

3D Seismic study of a shale expulsion syncline at the base of the Champion delta, offshore Brunei and its implications for the early structural evolution of large delta systems

P. Van Rensbergen*, C.K. Morley

Department of Petroleum Geosciences, University Brunei Darussalam, Brunei

Received 17 December 1999; received in revised form 26 May 2000; accepted 7 June 2000

Abstract

An example of a Late Miocene expulsion rollover syncline related to mobile shale is described from 3D seismic data offshore Brunei. Prodelta shales accumulated in the subsiding syncline were altered after deep burial by overpressure increase and hydraulic fracturing. Consequently seismic facies was modified from a continuous divergent reflection pattern to a low-amplitude, disrupted to chaotic seismic facies bounded by a high-amplitude event that cross-cuts original stratification. Without the resolution provided by 3D data, the high-amplitude event would be mistaken for early growth faults and the subdued country-rock reflections for mobile shale, typical features at the base of large deltas. This study shows the existence of expulsion rollovers related to mobile shale, which have not been described before, and demonstrates that not all bright reflections at chaotic-coherent facies boundaries are actually fault planes. It also suggests that expulsion synclines, even during early phases of delta development may be compaction-related features rather than ones that drive the shale mass out of the area of progradation. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: 3D Seismic study; Champion delta, Brunei; Mobile shale; Growth faults

1. Introduction

Thick shale sequences, especially in deltaic settings, are often overpressured or undercompacted. The primary overpressuring mechanism is disequilibrium compaction when pore fluids cannot escape at the rate necessary for the sediment to compact normally. The effect of disequilibrium compaction will dissipate with time and often secondary causes for overpressure need to be considered. Secondary overpressure mechanisms involve either pore space reduction (tectonic compression) or fluid volume increase, of which gas generation in mature, organic-rich shale is thought to be the most important (see review by Osborne & Swarbrick, 1997). In deltaic settings, overpressured prodelta shale constitutes the substratum for the prograding delta wedge. Analogous to salt, the overpressured shale is believed to be mobile and to respond to differential loading by shale withdrawal and shale diapirism. It is characterized

by a chaotic seismic facies that occurs in ridges, vertical intrusions and dome-shaped forms. The “mobile” shale contrasts with stratified prodelta shale, which is perceived as bedded and static. From 2D seismic interpretation and analogue models, biased by salt-related examples, it is suggested that shale expulsion from beneath the prograding delta creates delta-top grabens bounded by paired regional and counter-regional listric growth faults (Doust & Omatsola, 1990; McClay, Dooley & Lewis, 1998). Counter-regional faults occur near the delta front and often appear to detach over the landward flank of shale diapirs. The contrast in seismic facies between chaotic “mobile” shale and stratified overburden is typically used in seismic interpretation to locate the landward dipping fault. For example the association of structures, shale diapirs and paired regional and counter-regional growth faults, was described by Doust & Omatsola (1990) at the base of the onshore Niger delta as the main structure bounding large depobelts and has since inspired structural interpretation in deltaic provinces.

New 3D seismic data have enhanced the resolution of seismic studies. Some areas of poor to chaotic reflections on 2D data, when imaged on 3D data, reveal that while the chaotic regions are more weakly reflective and discontinuous than

* Corresponding author. Renard Centre of Marine Geology, Universiteit Gent, Krijgslaan 281-S8, 9000 Gent, Belgium. Tel.: +32-9-264-4590; fax: +32-9-264-4967.

E-mail address: pieter_vanrensbergen@yahoo.com
(P. Van Rensbergen).

surrounding areas, they do contain coherent data. Hence chaotic areas on 2D seismic data are not necessarily mobile shale but bedded shale, probably fractured by overpressured pore fluid and/or shale dyke intrusion (Van Rensbergen, Morley, Hoan & Lam, 1999). Early structures at the base of the delta are, on 2D seismic data, masked by this effect. As a result, the occurrence of mobile shale is overestimated and the variety of structural styles related to shale mobility has been poorly documented and limited to the classical examples of Doust and Omatsola (1990).

This paper describes an example of an expulsion rollover (Ge, Jackson & Vendeville, 1997) associated with shale tectonics as recognised on 3D data from offshore Brunei. On 2D seismic data the feature is masked because of dimming effects related to overpressure and used to be interpreted as a low-angle listric detachment over mobile shale. It is believed to be the first expulsion rollover, which has been identified in association with shale tectonics. Only recently have expulsion rollovers (synclines and anticlines) been recognised as salt features (see review in Ge et al., 1997) and only a few natural examples associated with salt have been described (Demercian, Szatmari & Cobbold, 1993; Mohriak et al., 1995; Ge et al., 1997).

The offshore area of Brunei is composed of thick Middle Miocene–Recent marine deltaic deposits up to 10 km thick, which display gravity structures associated with large deltas (growth faults, shale diapirs, toe thrusts) and (more unusually) inversion folds and thrusts related to episodic phases of compression (e.g. James 1984; Sandal 1996). The Champion delta is a Middle to Late Miocene system found on the eastern part of the Brunei shelf. The Baram delta is a Plio–Pleistocene system at the western part of the Brunei shelf. This study focuses on one of the early structural features associated with the Champion delta system. One dominant structural feature on this margin is the landward dipping (counter-regional) Perdana fault (Fig. 1). The expulsion rollover discussed in this paper occurs in the hanging wall of the Perdana growth fault at the base of the delta (Fig. 2).

For comparison, the discussion paragraph includes a brief description of the structure at the base of the outer part of the Baram delta, offshore Brunei. The Baram delta structure is much younger and undisturbed by effects related to extreme overpressure or Pliocene compressive tectonic pulses.

2. Data

The study is based on seismic data supplied by Brunei Shell Petroleum (BSP) which consist of a regional seismic line perpendicular to the shore and a post-stack time migrated 3D seismic survey covering part of the Perdana-Champion graben. The 3D dataset covers an area of 900 km² with a line and trace spacing of 25 m. The data were interpreted using Landmark Seisworks 3D software.

The study concentrated on the deeper part of the section between 3 and 5 s (about 4.8–8 km). Wells that penetrated the Peragam anticline provided information about lithology, depositional environment and approximate age correlation for some horizons. BSP also provided additional illustrations (selected screen dumps) of pre-stack migrated 3D data of the Perdana-Champion depocentre and of the outer part of the Baram delta.

