentological cycles.

1. Introduction

Since growth strata are defined as strata with thickness variations across faults, a synsedimentary fault can be defined as a fault for which incremental displacements have created a fault scarp at the Earth surface. Each incremental displacement of the fault is therefore synchronous with the sedimentary processes of erosion, transport, and sedimentation. Consequently, the degree to which fault evolution induces disturbances of the surface processes is controlled by the ratio between the height of the incremental fault scarp versus the nature and magnitude of the operating sedimentary processes (e.g. volume, thickness, velocity, turbulent/laminar flow, suspended/traction load).

Synsedimentary normal faults (Fig. 1a) originate at crustal scale due to long-term plate movements and at smaller scales in relation with the spreading of a sedimentary cover on a décollement layer (e.g. Edwards, 1976; Price, 1977; Coleman and Prior, 1978; Crans et al., 1980; White et al., 1986; Jackson and White, 1989; Childs et al., 1993; Doglioni et al., 1998; Dawers and Underhill, 2000; Morley et al., 2000; Back et al., 2006).

In the case of gravity-driven tectonics, the long-term behaviour of normal faults over several millions of years is controlled by (1) the evolution of the nature and quantity of the sediment supply and its implications for sedimentary loading and overpressure (e.g. Bruce, 1973; Vendeville and Cobbold, 1988; Ge et al., 1997; Mauduit and Brun, 1998; Gaullier and Vendeville, 2005), (2) the rheology and thickness of the décollement layer (shale versus salt for example) (e.g. Dula, 1991; Childs et al., 1993; Hardy and McClay, 1999; Vendeville, 2005) and (3) the topography of the basement (regional and local slope) (e.g. Crans et al., 1980; Koyi, 1991; Koyi et al., 1993; Mauduit et al., 1997; Loncke et al., 2006).

At higher frequencies of thousands to hundreds of thousand years the interactions between fault evolution and sedimentary process still remains less understood partly because, at these time scales, it is difficult to assess one independently of the other. However, numerous studies have considered that synsedimentary faults can react immediately to sedimentary loading variations. In this view, an increase of sedimentation rate induces an increase of fault displacement, and a decrease of sedimentation rate (i.e. of sedimentary loading) can lead to fault quiescence (e.g. Lowrie, 1986; Cartwright et al., 1998; Bhattacharya and Davies, 2001; Brown et al., 2004).

The main objective of the present work is to deconvolve the very high-resolution temporal and vertical evolution of the throw on

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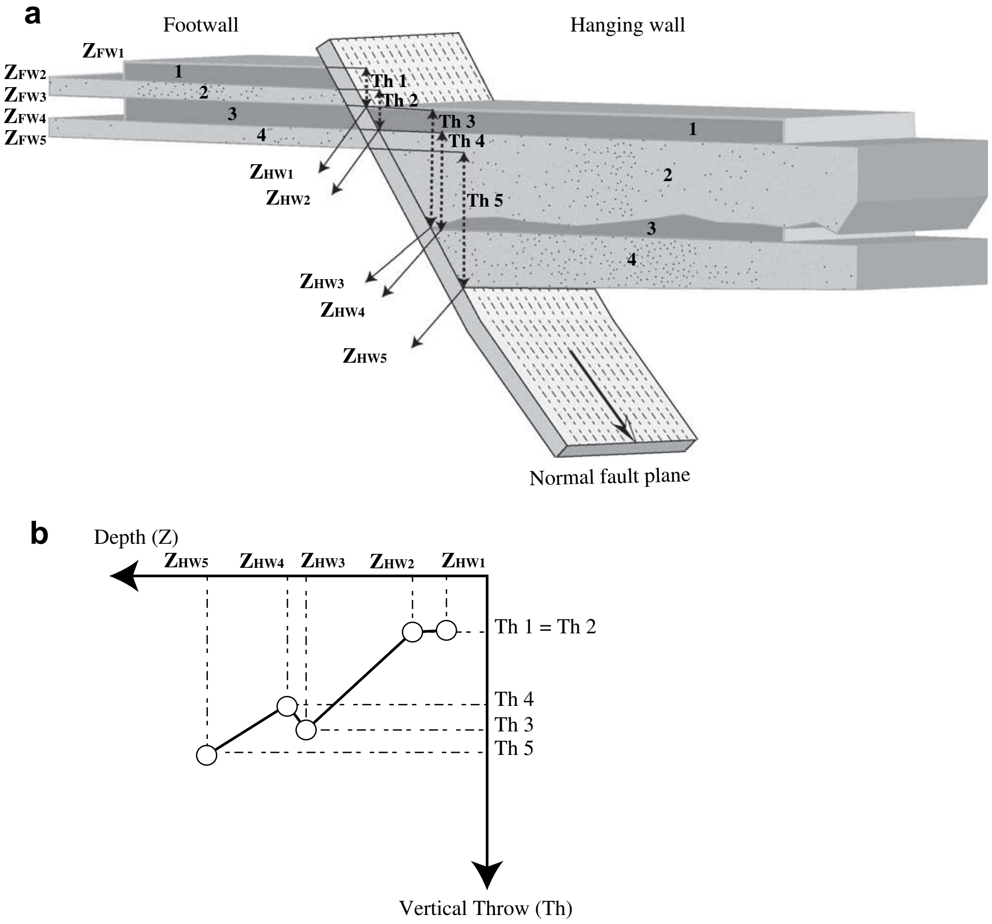

