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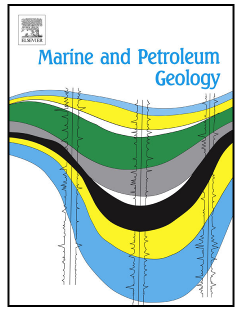

Title: Balancing deformation in NW Borneo: Quantifying plate-scale vs. gravitational tectonics in a Delta and Deepwater Fold-Thrust Belt System

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Balancing deformation in NW Borneo: Quantifying plate-scale vs. gravitational tectonics in a Delta and Deepwater Fold-Thrust Belt System.

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Abstract

Recent GPS measurements demonstrate that NW Borneo undergoes 4-6mm of plate-scale shortening a year, which is not accommodated by plate-scale structures. The only geological structure in NW Borneo described to accommodate on-going shortening is the Baram Delta System located on the outer shelf to basin floor. Delta toe fold-thrust belts are commonly thought to be caused by margin-normal compressional stresses generated by margin-parallel upslope gravitational extension.

The Baram Delta System is divided into three neotectonic provinces: 1) an inactive onshore and inner shelf region of inversion superimposed on an older extensional deltaic province, 2) an outer shelf region of present-day deltaic extension, and; 3) a compressional delta toe. However, it is uncertain whether compression in the delta toe area is purely driven by gravity (i.e. shortening is less than upslope extension) or if there is a component of regional shortening involved, which can only be demonstrated if shortening is greater than upslope extension.

In order to quantify the balance between the shortening related to the upslope gravitational extension and the shortening related to the regional geodynamic framework in the Baram Delta System, we have used a geomechanical code based on the Finite Element Method and conservation of mass and momentum, Dynel 2D. This enabled us to reconstruct the tectonic evolution of the delta and to demonstrate for the first time that the total shortening observed in the delta toe does not balance against the active extension in the delta top; with the system exhibiting >1.8% shortening overall (or ~2.0 km). This additional shortening is therefore attributed to plate-scale shortening across NW Borneo produced by far-field compression. Using a

convergence rate of 4 mm y^{-1}, demonstrated by GPS measurements, the delta toe has accommodated far-field compression only in the last 0.5 My.

Keywords: 2D Restoration; Deepwater Fold-Thrust Belt; Delta System; Numerical Modelling; Baram Delta; NW Borneo

1.0 Introduction

Tertiary delta systems typically sit on passive margins and deform purely by gravitational tectonics (e.g. Niger Delta System or Gulf of Mexico Delta System) and do not generally exhibit any evidence of far-field deformation (Bruce, 1973; Dailly, 1976). The Baram Delta System, NW Borneo, exhibits inversion of proximal delta structures due to far-field compression during the Late Miocene-Pliocene (Morley et al., 2003; Fig. 1A & D). At present-day, GPS measurements and in-situ stress orientations demonstrate far-field compression across NW Borneo (Simons et al., 2007). However, no structures in the area appear to accommodate this compression (shortening).

(Figure 1)

Delta and deepwater fold thrust belt systems are composed of a delta top, under extension, and a deepwater fold thrust belt (or delta toe), under compression (e.g. Mandl & Crans, 1981; Fig. 2A). Generally, most delta systems consist of two neotectonic provinces; an extension province and a compression province (Fig. 2A). The extension province coincides with the delta top and is composed of basinward or hinterland dipping normal faults and exhibits a margin-parallel σ_{Hmax} orientation

(Tingay et al., 2005b; Yassir & Zerwer, 1997; Fig. 2A). The compression province is synonymous with the delta toe or deepwater fold thrust belt; it comprises basinward verging thrust faults with associated folds and exhibits a margin-normal maximum horizontal stress (σ_{Hmax}) orientation (Tingay et al., 2005b; Fig. 2A). However, the Baram Delta System consists of three neotectonic provinces; a compression province, an extension province and an additional inverted province (King et al., 2009a; Fig. 1). The latter demonstrating large inversion structures consistent with far-field compression during the Late Miocene to Pliocene (Morley et al., 2003; Tingay et al., 2005a). The inverted province demonstrates an in-situ margin-normal σ_{Hmax} orientation, perpendicular to that expected in the delta top. However, inversion structures in the inverted province are inactive and no longer accommodate observed far-field compression (King et al., 2009b; Tingay et al., 2009).

Here, we present a two-dimensional (2D) restoration of the Baram Delta System using Dynel 2D software. These 2D restorations resolve the amount and distribution of extension and compression across the Baram Delta System exhibited by deformation of Miocene to Recent sediments.

(Figure 2)

2.0 Geological Setting

NW Borneo is part of Sundaland, which is surrounded by the Philippine subduction zone to the east and the Indonesian subduction zone to the south and west (Fig. 3A). To the north, Sundaland is bounded by the South China Block; part of the Eurasian Plate, which is dominated by extrusion tectonics associated with the Himalayas (Fig.

3A). This area of SE Asia has had a tectonically complex evolution throughout the Cenozoic and at present-day the tectonic plate configuration across the region remains complicated (Hall, 2002).

(Figure 3)

The Crocker-Rajang accretionary complex is a result of subduction of a Proto-South China Plate below NW Borneo, where the associated trough is now covered by modern sediment (Hall, 2002; Hutchison, 2005; Tan & Lamy, 1990). The Palawan Trough offshore NW Borneo is a remnant of the most recent South China Sea-NW Borneo subduction zone (Hall, 2002; Fig. 3B). This subduction zone ceased during the Early-Miocene (~16-17 Ma) due to jamming by the Dangerous Grounds attenuated continental crust (Hutchison, 2005; James, 1984; Levell, 1997).