3. Data description

3.1. General delta structure

The Champion delta has all the characteristics of a delta formed by differential loading of a mobile substratum. The delta toe consists of a succession of toe thrusts, which steepen landwards (Fig. 2). Intrusive mobile shale diapirs and pipes affect some of the thrusts, and become more frequent passing landwards. At the shelf edge, a series of counter-regional growth faults occur, of which the Perdana growth fault is the oldest and largest with an estimated maximum vertical offset of about 2.65 km. The Perdana growth fault is over 100 km long and probably continues into the eastern part of the Ampa shale ridge. It bounds the Perdana-Champion depocentre that accumulated about 4.5 s (about 6.75 km) of sediment since the Late Miocene and covers over 1400 km². Part of the depocentre lies in the adjacent territory of Sabah. The Perdana-Champion depocentre consists structurally and stratigraphically of a Late Miocene depocentre and a Plio–Pleistocene depocentre. The Plio–Pleistocene Perdana-Champion depocentre is a typical withdrawal graben bounded by paired counter-regional and regional growth faults. At its southeastern margin, the depocentre is bounded by a series of ‘en echelon’ regional growth faults (a.o. Amcott fault, Champion fault, ...). The growth section that expands into these faults dates from the Plio–Pleistocene. Some of the extensional structures, like the Amcott fault at the Iron Duke inversion anticline (Fig. 3), have been deformed in a series of compressional phases throughout the Pliocene. They form in this area the oceanward limit of tectonic deformation.

The Late Miocene depocentre has a half graben geometry, subsiding in the north and bounded in the south by the Late Miocene Peragam anticline. At the base, reflections exhibit an apparent downlap onto the sub-horizontal top of the acoustic substratum over a distance of about 9 km (Fig. 4). This top is a continuous, high-amplitude event (D-event) that can be traced in the southern part of the depocentre but is not properly imaged near the Perdana fault. According to the original interpretation from 2D seismic data, the apparent downlap resulted from continued subsidence along the early counter-regional growth faults at the base of the section (Fig. 2). The maximum differential subsidence measured between the Peragam anticline and the Late Miocene Perdana depocenter is approximately 2 s

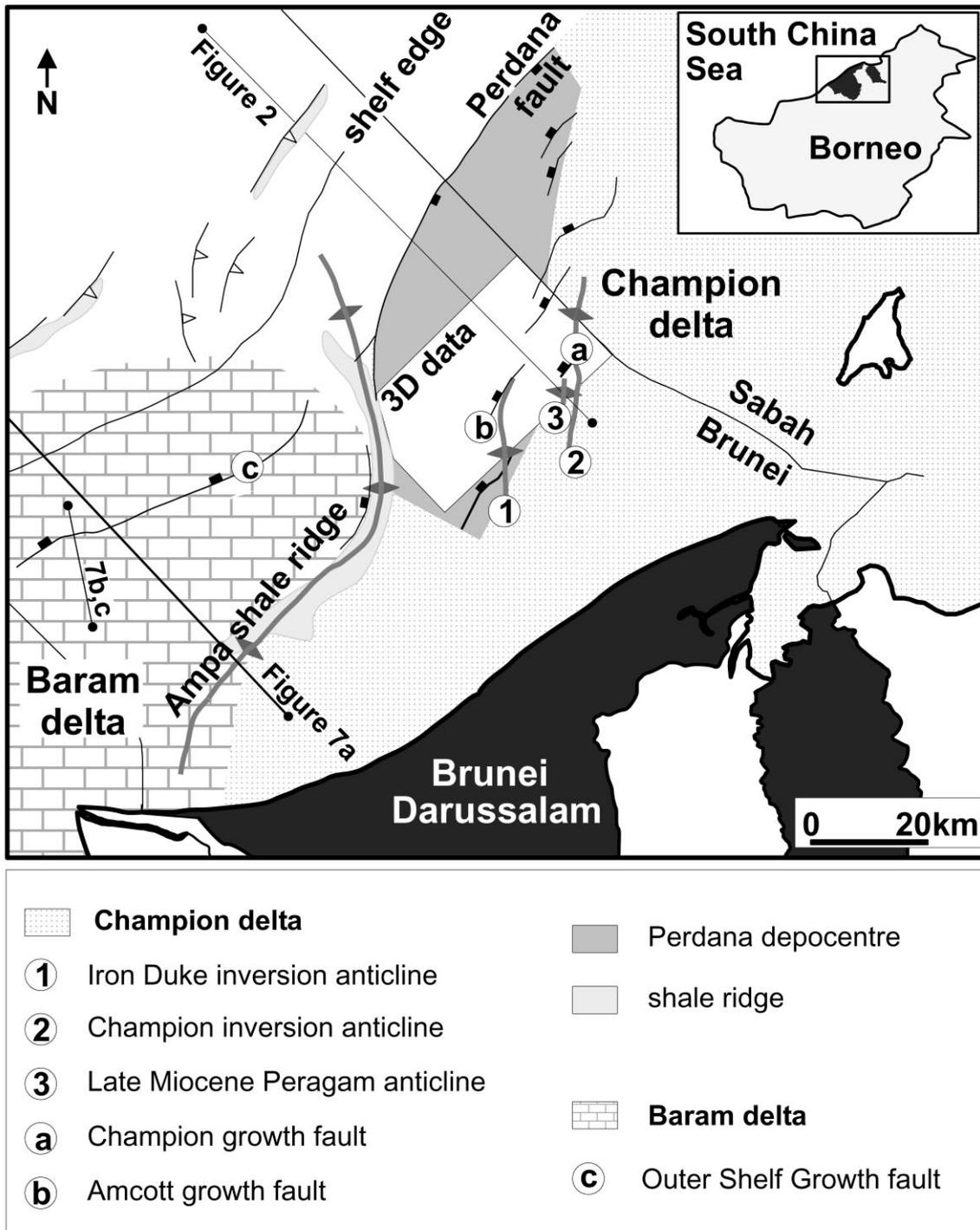


Fig. 1. Simplified structural map of offshore Brunei Darussalam. The 3D data used in this study (white box) are located north in the Perdana depocentre.

TWT (about 3 km). To the north, reflections converge and onlap a small anticlinal fold which occurs at the base of the large Pliocene Perdana growth fault (fig. 2).

4. 3D data description

The 3D data cover the southern part of the depocentre that

was active during the Late Miocene. The Late Miocene section is bounded by high-amplitude reflections at the base (Shell's V-horizons) and a continuous, erosional event at the top (Shell's K horizon, Figs. 3 and 4). The upper part of this section has a thickness ranging from 3 km in the north to 1.75 km at the Peragam anticline. The thinning is due to both decrease in accommodation space towards the anticline and erosion of the anticlinal

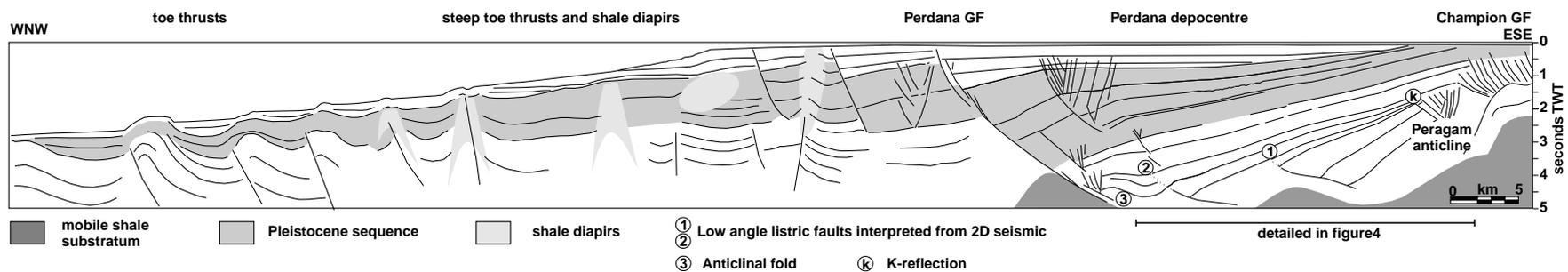


Fig. 2. Schematic cross-section of the Champion delta (see Fig. 1 for location) based on 2D regional seismic line. Faults 1 and 2 are listric normal faults interpreted from 2D data but do not actually appear to be present on 3D data.

