Influence of Hinterland Bedrock Lithologies on Aspect of Borneo's Deepwater Fold and Thrust Belt

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Abstract

Each of the catchment areas of Borneo's major river systems has distinct differences in their bedrock lithologies. As the provenance for the sediments delivered to the deepwater depositional systems, these lithological variations in the hinterland are an important consideration when predicting high quality turbidite reservoirs as they influence compaction and diagenesis. This paper examines these issues for the Baram, Sandakan, Tarakan, and Kutei Basins. Additionally, the role of hinterland bedrock composition of the Baram and Padas Rivers is considered in terms of influencing along strike changes in the structural style of the Northwest Borneo deepwater fold and thrust belts.

Introduction

Borneo's petroleum systems range in richness from prolific to non-commercial. The Kutei, Tarakan, and Baram Basins are the most prolific basins (Figure 1) with initial discoveries onshore dating back to 1897, 1905, and 1910, respectively. With the exception of the carbonate-dominated Luconia province of Sarawak, Malaysia, the bulk of this island's production has come from siliciclastic sandstone reservoirs deposited in coastal plain and shallow marine environments. Over the last decade, however, frontier exploration efforts focusing on Borneo's deepwater fold and thrust belts have extended the proven petroleum systems to include deepwater turbidites coeval with the up-dip producing shallow marine clastic reservoirs. Although the commercial success rate in Borneo's deepwater fold and thrust has been modest, large areas remain unexplored. Predicting the presence of high quality reservoirs (e.g., thick, well-connected, porous, and permeable sand bodies) is one of the critical success factors when exploring in deepwater fold and thrust belts. Methods for predicting the occurrence and distribution of turbidite reservoirs typically use 2D and/or 3D seismic to identify and map geometries indicative of canyons, shelf edge gorges, channel-levee and fan systems. This paper discusses the role that differences in the bedrock composition of the hinterland (onshore) can have with respect to not only the quality of Borneo's deepwater turbidite reservoirs, but also to control on the mechanical stratigraphy and structural style of the NW Borneo deepwater fold and thrust belts.