Uplift and deformation of the Crocker-Rajang accretionary complex continued to the Quaternary; sourcing the large Baram Delta System deposited from the Miocene to the present-day (Hutchison et al., 2000; Sandal, 1996). The Baram Delta System is located on- and offshore in Brunei and consists of several small deltas (James, 1984; Lambiase et al., 2002; Sandal, 1996). The majority of structures in the Baram Delta System and across NW Borneo strike NE-SW reflecting both the extensional tectonics associated with the NW prograding delta and the NW (basinward) migration of the active margin deformation front (Hinz et al., 1989; Hiscott, 2001; Ingram et al., 2004; Sandal, 1996; Fig. 1).

Three neotectonic provinces characterised by distinct structures and σ_{Hmax} orientations have been identified in the Baram Delta System (King et al., 2009a; Fig. 1). The compression province coincides with the deepwater fold thrust belt (or delta toe) and is located on the slope to basin floor, offshore NW Borneo. It is characterised by a margin-normal (NW-SE) σ_{Hmax} orientation and basinward verging, NE-SW striking imbricate thrust sheets (Hinz et al., 1989; Ingram et al., 2004; James, 1984; King et al., 2009a; Fig. 1B). Many of the thrust sheets have associated fault propagation folds, some of which form sea bed highs (e.g. Franke et al., 2008; Hinz et al., 1989; Ingram et al., 2004; Morley, 2007); which suggests that they are recent structures.

The extension province is consistent with the delta top of the Baram Delta System and is situated on the outer shelf to shelf edge (Fig. 1). It is characterised by a margin-parallel (NE-SW) σ_{Hmax} orientation and basinward dipping, NE-SW striking, normal growth faults (King et al., 2009a; Tingay et al., 2005a; Fig. 1C). Many of these faults display fault scarps at the seabed producing seafloor topography (Hiscott, 2001); inferring the faults are active at present-day or have been recently active. Together the extension and compression provinces form the actively deforming delta system at present-day.

The inverted province is located on the inner shelf and onshore regions of Brunei (Fig. 1). It is characterised by a margin-normal (NW-SE) σ_{Hmax} orientation (King et al., 2009a; Tingay et al., 2005a; Fig. 1) and large-scale (kms) NE-SW and N-S trending inversion structures (Sandal, 1996; Morley et al., 2003). The inverted province represents proximal, older delta areas that have been inverted due to migration of the deformation front from inboard NW Borneo during the Late

Miocene-Early Pliocene (Morley et al., 2003; Tingay et al., 2003; Tingay et al., 2005a; Fig. 1D). Restorations of these inversion structures, using classic restoration software has demonstrated >600m shortening in the inverted province (Back et al., 2008). However, these inversion structures are inactive at present-day and thus, do not accommodate any present-day far-field compression (King et al. 2009b; Morley et al., 2003; Tingay et al., 2003; Tingay et al., 2005a).

3.0 Evidence of Far-Field Compression

The absolute plate motion of Sundaland is 30 mm y^{-1} towards the ESE; and compilations of GPS measurements across NW Borneo clearly demonstrate that NW Borneo is undergoing compression relative to Sundaland (Michel et al., 2000; Simons et al., 2007; Fig. 3). The results from the GEODYSSEA station in Brunei exhibits 18 mm y^{-1} of relative (to Sundaland) movement towards the NW (Michel et al., 2000; Fig. 3B). More recent studies demonstrate motions from three stations, situated at Kinabalu, Labuan and Miri, observed over the previous decade (Simons et al., 2007). Results from the Kinabalu and Labuan stations demonstrate 6 mm y^{-1} of relative (to stable Sundaland) movement toward the west (Fig. 3B). Results from the Miri station demonstrate 4 mm y^{-1} of relative (to stable Sundaland) movement towards to the WNW (Simons et al., 2007; Fig. 3B). Thus, demonstrating 4-6 mm y^{-1} of far-field compression across NW Borneo at present-day.

In-situ σ_{Hmax} orientations in the inverted province of the Baram Delta System demonstrate the influence of far-field compression at present-day (King et al., 2009b). In-situ σ_{Hmax} orientations in the inverted province are margin-normal (NW-SE) and thus, perpendicular to what might be expected on a delta top (Tingay et al., 2005b;

Yassir & Zerwer, 1997; Figs 1 & 2). Furthermore, the σ_{Hmax} orientations are sub-parallel to the GPS motions; demonstrating they are consistent with the far-field compression (Figs 1 & 3). However, stress magnitudes in the inverted province are not so convincing. The magnitudes demonstrate a borderline normal fault to strike-slip fault stress regime, which infers that active inversion is not occurring at present-day in the inverted province (King et al., 2009b; Morley et al., 2008; Tingay et al., 2009). Therefore, inversion structures do not accommodate the observed shortening of 4-6 mm y^{-1}.

A deepwater fold-thrust belt situated offshore Sabah is composed of a series of imbricate thrust sheets striking NE-SW; each thrust is associated with a fault-propagation fold (Franke et al., 2008; Hinz et al., 1989; Ingram et al., 2004; Fig. 1B). Folds decrease in age toward the front of the fold-thrust belt; to the NW (Franke et al., 2008; Hinz et al., 1989; Ingram et al., 2004). The youngest folds produce sea-floor topography with the underlying thrusts intersecting the basin floor, inferring they have been recently active. The Sabah fold-thrust belt is associated with very little up-dip deltaic extension (e.g. Tan & Lamy, 1990; Hazebroek & Tan, 1993) inferring that recent far-field compression is a significant driving force.

