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Estimating hinterland exhumation from late orogenic basin volume, NW Borneo

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Abstract: A new approach for restoring sediment volumes onto the sediment source area to estimate uplift timing and magnitude is discussed and used in the context of late Tertiary basin and topographic development in NW Borneo. Sediment volumes for the Baram Deltaic Province were estimated for four time periods (latest Early, Middle and Late Miocene, and Pliocene–Recent), using 2D and 3D seismic horizons, wells and outcrops. Volume restoration onto the palaeo-sediment source area determined exhumation amount at the drainage divide (*c*. 5 km from 17 Ma to Recent) and provided a reasonable match with other denudation estimation methods (cooling ages and an older, regional sediment restoration study using 1979 vintage sediment isopach maps). Restoration took into account: (1) changing sediment densities during the erosion–deposition cycle; (2) changing area of the sediment source province with time (e.g. changing shoreline location as a result of eustacy, uplift and delta progradation, tectonic shortening); (3) uplift and partial erosion of Baram Deltaic Province sediment. Denudation at the drainage divide for the Middle Miocene, Late Miocene and Pliocene–Recent has proceeded at a similar rate for each period. Initial uplift of central Borneo has been attributed to buoyancy of thinned continental crust that jammed the subduction zone under NW Borneo in the Early Miocene. However, the absence of decay in the erosion rates with time from the Middle Miocene to Recent suggests operation of an additional uplift mechanism that may be related to delamination of mantle lithosphere; slab detachment is the favoured explanation.

Basins at a mature stage of hydrocarbon exploration are a rich source of geological and geophysical data, having provided over the years an increasing resolution of structural and sedimentary geometries, processes and mechanics. At the other end of the scale, regional mapping of seismic data can provide well-constrained (within the bounds of time–depth conversion) information about variations in sediment volume and depocentre location with time. Such regional data can provide important information about how the sediment source areas have evolved with time, which in turn can be used to make inferences about the effects of tectonics and climate on sediment source area development (e.g. Métevier *et al*. 1999; Hall & Nichols 2002; Clift 2006). Despite these studies, in general the sediment volume information from basins has tended to be an under-utilized source of information on hinterland uplift. In this paper an approach for restoring sediment volumes onto the sediment source areas is described (building on methods described by Métevier *et al*. 1999; Hall & Nichols 2002; Clift 2006) and applied to the Miocene–Recent basin development of NW Borneo to determine what inferences about tectonic and climate signatures can be made from the sediment volume record.

The recent literature on orogenic belts emphasizes that crustal thickening commonly results in gravitationally unstable orogenic interiors that collapse, with extensional faults causing remarkable amounts of crustal thinning and rapid exhumation of middle to lower crust (e.g. Fügenschuh *et al*. 1997; Searle *et al*. 1999; Ring & Reischmann 2002). The Tertiary orogenic belt of northern Borneo is different: the sedimentary basins fringing the island contain great thicknesses (up to >10 km) of Middle Miocene–Recent sediment (Hamilton 1979), indicating erosion of considerable volumes of sediment from the rising island (Hall & Nichols 2002). However, the main drainage divide of the island exposes rocks metamorphosed at only greenschist facies (Fig. 1; Hall & Nichols 2002). Hence the orogenic development of northern Borneo is not the now common one of extensional collapse and unroofing of high-grade terranes, but the opposite: rapid erosion of considerable rock volumes and continued exposure of low-grade terranes, as proposed in the lateral advection model (Willett *et al*. 1993). By restoring the volume of eroded sediment onto the hinterland of Borneo we seek to determine whether the exposed grade of metamorphism reasonably matches the eroded volume of sediments. To assess whether there has been any significant change in erosion rate with time, which could be related to changing tectonic or climatic processes, we determine not only the volume of sediment in the basins for different time periods, but also the likely magnitude of maximum exhumation and erosion in the sediment source area for each time period.

The approach to determining exhumation amount, rates and history by restoring the volume of sedimentary basins surrounding Borneo to the interior was first proposed by Hall & Nichols (2002). Using the isopach map of Hamilton (1979) as a guide, Hall & Nichols (2002) were able to demonstrate that erosion amounts from Neogene orogenic exhumation in Borneo were comparable in rate and eroded sediment per unit area with those from the Himalayas. Thus the Borneo example supports regional-scale work by Milliman *et al*. (1999) showing that tropical islands experiencing active tectonic uplift contribute disproportionately large amounts of sediment to the oceans for their area.

In contrast to the regional study of Hall & Nichols (2002), this study focuses on one segment of the NW Borneo margin, and utilizes industrial 2D seismic, 3D seismic and well information to estimate sediment volume, which is then used to estimate the timing and magnitude of exhumation on the northwestern side of Borneo. This study concentrates on offshore Brunei Darussalam, where the greatest thickness of Miocene–Recent sediment in NW Borneo was deposited in the Baram Deltaic Province (e.g. James 1984; Sandal 1996). The term deltaic province is used to indicate that more than one river contributed to the input of the