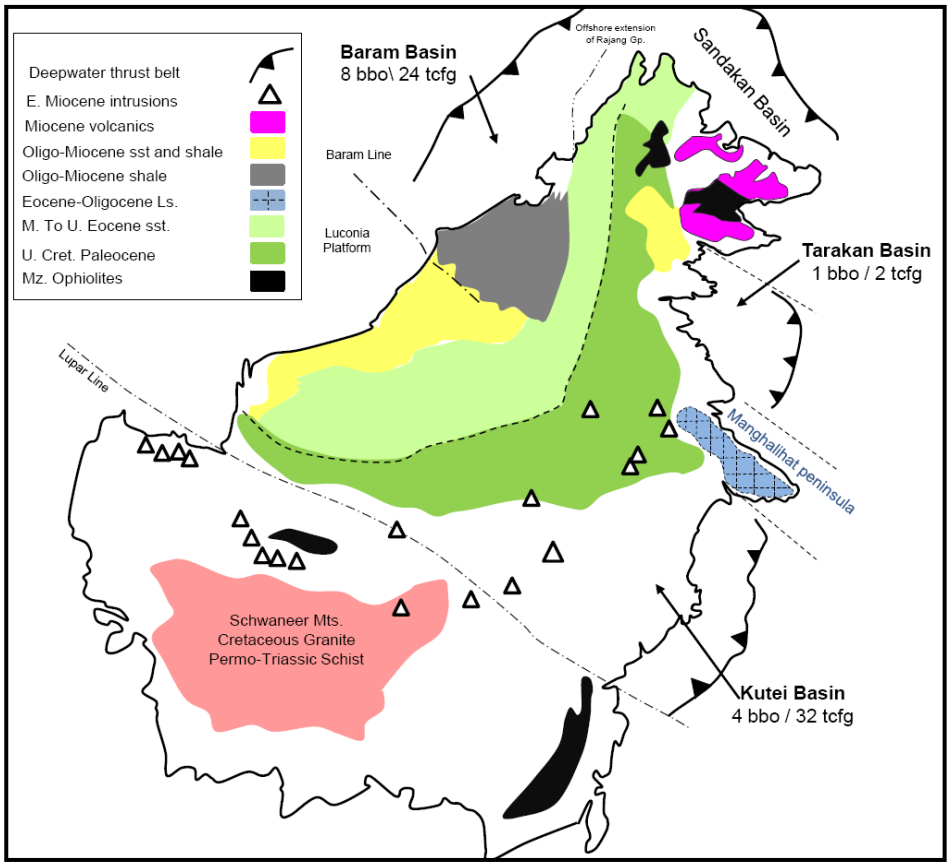


Figure 1. **Simplified geological map of Borneo showing deepwater fold and thrust belts. Modified from Tate (2001). Oligo-Miocene units shown on the NW side of the island represent the approximate paleogeography at that time when the shoreline trend was approximately orthogonal to the present day shoreline.**

Regional Setting

Lying at the edge of the Asian Plate, Borneo records a complex tectonic history that is still not fully resolved. The rugged and deeply dissected interior highlands of the island are dominated the Rajang-Embaluh Group, a thick series of Upper Cretaceous to Paleogene deepwater clastic successions. The Rajang-Embaluh Group is the major important source of the sediment shed into the Kutei, Tarakan, and Baram Basins and there are important regional lithological changes within its various units (see reviews by Tate, 2001; Hutchison, 2005) The older parts of the Group, such as the Menturang,

Layar, Kapit, and Sapulut units), generally record phyllite to lower greenschist facies metamorphism, whereas younger units do not (e,g., Pelagus and Crocker Formations). The Rajang-Embaluh Group was strongly deformed and bevelled during the Sarawak Orogeny, *ca.* 40 Ma (Hutchison, 1996), an event that probably extended into Sabah and possibly affected Palawan (Cullen, 2010). The Luconia, Barito, Kutei, and Tarakan basins all contain Late Eocene rift sequences that may represent post-orogenic collapse that followed the Sarawak Orogeny. The Sabah region experienced a second, younger, orogenic pulse around 20 Ma (Hutchison et al., 2000; Balaguru et al., 2008). Plate tectonic models for the regional generally attribute the Sarawak and Sabah Orogenies to the progressive SE to NE collision of the Luconia, Dangerous Grounds, and Reed Bank continental block with a subduction zone dipping SE beneath Borneo (Hall, 1997; 2002). These two orogenic pulses ultimately resulted in a major shift in the distribution of Borneo's deepwater depositional systems whereby shallow marine Neogene successions unconformably overlie the former Paleogene deepwater basins. The Neogene basins that rim Borneo contain as much as 10 km of sedimentary fill derived from extensive denudation of the interior and reworking of shelf sediments (Hamilton, 1979; Hall and Nichols, 2002).

The circum-Borneo shallow water Neogene basins have a contemporaneous deepwater fold and thrust belts. Each of these deepwater fold and thrust belts, however, occupies slightly different settings that are worth noting (Figure 1). The Baram Basin faces the South China Sea and its fold belt overlies rifted continental crust of the Dangerous Grounds which collided with Borneo, ending a phase of SE-directed subduction. The foldbelt of the Sandakan Basin overlies, at least in part, Miocene oceanic crust of the Sulu Sea, as well as deformed Paleogene turbidites. The deepwater Tarakan Basin appears to have built onto Eocene age oceanic crust of the Celebes Sea. The deepwater Kutei Basin fold and thrust