4.0 2D Restorations of the Baram Delta System

Extension on a delta top generates gravity-driven compression in a delta toe at the present-day and at all points during a delta system's evolution (Fig. 2A); thus, forming a balanced system that has been compared to a critical taper wedge (e.g. Bilotti & Shaw, 2005; Morley, 2007). A critical taper wedge describes the tectonics of fold thrust belts and accretionary prisms; it is a delicate balance of extension and compression (Elliott, 1976; Davis et al., 1983; Dahlen, 1984; Fig. 2A). Therefore, in an ideal delta system we would expect the amount extension in the delta top to balance against the amount compression in the delta toe. However, many deltas do not show this balance of extension and compression. For example, the Niger Delta (West Africa) demonstrates more extension than compression (Morley, 2003). This is consistent with prograding delta systems, whereby the extensional delta top cannibalises the delta toe fold-thrust belt as the delta progrades; resulting in a much larger region of extension than compression (Morley & Guerin, 1996; McClay et al., 2003; Fig. 2B). In the Baram Delta System, the amount of shortening should overcome the amount of extension if, as outlined above, the far-field compression across NW Borneo is accommodated by delta toe structures. To test this hypothesis, we carried out a 2D restoration of a geological cross-section across the Baram Delta System. A variety of techniques have been developed to restore deformed rocks to their initial geometry prior to deformation. The most common of these tools used are based on geometric and kinematic analysis of deformation (Dahlstrom, 1969; De Paor, 1988; Geiser, 1988; Hossack, 1979; Marshak & Woodward, 1988; Woodward et al., 1989), where the models have to respect strict geometric assumptions, such as preservation of area between beds, minimization of segment length changes, rigid blocks, fixed faults in space, constant fault slip and minimization of shearing (Maerten & Maerten, 2006). Balancing of a section is possible by applying flexural slip to accommodate the deformation caused by slip along an infinite number of bedding planes and inclined or vertical shear to model slip along fault surfaces.

Geometric restoration techniques provide a valid proxy to test the validity of a cross-section in various tectonic settings (Griffiths et al., 2002). However, the basic assumptions formulated while using these tools are proved invalid when considering fault block deformation, fault slip distribution and potential interactions of different sets of faults during a given tectonic stage. Furthermore, different mechanisms are used to mimic deformation in different tectonic settings, preventing any direct study of the development of compressive structures directly related to extensional structures. Finally, variations in the rheology of the different units are not taken into account during the balancing of a section, which constitutes a significant drawback when considering heterogeneous sedimentary packages, as found in deltas.

The originality of our methodology lies in using a recently developed continuum code, Dynel 2D (Maerten & Maerten, 2006). This is based on the finite element method (FEM; Hughes, 1987) and combines geomechanics and stochastic techniques (e.g. Walsh & Watterson, 1988) used for modelling and restoring complex geological structures; e.g. folded, fractured or faulted rock (Maerten & Maerten, 2006). It differs from classic restoration software because it uses fundamental physical laws that govern rock deformation (including conservation of momentum, mass and energy) and linear-elastic theory, with the kinematic constraints necessary for restoring geological structures (Maerten & Maerten 2006). This approach provides more realistic models (Bourne et al. 2000, Maerten & Maerten 2006).

The finite element method formulation and solution is divided into a series of individual steps necessary to achieve a comprehensive model. This numerical method yields approximate values of the unknown at discrete numbers of points in the continuum; the values yielded in Dynel 2D are displacement values for each element. This process involves the discretization of the modelled body into a smaller linear triangular mesh (the finite elements) interconnected at nodes and connected to boundaries (Fig. 4A). Each element is assigned material properties (Young's Modulus, Poisson's Ratio and density), which may differ from element to element. Each element behaves according to a prescribed linear-elastic law depending on the applied forces, internal forces, displacements and interface contact reactions. While other codes used the global stiffness method (Hughes, 1987), Dynel 2D uses an iterative solver based on the Gauss-Seidel method. The Gauss-Seidel method allows forces to be transmitted from node to node through the system until equilibrium is obtained (Golub & Van Loan, 1996; Maerten & Maerten, 2006).

The use of this new approach enabled us to study the balance between extension and compression in the Baram Delta System by taking into account the mechanical interaction between the normal faulting in the delta top and the subsequent folding and thrusting in the delta toe. This differs from previous kinematic and geometric balancing tests, where folding and normal faulting had to be balanced in two separate and independent stages (e.g., Back et al., 2007).

4.1 The Model

The model of the Baram Delta System was constructed using published seismic and detailed cross-sections derived from seismic lines using GOCAD and later imported into Dynel 2D (Hinz et al., 1989; Sandal, 1996; Hiscott, 2001; Morley et al., 2003; Ingram et al., 2004; Hutchison, 2005; Morley, 2007; Morley & Back, 2007; Back et al., 2008; Figs 1 & 4A). The section line crosses only the extension and compression provinces of the Baram Delta System because the model tests the active tectonics of the delta system (Fig. 1). The section line does not include the inverted province because inversion occurred during the Miocene-Pliocene and is not active at present-day so has no effect here (Fig. 1). Restoring the inverted province would significantly contribute to the shortening component of the delta system; thus, skewing the final results toward the known Miocene-Pliocene uplift-shortening event.

The section line is approximately 110 km in length. The model exhibits three main rock units overlying the Early-Middle Miocene Deep Regional Unconformity; the oldest rock unit is the Middle Miocene Setap Shale, the second rock unit is the Late Miocene deltaic deposits and the youngest rock unit is the Pliocene to Recent deltaic deposits (Fig. 4A). These three rock units form the Baram Delta System. Rock properties, such as Poisson's Ratio, Young's Modulus and density were assigned to each of these units and, where available, wireline log derived rock properties were used (Table 1). Log derived rock properties were calculated from sonic logs and density logs. The log derived values of Poisson's Ratio and Young's Modulus were converted from their dynamic form to a static form using Lacy's (1997) relations. Wireline logs are taken from in situ rocks during wellbore drilling operations; resulting in calculated rock properties that are close to the actual values. Rock properties are key parameters in this modelling so inaccuracies may contribute to invalid results. However, Backé et al. (2008) have shown that variations of rock properties in this model do not significantly affect the resulting shortening estimates. Thus, any small deviation of calculated rock properties from actual rock properties is considered negligible to the modelling results. Decompaction was also applied to the sediments during restoration; the Sclater and Christie (1980) relation for marine sediments was used.