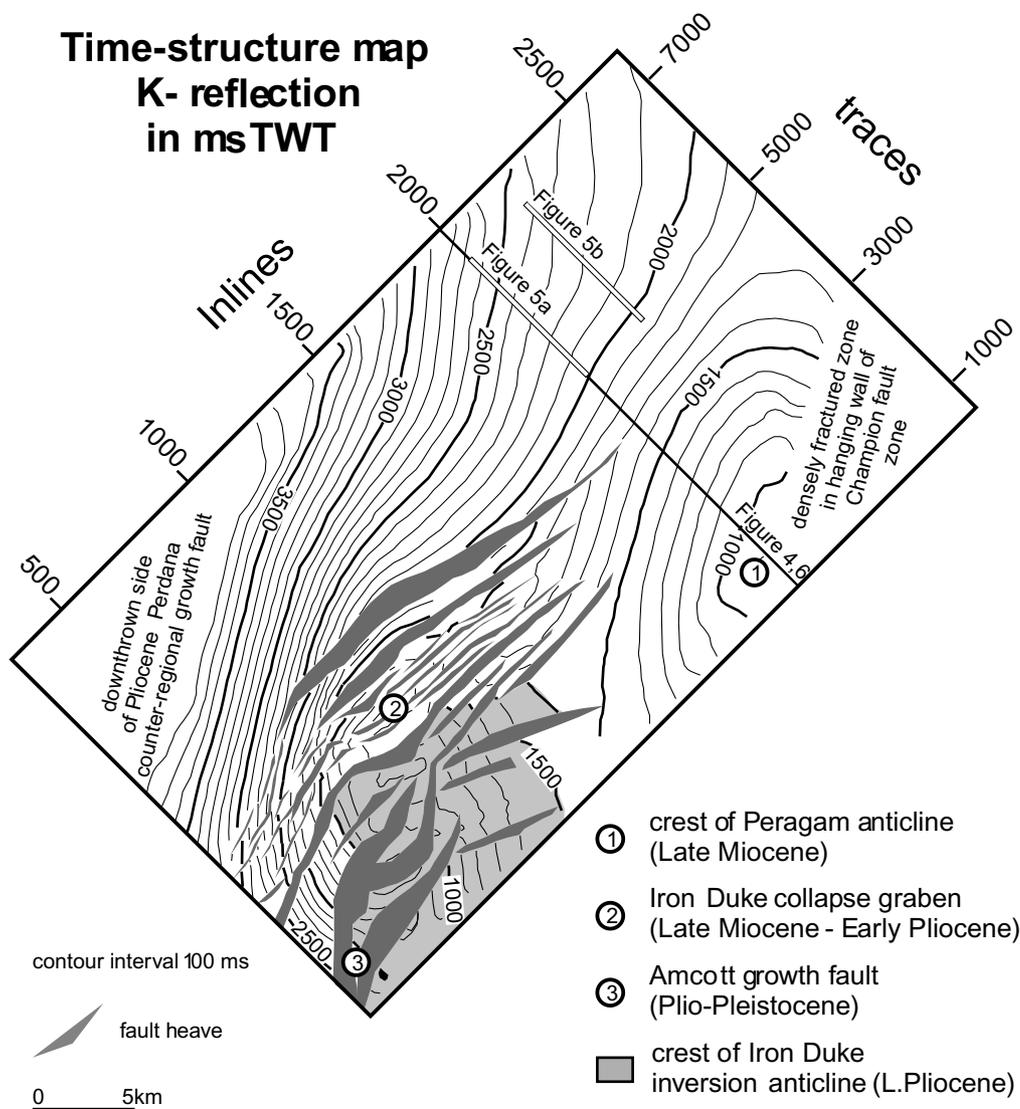


Fig. 3. Time structure map of the K-reflection, top of the Late Miocene depocentre. See Fig. 1 for location.

crest. The V reflections are high-amplitude, low-frequency, continuous reflections. The Peragam anticline consist of a succession of coastal plain deposits of alternating 80–120 m thick sandstone packages and 150–200 m thick shale (Sandal 1996, p. 183). A near to lithostatic pressure gradient of 22.57 kPa/m was measured in the sandstone packages (Sandal 1996, p. 182). The seismic facies changes upward to high-frequency, medium-amplitude, continuous reflections that correlate at well locations to thinner more closely spaced sandstone-shale alternations. The K-horizon represents shallow-marine, fine to medium-grained sandstone, deposited in a high- to medium-energy environment (Sandal 1996, p. 186). Basinwards, the shelf break is marked by an increase in amplitude, a distinctive break in slope and basal reflections onlapping the slope.

The D-event, against which reflections apparently downlap, is superficially a high-amplitude, continuous reflection (Fig. 4). However, when looking at it in detail

the D-event does not appear to be a single continuous surface. The high-amplitude continuous reflection consists of individual, aligned, high-amplitude patches that cross-cut original stratification (Fig. 5). The original reflections are subdued, but still visible, below the high-amplitude patches. Along strike, the depth of the D-event changes abruptly to deeper and shallower levels. It is impossible to map the D-event as a horizon or as a listric fault without at some point cross-cutting undisrupted, continuous reflections. On dip sections, the D-event cuts the original horizons below the shelf break and seems to run roughly parallel to the position of the shelf edge throughout the section (Fig. 5).

