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The role of tectonics in geopressure compartmentalisation and hydrocarbon leakage in the deep offshore Niger Delta

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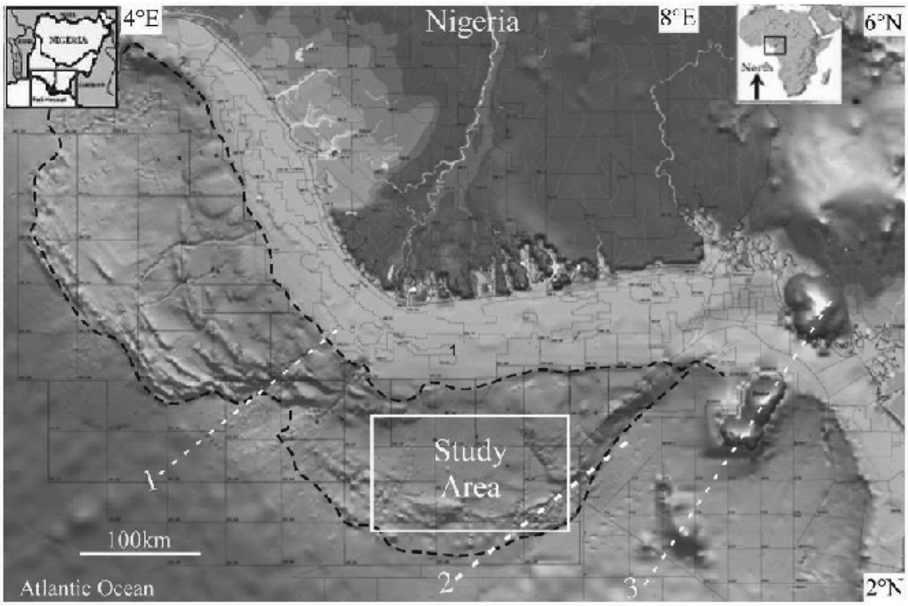
Abstract: The Niger Delta's deformation regime, controlled by NE-SW gravitational tectonics, forms imbricate thrust structures in the deep offshore, and generates profuse fluid expulsions expressed as pockmarks ±700 m and mud volcanoes ±2800 m in diameter. Gravity loading by sediment alone is not sufficient to explain the expulsions, and their classified morphology and proximity to the folds suggest a link with the structural compartmentalisation and pressure distributions. This work used 3D-seismic and well-data to link the leakages to active and inactive tectonic processes, highlighting the role of main and subsidiary faults and changing stress regimes before suggesting a "layer-by-layer" behaviour to explain the vertical and lateral geopressure compartmentalisation.

Keywords: leakage, pockmarks, geopressure cells, thrust fault, fault-propagation fold, ramp.

The Niger Delta, located in the Gulf of Guinea and forming part of the West African passive margin, is one of the most prolific petroleum basins in the world (Bilotti and Shaw, 2005). It covers an area of about 200,000 km^2 (Saugy and Eyer, 2003) and is situated approximately between latitudes 2 to 6° N and longitudes 3° to 8° E, extending from onshore to the conventional and deep offshore (Fig. 1). With growing interest in deeply buried reservoirs, understanding the role of tectonics in pressure distribution is becoming of the utmost importance, making the evaluation of its impact on seal retention and hydrocarbon trapping a key to successful petroleum exploration (Grauls and Baleix, 1994; Burrus, 1998; Law and Spencer, 1998; Finkbeiner *et al.*, 2001).

Hydrocarbon seeps, pockmarks and other chemosynthetic processes are observed by Remote Operated Vehicle (ROV) video, from directly sampled core data and mainly from 3D seismic images of this deep offshore zone. IFREMER and TOTAL's in-house studies in the area have shown that gravity loading by the sediment weight alone is not sufficient to explain the observed expulsions. The existence of regional seals suggests that expulsion of fluids originating from depth could only be possible either by breaching of the cap rock due to overpressure build-up, or through fractures and faults formed by structural processes. The close association of the pockmarks to fold axes, the classed morphology –sizes, alignments and separation distances– also shows structural control and the effect of changing subsurface pressure conditions (Fig. 2).