(Table 1)

As our model aimed to test the balance between extension and compression in the Baram Delta System, we have focused our study in the wedge formed between the Deep Regional Unconformity at the base of the delta and the present-day bathymetry. The lateral boundaries of the model are considered free to move, whereas the nodes along the Deep Regional Unconformity are free to move along the x direction only. We used an idealized shape of a sub-marine slope (dipping <4°; Porébski & Steel, 2003) as a target line for the restoration of the various horizons prior to deformation (Fig. 4).

(Figure 4)

4.2 The Restoration Process and Results

Firstly, the section line built from seismic and cross-sections was imported into Dynel 2D and names were assigned to each rock unit. A sealed model was created and properties were assigned to each formation and fault (Table 1). Rock contacts and faults must be identified as sliding or locked surfaces. This study locked all contacts and faults were allowed to slide. Rock properties such as Poisson's Ratio, Young's Modulus and density, were allocated to each rock unit; where possible log derived values were used (Table 1).

Restoration of the model was undertaken by restoring each rock unit individually, starting with the youngest (the Pliocene to Recent deltaic deposits). The structure of each rock unit was restored to a planar, horizontal target line. There were three steps, in total, to restore the Baram Delta System, consistent with the three rock units forming the delta: 1) the Pliocene-Recent deltaic deposits (Fig. 4B); 2) the Late Miocene deltaic deposits (Fig. 4C), and; 3) the Middle Miocene Setap Shale (Fig. 4D).

The model results demonstrate that the overriding driving force of deformation in the Baram Delta System is gravity. Extension in the delta top is driven by loading of a mobile substratum by prograding deltaic sequences, which results in gravity driven compression in the delta toe (Bruce, 1973; Dailly, 1976). However, across the entire model there is a net compression of ~1.8%, equivalent to ~2.0 km shortening (total section line length is 110 km). Thus, the amount of extension does not balance against the amount of compression. It should be noted that ~1.8% shortening does not account for the shortening that is potentially accommodated by out of plane movement and by the lower shale unit. Therefore, 1.8% is a minimum value of shortening across the, present-day tectonically active, Baram Delta System. The model shows considerably more shortening in the delta toe than there is extension in the delta top; inferring that additional shortening from far-field compression is, in part at least, accommodated by the delta toe. The excess >1.8% shortening in the delta toe equates to the far-field compression consistent with GPS measurements. Assuming a constant compression of ~4 mm yr^{-1} (consistent with the recent GPS measurements), the additional compression, accommodated by the delta toe, has occurred only in the last 0.5 My.

Discussion: Potential Sources of Far-Field Compression across NW Borneo

We have demonstrated that far-field compression across NW Borneo is accommodated by thrusts and associated folds in the Baram Delta toe. Here, we discuss the potential sources of far-field compression across NW Borneo. NW Borneo sits in the middle of Sundaland well away from any plate edge deformation effects. The local Palawan subduction zone (Fig. 3B) is the most obvious local candidate that could potentially accommodate far-field compression. However, it has been quiescent since the Early-Miocene when it was jammed with attenuated continental crust, known as the Dangerous Grounds (Levell, 1989; Sandal, 1996). Relatively, low amounts of seismicity have been recorded at present-day across northern Borneo, inferring no subduction at present-day and that little internal deformation of the plate is occurring (Fig. 5). Other sources of compression, discussed below, may be active ridge push from sea floor spreading to the southeast of Borneo, slab detachment, Philippine Plate push, Indo-Australian Plate push or influences from the escape tectonics associated with the Himalayas (Fig. 3A).

(Figure 5)

Compression across NW Borneo may potentially be driven by extension behind Borneo in the Celebes Sea area (Fig. 3A). Indeed, extension (ridge push) in the Celebes Sea was one of the driving mechanisms of the ancient Palawan subduction zone during the Eocene and Oligocene (Silver & Rangin 1991, Hall 2002). However, this extension ceased during the Late Oligocene (Hall 2002). At present-day, there appears to be no active ridge push from sea floor spreading to the southeast of Borneo, which might have contributed to the compressional driving force across NW Borneo.

Slab detachment is associated with the early stages of continental collision and a decrease in the subduction rate due to the buoyancy of continental lithosphere in the subduction zone (Davies & Von Blanckenburg 1995, Wong A Ton & Wortel 1997). Slab detachment is a process of thermal diffusion that occurs after the termination of subduction (Gerya et al. 2004). Changes in topography and significant volcanic activity are associated with slab detachment (Gerya et al. 2004).

Previous authors have suggested that slab detachment is the mechanism by which uplift has continued across NW Borneo long after the jamming of the Palawan subduction zone (e.g. Morley & Back, 2008). If this were the case, we would expect to see hinterland uplift and volcanic activity. Hinterland uplift has been observed since the Early-Miocene after the subduction ceased; thus, supporting this alternative mechanism for uplift (e.g. slab detachment). However, there is no volcanic activity at present-day across NW Borneo.