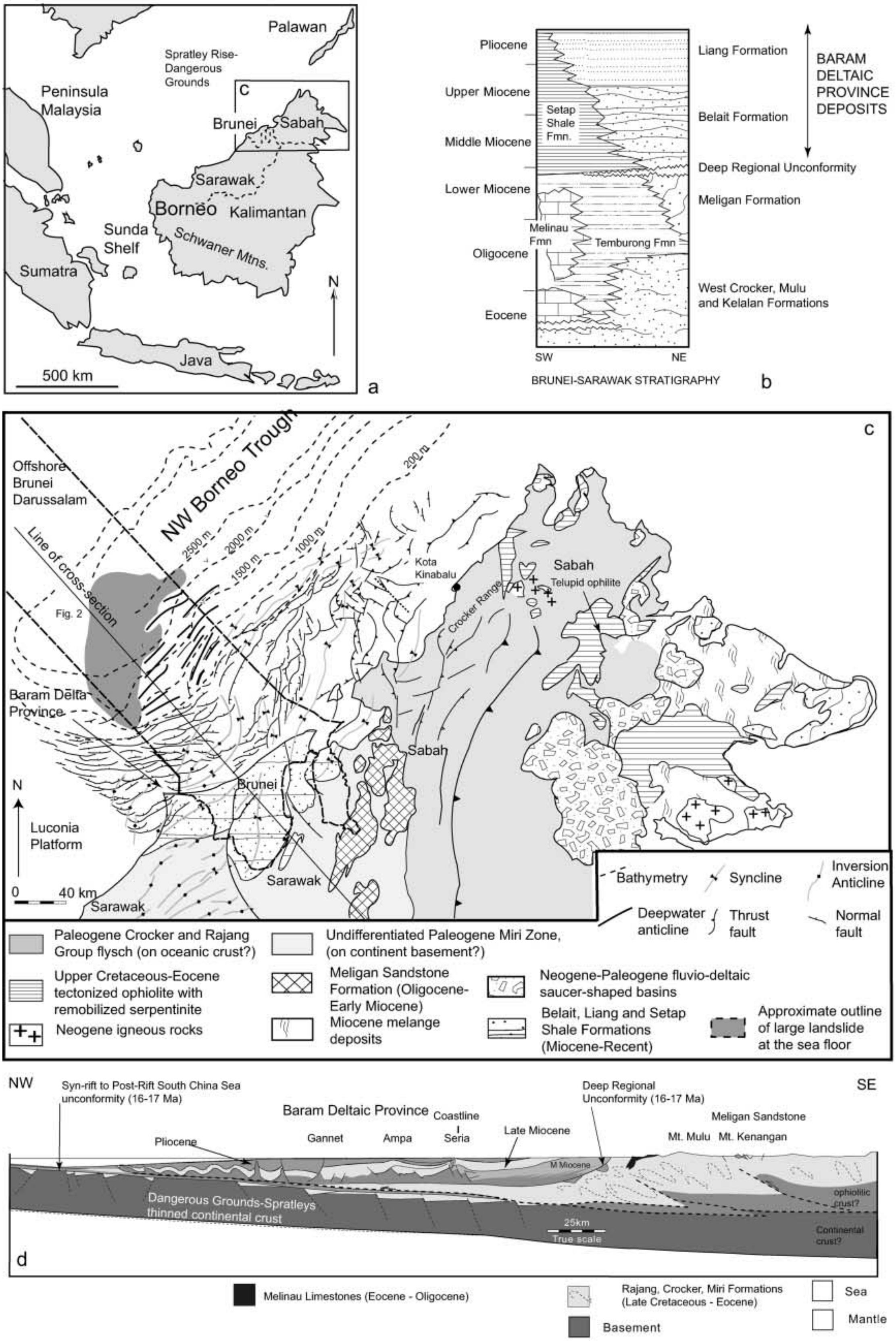

Fig. 1. Regional setting of the Baram Deltaic Province, modified from Morley *et al*. (2003). (**a**) Location of study area; (**b**) simplified stratigraphy of Brunei, Sarawak and Sabah; (**c**) regional geology of NW Borneo; (**d**) NW–SE-oriented cross-section between NW Borneo Trough and Crocker Ranges.

sediment onto the margin; the literature describes a northern 'Champion Delta' and a southern 'Baram Delta' influence on the province (James 1984; Sandal 1996). Sediment volumes of four time periods (late Early Miocene; Middle Miocene; Late Miocene; Pliocene–Recent) are estimated based on proprietary and published exploration data (particularly horizons mapped from seismic reflection data) for onshore and offshore Brunei Darussalam (e.g. Sandal 1996; Van Rensbergen 2000; Morley *et al*. 2003; Saller & Blake 2003; Back *et al*. 2005), augmented by published seismic reflection data from the adjacent areas of Sabah and Sarawak (Bol & van Hoorn 1981; Levell 1987; Hinz *et al*. 1989; Petronas 1999; Ping & Liu 2004). In this study emphasis is placed on methods to reasonably estimate how sediment should be restored onto the sediment source area of the Baram Delta defined by the modern Baram and Brunei Bay drainage systems (Fig. 2). Understanding how the drainage area has changed in size with time is important for understanding the significance of temporal changes in sediment volume in the basin. This more detailed variation on the method of Hall & Nichols (2002) examines the one segment of the Crocker–Rajang fold and thrust belt where considerable geological and geophysical detail is available, testing the potential error range in their more regional-scale approach.

Geological background

The main features of the evolution of northern Borneo as summarized by Hutchison (1996a, 1996b), Petronas (1999), Hall & Wilson (2000), Hutchison *et al*. (2000) and Morley *et al*. (2003) are as follows: Northern and Central Borneo (Fig. 1) were built from Mesozoic to Recent time by a complex interaction of oceanic and continental crust plate boundaries. Western Sabah is a mountainous region composed predominantly of Oligocene–Lower Miocene sandy turbidites (West Crocker Formation). To the east lies the extensive region of the Cretaceous–Eocene, deep-water clastic Rajang Group. The Rajang Group is thrust, folded and locally metamorphosed to phyllites (Hutchison 1996*a*, *b*). The Cretaceous–Oligocene sediments mostly represent deep-water sedimentation in or adjacent to an accretionary prism complex. NW Borneo is thought to be at least partially floored by Mesozoic oceanic crust, particularly because of presence of the Telupid ophiolite, which crops out in central Sabah, as well as other mafic and ultramafic bodies (Fig. 1; Hutchison 1996a; Hall & Wilson 2000). Continental crust of the Dangerous Grounds crust underlies the western side of Sabah. How far east this crust extends, and how much it is thickened is controversial, but possibly the crust reaches thicknesses of 40–50 km in places of high topography (Milsom & Holt 2001). Whether the original crust of Borneo was partly composed of continental crust is more controversial. The discussion and reply by Milsom & Holt (2001) and Hutchison *et al*. (2001) on how to interpret the geological and gravity data in terms of the type of underlying crust and its thickness is instructive on these problems.

During Oligocene–Early Miocene times sea-floor spreading of the South China Sea resulted in thinned passive margin continental crust of the Dangerous Grounds region being rifted from the southern margin of China (e.g. Holloway 1981; Hinz & Schülter 1983; Taylor & Hayes 1983; Briais *et al*. 1993). On the southeastern side of the Dangerous Grounds region lay an older region of oceanic crust, the Proto-South China Sea. During the early Tertiary the Proto-South China Sea was closing up as a result of SE-directed subduction beneath NW Borneo. Following complete subduction of the Proto-South China Sea oceanic crust, the Dangerous Grounds crust was partially subducted beneath the West Crocker Formation basin of NW Borneo in the latest early Miocene, then its buoyancy locked the system (James 1984; Levell 1987; Hazebroek & Tan 1993; Hall 1996; Hutchison 1996*a*, *b*; Sandal 1996; Milsom *et al*. 1997).

Patchy data are available from a variety of sources concerning the Cenozoic exhumation history of rocks in central and northern Borneo (Fig. 2). Some areas locally show evidence for considerable uplift and erosion; for example, the glaucophane schists at Telupid (Fig. 1) may represent 20 km of exhumation (Hutchison *et al*. 2000). The Telupid ophiolites have probably undergone exhumation by a series of uplift and erosion events during the Late Cretaceous and Tertiary. One specimen near Telupid yielded an apatite age of 14.5 ± 1.9 Ma suggesting important Middle Miocene exhumation (Hutchison *et al*. 2000). To the south, in Sarawak, the central region of Borneo, where a regional unconformity caps the Rajang Group, appears to have been exhumed in the Late Eocene (Hutchison 1996b). Locally, metamorphic grades are greenschist phyllite and slate (Wolfenden 1960; Tan 1979; Hutchison 1996b). The turbiditic Crocker Formation (Eocene–Lower Miocene) has been interpreted as being sourced from the Rajang Group (Hutchison *et al*. 2000; Williams *et al*. 2003). However, analysis of heavy minerals indicates an important source of Crocker Formation sediment from the Schwaner Mountains in southern Borneo (Fig. 1) and/or the Thai–Malay Peninsula (van Hattum *et al.* 2006). Although the Rajang Group in Malaysia is consistently of phyllitic greenschist facies, Moss (1998) demonstrated the lack of metamorphism at the southern margin of the Rajang Group in Kalimantan. Fission-track studies by Moss (1998) and Moss *et al*. (1998) of apatite and of zircon crystals show that there has been relatively subdued burial and exhumation, with apatite fission-track data yielding central ages ranging from 22 to 31 Ma. Moss *et al*. (1998) interpreted these ages to indicate a period of rapid cooling (exhumation) in the Late Oligocene of about 1.3 km associated with a temperature drop of over 40 °C within about 2 Ma. Subsequently, the region underwent a further 2 km of exhumation. In Sabah samples from the western margin show apatite fission tracks that were annealed prior to 13–14 Ma (Hutchison *et al*. 2000). Apparently, exhumation began in the Middle Miocene, culminated in the Late Miocene and continued into the Pliocene (Hutchison *et al*. 2000). Whereas Late Miocene–Pliocene exhumation in northwestern Sabah is of the order of 4–8 km, late Tertiary uplift and erosion in eastern Sabah appears to have been limited, as apatites and zircons have retained their Cretaceous provenance ages (Hutchison *et al*. 2000).

