Shale mobility: From salt-like shale flow to fluid mobilization in a gravity-driven deformation, the Late Albian-Turonian White Pointer Delta (Ceduna Basin, Great Bight, Australia)

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Abstract:
Large offshore depocenters above a weak detachment level (either salt or shale) can undergo gravity spreading and/or gliding. The gravitational systems (e.g. gliding deltas) are classically composed of an up-dip domain affected by extensional listric normal faults and a down-dip domain affected by toe thrusts. While the role of salt in such systems is a classic of tectonic lesson, the role and mechanical behavior of mobile shale levels in shale-prone gravity driven systems are increasingly questioned. A 3D seismic dataset in the Ceduna sub-basin displays the Late Albian-Turonian White Pointer Delta (WPD) as having an unusual diversity of shale-cored structures. The early flow of shale results in depocenters showing wedges, internal unconformities, and shale diapirs and ridges, while fluidization of shales underneath a significant burial results in mud volcanism, secondary radial fault sets and collapse features beneath the Campanian-Maastrichtian Hammerhead delta (HHD) which lies above the WPD. Massive shale mobilization together with downdip shortening and a distal margin uplift localizes a major thrust in the core of the basin ending the downward propagating failure of the WPD. Mobilization of thick shale intervals, either as salt-like flow or mud volcanism, appears as a key process of deformation to be considered at large scale for worldwide gravity-driven deformation systems.
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ABSTRACT

Large offshore depocenters above a weak detachment level (either salt or shale) can undergo gravity spreading and/or gliding. The gravitational systems (e.g. gliding deltas) are classically composed of an up-dip domain affected by extensional listric normal faults and a down-dip domain affected by toe thrusts. While the role of salt in such systems is a classic of tectonic lesson, the role and mechanical behavior of mobile shale levels in shale-prone gravity driven systems are increasingly questioned. A 3D seismic dataset in the Ceduna sub-basin displays the Late Albian-Turonian White Pointer Delta (WPD) as having an unusual diversity of shale-cored structures. The early flow of shale results in depocenters showing wedges, internal unconformities, and shale diapirs and ridges, while fluidization of shales underneath a significant burial results in mud volcanism, secondary radial fault sets and collapse features beneath the Campanian-Maastrichtian Hammerhead delta (HHD) which lies above the WPD. Massive shale mobilization together with downdip shortening and a distal margin uplift localizes a major thrust in the core of the basin ending the downward propagating failure of the WPD. Mobilization of thick shale intervals, either as salt-like flow or mud volcanism, appears as a key process of deformation to be considered at large scale for worldwide gravity-driven deformation systems.
INTRODUCTION

Development of large sedimentary deltas on passive margins is often associated with gravity-driven collapse (e.g. Rowan 2020; McClay et al., 2003), which is controlled either by pure gliding/spreading, or a combination of both, above a ductile decollement level, usually made up of evaporites or mobile shales (Peel 2014). Gravity collapse shows three main domains connected by a basal detachment: (1) an up-dip extensional domain associated to listric normal growth faults, (2) a translational domain showing symmetrical structures (e.g. rafts, turtle structures, etc.) and (3) a down-dip compressional fold and thrust belt (Morley et al., 2011; Rowan et al., 2000; 2004; Schultz-Ela, 2001; Hudec and Jackson, 2004). Evaporite properties allow for an efficient decoupling in any condition, but shale levels are considered to be mobile only when overpressured (e.g. Mourgues and Cobbold, 2006).

