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Salt geometry influence on present-day stress orientations in the Nile Delta: Insights from numerical modeling

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A B S T R A C T

The offshore Nile Delta displays sharply contrasting orientations of the maximum horizontal stress, S_H, in regions above Messinian evaporites (suprasalt) and regions below Messinian evaporites (subsalt). Published stress orientation data predominantly show margin-normal suprasalt S_H orientations but a margin-parallel subsalt S_H orientation. While these data sets provide the first major evidence that evaporite sequences can act as mechanical detachment horizons, the cause for the stress orientation contrast remains unclear. In this study, 3D finite element analysis is used to investigate the causes for stress re-orientation based on two different hypotheses. The modeling study evaluates the influence of different likely salt geometries and whether stress reorientations are the result of basal drag forces induced by gravitational gliding or whether they represent localized variations due to mechanical property contrasts. The modeling results show that when salt is present as a continuous layer, gravitational gliding occurs and basal drag forces induced in the suprasalt layers result in the margin-normal principal stress becoming the maximum horizontal stress. With the margin-normal stress increase being confined to the suprasalt layers, the salt acts as a mechanical detachment horizon, resulting in different S_H orientations in the suprasalt compared to the subsalt layers. When salt is present as isolated bodies localized stress variations occur due to the mechanical property contrasts imposed by the salt, also resulting in different S_H orientations in the suprasalt compared to the subsalt layers. The modeling results provide additional quantitative evidence to confirm the role of evaporite sequences as mechanical detachment horizons.

1. Introduction

The offshore Nile Delta is the largest clastic wedge in the Mediterranean Sea region and represents a typical tertiary delta. It was created by an influx of clastic sediments from the Nile River since the late Miocene (Badawy, 2005). Due to the tectonic activity since the Cenozoic, the Nile Delta is composed of two separate clastic delta systems: an inert Jurassic-Miocene delta system located in the lower part and an active Pliocene–Holocene delta system deposited in the upper part (Sestini, 1989). An unconformity comprised of Messinian evaporites isolates the two systems (Marten et al., 2004). As a result the offshore Nile Delta is characterized by both typical deltaic structures (e.g. listric-growth faults and rotational block faults) and salt-associated structures (such as normal and strike-slip faults, folds, collapsed depocenters, and polygonal mini-basins), which have been discovered in sequences above Messinian evaporites (Loncke et al., 2006). Due to their low shear strength, evaporite layers in sedimentary basins have been considered to act as a mechanical detachment layer (e.g. Davis and Engelder, 1985; Bell, 1996; Bowers, 2007; Tingay et al., 2011), decoupling the stress regimes in the overlaying (termed suprasalt) and underlaying (termed subsalt) sequences. Data available from the North Sea (Grollimund et al., 2001), the Jeanne D'Arc Basin offshore Canada (Courel and Bell, 1996) and the North German Basin (Roth and Fleckenstein, 2001) show different stress orientations of sedimentary regions structurally attached vs. regions structurally detached from the basement rocks. Yet, as summarized and stated by Tingay et al. (2011), most of these data sets only represent suprasalt sequences and hence conclusive evidence to support this hypothesis was not present. In their study, Tingay et al. (2011) presented stress orientation data of the maximum

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horizontal stress, S_H, from 44 wells in the offshore Nile delta showing sharply contrasting stress orientations (~90° variations) in supra-vs. subsalt layers. Wells drilled through sequences with evaporates either show a NNE–SSW suprasalt S_H orientation in field A (i.e. margin-normal; Fig. 1a), but an ESE–WNW subsalt S_H orientation (i.e. margin parallel; Fig. 1a), or show ESE–WNW S_H in suprasalt sequences (i.e. margin-parallel; Fig. 1b), but a NNE–SSE S_H below the Messinian evaporites in field B (i.e. margin-normal; Fig. 1b). These data sets provide the first major evidence that evaporite sequences can act as mechanical detachment horizons (Tingay et al., 2011, 2012).