On a schematic cross-section flattened on the K-horizon (Fig. 6) the Late Miocene sequence (between V and K reflections) appears to be a rapidly aggrading sequence, with a subsiding syncline in front of the shelf break. The syncline migrates to the south, synchronously with progradation of the shelf edge. On the regional line (Fig. 2), it can

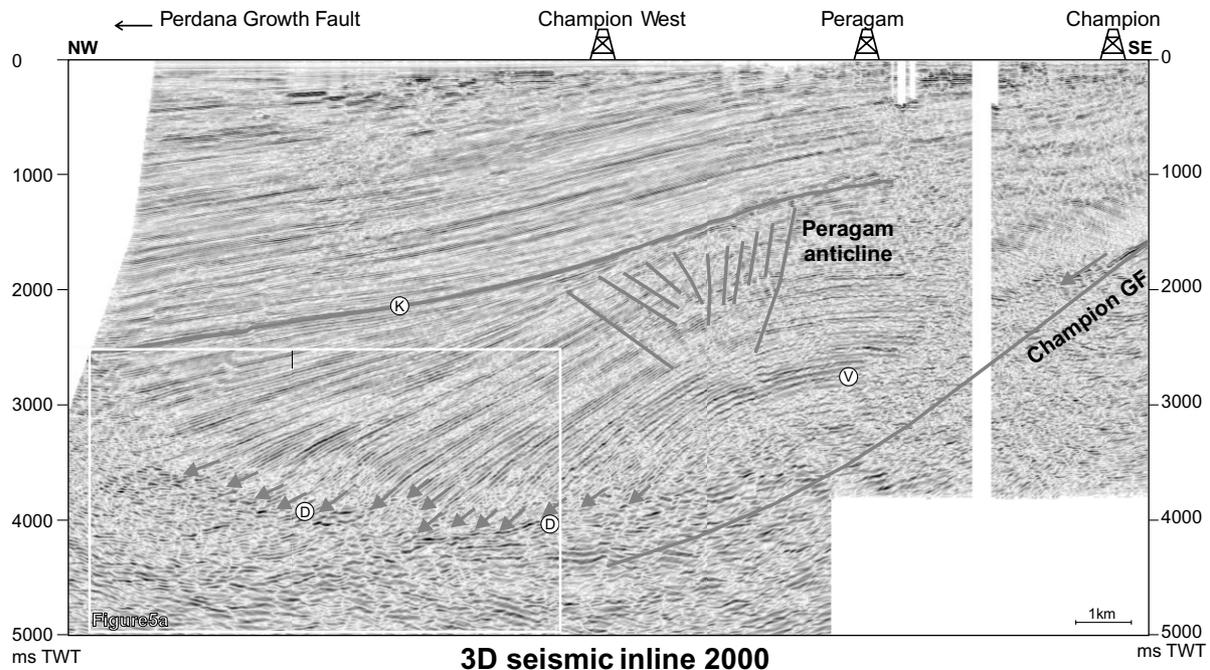


Fig. 4. 3D Seismic line 2000 through the Late Miocene Perdana depocentre (about similar position as Fig 2). Note the apparent downlap on a high-amplitude event (D-event).

be seen that the syncline, below the K-reflection, is flanked basinward by a small anticlinal fold north of the 3D block. The northern flank of the anticlinal fold is truncated by the Perdana fault.

5. Interpretation

The D-event could be interpreted as a low-angle normal fault if the section below it were simply regarded as composed of incoherent reflections, as it appears on 2D data. The 3D data presented here show the presence of subdued reflections below the high-amplitude D-event. The subdued reflections have similar dips to the strong reflections overlying the D-event and do not appear to be offset much by it. Listric normal faults in deltas typically display strongly rotated beds in the hanging wall and sub-horizontal beds in the footwall. Drag faults associated to a larger listric fault may cause small offsets between reflections of similar dips at the base of the rollover (Mauduit & Brun, 1998). This is unlikely in this case since the onset of the major listric growth fault, the Perdana fault, clearly post-dates deposition of the Late Miocene sequence. Consequently, both from offset of reflections and geometrically, the D-event does not, in detail, resemble a typical growth fault and the section below it cannot be interpreted as “mobile” shale.

The D-event is not random noise but occurs in coherent patches and is restricted to the prodelta sediment. The high-amplitude D-event marks the top of a zone where original prodelta reflections are subdued. A similar lateral facies

change from high-amplitude, continuous reflections to subdued, disrupted reflections has also been documented for a Late Miocene depocentre near the Ampa Field in the Baram delta, offshore Brunei (Van Rensbergen et al., 1999). In the Ampa Field area the facies change also only affected prodelta sediments. The effect was attributed to increasing overpressure within already overpressured shale after deep burial, probably by hydrocarbon maturation and cracking of oil to gas. Hydrofracturing and expulsion of highly overpressured fluid was the proposed mechanism for degeneration of the seismic reflections and resulted in the formation of a swarm of intrusive shale dykes and sills in the Pliocene overburden. For the Ampa Field the overpressuring event was found to occur about 9 Ma later than initial syndepositional deformation of the underlying Setap shale.

The modification of the seismic facies at the base of the Champion delta is, in accordance to the example in the Ampa field area, interpreted as a result of extreme overpressure increase and hydrofracturing within bedded prodelta deposits. The D-event is interpreted to represent the front of hydraulic fracturing related to overpressured fluid migration, from an underlying region of mobile shale into stratified prodelta sediments, or to secondary overpressure generation within the prodelta sediment itself. The consequences of our interpretation imply that overpressure may be generated within the Late Miocene prodelta sediment rather than caused by migration of overpressured fluids from below. If overpressure is generated locally it may attain lithostatic values within the prodelta shale but it will dissipate where sandstone is sufficiently abundant to