Overpressurization is commonly attributed to compaction disequilibrium, resulting either from rapid sedimentation of low permeability materials, or fluid generation and expansion (e.g. hydrocarbon maturation, clay diagenesis, Tingay et al., 2007; Morley et al., 2018; Blouin et al., 2020). However, alternative explanations to this phenomenon have also been proposed (such as a decrease of friction coefficient due to graphite, Rutter et al., 2013) as it partly fails to explain mobilization of shales having already gone under significant burial, as well as fluidization of clays (Soto et al., 2021). Gravity-driven collapse related to shale mobilization is observed in many regions including the South Atlantic Margins (e.g. Niger Delta, Amazon Fan), the South Australia Margin (Ceduna Sub-Basin), the Southeastern Asia and Indian Ocean margins (e.g. Baram and Rovuma Deltas, Krishna Godavari domain), as well as in back-arc basins and compressional prisms (e.g. Alboran Sea, Venezuela and Makran prisms) (Ahmed et al., 2022; Hudec and Jackson, 2004; Choudhuri et al., 2010; Reis et al., 2010; Ruh et al., 2018; Soto et al.,
Involvement of salt-like deformation in shale tectonics (e.g. diapirs, minibasins, welds, etc.) has long been debated, following developments of deep offshore seismic acquisition on the one side, improvement of seismic imaging and processing techniques on the other (Morley and Guérin, 1996; Soto and Hudec 2021; Soto et al., 2021a, b, among others). Understanding of shale mechanics helped to set the ground for understanding the ability of already compacted and cemented shales to behave in a viscous manner (Brown, 1990; Soto et al., 2021a) and salt-like shale tectonics was put at the forefront in various settings recently (e.g. Hudec and Soto 2021; Dinc, 2020; Back and Morley 2016; Ruh et al., 2018).

Our study gives insights into the involvement of massive shale mobilization, over more than $10^5$ km$^2$, during the development of the Ceduna Sub Basin which consists of two structurally independent and yet laterally stacked deltas, namely the Albian to Cenomanian White Pointer Delta and the Campanian to Maastrichtian Hammerhead Delta (WPD & HHD) above thick shale detachments (figure 1, Espurt et al., 2009; Totterdell et al., 2000; Ahmed et al., 2022). Here we focus on the WPD, which has been subjected to shale mobilization all along its development, evolving from salt-like shale flow to fluidization.

**GEOLOGICAL SETTING**

The Great Bight Basin (GBB) is part of the south Australia passive margins. The offshore portion of it is composed of five sub-basins, among which the Ceduna Sub-Basin stands as a Late Jurassic-Early Cretaceous rifted basin, covered by a maximum of 15 km of Late Jurassic to Late Cretaceous sediments, which propagated the break up during Early Cretaceous between Australia and Antarctica (figure 1). The post-rift succession starts with the continental, Berriasian-Lower
Valanginian Southern Right and Valanginian to Mid Albian Bronze Whaler megasequences (Totterdell et al. 2000).

The Ceduna Sub-basin gravity-driven and collapsing deltaic supersequences initiated during the Late Albian-Santonian marine WPD, which involved massively the Albian Blue Whale shale detachment (BW, figure 1B1, Espurt et al., 2009). This megasequence is formed of two collapsing, gravity-controlled, systems (figure 1B2, see Ahmed et al., 2022 for a review). First, a Late Albian-Early Cenomanian gliding system (Ahmed et al., 2022), located in the core of the basin composed of a set of extensional up-dip listric faults, connected to the early downdip thrust faults. This collapse system is followed by a Late Cenomanian set of extensional listric faults initiating in the core of the delta and associated to down-dip thrust faults, offsetting the earlier thrusts, which form a buttress for the main collapse system and localizes the decollement of the secondary collapse system (Ahmed et al., 2022).

The deep margin uplift (Hill et al., 2019) results in the cessation of gravity gliding and a slight inversion phase for the WPD. The deposition of the Turonian-Santonian Tiger megasequence is coeval with the final separation of Australia and Antarctica (Totterdell et al., 2000), and the Late Santonian-Maastrichtian Hammerhead megasequence (HHD), starts to develop above the WPD.