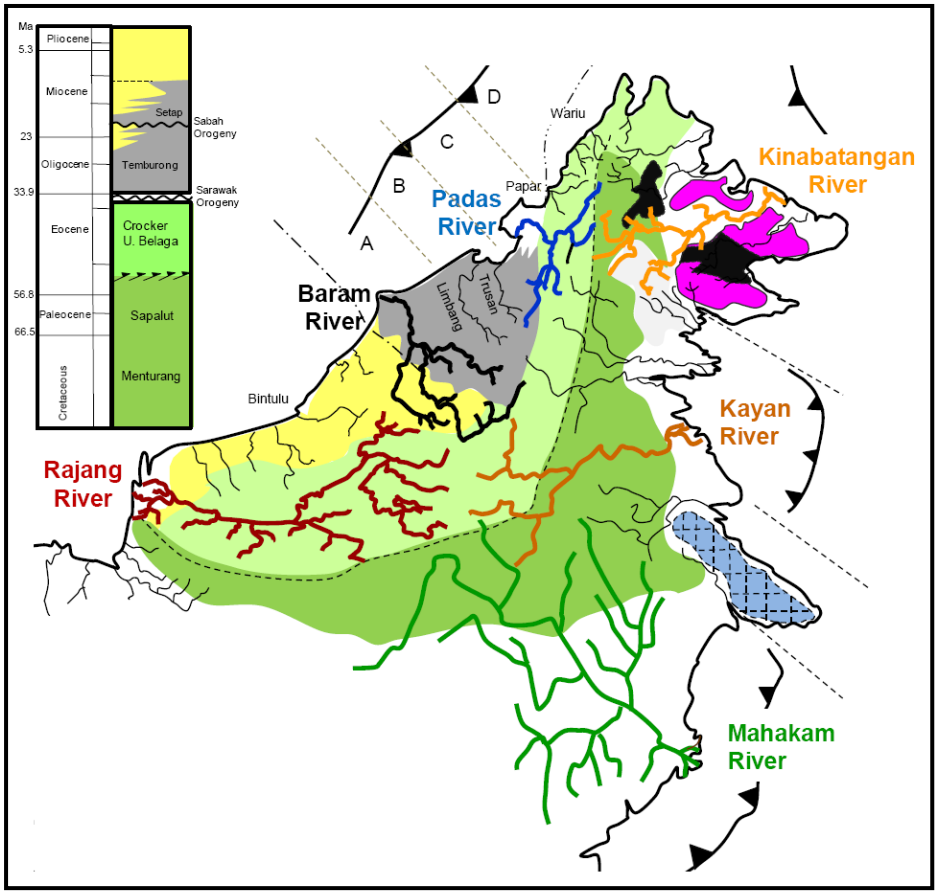


Figure 2. Enlarged area of the geological map of Figure 1 with drainages and major rivers shown. The inset stratigraphic column applies to areas within the catchments of the Baram and Padas Rivers.

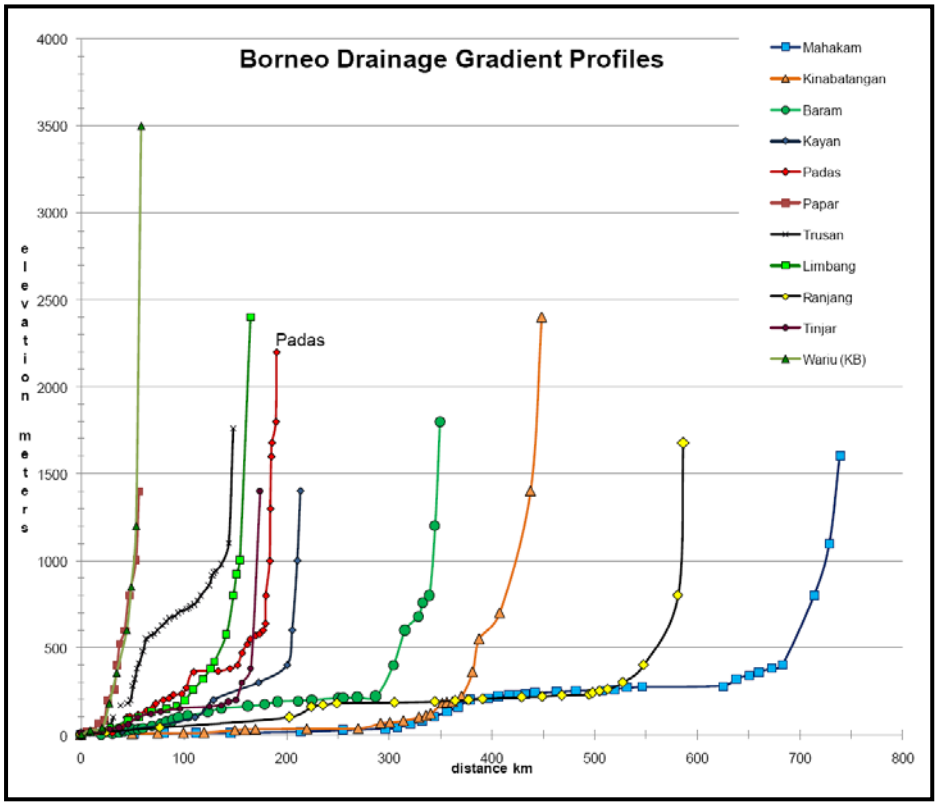


Figure 3. Gradient profiles of Borneo's major rivers and selected smaller rivers. Data have been digitized using Google Earth and Wikimapia.