The presence of Middle Miocene and younger basins onshore in Sabah places a limit on which regions have undergone exhumation during the Middle Miocene (as summarized in Fig. 3). In northern Borneo there is only a narrow region that could have been exhumed significantly during the Middle Miocene, and this region flares out to the south. The implications of the data reviewed above are as follows. (1) By the Oligocene, the northern part of the Rajang Group was uplifted sufficiently to form a sediment source for basins further north. During the Early and Middle Miocene this area grew, apparently propagating to the north and probably linking with an island chain where the Telupid ophiolites were exposed (Figs 2 and 4). (2) The exhumation pattern suggests that the northerly drainage province for the Baram basin, the Padas river drainage (Fig. 2), may have only been initiated when Sabah became uplifted in the Late Miocene. Drainage for the Middle Miocene sediments of the Baram Deltaic Province

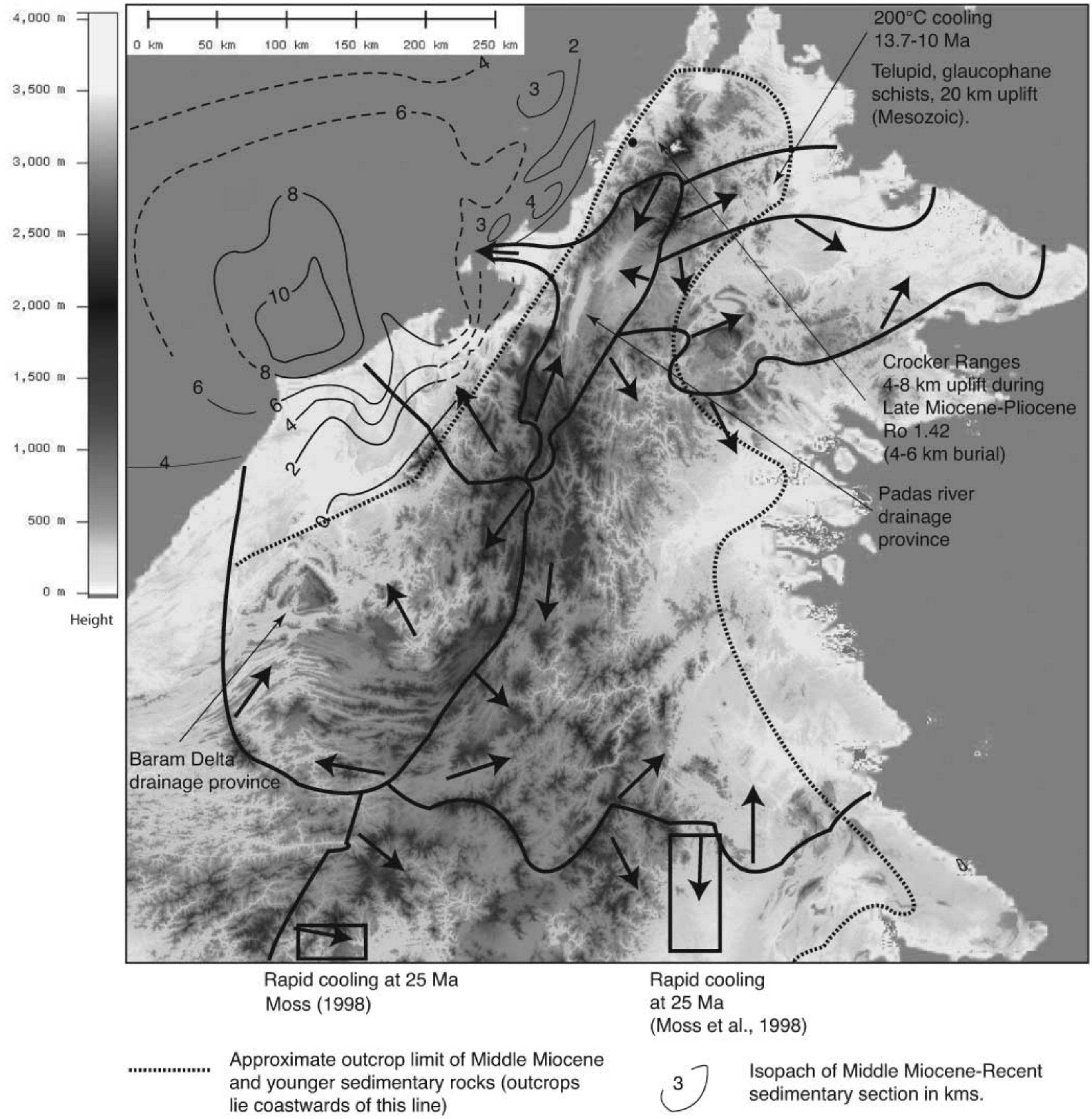

Fig. 2. Drainage patterns and regional isopach for the latest Early Miocene–Recent section on the NW Borneo margin. Apatite-fission track data from Moss *et al*. (1998) and Hutchison *et al*. (2000).

probably came from the east and south. (3) Uplift along the western side of Borneo appears to have been considerably greater than uplift on the eastern side of the island. This is reflected in the extensive low-lying areas on the east coast today, compared with the NW coast (Fig. 3).

The erosional products of the Neogene exhumation of NW Borneo were deposited in basins along the NW Borneo margin, in particular offshore and onshore Brunei (see Figs 2 and 4). The details of the sedimentary record in the late Tertiary basins of Brunei and adjacent areas of Sarawak and Sabah, East Malaysia, are discussed below.

Neogene sedimentary archive onshore and offshore NW Borneo

In this study, units of late Early Miocene–Recent age subdivided into *c*. 5 Ma increments have been used because they are known in sufficient detail to allow regional isopach maps to be

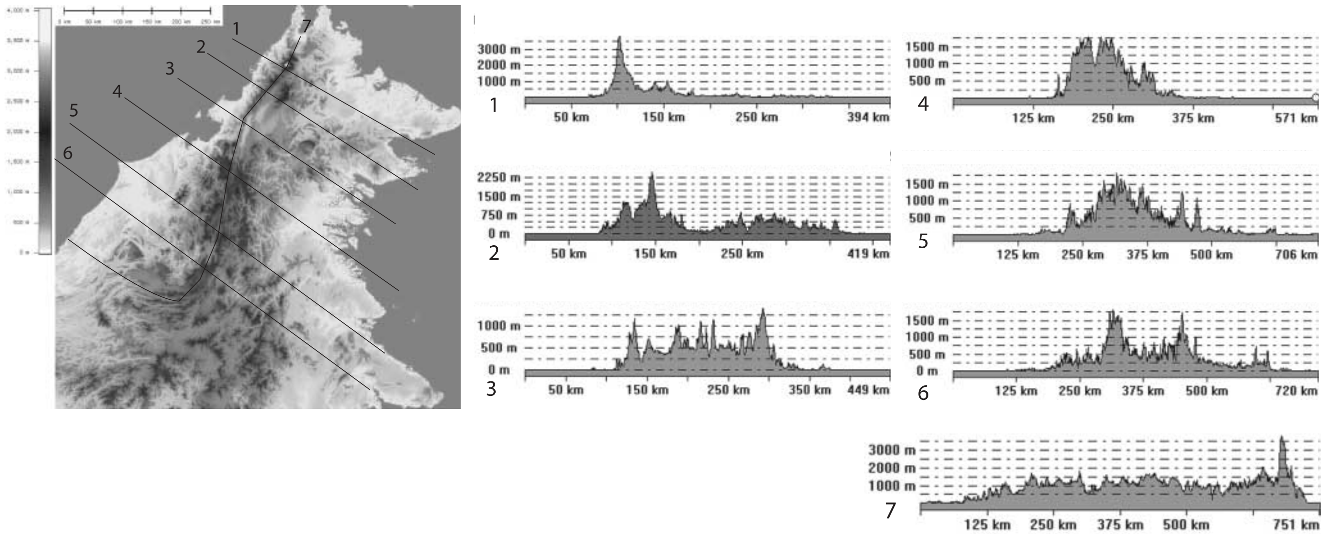

Fig. 3. Topographic cross-sections across Borneo.