DATA AND METHODS

The main dataset used in this study is the Ceduna PSDM 3D cube acquired by PGS in 2011. The survey covers an area of 12,413 km² with an inline and cross-line spacing of 12.5 m and 15 m respectively (see figure 1A for cube and lines orientation). On top of this Ceduna dataset, additional 2D seismic composite lines are used to connect the 3D survey up-dip to the nearest exploration wells to have seismic marker ties, and down-dip to the distal margin. The 2D
lines (used in particular to tie the cube to the existing well but not displayed in the figure) were extracted from the 2001 PSTM Flinders survey (lines w00fdw003, 0014 and 0023), 1997 AGSO 2D PSTM survey (line GA199-05B), and 1986 2D PSTM BMR 1986 survey (lines 065-07P1, 02P2, and 09P1) (Espurt et al. 2009; Totterdell and Bradshaw, 2004).

Three offshore wells have been used to tie the seismic picking to stratigraphic horizons, Potoroo-1, Jerboa-1 and Gnarlyknots-1A, which are located outside the 3D survey, yet crossed by the 2D regional lines (Totterdell et al., 2000; Dinc, 2020). Four key horizons are used in this study (figure 1D): the top Blue Whale (BW, Late Albian), the top White Pointer (Cenomanian to Early Turonian), the top Tiger (Late Turonian to Santonian), and the top upper Hammerhead (Maastrichtian). Based on the recent recognition of the early collapse system (BW to lower WPD, Ahmed et al., 2022), we also tracked three additional horizons: two within the WPD (the Top Lower-Mid WP and Top Mid WP), and one within the Tiger Formation (Mid Tiger), where they get available as they do not continuously extend and/or are poorly tied outboard the core of the Ceduna Sub-Basin.

RESULTS AND DISCUSSION

A representative inline (n°2150), together with a connecting xline (n°11000) (figure 1A) are displayed in figure 2, associated with two time slices from the 3D dataset, localized at 8km and 5km depth, i.e. cutting through the BW and the Upper WPD megasequences respectively (figure 3). In that perspective, the 8km depth time slice focuses on the first collapse system (Mid Albian to Early Cenomanian) whereas the 5km depth time slice investigates the late stage of evolution of the second collapse system (Early Cenomanian to Early Turonian).

Evidence of shale mobility
Evidence for salt-like shale mobility is mostly confined to the core of the Ceduna Sub-
Basin, where the phenomena is stratigraphically constrained to the early collapsed system
(Lower WPD). It mainly consists of low angle wedging observed at the edges of flat, low-
dipping depocenters, which abut chaotic ridges which are composed of mobilized shales (figure
2 A1-2, B1-2). These depocenters form pod-like minibasins with internal unconformities related
to their successive stages of growth. They present onlaps on the slopes of the ridges (Figure 2A1-
2, B2), similar to the shale-controlled minibasins observed onshore in the Makran (Ruh et al.,
2018). These minibasins are controlled by the ductile flow of the underlying BW shales, and
show an elongation parallel to the overall gliding direction (figure 3B1).

To the north, the proximal domain of the delta lacks good examples of minibasins.
However, when expressed, the top part of the depocenters localize the decollement horizon
responsible for the secondary collapse system development (figure 2A-A2-4). On the contrary,
within the distal domain of the WPD (figure 2B), these depocenters appear to be well expressed
and duplicated by a major thrust plane localized onto the BW detachment level (figure 2A, A1-2,
B2, figure 3A2, figure 4d-e). This part of the sub-basin shows extensive patterns of shale
mobilization controlling a large portion of Early WPD deposits downlapping onto the BW
shales. Above the duplexes, the transported depocenters show a more mature pattern, with
numerous welds and remnant of mobile shale masses separating the depocenters (figures 2B3-4).
Localization of the compressional deformation on these duplexes is associated with the decrease
of decollement depth and correlative of the translated listric fault spacing (figure 2B1).