Two major plate-boundaries are present to the south, west, and east of Borneo (Fig. 3A). A subduction zone exists to the east, where the Philippine Plate is actively subducting beneath Sundaland (Hall 2002). The Philippine Plate moves to the WNW at a rate of 60 mm y^{-1} (Simons et al. 2007, Fig. 3A). To the south and west, the Indo-Australian Plate is moving NNE at a rate of 58 mm y^{-1} and is actively subducting beneath Sundaland (Hall 2002, Simons et al. 2007, Fig. 3A). The Philippine and Indo-Australian Plates are moving at significantly larger rates towards Sundaland than Sundaland is moving toward them (i.e. 30 mm y^{-1} ESE); implying greater stresses are present at plate boundaries adjacent to the Philippine and Indo-Australian Plates. These stresses may well be transmitted into Sundaland.

The WNW direction of the Philippine Plate is consistent with the west and WNW GPS measurements from all stations in northern Borneo at present-day (including the Kinabalu, Labuan and Miri stations) and the N-S trending Miocene-Pliocene inversion structures observed across NW Borneo (Morley et al. 2003, Figs 1 & 3B). The NNE motion of the Indo-Australian Plate is not consistent with any features that reflect far-field compression across NW Borneo at present-day; suggesting that the Philippine Plate has more influence on NW Borneo than the Indo-Australian Plate. The Banda Arc and Sulawesi regions, directly between the Philippine and Indo-Australia Plates, are tectonically very complex regions, with Sulawesi itself exhibiting large NW directed relative plate motions (Michel et al. 2000, Simons et al. 2007). Thus, there may be geometrical effects between the Philippines and Indo-Australian Plates that result in a NW to WNW directed compression in NW Borneo. However, the gravity driven component of stress is strong, as demonstrated by our 2D restorations of the delta system. The magnitude of the gravity driven component of the stress tensor is sufficiently large that offshore the σ_{Hmax} orientation becomes reoriented to a NW-SE, whilst onshore, where the system is coupled to basement and there is no detached gravity system the σ_{Hmax} orientation is expected to be sub-parallel to the west to WNW directed GPS motions. The ancient Palawan subduction zone is also a large pre-existing zone of weakness. It exhibits reactivated overthrusting associated with Australia-Indonesia and India-Eurasia collision during the Late Miocene to Recent (Hall, 1996; Hall & Morley, 2004; Morley et al., 2008). The orientation of these structures is consistent with the NW directed σ_{Hmax} orientations in the delta toe.

Escape tectonics dominate the northern edge of Sundaland, where India is being forced into the Eurasian Plate; resulting in north-south striking, kilometric-scale strike-slip faults (Morley et al., 2001). Escape tectonics of this region imply a significant south directed push into Sundaland, which may result in far-field compression across NW Borneo.

Here, we favour a combination of the three major bounding forces; Philippine Plate push, Indo-Australian Plate push and Himalaya escape tectonics, as the mechanisms of compression across NW Borneo; with reorientation of the resulting far-field west and WNW σ_{Hmax} orientations in the Baram Delta System to NW due to the significant gravity-driven stresses of the delta and pre-existing weakness of the Palawan subduction zone.

5.0 Conclusions

The presented study tests the balance between compression and extension by restoring the deformation in the Baram Delta System using a geomechanical restoration software, Dynel 2D. Unlike other restoration methods, which are based on kinematics and geometric assumptions, our model takes into account rock mechanics (constrained from our own work), mechanical interaction between faults and passively deforming boundaries.

The 2D restoration of the Baram Delta System presented herein demonstrates that present-day west and WNW directed far-field compression observed across NW Borneo is accommodated by the actively deforming Baram delta toe fold-thrust belt. An overall shortening of >1.8% has been quantified for the present-day tectonically active Baram Delta System (Fig. 4). The dominant driving mechanism of deformation in the Baram Delta System is gravitational deltaic tectonics and this additional far-field shortening is accommodated by the delta toe. GPS measurements, demonstrating 4-6 mm y^{-1} of far-field compression, show that formation of the most distal delta toe structures occurred in the last 0.5 My. The source of this west and WNW far-field compression has been discussed and a combination of Philippine Plate and Indo-Australian Plate push is favoured. However, the stresses resulting from far-field compression in the vicinity of the Baram Delta System are reoriented from east-west and ESE-WNW to NW-SE due to the significant influence of gravity-driven tectonics in the Baram Delta System itself.

From the modelling we can demonstrate 2.0 km excess shortening in the deepwater fold thrust belt that cannot be explained as being linked to up-dip extension. This translates to 0.5 My worth of convergence at present day NW Borneo-Sundaland convergence rates of ~4 mm/yr. The fold thrust belt has been active since the late Miocene, which coincides with the deformation in Sulawesi, on the western margin of the Australia-Timor collision zone (e.g. Hall, 2002; Fig. 3A). The syn-kinematic sedimentary section associated with deepwater fold development is of latest Miocene-Recent age (e.g. Ingram et al. 2004), so if the main period of shortening is assumed to have lasted ~ 6 My, then it would appear that the excess shortening in the deepwater fold thrust belt is not sufficient to account for the total shortening along the margin.

Several factors can explain this discrepancy: 1) inversion of growth faults along the inner shelf and onshore has accommodated some shortening, but this is only along 2-3 folds wide, and could not account for the missing 15+ km of shortening; 2) much more of the deepwater fold and thrust belt shortening is related to far field stress, and extension is not driving shortening in the slope area, and; 3) shortening is also occurring by overthrusting along the Palawan subduction zone, where the Dangerous Grounds crust is being overthrust by NW Borneo. A combination of 1) and 3) above are the most likely explanation for accommodation of the shortening not taken up by the deepwater fold thrust belt.

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Figures, Tables and Captions

Figure 1: A) Location map for the Baram Delta System, NW Borneo demonstrating the neotectonic provinces; including the characteristic maximum horizontal stress orientations and structures observed in each province. Location of sections displayed in Figures 1B, C, D and Figure 4 are depicted. B) Line drawing from seismic section across the Compression Province exhibiting imbricate thrust sheets and associated fault-propagation folds (modified from Hinz et al., 1989). C) Seismic section across the Extension Province demonstrating margin-parallel normal faults with scarps at the sea floor (from Hiscott, 2001). D) Schematic cross-section across the Jerudong Anticline in the Inverted Province illustrating the inversion of ancient deltaic normal faults (from Morley et al., 2003).