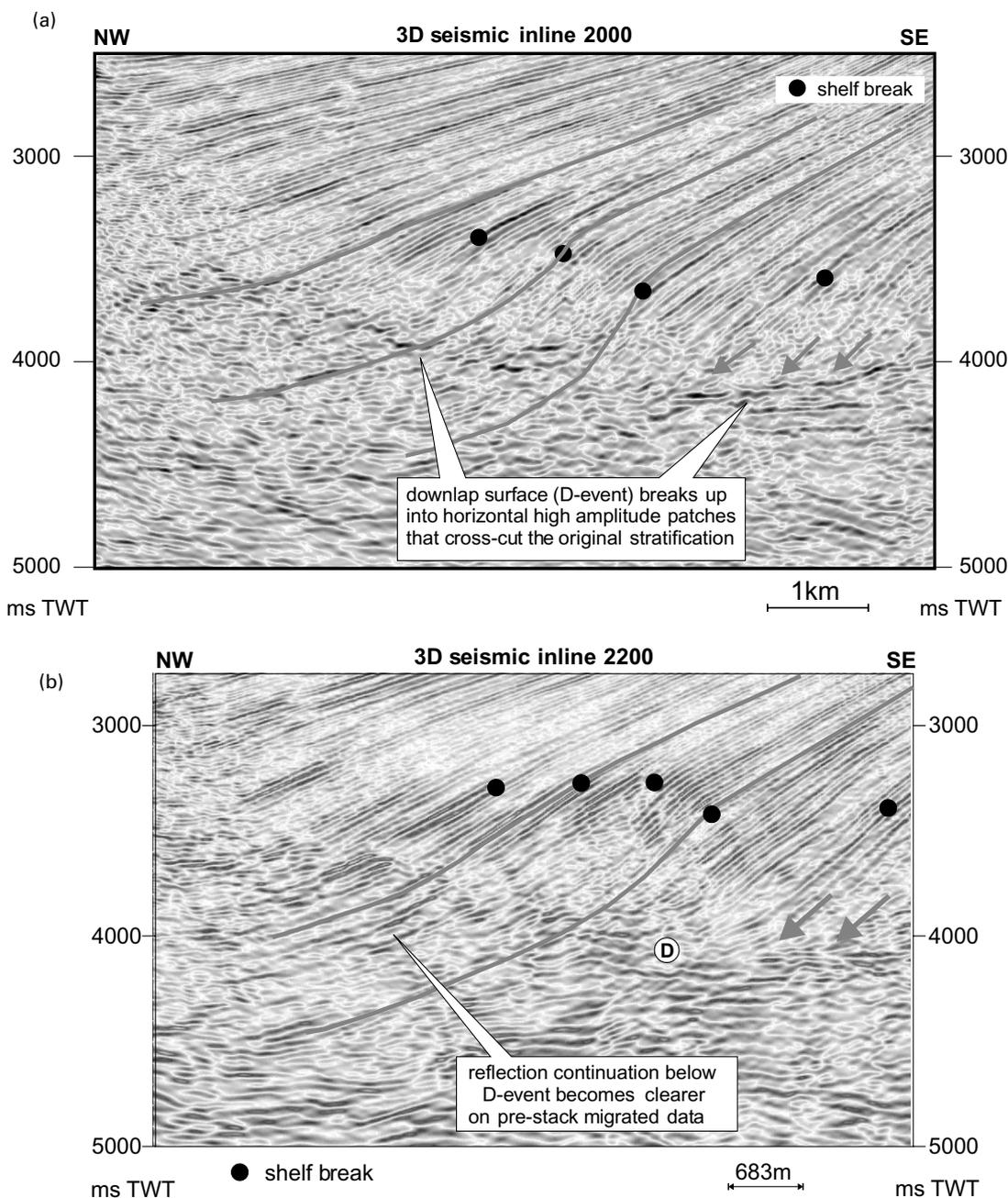


Fig. 5. (a) Detail of post-stack migrated 3D seismic line 2000 (see Fig. 4) showing high-amplitude events cross-cutting prodelta reflections. (b) Detail of pre-stack migrated 3D seismic line 2200, 5 km to the east of line 2000, showing more clearly the continuation of original reflections below the D-event. The location of this section is indicated on Fig. 3.

laterally drain the overpressure (cf. the high-pressure gradient in the sandstone at the Peragam anticline). The pressure front will be located where the sedimentary setting changes from the shale-prone prodelta to the sand-prone delta front. The D-event is therefore not interpreted as a permeability barrier for upward fluid migration but probably marks the transition from highly overpressured, hydro-fractured shale to undisrupted permeable sandstone. At the transition, shale compaction, mineral diagenesis, and cementation, all may add to the reflectivity of the event. Highly reflective patches, caused by intense carbonate cementation

in sandstone around hydrocarbon seeps, are also documented in the Timor Sea (O'Brien, Lisk & Duddy, 1997) in Eocene sandstone. Rims of cemented sandstone are also often encountered in sandstone blocks which are incorporated and transported upwards in mud volcanoes (Lewis & Byrne, 1996).

An abrupt increase in pore fluid overpressure should cause an abrupt discontinuity in the increase of acoustic velocity with depth. Increase of overpressure also reduces acoustic velocity differences between sand and shale and causes dimming of seismic reflections by lack of impedance

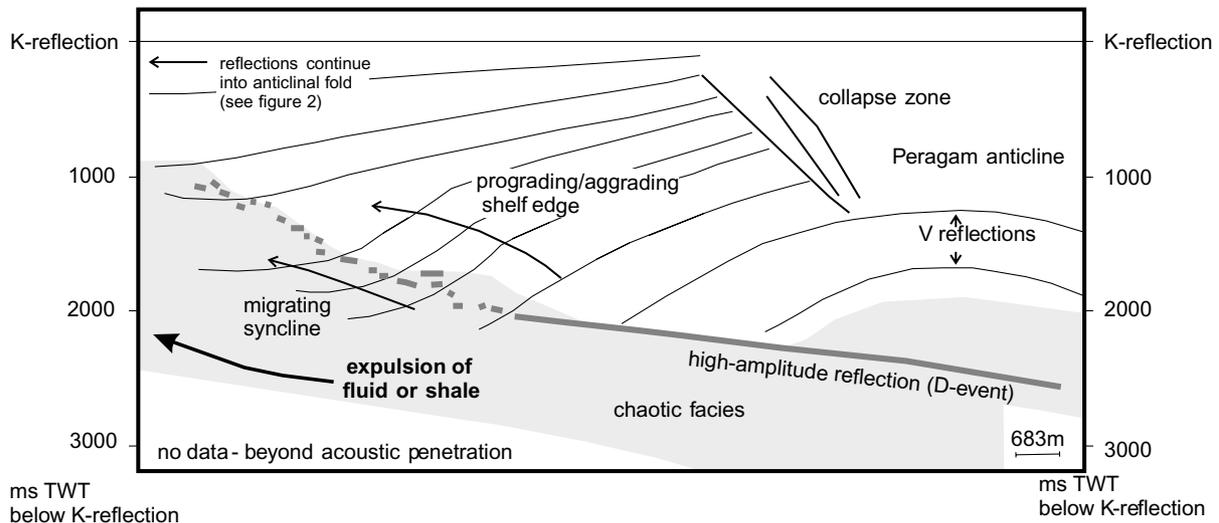


Fig. 6. Schematic drawing of seismic line 2000 (see Fig. 4 for original seismic section) flattened on the K-reflection.

contrast (Maucione & Surdam, 1997). On section 2200 (Fig. 5b), normal move-out (NMO) corrections showed a near-constant acoustic velocity where subdued reflections are resolved below the D-event (BSP, personal comm.), which may indicate an abrupt increase in overpressure at the D-event.

The Late Miocene sequence at the base of the Perdana depocentre appears to be a prograding shale expulsion syncline. Basinward of the expulsion syncline lies an anticline, which is interpreted to be a remnant compressional fold in front of the prograding delta and maybe the equivalent of the rolling monocline in front of a salt expulsion syncline (Ge et al., 1997). The expulsion syncline seems to have migrated, along with shelf progradation. The entire Late Miocene sequence was rotated by subsidence along the younger Perdana growth fault during the Pliocene. Its seismic signature was probably modified (decrease in reflection amplitude and coherency) at the Late Pliocene, the time of peak oil generation offshore Brunei (Sandal 1996, p. 150).