In the present work the lateral and vertical architecture of the folds have been analysed from map and section views, and pressure evaluation carried out to help understand how thrusting and secondary fault activities affect the evolution of geopressure in the deep offshore context. A good understanding of these



1: Charcot Fracture Zone
2: Fernanda Po Fracture Zone
3: Cameroon Volcanic Line

Figure 1. Map of the Niger Delta showing the study area and regional lineaments.

would help to better constrain dynamic/static leakages, up-fault migration vs. hydraulic fracturing, and consequent hydrocarbon leakage to the seabed. The objective is to understand the role of continuing tectonic activities in these fluid leakages, in the fluid pressure distribution and the impact on the reservoirs.

Approach and methods

Seismic mapping and interpretation

The 3D seismic block was supplied from the database of TOTAL's subsidiary TEPNG, a major operator in the Nigerian deep offshore. The full-offset stack seismic cube (25 Hz dominant frequency with a bandwidth of 12-40 Hz) is a merge (trace interval of 25.0×25.0 m), but sampled for every other inline or cross-line and covering the whole study area, of about 80×42 km = 3360 km^2. The seismic mapping of the main horizons was achieved by the use of SISMAGE™, TOTAL's in-house seismic interpretation software. The process involved either manually tracing the amplitude reflectors on a seismic section or picking "seeds" propagated automatically to map the horizons. Isochron/isochors, coherency, dip, amplitude maps, and recalculated seismic blocks (e.g. coherency, fault) were then produced.

Measurement of fault parameters

Measurement of displacement, cut-off angles, and inclination of faults, on the seismic lines, was carried out. This highlighted irregularities, small fault bends, and change in the dip of the faults laterally; weak and fractured or rotated locations within fault zones. It also helped to infer tilting history and fault gouge properties (Wibberley *et al.*, 2007) or their sealing capacity. Using SISMAGE™, the fault and coherency attributes were extracted for different portions of the seismic block to bring to light subtle structural characteristics and made it possible to view particular geologic features from their seismic expression (lineation, folds, faults and fractures, etc) in section, slice and in 3D.

Integration of well data

In addition to the 3D seismic block, our data base included wireline formation tester (WFT) pressure values and fluid samples, and other derived well data such as equivalent mud weight, temperature, waterhead/overpressure, for 16 wells drilled in the study area. Well logs –sonic, resistivity, gamma ray, density and neutron porosity– were also available. The lithology characterised from the seismic facies or amplitude anomalies was compared with the logs. Time-depth curves were extrapolated and used for well-seismic matching and for the integration of WFT values. The principal stresses in the top seal were evaluated from the Leak-Off Test (LOT) and Formation Integrity Test (FIT). Where the pressure within the reservoir top was very close to or the same as the LOT result of the top seal, leakage by

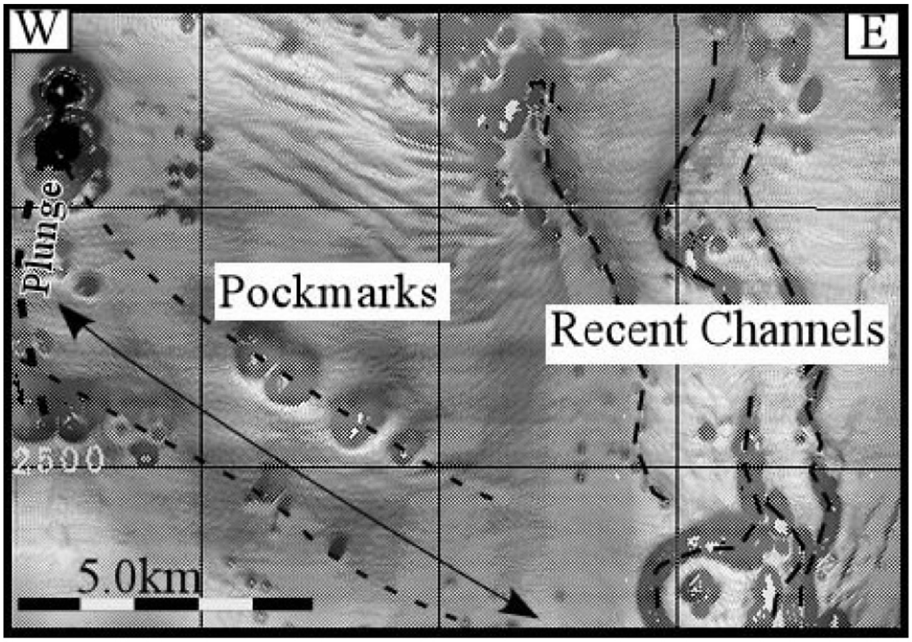


Figure 2. Seabed isochron showing pockmark alignments parallel to known deep anticlinal axis, pronounced at plunge, and a different organisation trailing recent channels.

hydraulic fracturing was considered most likely, suggesting that the fault/lateral geopressure cell boundary was relatively efficient. On the other hand, a leakage, despite far lower fluid pressure in the reservoir than the LOT value of the cap rock, suggests up-fault leakage.