Figure 2: The generally expected structure of a delta system (A), with the delta top under extension and the delta toe (deepwater fold-thrust belt) under compression and the structure of a prograding delta (B) with significantly more extension than compression (modified from Tingay et al., 2005b).

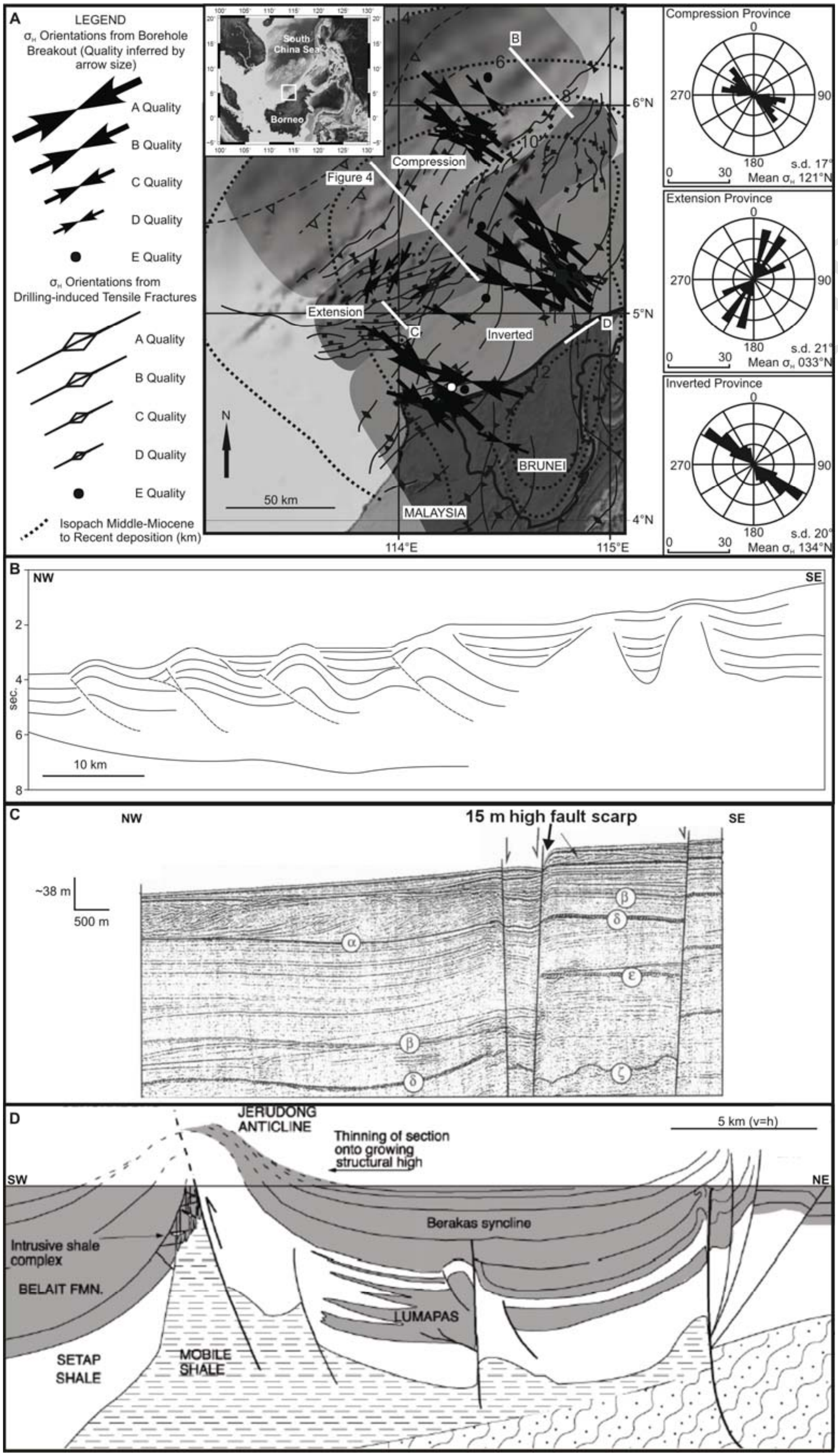
Figure 3: Compilation of GPS measurements from Michel et al. (2000) and Simons et al. (2007) demonstrating the absolute plate motions for the Sundaland and the Eurasian, Philippine and Indo-Australian Plates (A), as well as plate motions across Borneo relative to a stable Sundaland (B).