belt overlies attenuated continental crust of the Makassar Straits and faces the Sulawesi deepwater fold-thrust belt which has an opposed sense of vergence. Although the present-day edge of the Asian plate lies on the eastern side of the Makassar Straits, Latest Miocene to Pliocene tectonic shortening (Hess et al., 2009), multiple tilted Early Miocene to Pliocene unconformities (Levell, 1987) in the Baram-Balabac Basin, as well as GPS motions and regional seismicity (Simmons et al., 2007) show that Borneo remains tectonically active even 1000 km from the plate edge. Balanced relationships between up-dip extension driven by sediment loading and concomitant down-dip contraction relative to tectonic shortening have yet to be determined at the island-wide scale.

Rivers, Catchment Areas and Provenance

The catchment areas of Borneo's rivers can be grouped into two main categories. Major river systems, such as the Mahakam, Rajang, Baram, Kinabatangan, Kayan and Padas Rivers, extend well into the interior of the island and have large catchment areas fed by numerous tributaries (Figure 2). Gradient profiles of the major rivers have long stretches with gentle gradients at relatively low elevations even far into the rugged interior (Figure 3). The major river systems are interpreted as long-established drainages that potentially represent major low-stand sediment delivery systems for the turbidites in the deepwater fold and thrust belts of Borneo. Minor rivers systems, such as the Bintulu, Limbang, Trusan, Papar, and Wariu, are relatively short and straight, have short high gradient profiles, and much smaller catchment areas (Figure 3). Because Borneo's coastlines are characterized as meso-tidal and have modestly strong wave action, the sediment that these smaller rivers deliver to the coast tends to be reworked along the shore, thus limiting the amount of deltaic progradation. The minor river systems with their smaller catchment areas tend to occur off the NW side of Borneo. The short and extremely steep gradient profiles

Table 1. Considerable range in bedrock compositions between the different catchments of Borneo's major river systems

River	Catchment Bedrock	Reservoir Considerations	Compositional Risk
Rajang	Eocene turbidites and shale	re-worked quartzose sands	Low
Baram	Oligo-Miocene marines shale	high percentage detrital clay	High
Padas	Eocene turbidites and shale	re-worked quartzose sands	Low
Kinabatangan	Mesozoic ophiolite,Paleogene phyllite & turbidites, Miocene volcanics	high percentage of unstable rock fragments	Medium
Kayan	Paleogene phyllite & turbidites	re-worked quartzose sands with mica	Low
Mahakam	Paleogene phyllite & turbidites, Reworked Neogene marine clastics	re-worked quartzose sands	Low