Results and discussion

Structurally-controlled seabed leakages

The adjacent regional lineaments (shown in figure 1) act as lateral barriers to the edges of the NE-SW gravity-driven decollement layer. The structural analysis shows how this, among other factors, created the cuspate-lobate patterns of the imbricate thrust structures, lateral transfer/strike slip, tear faults and local relays. The consequences are the perpendicular transfer fault, lateral-ramp-type architecture and en echelon faults observed adjacent to and above the reservoirs in this area. The stress rotation resulted in 4-way fold closures, fault-intersections and weak zones and enhanced focused fluid leakages from the reservoir and fluid pressure compartments across lithological seals to form pockmarks (Fig. 3).

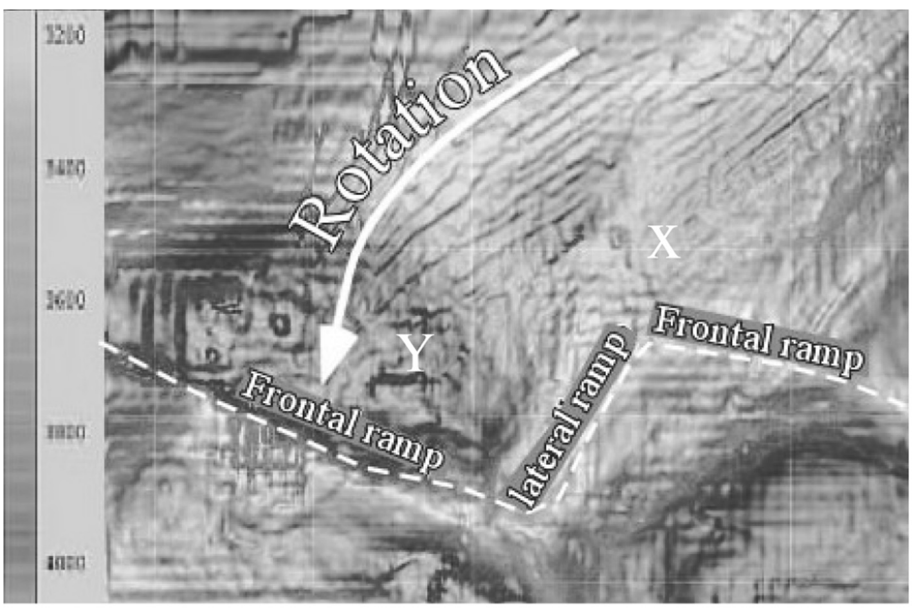


Figure 3. Dip map and superimposed isochron showing stress rotation and fold closure (point X) in the area of lateral ramp development and enhanced fluid leakages (point Y).

Up-fault and anticlinal apex leakages

The major determinant leakage types above the anticlinal thrust axes were: 1) up-fault/thrust tip, and 2) top seal/anticlinal apex leakages (Fig. 4). The double row of pockmarks seen in figure 2 was emplaced by these two leakage types. The layers are bounded by similar vertical lithological seals (vertical geopressure stratigraphic limits), but the combined effect of anticlinal and up-fault leakages for each strati-