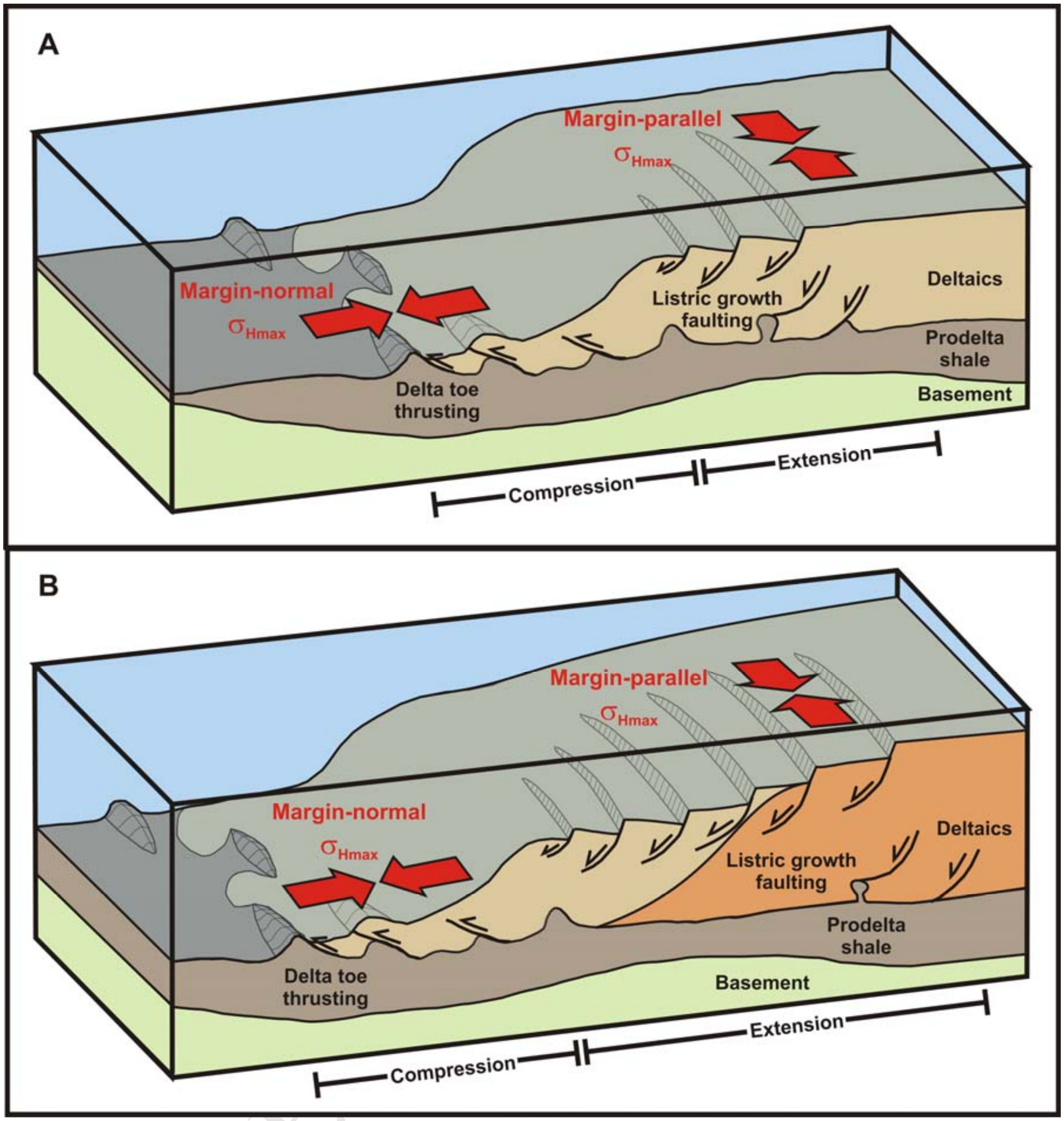
Figure 4: Structural model of the Baram Delta System restored using Dynel 2D, location of line depicted in Figure 1A. A) The unrestored model of the Baram Delta System (L_1), illustrating the Finite Element Model mesh used for restoration. B) Restoration of the Pliocene to Recent deltaic deposits (L_{01}). C) Restoration of the Late Miocene deltaic deposits (L_{02}). D) Restoration of the Middle Miocene Setap Shale unit (L_{03}).

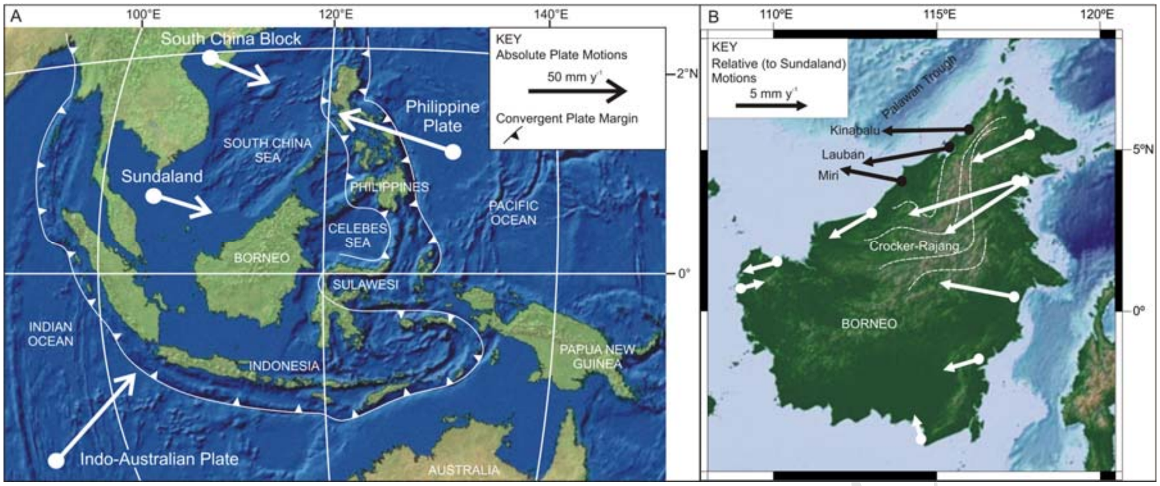
Figure 5: Map of recent shallow seismic activity (1973-2006) across NW Borneo (USGS, 2004).