6. Discussion

6.1. Expulsion synclines

The overall structure of the Champion Delta is comparable with, but much smaller than, that of the Niger delta. The structure of the Niger delta has been extensively mapped and described, onshore by Doust and Omatsola (1990) and offshore by Damuth (1994) and Morley and Guerin (1996). Despite the large database, expulsion structures as described above have not been documented in the literature. However, early prograding counter-regional growth faults at the base of the delta are commonly identified within industry and have been described in the literature (Doust & Omatsola, 1989; Morley & Guerin, 1996; Cohen & McClay, 1996). Counter-regional faults interpreted at the

down-dip limit of depobelts in the Niger delta also occur at a lithology change from delta top sand to prodelta shale (Doust & Omatsola, 1990) and may in fact correlate with a front of hydraulic fracturing and high overpressure. Morley and Guerin (1996) and Cohen and McClay (1996) already mentioned in their studies how modification of the seismic signal (from coherent to chaotic seismic facies) at the base of the Niger delta caused problems and inconsistencies in their seismic interpretation. It is therefore probable that some of the early structures in the Niger delta may have been masked by chaotic reflections and that migrating expulsion synclines may be more common than considered so far in the structural evolution of large deltas. In fact many industrial seismic lines in regions of shale tectonics show very bright reflections that appear to coincide with fault planes. However not all may actually be fault planes, some could represent pressure fronts or limits of migration of fluids and shale through hydrofractures in the country rock.

Overpressured shale occurs as bedded strata or in shale ridges with chaotic seismic facies (Al-Ghamdi & Watkins, 1996). According to Morley and Guerin (1996) stratified overpressured shale in the Niger delta converts into chaotic, mobile shale below the depth of peak oil generation (4–6 km). It is inferred that pore fluid overpressure, increased by gas generation (Barker, 1990) results in highly overpressured, undercompacted low-density, low-viscosity shale that is mobile and isostatically unstable. The study of the Ampa Field (Van Rensbergen et al., 1999) and this study demonstrate that conversion from stratified to chaotic seismic facies does not necessarily result in a mobile and unstable shale mass as is often intuitively assumed. The facies change can occur by increase of overpressure due to fracturing and dimming effects. But, increase of overpressure does not necessarily result in a deformable shale mass. On the contrary, laboratory experiments by Bolton and Maltman (1998) demonstrate that ductile deformation

of shale only occurs when overpressure is below lithostatic. Overpressure increase above lithostatic results mainly in brittle deformation, fracturing and fluid expulsion. As is demonstrated onshore and offshore Brunei (Morley et al., 1998; Van Rensbergen et al., 1999), shale diapirism associated with hydrocarbon-generated overpressuring occurs through upward flow of low-viscosity shale along shale dykes and results in mud volcanism at the sea floor.

Most mobilisation of shale is interpreted to occur at some considerable depth (several kilometres) when overburden loading of undercompacted shale leads to overpressured conditions of the pore fluids. However there is also evidence for mobile shale activity at very shallow (upper few hundred meters) depths of burial as well, for example in the Palaeocene clays of the North Sea (Henriet et al., 1991). The creation of an expulsion syncline requires loading of the mobile unit at a relatively shallow depth (e.g. Ge et al., 1997). In the case of salt, expulsion is achieved by driving the salt out from underneath the prograding wedge to form a primary weld. Expulsion associated with shale is still poorly understood. It may include some movement of the shale mass, but it may be primarily a compaction-related mechanism where fluids are driven out from the shale mass underneath the prograding wedge, but most of the shale remains behind. If in the shallow subsurface shale contains about 50–60% water then there would clearly be the potential to create considerable accommodation space by compaction and loss of pore fluids accompanied by extensive minor faulting, as described by Henriet, De Batist and Verschuren (1991). This interpretation is further elaborated in the following paragraph that shortly describes an example of a shale ridge in the footwall of a large, down-to-basin, Outer Shelf Growth Fault in the Baram delta province.

6.2. Shale ridges

Shale rollers or shale ridges at the base of large down-to-basin growth faults are often interpreted as rising shale bulges or reactive diapirs created by shale withdrawal from beneath the prograding/aggrading delta (Doust & Omatsola, 1990; Bradshaw & Watkins 1996; McClay et al., 1998). It can be expected to find a shale ridge basinwards of a migrating expulsion syncline but the data described above do not-except for a small anticlinal fold-image such structure. In the Champion delta area the outline and structure of early shale rollers are concealed by overpressure-induced chaotic seismic facies and probably deformed into inversion anticlines (e.g. the Ampa anticline) during the Late Pliocene. For comparison, a seismic section of the outer part of the Baram delta is discussed here (Fig. 7). The outer part of the Baram delta is mainly Late Pliocene to Pleistocene in age and the seismic facies has not been altered by extreme overpressure increase induced by gas generation. The discussion is illustrated with some selected

screen dumps kindly provided by BSP but no detailed horizon interpretation could be made.

The Pliocene Baram delta prograded over the eastern margin of the Champion delta and accumulated over 6 km of sediment. Maximum thickness is reached in the hanging wall of the Outer Shelf Growth Fault, close to the present day shelf edge (Fig. 1). The structure of the Baram delta is characterized by a Gulf of Mexico structural style (e.g. Bradshaw & Watkins, 1996) of parallel, down-to-basin growth faults perpendicular to the direction of sediment supply from the Baram river (Fig. 7). The Outer Shelf Growth Fault is up to 50 km long and has a maximum throw of about 6 km. In its footwall, a large shale ridge of about 9 km wide and 1.5 s (about 4.5 km) high occurs along the entire length of the fault (Fig. 7).

Fig. 7 compares a 2D seismic section through the shale ridge with a 3D seismic section at about the same location. On 2D seismic data the shale ridge is characterized by a typical chaotic facies interpreted as mobile shale. But, on 3D seismic data the shale ridge appears to be a stratified horst block of probably prodelta shale. The weak stratification of shale is on 2D data lost in noise below faults. The almost undeformed shale ridge occurs between two subsiding basins filled with prodelta to sandy delta top sediment. The sediment in the subsiding basin in the footwall of the growth fault consists of a lower sequence of densely faulted prodelta shales (sequence 1), a sequence containing a series of prograding/aggrading delta fronts (sequence 2), and an overburden of delta top sediment (sequence 3). Sequence 1 is densely faulted and fractured, sequences 2 and 3 are affected by subsidence along paired regional and counter-regional growth faults.

The most striking difference between prodelta sediment in the shale ridge and the prodelta sediment in the adjoining subsiding basin (sequence 1) is the degree of fracturing. Sequence 1 is affected by intense, extensional faulting. This deformation can be interpreted as result of fluid expulsion and subsequent collapse of undercompacted, shale (Cartwright & Dewhurst, 1998). This process is limited to sequence 1 and occurred during relatively shallow burial and probably triggered growth faulting of the overburden. The shale ridge stands out as an unfaulted horst block and shows that shale ridges are not necessarily diapiric structures of isostatically unstable shale and that adjacent expulsion depocentres can be created by localised compaction and fluid expulsion without much movement of shale (Fig. 8).