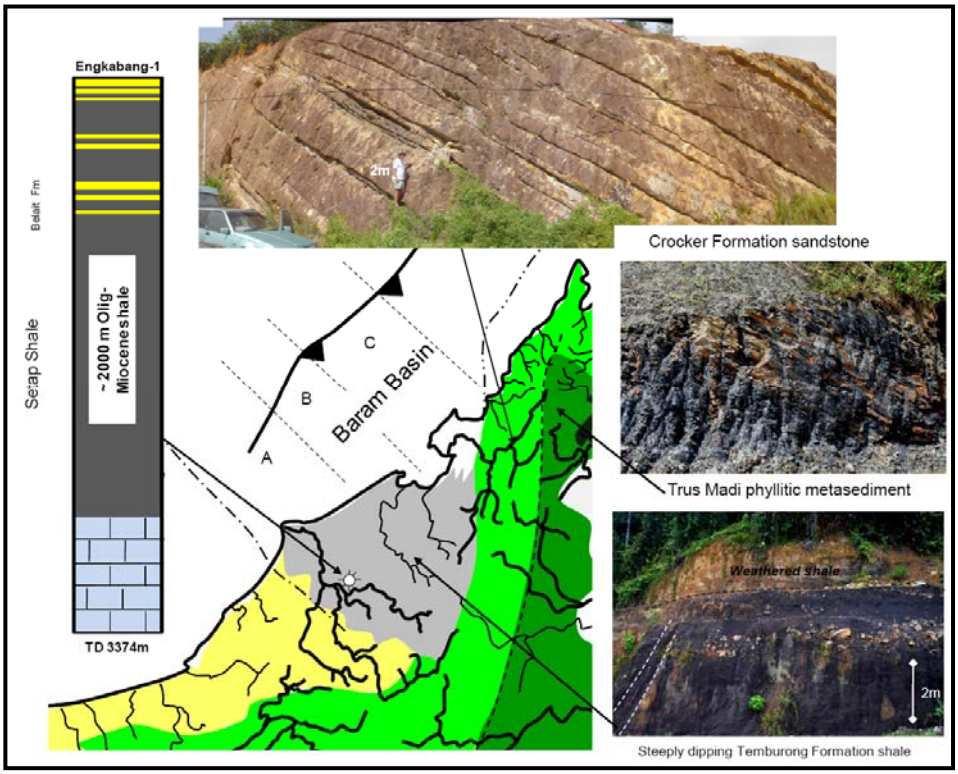


Figure 4. Photographs of representative outcrops of the lithostratigraphic units discussed in text and shown on the stratigraphic column of Figure 2. Engkabang-1 well data are modified from Hutchison (2005).

from Sabah attest to relatively youthful uplift. In this context the Padas River represents an important exception; it is the only river that has cut through the Crocker Range and has an expanded catchment area that includes intermontane valleys on the east side the range.

There is a considerable range in bedrock compositions between the different catchments of Borneo's major river systems (Figure 3 and Table 1). The range of hinterland bedrock lithologies has implications with respect to predicting reservoir quality at regional scale. Areas capable of delivering cleaner quartz-rich turbidites to the deepwater basins are preferable to those areas that could supply a high percentage of unstable rock fragments, feldspars, and detrital clay (Table 1). The Holocene deltas of Rajang and Mahakam Rivers offer a good example of the influence of hinterland provenance on depositional systems. The catchment area of Rajang Rivers is dominated by Eocene sandstones and the Holocene delta has a higher percentage of mixed layer clays (60%) than the Mahakam delta (15% to 40%) which drains phyllitic bedrock (Kapit and Layar members of the Belaga Formation). The relatively high proportion mixed layer clays

minerals in the Rajang River results in the development of a regionally extensive aquiclude that promotes the development of thick (13m) peat domes in the Rajang delta, whereas the such domes are rare in the Mahakam delta (Gastaldo, 2010). It is interesting to consider what role the presence or absence of raised peat mires could have on the stability of lateral facies changes and the sequestration of organic carbon in terms of the development of potential coastal plain vs deepwater source rock intervals.

Hinterland Influence on Thrust Belt Structural Style

The hinterland of the Baram Basin consists of two contrasting types of bedrock. The hinterland of the southwest part of the basin is dominated by the shales of the Setap and Temburong Formations; whereas the hinterland of the northeast part of the basin is dominated by sandstones of the Crocker Formation (Figures 2 and 4). These relationships suggest that the large drainage systems of the Baram and Padas Rivers represent mud-dominated vs. sand-dominated delivery systems to the basin.

Along strike (SW to NE) differences in the structural style of both the shelf and deepwater areas of NW Borneo define four transverse structural domains in the Baram Basin (Figure 5). The B-C and C-D domain boundaries appear to be basement controlled, whereas the A-B boundary is interpreted to reflect differences between the Baram and the Padas-Champion depositional systems (Cullen, 2010). The deepwater structures in Domain A are characterized by high amplitude, symmetric, detached folds (Figure 6a). The deepwater parts of Domains B and C are dominated by asymmetric fault-propagation folds that ultimately root into a common detachment level (Figure 6b). The structural style of Domain A likely reflects the presence of low strength, possibly over-pressured, mud-rich rocks that deform by penetrative bed-parallel slip (Erslev and Hennings, 2003), which is consistent with a provenance of the shale-prone hinterland for the Baram Delta.