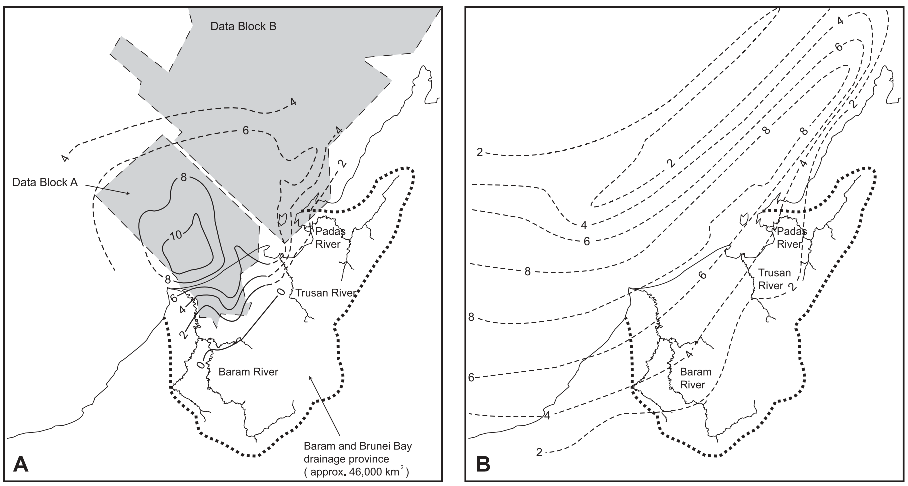

Fig. 4. Comparison between the isopach map for late Early Miocene–Recent sediment thickness derived from this study (**a**), and the Oligocene–Recent isopach map of Hamilton (1979) (**b**).

constructed and sedimentary rock volumes estimated (e.g. Saller & Blake (2003), included in Figs 4b and 5). Estimates of the volume of Miocene–Recent sediments in onshore Brunei Darussalam and the adjacent onshore areas of Sabah were made using outcrop maps, down-plunge projections of those maps, and regional 2D seismic reflection data and wells, whereas regional 2D and 3D seismic reflection data and well information were used offshore Brunei and Sabah. The greatest souces of error in our volume calculations are likely to result from: (1) estimating the thickness of the mobile Miocene–Recent shale section offshore, (2) subdividing that section into late Early Miocene, Middle Miocene, Late Miocene and Pliocene–Recent components and (3) time–depth conversion. We used seismic velocities that seemed reasonable minimum velocities for the conversion; faster velocities might easily increase volumetric estimates by 10%. On the shelf, the base of the mobile shale section is not seen on seismic reflection data (which images to a maximum depth of *c*. 10–11 km). However, the sediments forming the distal toe thrust region are completely imaged down to the basal detachment in the deepwater NW Borneo trough offshore Sabah (Data Block B, Fig. 4b; see, e.g. James 1984; Hinz *et al*. 1989; Sandal 1996; Yan & Liu 2004; Hesse *et al*. 2006). Over a NW–SE distance of about 70 km, the latest Early Miocene–Recent toe thrust wedge expands from about 3 km thickness to >10 km near the shelf–slope transition. A south-eastwards projection of the wedge geometry, and a northwards projection of the onshore–nearshore base of the deltaic section into the offshore Brunei part of the study area allowed some constraints to be placed on the minimum Miocene to Recent sediment thickness.

The 3D subsurface model constructed for the volume estimates of this study (Fig. 6) is based on conservative depth estimates in both onshore and offshore parts of the study area; that is, it was generated by using minimum likely seismic velocities for depth conversion in all regions below well penetration. Consequently, the following uncorrected volumetric estimates for the four time intervals are minimum volume estimates: Latest Early Miocene (21.8–16.2 Ma) 15 000 km^3; Middle Miocene (16.2–10.6 Ma) 36 000 km^3; Late Miocene (10.6–5.0 Ma) 40 000 km^3; Pliocene to Recent (5.0–0 Ma) 38 000 km^3 (Fig. 6). Therefore, the total volume of sediments preserved in the study area is at least 129 000 km^3.

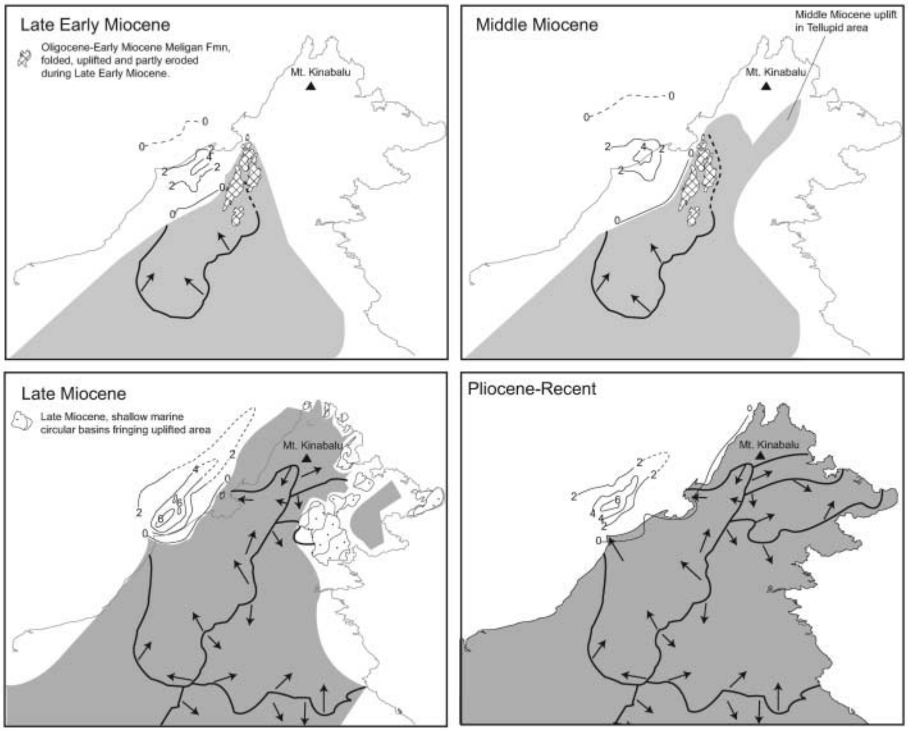

Fig. 5. Sediment isopachs for the four stages (Miocene–Recent) investigated in this study. The likely onshore area of landmass is shown varying with time, based on sedimentology of the Tertiary sediments discussed in the text and apatite-fission track data (Hutchison *et al*. 2000).