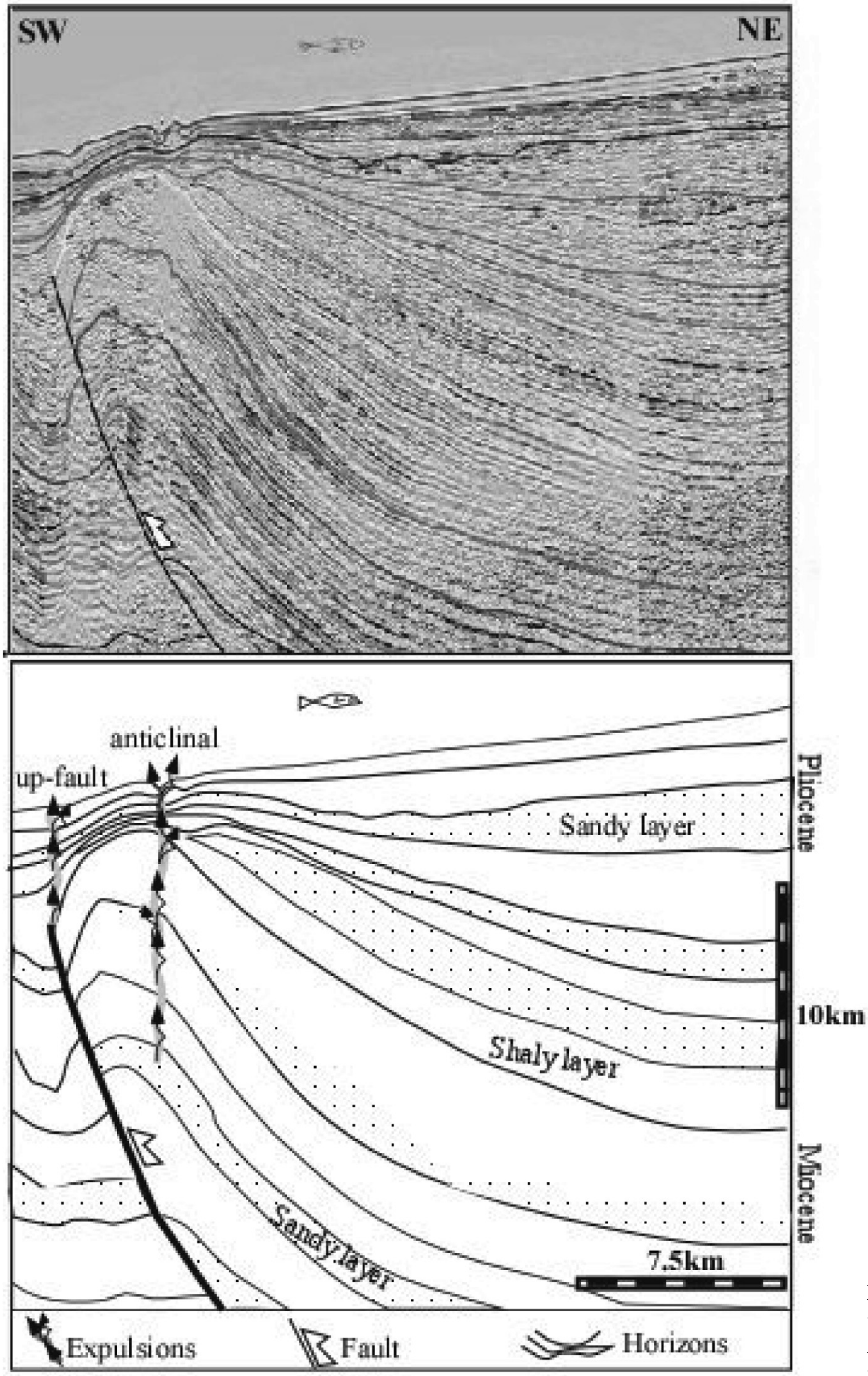


Figure 4. Interpreted seismic section showing up-fault and anticlinal leakages at fault-propagation fold.