7. Conclusions

This paper describes an example of a migrating expulsion syncline related to mobile shale, interpreted from 3D seismic data offshore Brunei. Such structures have not been previously described for mobile shale, partly due to the

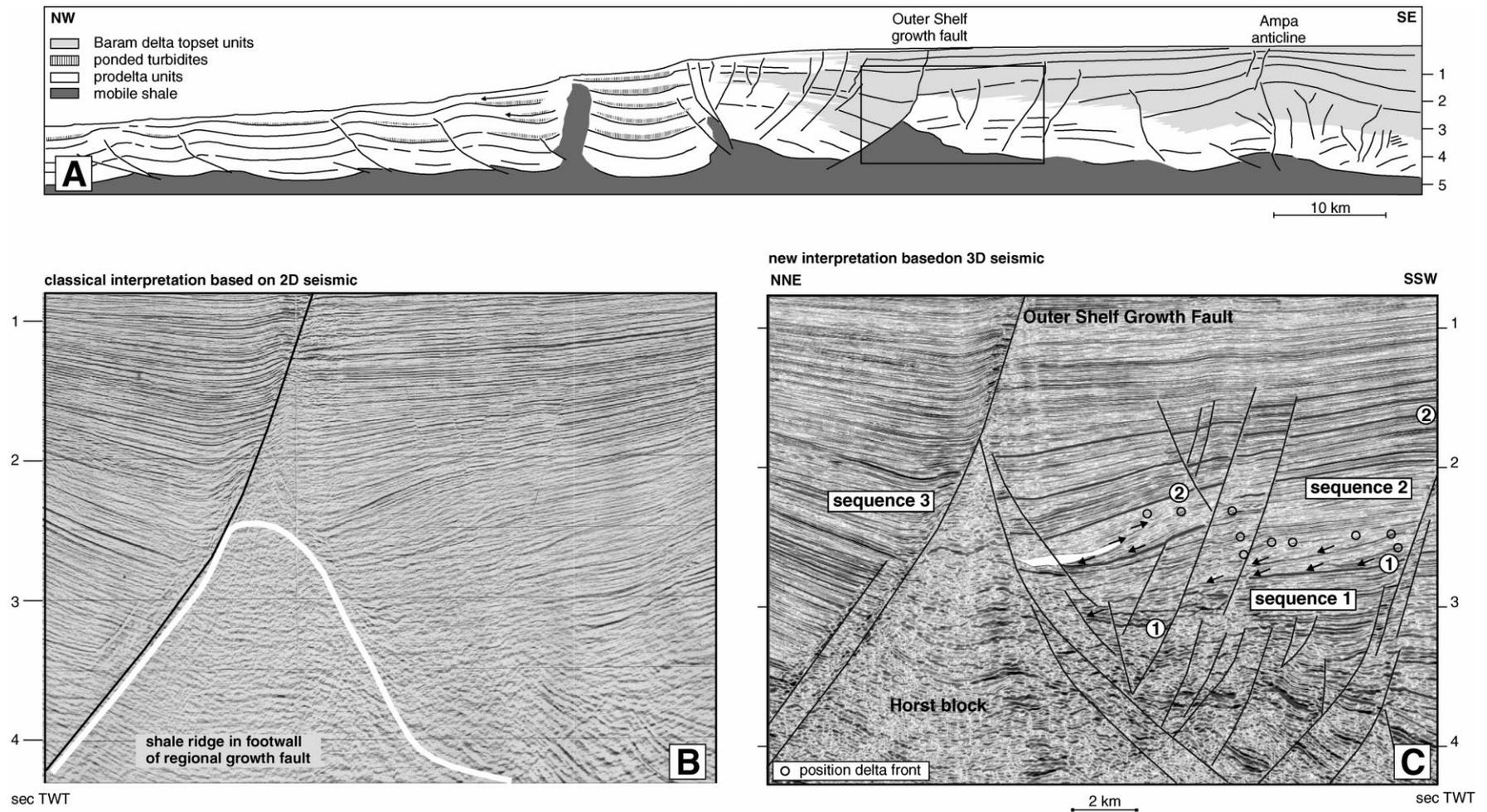


Fig. 7. (A) Line drawing of section through the Baram delta at the western part of the Brunei shelf (after Sandal, 1996). See Fig. 1 for location. (B) Detail of 2D seismic section of the Baram delta at the Outer Shelf Growth Fault. The ridge with chaotic seismic facies in the footwall of the Outer Shelf Growth Fault is traditionally interpreted as a bulge of mobile shale formed by differential loading and shale expulsion in front of a prograding delta. (C) Detail of 3D seismic section at about the same location showing undisturbed stratification within the shale ridge. The ridge appears to be horst block of prodelta shale between two subsiding basins filled with delta top sediment.

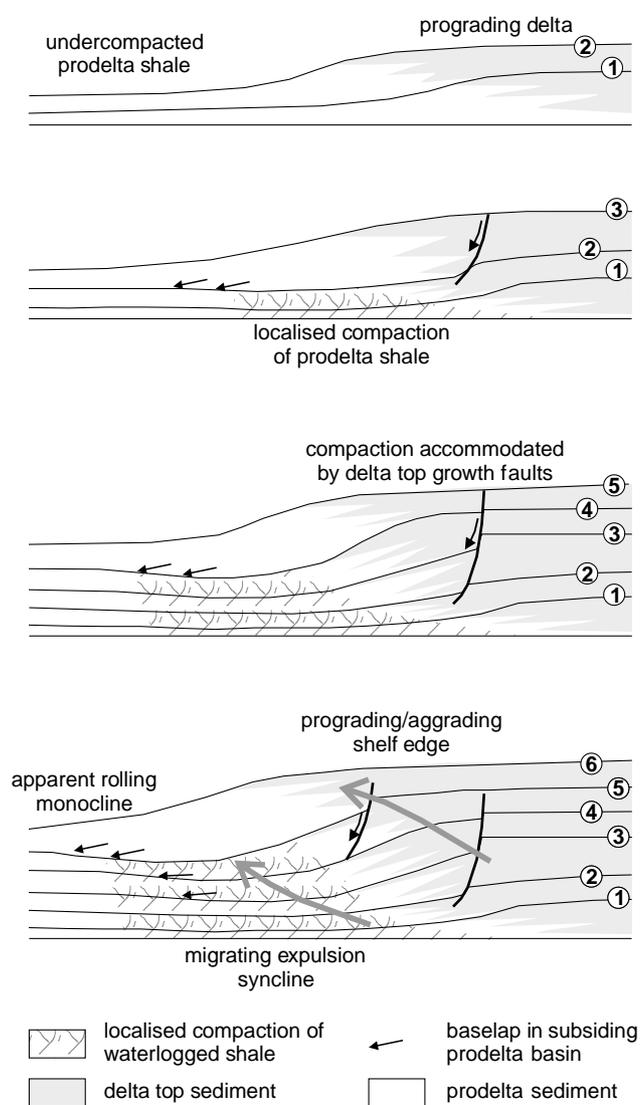


Fig. 8. Cartoon illustrating the possible formation of a migrating expulsion syncline in front of a prograding/aggrading delta. Compaction of waterlogged prodelta shale under a prograding delta front can create localised subsidence that proceeds in pace with delta progradation. Basinwards, undercompacted shale may form a rolling monocline that traps turbidites and slope sediments. Later, after deep burial, deterioration of the acoustic stratification due to hydrocarbon generation often masks early expulsion synclines on seismic data. See text for discussion.

limited resolution of seismic data in areas of mobile shale. Associated with the feature is a sub-horizontal reflection, which divides steeply dipping strongly reflective units above from similarly dipping, weakly reflective units below. It is interpreted to represent a front associated with hydraulic fracturing due to overpressure increase in prodelta shale. Without the resolution provided by 3D seismic data such features could easily be interpreted as detachments related to listric normal faults over a substratum of mobile shale. Expulsion synclines associated with mobile shale may develop more by compaction and expulsion of pore fluids, than by driving the entire shale mass out of the

area of progradation. In this mechanism shale expulsion synclines differ from those associated with salt.