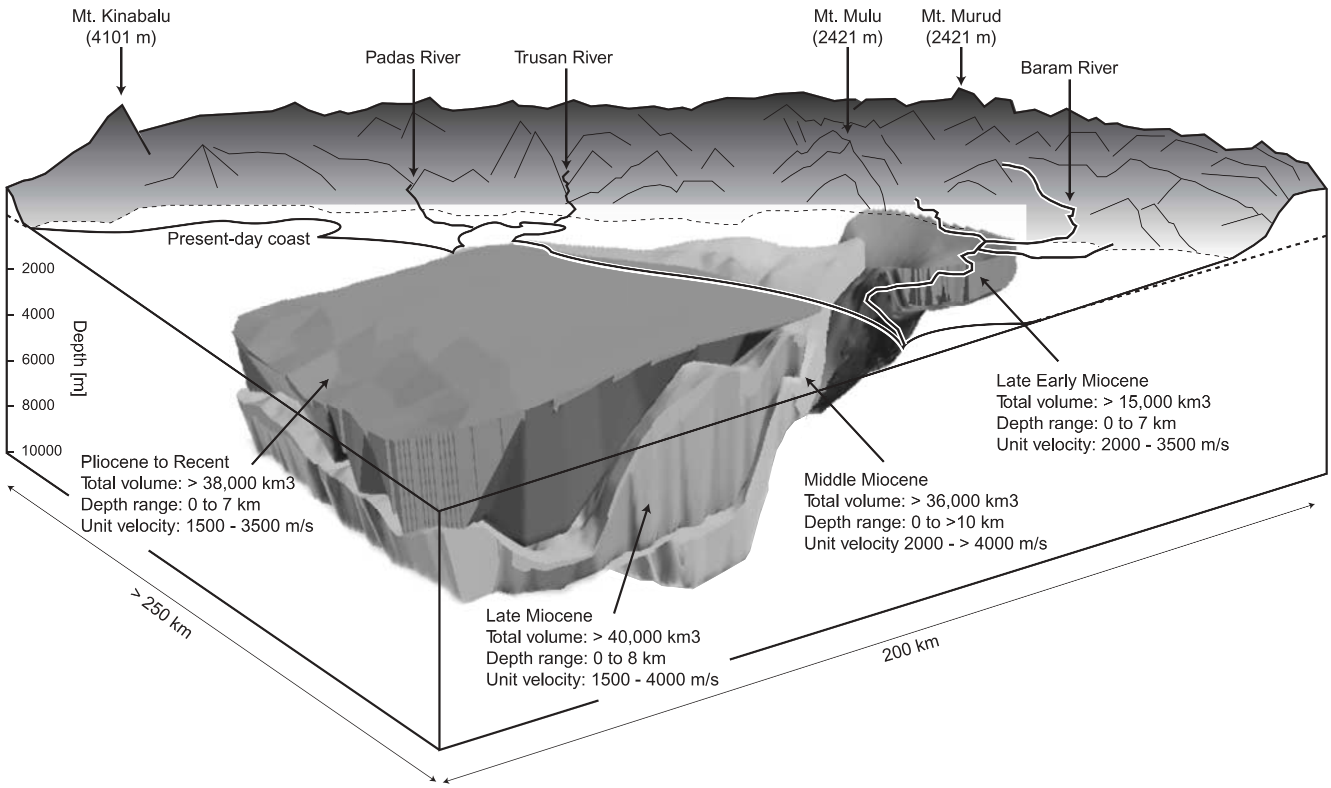

Fig. 6. Three-dimensional representation of the sediment volumes determined in this study based on seismic marker horizons mapped from 2D and 3D seismic reflection data.

Volumetric restoration

The restoration of the sediment volume in the NW Borneo basins to the hinterland source areas required a number of modifications to the present-day values for the various parameters used. In this section, a very simple approach is presented first, then the complexities of the restoration are discussed.

The simplest method of restoring basin fill is to restore a uniform tabular volume onto the drainage basin. Using uniform thickness provides a minimum exhumation estimate. Restoring the minimum volume of sediment estimated in this study (129 000 km^3) uniformly onto the present-day drainage area of 46 200 km^2 would require around 2.8 km of exhumation of the sediment source area. This highly simplified approach ignores several important issues such as (1) the tendency for thrust belts to have undergone greater uplift of the interior than the external zones, (2) changing drainage areas with time, and (3) differences in density, and hence volume, between the rocks being eroded and the sediments deposited in the basin. To try and take these factors into account the following methods have been used.

The sediment volume was restored to a simple wedge-shaped cross-sectional area (Fig. 7). This is an assumption accepted for the critical wedge theory of thrust belt development (e.g. Dahlen *et al*. 1983; Hilley & Strecker 2004, and references therein). The amount of exhumation along the central ranges of NW Borneo can be estimated using the following assumptions: (1) the restored sediment volume has a wedge-shaped geometry, which expands towards the interior, and the wedge is thickest at the main drainage divide between east and west Borneo (Fig. 7); (2) the wedge taper and area is similar on any section through the drainage basin. Cosmogenic nuclide-derived denudation rates for the the Middle European Uplands and Central Alps show an approximately linear increase in denudation rate with catchment relief (von Blanckenburg 2005) that supports the use of a prismatic cross-section in this study. This assumption seems generally valid for mountain ranges that are characterized by a

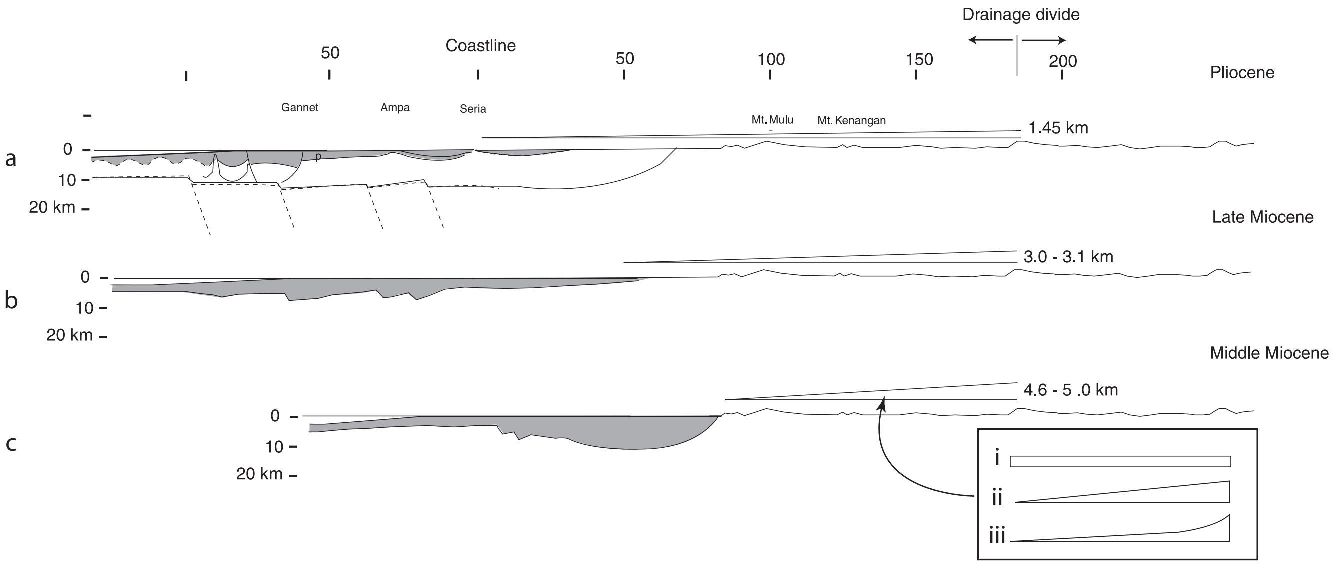

Fig. 7. Illustration of the restoration of sediment onto the hinterland of the Baram drainage area. Greater erosion is assumed to have occurred in an approximately linear fashion up to the drainage divide; hence the sediment volume in the basin can be restored onto a triangular cross-section. (**a**) Present-day cross-section, Pliocene–Recent sediment volume; (**b**) cross-section at 5 Ma, 10 Ma–5 Ma sediment volume; (**c**) cross-section at 10 Ma, 15 Ma–10 Ma sediment volume. i, ii and iii illustrate the various basic patterns that could be employed for restoring the sediment volume: i, tabular; ii, triangular; iii, non-linear (could be exponential) increase in erosion with increasing topography.