Fig. 1. Signification and construction of a theorical Th–*z* plot curve: a) Cross-section of a synsedimentary normal fault with growth strata in the hanging wall. $Z_{\mathrm{HW}\ 1\text{–}5}$ and $Z_{\mathrm{FW}\ 1\text{–}5}$ represent the depth of each sedimentary layer limit in the hanging wall and on the footwall respectively. Th1 to Th5 represent the vertical throw of each sedimentary layers limit between the footwall and the hanging wall. b) Vertical throw (Th) versus depth of sedimentary layers in the hanging wall (Z_{HW}) or for the rest of this paper Th–*z* plot diagram. Note that such a diagram generally shows numerous changes in slope values from positive, null to negative slope which reflects highly variable behaviour in the thicknesses of growth strata between each compartment of the fault.

a well documented normal fault in order to understand the evolution of the long-term to short-term fault movement and the influence of the nature of sedimentary processes (suspended-load, bedload, erosion) on the geometry of the syntectonic layers. We show that high-frequency variations of the growth strata thicknesses across the studied fault are primarily controlled by variations of sedimentary processes and dynamics.

2. Determining fault kinematics from growth strata: an overview

The analysis of the variation of growth strata thickness across a synsedimentary structure allows in principle the reconstruction of its kinematics. For example, the Expansion Index (EI) established by Thorsen (1963) measures the ratio of thickness variation between the layers on the footwall and in the hanging wall of a synsedimentary normal fault (Fig. 1a):

$$\mathrm{EI} = \frac{\mathrm{HWt}}{\mathrm{FWt}} \qquad (1)$$

with HWt and FWt corresponding to the thickness of the layers in the hanging wall and the footwall respectively. EI $>$ 1 represents a thickening in the hanging wall. Thus, assuming that sedimentation rate is constant over the footwall, positive and variable values of EI (i.e. increase or decrease of HWt relative to FWt) can be directly related to variations of the fault movement rate (Hardin and Hardin, 1961; Thorsen, 1963).

The Th–*z* plot (Fig. 1a, b) is a graphical method which simply consists in plotting, for each horizon, the vertical throw Th of a stratigraphic marker versus its depth *z* in the hanging wall (Tearpock and Bischke, 1991; Bischke, 1994) (Fig. 1a, b). This kind of plot generally shows alternation of segments of positive, null and negative slopes which directly reflect variations in the degree of thickening of the strata towards the hanging wall (Bischke, 1994; Mansfield and Cartwright, 1996; Cartwright et al., 1998; Castelltort et al., 2004a, b; Pochat et al., 2004; Back et al., 2006; Baudon and Cartwright, 2008) (Fig. 1b).

If the sedimentation rate in the hanging wall always exceeds the fault displacement rate (“fill-to-the-top” model) the Th–*z* plot can be used to constrain the displacement history of synsedimentary faults (Tearpock and Bischke, 1991; Bischke, 1994; Mansfield and Cartwright, 1996; Cartwright et al., 1998). Thickening of strata towards the hanging wall indicates a period of fault activity (positive slopes, between Z5–Z4 and Z3–Z2 in Fig. 1b), non-thickened intervals indicate periods of fault quiescence (null slopes, between Z2 and Z1 in Fig. 1b), and negative slopes (between Z4 and Z3 in Fig. 1b) may indicate fault linkage (Tearpock and Bischke, 1991; Bischke, 1994; Mansfield and Cartwright, 1996; Cartwright et al., 1998) or fault inversion (Castelltort et al., 2004b). Castelltort