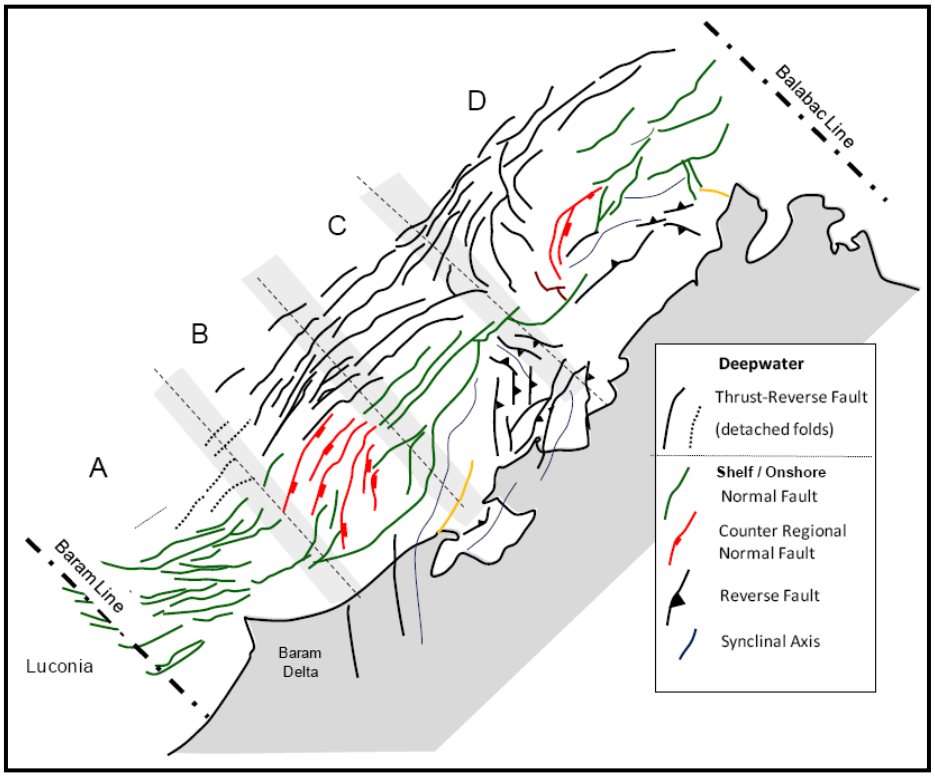


Figure 5. Linked shelf and deepwater structural domains of the Baram Basin (Cullen, 2010).

The deepwater sediments in Domains B and C are derived primarily from the Padas River catchment where the bedrock geology is dominated by sandy turbidites of the Crocker Formation. The fault propagation folds in the deepwater area of Domains B and C suggest a stronger mechanical stratigraphy than in the detached folds of Domain A, which is consistent with a higher percentage of sandstones in Domains B and C owing to a provenance in the Padas River catchment. Although differences in the total amount of strain in different domains of the NW Borneo fold and thrust belt may account for some of the differences in the structural styles between domains, lithology and layering represent more fundamental controls on such interrelated variables such as the strength of basal detachment, the coefficient of internal friction and the critical taper angle.

Thus, differences in the sand to shale ratios in the hinterland of the NW Borneo fold and thrust belt fold thrust belt potentially offers an example of hinterland control on the structural style of deepwater fold and thrust belts.

Conclusions

The different bedrock compositions of the catchments of Borneo's major river systems result in the erosion and transport of compositionally different sediment loads to respective receiving basins, which in turn influences lithostratigraphic aspects of those basins, such as the development of raised peat mires, the framework mineralogy of reservoir sands, and regional differences in ratio of sand to shale. In the Baram Basin, regional along-strike differences in the structural style of its deepwater fold and thrust belt appear to reflect contrasts in mechanical stratigraphy that can ultimately be related to differences in the dominant bedrock lithologies in the catchment areas from which the basin's sediments were derived; offering an example of hinterland influence on structural style.