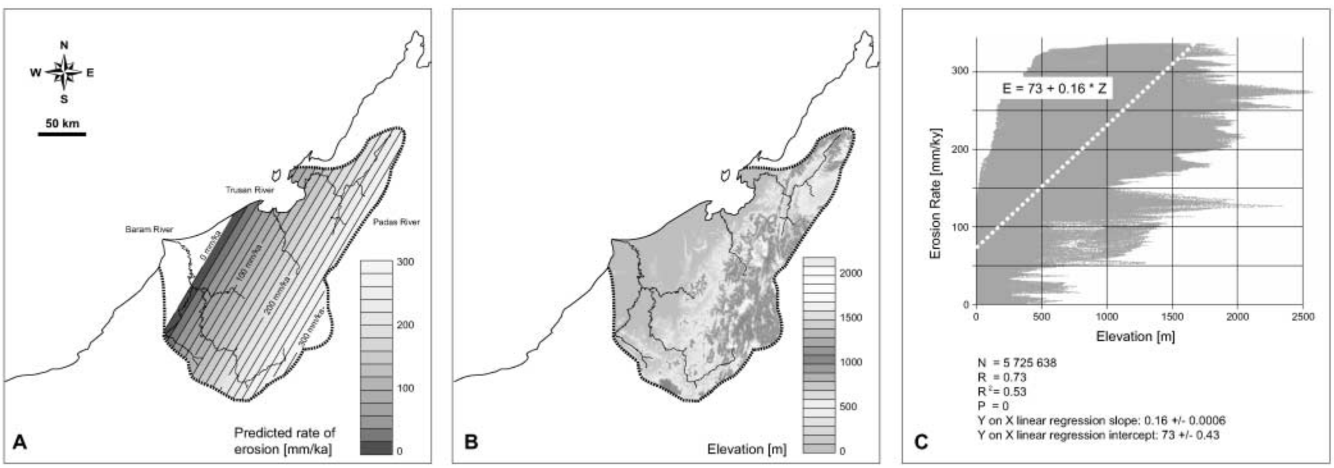

Fig. 8. Statistic validation for the volume-restoration approach, applied using a cross-plot of predicted long-term erosion rates (**a**; also see Table 2) against SRTM 90 m elevation data for the Brunei hinterland (**b**; data from CIAT 2005). This resulted in a stable linear relation (**c**) indicating the elevation dependence of erosion ($E = 73 + 0.16Z$, $R^2 = 0.73$, $P = 0$; erosion rate E is in mm ka^{-1}, elevation Z is in metres, intercept 73 is the chemical background erosion rate in mm ka^{-1}).

mean local relief not exceeding 1000–1500 m and mean hillslope below 25° (Montgomery & Brandon 2002, and references therein), providing a topological threshold well above the entire Baram and Brunei Bay drainage province (Figs 3 and 8).

The exhumation history was then estimated using the sediment volumes for the Pliocene, Late Miocene, Middle Miocene and late Early Miocene. The sediment volumes were restored using the present-day drainage area as the basis of the volumetric calculation, but modifying the area for the effects of tectonic shortening, variable timing of uplift, and varying shoreline position with time. These modifications are as follows.

Modification 1: varying width of drainage areas with time due to shoreline progradation (parameter a_1, Table 1). For the late Early Miocene–Recent period, the shoreline has shifted 100 km NW from an initial position south of the Belait syncline (e.g. Sandal 1996; Back *et al*. 2005). The foreland propagation of uplift and erosion is well demonstrated by the pattern of unconformities offshore Sabah (Levell 1987). The width of the thrust belt was based on the distance from the present-day drainage divide to the approximate shoreline position at the start of the late Early Miocene, Middle Miocene, Late Miocene and Pliocene, indicated by sedimentary facies in outcrop, wells and seismic reflection data (Sandal 1996; Simmons *et al*. 1999; Back *et al*. 2001). A similar pattern for the shelf edge progradation has been determined by Sandal (1996).

Modification 2: varying width of drainage area with time as a result of syn-erosional shortening (parameter a_2, Table 1). The amount of shortening between the drainage divide and the thrust front that occurred from the late Early Miocene to the Pliocene is largely unknown. Although most workers tend to place the end of major shortening (in an accretionary prism setting) within the Early Miocene (e.g. James 1984; Sandal 1996; Hutchison 1996*a*, *b*), episodes of thrusting have occurred during the Middle Miocene to Pliocene (Levell 1987; Hutchison 1996; Sandal 1996; Morley *et al*. 2003). It is not clear whether this later phase of shortening was confined to the external part of the thrust belt (i.e. the sedimentary basins where inversion structures are present) and the Crocker Range units rode passively piggy-back style, or whether significant shortening affected the Crocker Range as well. If significant shortening did affect the Crocker Range, this would have the effect of increasing the unstrained length of the wedge; therefore, to preserve the wedge area (see Fig. 7) would require less exhumation at the drainage divide. The scarcity of outcrops in the island's interior and problems of age-dating the outcrops means that the amount of shortening cannot be estimated from balanced cross-sections based on surface mapping. However, the Middle to Upper Miocene units closest to the internal zones of the thrust belt are the Tanjong and Sandakan Formations. They form unusual elliptical to circular saucer-shaped basins constructed of nearshore sandstone–shale sequences. Typically, steep dips occur around the edge of the basin and flatten out towards the basin centre. The apparent isolated basinal nature of the Tanjong and Sandakan Formations has been interpreted by Noad (1998) and Balaguru *et al*. (2003) as the result of inversion, leaving synclinal erosional outliers. Their NNE–SSW- and WNW–ESE-trending bounding faults may represent reactivated basement trends. Balaguru *et al*. (2003) concluded that the early synclinal structures were folded approximately perpendicular to their synclinal axes, causing them to become compartmentalized. Later erosion left these rocks preserved as small (<50 km diameter), subcircular outliers, which he called 'egg box' structures. The amount of shortening associated with these basins is not high (<20%). The style of deformation suggests that the major thrusting events occurred earlier than the Middle Miocene. The amount of shortening is ultimately important for estimating the amount of hinterland exhumation: assuming no shortening occurred produces a total exhumation of *c*. 5.7 km between the Early Miocene and today, whereas 25% shortening reduces the total exhumation to *c*. 5.2 km (Table 2).

Modification 3: changes in uplift areas with time (parameter a_3, Table 1). If the Padas drainage area in Sabah became uplifted only in the Late Miocene, then the late Early Miocene to Middle Miocene drainage basin lay mainly to the east and south of the Baram deltaic basin (Fig. 5). This means that the volume of sediments is restored onto a smaller drainage area than today, which increases the amount of exhumation at the drainage divide. When taken into account, the absence of the Padas drainage area in the late Early Miocene and Middle Miocene decreases the total drainage area by about 10%.