For a clearer understanding of the data presented by Tingay et al. (2011, 2012), the typical stress field characteristics of a clastic wedge in a deltaic region is reviewed and illustrated (Fig. 2a; adopted from Tingay et al. (2012)). For such systems, the delta shelf province (on the continental side) has an extensional stress regime, where S_H orientations are margin-parallel and normal faulting prevails, and the delta toe province (on the sea side) has a compressional stress regime, where S_H orientations are margin-normal and thrust faulting exists (Bell, 1996; King and Backé, 2010; Tingay et al., 2011, 2012). Stress data from the Nile delta supports this model for wells in the eastern Nile Delta

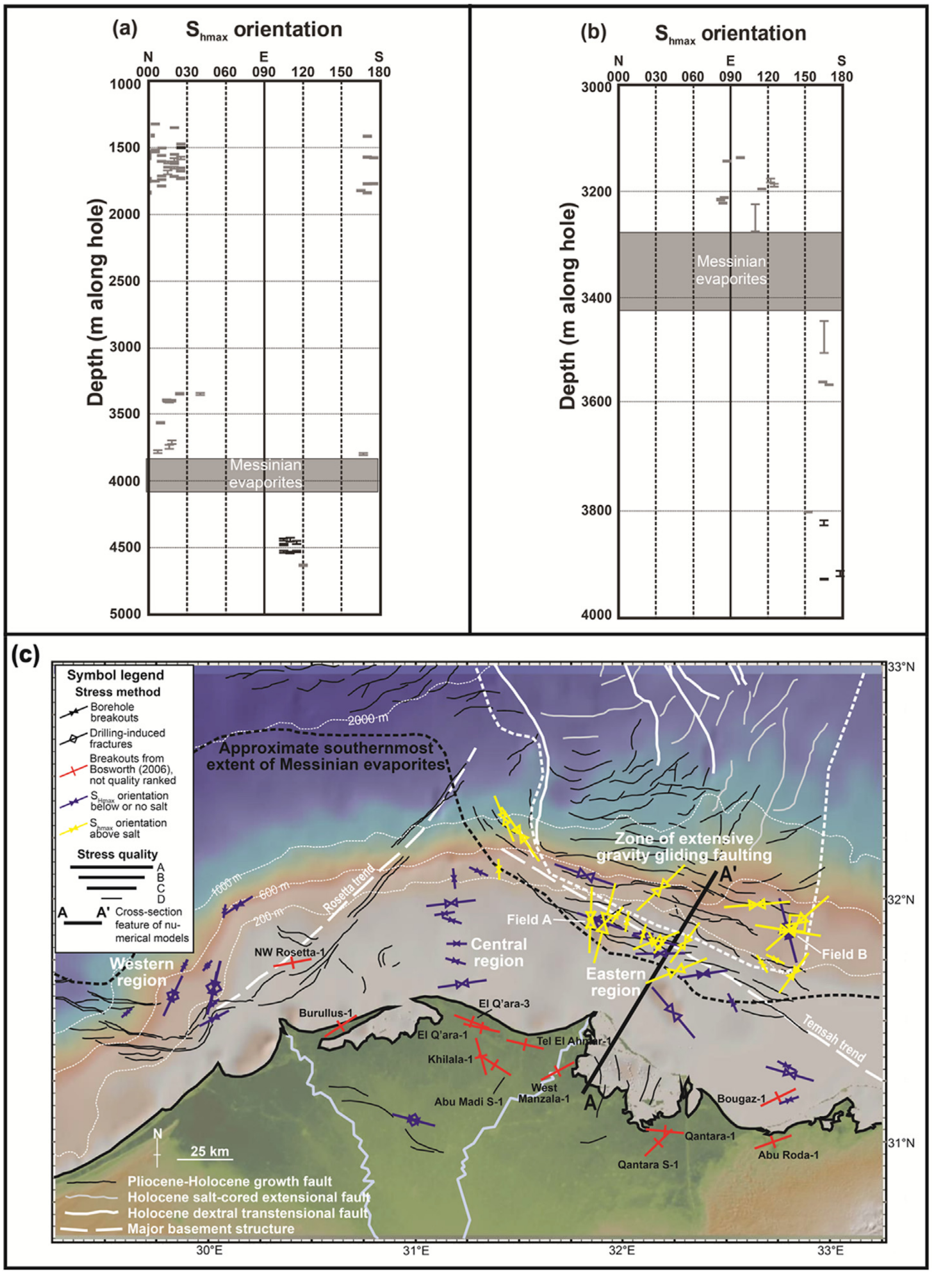

Fig. 1. a) S_H orientations for field A showing suprasalt margin-normal and subsalt margin-parallel orientations (data from Tingay et al., 2011). b) S_H orientations for field B showing suprasalt margin-parallel and subsalt margin-normal orientations (data from Tingay et al., 2011). c) Map of the offshore Nile Delta (from Tingay et al., 2011) showing stress orientation data from the World Stress Map (Heidbach et al., 2008) and from Bosworth (2006). Suprasalt stress data are shown in yellow, subsalt orientations in dark blue. The map also features the outline of the Messinian evaporites and the zone of gravitational gliding containing typical growth faults. The line A – A′ represents the approximate cross-section featured in the finite element models. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)