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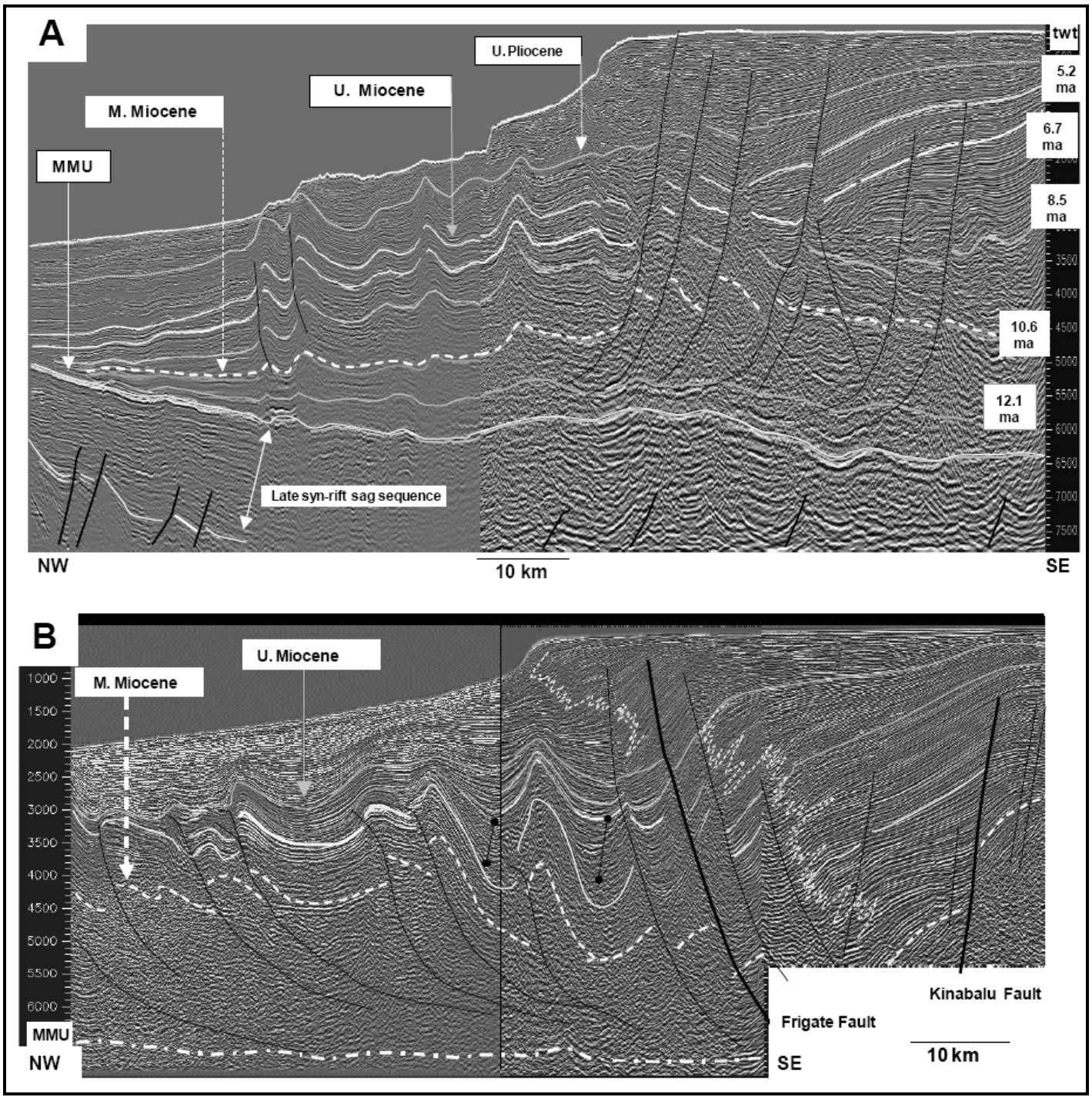


Figure 6. **Seismic lines from structural Domains A (6a) and B (6b) illustrating the different structural styles in the deepwater fold and thrust belts of those domains. MMU is a Middle Miocene unconformity above which a regional detachment level appears to represent a mechanically weak decollement.**

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