Modification 4: changes in sediment density with time (parameter ρ_d, Table 1). Relatively highly compacted and dense sedimentary rocks making up the West Crocker Formation and Rajang Group were eroded, transported and redeposited as poorly compacted, less dense, high-porosity sediments during the Middle Miocene–Recent. Subsequently, these sediments have been buried, lost porosity and to varying degrees compacted again. Some have subsequently been subjected to further cycles of uplift, erosion and deposition. A considerable portion of the Pliocene section is likely to comprise reworked Middle and Late Miocene sedimentary rocks. The problem concerning compaction has two main effects: (1) if it is neglected, this will lead to overestimation of exhumation amounts; (2) the overestimate will be greatest for the Pliocene to Recent and least for the late Early

Table 1. *Input values for equation (1)*

	Late Early Miocene	Middle Miocene	Late Miocene	Pliocene–Recent
v_s (km^3)	15 000	36 000	40 000	38 000
a (km^2)	46 200	46 200	46 200	46 200
a_1 (km^2)	9000	6000	2000	1000
a_2 (km^2)	Minor to 13 600?	Minor to 5500?	1000	0
a_3 (km^2)	4600	4600	0	0
ρ_d	0.91	0.91	0.89	0.86
v_{rw} (km^3)	10 000	6000	2000	0

v_s, volume of sedimentary basin; ρ_d, difference in average density between rocks in the basin and rocks eroded from the mountains; v_{rw}, volume of eroded and redeposited sediment lacking from sedimentary record at time of reconstruction; v_o, volume of material (in solution or as sediment) added to or lost from the basin is not shown, as it is assumed to be zero; a, present-day drainage area; a_1, drainage area between present-day shoreline and palaeoshoreline at time of reconstruction; a_2, drainage area lost by shortening between time of restoration and the present day; a_3, drainage area submerged below sea level at time of restoration.

Table 2. *Results for input values (Table 1) using equation (1) as estimate of exhumation at drainage divide for the four time periods, and as total exhumation*

	Late Early Miocene	Middle Miocene	Late Miocene	Pliocene to Recent	Total exhumation
Exhumation scenario 1 (km); including ρ_d, a_1, a_3, and excluding a_2, v_{rw}	0.83	1.84	1.61	1.45	*c*. 5.7
Exhumation scenario 2 (km); including ρ_d, a_1, a_2, a_3, and excluding v_{rw}	0.59	1.59	1.57	1.45	*c*. 5.2
Exhumation scenario 3 (km); including ρ_d, a_1, a_2, a_3, v_{rw}	1.02	1.88	1.66	1.45	*c*. 6.0
Time span (Ma)	5.6	5.6	5.6	5.0	21.8
Erosion rate (mm ka^{-1})	105–182	283–335	280–296	290	238–275

Miocene. Tingay *et al*. (2004) presented extensive density data from well logs in the Baram Deltaic Province. From well logs, the density profile of sedimentary rocks in the upper 4 km ranges from about 1.8 g cm^{-3} near the surface to 2.52 g cm^{-3} at around 4 km. The average density integrated over this depth range is 2.3 g cm^{-3}. Densities below 4 km are not well established, but the increase in density is greatest in the subsurface between the surface and 2 km, then it lessens considerably (Tingay *et al*. 2004). Density increases are consequently assumed to be modest between 4 and 10 km, and for this interval an average density of 2.6 g cm^{-3} was used. Thus, the total average basin fill density between 10 km and the surface (sea bottom) is *c*. 2.48 g cm^{-3}. For the Crocker Range, if typical densities for quartzite (2.64 g cm^{-3}) and slate (2.80 g cm^{-3}) are assumed (Berkman 1989), then average rock density will be in the range of 2.7–2.75 g cm^{-3}. Consequently, the variations in density from basin to source area indicate that the sedimentary basin volume should be reduced to *c*. 90% for restoration onto the drainage area.

Modification 5: incomplete preservation of sediments (parameter v_{rw}, Table 1). Significant portions of late Early Miocene and Middle Miocene deposits were originally deposited in areas close to the Crocker Range, and have since been uplifted, eroded and redeposited in younger sedimentary units. This process of cannibalization of sedimentary predecessors led to the constant reworking of older deposits (Sandal 1996), which are now lacking from the sedimentary record. In particular, the most landward late Early Miocene section has been significantly eroded and deposited further offshore during the Middle Miocene to Recent. The original uneroded volume estimates of the onshore basins need to be established for the various period estimates. Horizons within the Miocene section were mapped using 2D seismic and outcrop data combined in Gocad; the trends (of upwards converging horizons) defined in 3D could then be projected into the air, to estimate the volume of eroded material. A conservative estimate for the amount of eroded section is: late Early Miocene 10 000 km^3, Middle Miocene 6000 km^3 and Late Miocene 2000 km^3. As this modification has a significant influence on the calculation of the early exhumation history of the study area, Table 2 provides calculations on exhumation and erosion excluding and including this modification.

Modification 6: the degree to which the basin is an open system. We assume that the system is essentially closed and that the products of mechanical and chemical weathering from clearly identified sediment source areas are deposited in the basin. This may not be the case where fine-grained sediments and minerals and elements in solution are carried beyond the basin, or where material from other (poorly identified) source areas is added to the basin. There is probably little loss from sediment in suspension: the rapidly tapering sediment profile passing offshore and the thick fine-grained wedge of material defining the continental slope suggest that the bulk of the fine-grained material is deposited within the basin, and reworked in the slope–NW Borneo trench area. Although some fine-grained material might leave the system in the northernmost part of the study area, we would estimate this amount at a few per cent at most. Subduction along NW Borneo ceased prior to development of the Baram Deltaic Province (e.g. Levell 1987; Hall 1996; Sandal 1996; Hutchison *et al*. 2000; Hutchison 2004), hence we do not consider loss of sediment during subduction to be a factor in our calculations. The effects of chemical weathering are difficult to quantify, but the volume of highly soluble rocks and minerals in the Borneo hinterland appears to be small given the quartz-rich nature of the metasediments in the hinterland (Hall & Nichols 2002). The volcanic rocks present would tend to weather to clays. Some carbonate massifs (e.g. Mulu) are present, but they represent a small volume ($<5\%$) of the predominantly clastic rocks forming the Borneo hinterland. The percentage of carbonates removed in solution and redeposited as carbonate cements, shells or small reefs within the sedimentary basin is also difficult to quantify, except to note that carbonate cements filling sandstone pore space are extensively present in the subsurface, whereas carbonate deposits make up than 1% of the total sediment volume in the basins surrounding Borneo (Wilson *et al*. 1999). Assuming that on average throughout the basin 20% cement-filled pore space in siltstones and sandstones, that siltstones and sandstones make up 25% of the sediment volume, and that 75% of the pore cements are carbonates, then the percentage carbonate cements in the whole sediment volume is estimated at about 4%. It may even be possible to argue for a modest net influx of dissolved carbonate into the basin (via marine waters trapped in pore spaces) compared with carbonates derived from the source area. Hall & Nichols (2002) recognized the uncertainty in assessing the volume of carbonates in the source area and basin, but assumed the volume of eroded and deposited carbonates to be equal; given the uncertainties and estimates above we make the same assumption.

Assuming a triangular cross-section profile, and using the modifiers discussed above, the amount of exhumation at the drainage divide (U) is related to the volume of the sedimentary basin by the equation:

$$U = 2\{(v_s\rho_d + v_{rw} + v_o)/[(a + a_2) - (a_1 + a_3)]\} \quad (1)$$

where U is the exhumation amount at the back of the wedge, v_s

is the volume of the sedimentary basin, ρ_d is the difference in average density between rocks in the basin and rocks eroded from the mountains, v_{rw} is the volume of eroded and redeposited sediment lacking from the sedimentary record at the time of reconstruction, v_o is the volume of material (in solution or as sediment) added to or lost from the basin (positive or negative number), a is the present-day drainage area, a_1 is the drainage area between the present-day shoreline and palaeoshoreline at the time of reconstruction, a_2 is the drainage area lost by shortening between the time of restoration and the present day, and a_3 is the drainage area submerged below sea level at the time of restoration

A distinction between a_1 and a_3 is made on the following basis. Assuming a general oceanward shift in shoreline with time, a_1 is the measure of area that lies between the present shoreline and the palaeo-shoreline defined from sedimentology. a_3 represents any part of the drainage area inundated by water that cannot be measured with respect to the present-day shoreline (e.g. a marine embayment entering the drainage area unlinked to the present-day shoreline).