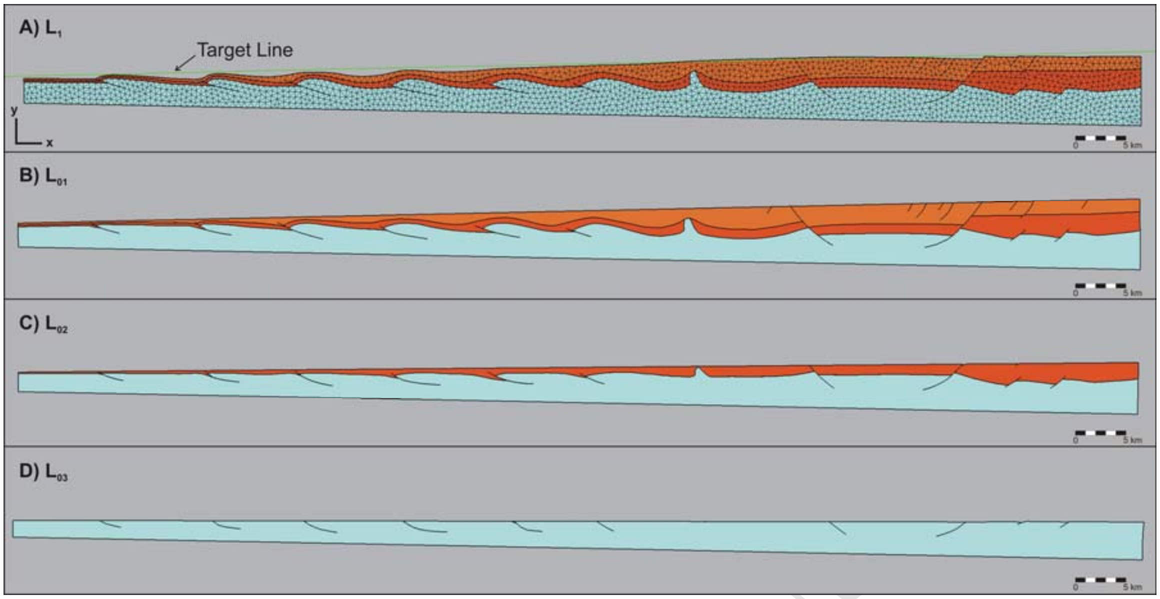
Table 1: Log derived rock properties* and assumed rock properties (Dynel 2D defaults) used for Dynel 2D model of the Baram Delta System. Log derived rock properties were converted from dynamic to static values using Lacy's (1997) relations.

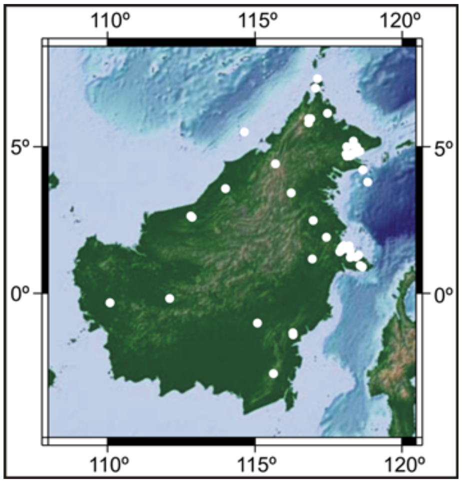
Model Layer		Poisson's Ratio	Young's Modulus	Density (g cm^{-3})
Pliocene-Recent	Proximal Delta	0.10	1.12	2.24*
	Distal Delta	0.40*	4.98*	2.13*
Late Miocene	Proximal Delta	0.29*	2.11*	2.41*
	Distal Delta	0.37*	6.45*	2.38*
Middle Miocene	Setap Shale	0.30	2.80	2.53


A
LEGEND
σH Orientations from Borehole Breakout (Quality inferred by arrow size)
A Quality
B Quality
C Quality
D Quality
E Quality
σH Orientations from Drilling-induced Tensile Fractures
A Quality
B Quality
C Quality
D Quality
E Quality
Isopach Middle-Miocene to Recent deposition (km)
South China Sea
Borneo
Compression
Figure 4
Extension
Inverted
BRUNEI
MALAYSIA
50 km
N
114°E
115°E
6°N
5°N
4°N
Compression Province
s.d. 17°
Mean σH 121°N
Extension Province
s.d. 21°
Mean σH 033°N
Inverted Province
s.d. 20°
Mean σH 134°N
B
NW
SE
sec.
10 km
C
NW
SE
15 m high fault scarp
~38 m
500 m
α
β
δ
ε
ζ
D
JERUDONG ANTICLINE
Thinning of section onto growing structural high
5 km (v=h)
SW
NE
Berakas syncline
Intrusive shale complex
BELAIT FMN.
LUMAPAS
SETAP SHALE
MOBILE SHALE


A
Margin-parallel
σ_{Hmax}
Margin-normal
σ_{Hmax}
Listric growth faulting
Deltaics
Prodelta shale
Basement
Delta toe thrusting
Compression
Extension
B
Margin-parallel
σ_{Hmax}
Margin-normal
σ_{Hmax}
Listric growth faulting
Deltaics
Prodelta shale
Basement
Delta toe thrusting
Compression
Extension


A
100°E
120°E
140°E
South China Block
KEY
Absolute Plate Motions
50 mm y⁻¹
Convergent Plate Margin
Philippine Plate
SOUTH CHINA SEA
Sundaland
PHILIPPINES
PACIFIC OCEAN
CELEBES SEA
BORNEO
SULAWESI
INDIAN OCEAN
INDONESIA
PAPUA NEW GUINEA
Indo-Australian Plate
AUSTRALIA
2°N
0°
B
110ºE
115ºE
120ºE
KEY
Relative (to Sundaland) Motions
5 mm y⁻¹
Palawan Trough
Kinabalu
Lauban
Miri
Crocker-Rajang
BORNEO
5ºN
0º


A) L_1
Target Line
y
x
0
5 km
B) L_{01}
0
5 km
C) L_{02}
0
5 km
D) L_{03}
0
5 km



110º
115º
120º
5º
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110º
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120º