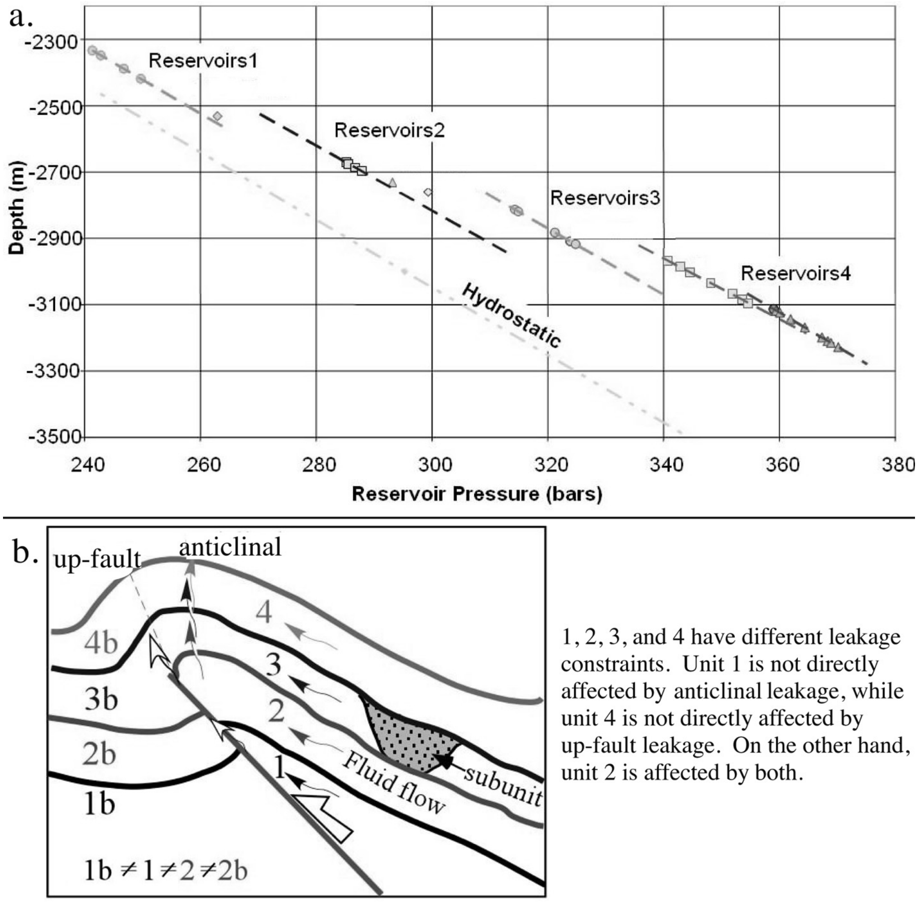


Figure 5. Pressure-depth plot and layer-by-layer model describing vertical and lateral geopressure cell compartmentalisation. (a) Pressure-depth plot showing overpressure shift at vertical pressure cell transitions, (b) layer-by-layer model showing different fluid-pressure dissipation constraints.

graphic unit varies with the nature of the thrust-propagation folds. This affects fluid-pressure dissipation differently from each unit, around the thrust fault (lateral geopressure structural limits) and associated anticline.

Vertical and lateral compartmentalisation model

The overpressure shifts from pressure-depth plots (Fig. 5a) also seemed to occur where there was a variation in the degree or nature of the fault-flanking fold. Apart from the leakage types mentioned earlier on, rates of folding could locally alter the petrophysical properties of the top and lateral seals. This implies changing volumetric properties with relative effects on fluid-pressure dissipation of each stratigraphic unit of the fold flanks. In the light of this, and by integrating other observations, we suggest a conceptual "layer-by-layer" model (Fig. 5b) to describe the lateral and vertical geopressure cell compartmentalisation. These scenarios show that every other factor of geopressurisation or compartmentalisation (folding, shortening, compaction, collapse, juxtaposition, anticlinal and up-fault leakages, etc) affects the various layers in a fold (especially fault-flanking) differently, relative to the degree of folding (and inclination of walls to fault plane) of each of the stratigraphic units. The smaller sedimentary subunit (reservoirs: sand lenses, channels, turbiditic deposits, etc) are enveloped and controlled by the larger geopressure unit.

Conclusion

The NE-SW displacement, occurring in the study area since Early Miocene, forms imbricate thrust structures in the deep offshore. The results obtained in this work have shown that the cuspate-lobate patterns of these structures are partly due to the regional structural lineaments confining the sediments and acting as barriers to their edges. The differential accommodation of shortening by the distal fold structures, resulting from this effect of flanking barriers, created strike slip, transfer and tear faults, and lateral ramp architecture during the Late Miocene and Early Pliocene. With rapid sedimentation, burial and compaction, pressure build-up within underlying stratigraphic units breached efficient vertical lithological seals and hydrocarbon fluids leaked through conduits created from faults and fractures. Variations in the effect of folding affected pressure distribution and produced a "layer-by-layer" behaviour that stacked geopressure compartments vertically across stratigraphic units as well as laterally across major thrust faults acting as compartment limits. The preservation of the observed pockmarks and other seabed leakage features is enhanced by the relatively calm nature of the present-day seabed.

Acknowledgements

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