Shale mobility is quickly abandoned and buried beneath the growing WPD as early as the
first stage of gravity collapse (Late Albian-Early Cenomanian), displayed by the abandonment of
the early minibasins, passively transported and buried (figures 2A-B). During their burial, these
early minibasins are crosscut and deformed in the distal part by the development of fold and thrusts related to the propagation of gravity collapse basinward. After the end of the WPD deposition, transported minibasins are progressively welded, squeezing the shale plugs (figure 2B). During the Upper Tiger deposition, domal uplifts (figure 2A5) show the development of sets of both radial and concentric normal faults (figure 3B1), which are stratigraphically bracketed during the deposition of the lower HH Formation, and rooted in the top WPD deposits. Polygonal faults system in the core of these radial normal faults sets, confined in this stratigraphic interval, suggest high overpressures and two types of shale mobilization, here involving fluidization (figure 3B1).

**Imbrication of gravity collapse: an updated scenario**

Both salt-like shale mobilization and shale fluidization together with the duplication of the early minibasins along thrust faults are key features, improving the delta kinematic scenario (figure 4). Following the deposition of the BW shales, early clastics of the lowermost WPD megasequence trigger shale mobilization in the distal part (e.g. Morley et al., 2018), resulting in the building of small, down-dip elongated, withdrawal minibasins similar to what is observed in the western Gulf of Mexico (McDonnell et al., 2010; figure 4a, b), while the early collapse system develops up-dip (figure 4b-c). During Early Cenomanian, the WPD early collapse system forms in the inner domain and progressively migrates downdip, reactivating early developed down-dip toe thrust (figure 4d). Buttressing against the early thrusts and deep margin uplift helps to localize the major thrust duplex within the thickest part of the basin during the deposition of the upper WPD sequence, duplicating the early minibasins (figure 4d-e). Although the ramp developed at the toe of the delta slows down the WPD collapse, it favors the focus of shortening above the major thrust and subsequent squeezing of the transported shale diapirs. This leads to
the final fluidization of the shales after Tiger deposition (figure 4e-g, Turonian). The entire WPD system eventually gets frozen beneath the HHD megasequence (figure 4h).

Controlling factors of shale mobility

Even though bowl-shaped, subsiding depocenters (i.e. minibasins bordered by rising chaotic mobile masses) are common features in salt tectonics, withdrawal depocenters related to mobile shales are less common, yet repeatedly proposed and generally attributed to overpressures and undercompaction during rapid sedimentation (e.g. Morley et al., 2018). In the case of early WPD deposits, we suggest that the early shale mobilization is not related to the overpressure with increasing burial depth due to clay dewatering, they are rather large mobile masses of poorly compacted, water-rich unconsolidated sediments, with low viscosity and density, mobilized early following their deposition, similarly to the olistostromes of the Makran Prism (Ruh et al., 2018). Early mobility is responsible for mechanical weakening of the shale masses by penetrative deformation, up to a critical state, while repeated input of sediments increases loading and pressurization and maintains the mobile shales at a critical state for plastic deformation (Soto et al., 2021; Hudec and Soto, 2021).

The late stage of shale mobilization, i.e. fluidization at the crest of squeezed shale plugs, occurs during the Turonian-Santonian time. This is coeval with generation of oil in the Blue Whale formation and gas within the synrift Bronze Whaler megasequence of the Jerboa-1 well (Ruble et al., 2001), which is considerably less buried than the core of the basin. Basin modelling of the Potoroo and Gnarlyknots wells suggest that the Turonian source rocks generated liquid products as early as Campanian (Toterdell et al., 2008). Oil and gas generation and migration most probably occurred much earlier within the deeper, gas prone synrift sequence, thus leaving time for gas to migrate and reach the shale plugs and withdrawal minibasins undergoing
shortening above the main thrust fault. Gas generation has a strong impact on the mechanics of shale, promoting the complete loss of cohesive resistance (Tingay et al., 2018; Blouin et al., 2020), a mechanism which may help shales to achieve critical state and enhance mobility (Soto et al., 2021a), eventually leading to fluidization and through fracturing processes, to loss of material.