Acknowledgements

We would like to thank Brunei Shell Petroleum (BSP) and the Petroleum Unit (PU) for supporting the Department of Petroleum Geosciences at the University of Brunei Darussalam (UBD) and making the seismic data available for research. Seismic interpretation software was supplied by Landmark Graphics Cooperation under the Strategic University Alliance Grant Agreement (no. LG137V166/122). P. Van Rensbergen holds a UBD research fellowship.

The manuscript was reviewed for Marine and Petroleum Geology by P. Cobbold.

References

- Al-Ghamdi, A. M., & Watkins, J. S. (1996). Structural styles and depositional history of North and South Padre Island OCS areas, Offshore South Texas. In J. O. Jones & R. L. Freed, *Structural framework of the Northern Gulf of Mexico. Special Publication of the Gulf Coast Association of Geological Societies* (pp. 1–8). Gulf Coast Association of Geological Societies.
- Barker, C. (1990). Calculated volume and pressure changes during the thermal cracking of oil to gas in reservoirs. *AAPG Bulletin*, 74, 1404–1413.
- Bolton, A., & Maltman, A. (1998). Fluid-flow pathways in actively deforming sediments: the role of pore fluid pressures and volume change. *Marine and Petroleum Geology*, 15, 281–297.
- Bradshaw, B. E., & Watkins, J. S. (1996). Growth fault evolution in offshore Texas. In J. O. Jones & R. L. Freed, *Structural framework of the Northern Gulf of Mexico. Special Publication of the Gulf Coast Association of Geological Societies* (pp. 103–110). Gulf Coast Association of Geological Societies.
- Cartwright, J. A., & Dewhurst, D. N. (1998). Layer-bound compaction faults in fine grained sediments. *Geological Society of America Bulletin*, 110, 1242–1257.
- Cohen, H. A., & McClay, K. (1996). Sedimentation and shale tectonics of the northwestern Niger Delta front. *Marine and Petroleum Geology*, 13, 313–328.
- Damuth, J. E. (1994). Neogene gravity tectonics and depositional processes on the deep Niger Delta continental margin. *Marine and Petroleum Geology*, 11, 320–346.
- Demercian, S., Szatmari, P., & Cobbold, P. R. (1993). Style and pattern of salt diapirs due to thin-skinned gravitational gliding, Campos and Santos basins, offshore Brazil. *Tectonophysics*, 228, 393–433.
- Doust, H., & Omatsola, E. (1990). Niger Delta. In J. D. Edwards & P. A. Santogrossi, *Divergent/Passive Margin Basins. AAPG Memoir 48* (pp. 201–238). AAPG.
- Ge, H., Jackson, M. P. A., & Vendeville, B. C. (1997). Kinematics and dynamics of salt tectonics driven by progradation. *AAPG Bulletin*, 81 (3), 398–423.
- Henriet, J. P., De Batist, M., & Verschuren, M. (1991). Early fracturing of Palaeogene clays, southernmost North Sea: relevance to mechanisms of primary hydrocarbon migration. In A. M. Spencer, *Special Publication of the European Association of Petroleum Geosciences* (pp. 217–227), vol. 1. European Association of Petroleum Geosciences.
- James, D. M. D. (1984). *The geology and hydrocarbon resources of Negara brunei Darussalam*, Berhad: Muzium Brunei and Brunei Shell Petroleum Company (special publication).
- Lewis, J. C., & Byrne, T. (1996). Deformation and diagenesis in an ancient mud diapir, southwest Japan. *Geology*, 24, 303–306.

- Maucione, D. T., & Surdam, R. C. (1997). Seismic response characteristics of a regional scale pressure compartment boundary, Alberta Basin, Canada. In R. C. Surdam, *Seals, traps, and the petroleum system AAPG Memoir 67* (pp. 269–281).
- Mauduit, T., & Brun, J. P. (1998). Growth fault/rollover systems: birth, growth, and decay. *Journal of Geophysical Research*, 103 (B8), 18, 119–18,136.
- McClay, K. R., Dooley, T., & Lewis, G. (1998). Analog modeling of progradational delta systems. *Geology*, 26 (9), 771–774.
- Mohriak, W. U., Macedo, J. M., Castellani, R. T., Rangel, H. D., Barros, A. Z. N., Latge, M. A., Ricci, J. A., Mizusaki, A. M., Szatmari, P., Demercian, L. S., Rizzo, J. G., & Aires, J. R. (1995). Salt tectonics and structural style in the deep water province of the Cabo Frio region, Rio de Janeiro, Brazil. In M. P. A. Jackson, R. G. Roberts & S. Snelson, et al., *Salt tectonics: a global perspective. AAPG Memoir 65* (pp. 273–304).
- Morley, C. K., & Guerin, G. (1996). Comparison of gravity-driven deformation styles and behaviour associated with mobile shale and salt. *Tectonics*, 15, 1154–1170.
- Morley, C. K., Crevello, P., & Haji Ahmad, Z. (1998). Shale tectonics and deformation associated with active diapirism: the Jerudong Anticline, Brunei Darussalam. *Journal of the Geological Society of London*, 155, 475–490.
- O'Brien G. W., Lisk, M., & Duddy, I. (1997). Fault reactivation as a primary control on trap breach and fluid migration histories: Timor Sea, north-western Australia. In: J. Hendry, P. Carey, J. Parnell, A. Ruffel, R. Worden (Eds.), *Geofluids II Extended Abstract Volume*, University of Belfast, pp. 166–169.
- Osborne, M. J., & Swarbrick, R. E. (1997). Mechanisms for generating overpressure in sedimentary basins: a reevaluation. *AAPG Bulletin*, 81, 1023–1041.
- Sandal, S. T. (1996). *The Geology and Hydrocarbon Resources of Negara Brunei Darussalam, (1996 revision)*. Brunei Shell Petroleum Company/Brunei Museum, Syabas Bandar Seri Begawan, Brunei Darussalam.
- Van Rensbergen, P., Morley, C. K., Ang, D. W., Hoan, T. Q., & Lam, N. T. (1999). Structural evolution of shale diapirs from reactive rise to mud volcanism: 3D seismic data from the Baram delta, offshore Brunei Darussalam. *Journal of the Geological Society of London*, 156, 633–650.