CONCLUSION

The Great Bight Ceduna Sub-Basin displays a multi stage gravity collapse solely based on shale mobility, over an area of more than $10^5$ km$^2$, making the WPD one of the largest known example of its kind at present. Our study shows that early shale mobilization led to the formation of shale withdrawal minibasins at the distal part of the system, which eventually gets duplicated in response to the propagation of the WPD collapse. A second stage of mobilization allows for the fluidization of transported shale plugs due to hydrocarbon generation. More generally, our results emphasize the need to consider salt-like mobilization of shale as a mechanism involved in gravity-controlled tectonic systems and their evolution. Thus, even though salt and shales tectonics bear thus strong analogies, contrarily to salt tectonics (i.e. halokinesis), argilokinesis may involve a secondary deformation mechanism based on fluidization.

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FIGURE CAPTIONS

Figure 1. A) Geographic setting of the Ceduna Sub-Basin, location of the 3D data set (with displayed inlines and crosslines) and the utilized composite 2D regional seismic lines; B) Two
previously published interpretative cross-sections; C) Simplified lithostratigraphic chart and main targeted horizons.

Figure 2. A) Two interpreted 3D seismic lines located at the distal part of the delta (inline 2150), and B) cross view of the delta (xline 11000). A1 and A3) Examples of wedging patterns in the lower White Pointer. A4 and A5) Examples of intra minibasin unconformities; A2 and B1) Example of concentric normal faults above a shale plug. B1) The main zone of minibasin duplexation; B2) Example of wedging patterns in the lower White Pointer; B3) example of translated WPD rollers and depocenters.

Figure 3. Top: 5km depth slice cutting across the Top WP/Tiger megasequence. A1 Concentric rounded closures of translated minibasins. B1 Close up on the radial and concentric fault sets associated to polygonal faults in the core ontop a shale dome. Bottom: 8km depth slice showing the shale withdrawal minibasins base (lower WP). B2. Close up on the elongated withdrawal minibasins’ base.

Figure 4. Kinematic evolution scenario of Ceduna Sub-Basin, White Pointer Delta (for the sake of simplicity the double collapse system of the WPD is not fully sketched).

REFERENCES CITED


Response to the main comments and remarks by reviewers and Editor

Prof. J. Soto

Structures related to shale fluidification: Polygonal or radial faults around the culmination of shale diapirs are, by itself, non-diagnostic of fluidification. I recommend to revise the text in lines 143 to 145, for example, to better constrain the structures observed by the authors to document this process (e.g., fluid pipes, feeders and conduits for mud volcanoes, etc.).

We agree that polygonal cracks as well as radial faults may derive from other processes and that only fluid conduits and/or mud volcanoes would surely demonstrate the importance of the fluid role. Nevertheless, these features are quite common in fluid-controlled domains and rather scarce (apart from volcanics systems) elsewhere. However, mainly due to seismic resolution, those features have not been demonstratively been observed. On places such as the inline of figure 2, it may be suspected if zoomed accordingly (e.g. considering vertical succession of enhanced portion of the reflectors, ...), but we rather think that the observed association of stratigraphically bracketed polygonal fault system surrounded by radial and concentric faults is sufficiently well established and comparable to other fluidized shale systems (e.g. Nigeria, offshore Azerbaijan, ...) to propose that the same phenomenon has occurred too in the Ceduna Sub-basin as well.

Include some information about timing of the sequences in figures 1 and 2. Nowadays, it is rather difficult to correlate many of the statements in the text regarding timing with those illustrations, because these figures do not contain any information regarding the age of the sequences and/or the key reflectors.

This is right and the figures have been modified accordingly and the labelling referred too better in the body of the manuscript.

All remarks made on the associated pdf file have been taken into account.

Pau, September the 20th 2022,

On behalf of G. Dinc and co-author, JP Callot
Figure 4

Gravitational Cell 1: Formation of White Pointer Delta

Gravitational Cell 2: Formation of Hammerhead Delta

Imbricated Thrust Complex / Front of White Pointer Delta

Duplexed and Translated Thrust Media

Fault Legend:
- Active
- Inactivate

Stage 3: Late WPD
Stage 2: Mid WPD
Stage 1: Early WPD