Table 2 provides three possible reconstruction scenarios for the latest Early Miocene to Recent erosion pattern of the Baram and Brunei Bay drainage area, based on the above equation. Relatively high exhumation and erosion estimates through time result from the exclusion of structural shortening as an equation parameter (exhumation scenario 1) or the inclusion of originally deposited but eroded sediment (v_{rw}) in the exhumation equation (exhumation scenario 3). Minimum exhumation values through time are achieved including structural shortening a_2, but excluding originally deposited but eroded sediment (v_{rw}). All three scenarios indicate that the exhumation rate at the Baram and Brunei Bay drainage divide was probably greatest in the Middle Miocene, and has diminished during the Late Miocene and Pliocene. Average rates of exhumation for the drainage divide in Middle Miocene times are around 300 m Ma^{-1}. One independent check of the exhumation estimates obtained by restoring sediment volumes to the drainage areas is apatite fission-track analysis. Fission-track data for the Sabah Crocker range indicate 4–8 km uplift and erosion since the late Miocene (Swauger *et al.* 1995; Hutchison *et al.* 2000). The estimated exhumation in Table 2 of more than 5 km (all scenarios) for the Late Miocene and Pliocene shows a reasonable agreement between the two methods, particularly considering that exposure of the Kinabalu granite indicates that Sabah has undergone greater exhumation than the Baram and Brunei Bay drainage area to the south. In the Baram drainage area the exposure of greenschist-facies metasediments at the drainage divide and the absence of higher grade metamorphic facies provides a loose constraint on the exhumation estimates made for this study. For the external part of the fold and thrust belt, average rates of uplift for the last 2 Ma have been estimated from the history of sedimentary fill in the Mulu caves at 190 +3/−4 mm ka^{-1} (Farrant *et al.* 1995). The location of Mulu on a simple triangular cross-section restoration of the Pliocene basin fill has a predicted exhumation amount of around 800 m (Fig. 7). Over 5 Ma this yields an average exhumation rate of 160 mm ka^{-1} for the Pliocene (Fig. 7). Thus there is a reasonable agreement between our regional exhumation estimates for the Mulu caves area and recent exhumation rate estimates of Farrant *et al.* (1995).

In a fast-track statistic validation for the volume-restoration approach applied, we cross-plotted the predicted long-term erosion rates of Table 2 (Fig. 8a) against SRTM (Shuttle Radar Topography Mission) 90 m elevation data for the Brunei hinterland (Fig. 8b). This resulted in a stable linear relation (Fig. 8c) of the elevation dependence of erosion ($E = 73 + 0.16Z$, $R^2 = 0.73$, $P = 0$; erosion rate E is in mm ka^{-1}, intercept 73 is the chemical background erosion rate in mm ka^{-1}, and elevation Z is in metres). Hence, we are confident that the studied catchment area exhibits an approximately linear relation between elevation and long-term erosion rate, and that the use of a prism-based sediment-restoration approach is a reasonable approximation.

Origin and sedimentary consequences of Miocene to recent exhumation

The results of the exhumation estimation from the volumetric restoration suggest that NW Borneo experienced approximately steady-state tectonic conditions for the last 17 Ma, leaving great uncertainty in Early Miocene times and earlier. The incomplete preservation of Early Miocene and older rocks mainly results from the formation of the deep regional unconformity, which records major erosion of Borneo that was initially across a broad region, then narrowed and became restricted to the highlands of NW Borneo as basins developed on the margins (Levell 1987). Generation of the deep regional unconformity can be explained as a response to the entry of thinned continental crust into the NW Borneo trench, which ultimately blocked subduction (e.g. Hamilton 1979; Taylor & Hayes 1983; Levell 1987; Hazebroek & Tan 1993; Hall 1996; Hutchison 1996; Hutchison *et al.* 2000; Hall & Nichols 2002).

The onset of deposition above the deep regional unconformity appears to have occurred regionally at approximately the same time in the late Early Miocene (Simmons *et al.* 1999). Around Brunei for the Middle Miocene to Recent, the greatest deposition has always occurred around the shelf edge, not in the deep water. Deltaic growth faulting above mobile shales started at only about 12 Ma (Back *et al.* 2005), permitting the accumulation of up to (and possibly over) 10 km of Miocene to Recent sedimentary rock (Figs 2 and 6). Attaining this critical thickness in combination with constant hinterland uplift resulted in a major progressive oceanward shift of depocentres, with the shelf edge in Brunei and southern Sabah prograding between about 120 and 160 km to the NW. Today, this progradation has covered the former NW Borneo trench and hence the old suture between continental and oceanic crust.

Between the Middle Miocene and Pliocene, much of the inner 30–50 km width of the Sabah margin north of the study area experienced little subsidence, and six uplift and deformation phases have been recognized based on seismic interpretation (Levell 1987). Regionally, basins were progressively tilted northwestwards, indicating continuing uplift of northern Borneo. In the study area in and around Brunei Darussalam, the same degree of Miocene–Recent uplift and erosion along the coastal margin and shelf is not seen. Maintenance of uplift of the hinterland is documented by partial erosion and redeposition of Middle Miocene rocks (e.g. Sandal 1996), however, the thick onshore and offshore Miocene–Recent sedimentary pile indicates a different history: the presence of over 7 km thickness of Miocene sedimentary rocks onshore Brunei Darussalam is a particularly noteworthy difference that requires a mechanism to explain how a substantial basin developed in the external zones of the uplifted and eroded Crocker mountain belt. Various onshore studies document that most deposition occurred under shallow marine, shelfal conditions (e.g. Simmons *et al.* 1999; Back *et al.* 2001). At the southern end of the Belait syncline, coals with some fluvial units are present (Wilford 1968). Prograding delta clinoforms visible on satellite images and in outcrop indicate progradation of shallow-marine sandstones onto shelfal shales (Back *et al*. 2001, 2005). Hence the thickness of the basin fill cannot be mitigated by deposition in a pre-existing, deep marine depression. The only basin types in thrust-belt settings that attain comparable thicknesses are foredeep basins. Thus, the Middle Miocene sedimentary record of onshore Brunei Darussalam is probably best interpreted as the depositional remnant of a former foreland basin undergoing inversion associated with sustained erosion and exhumation of the Crocker Range orogenic wedge.

Discussion

Hall & Nichols (2002) estimated for the Neogene basins of Borneo that an average of 6.5 km section had been removed by erosion from Borneo. They discussed a number of reasons why this average was probably an underestimate. We obtained a similar maximum exhumation estimate but with only about half the volume of sediment. Our estimate of 0.129×10^6 km^3 for the Baram Deltaic Province represents about 4.3% of the total volume of Neogene sediment for Borneo of 3×10^6 km^3 estimated by Hall & Nichols (2002). The province occupies about 6.25% of the coastline studied by Hall & Nichols (2002), and is one of the deepest Neogene basins along the margin (Fig. 4b). Although all the numbers are of a similar magnitude there remains a significant difference in our volume estimate compared with the more regional-scale study of Hall & Nichols (2002). The present study is focused on the latest Early Miocene–Recent section, whereas Hall & Nichols (2002) studied the Oligocene to Recent; hence their volumes should be somewhat larger. We have discussed in a previous section potential errors in our estimates; however, there appear to be two other sources of difference between the two estimates: (1) overestimates of sediment volume in the Hamilton (1979) map; (2) how sediment is restored onto the source area.

The key differences between our map (Fig. 4b) and the Hamilton (1979) map (Fig. 4a) are as follows. (1) In Figure 4a (Hamilton 1979) the basin section onshore extends further south than in our map (Fig. 4b). This is due to the presence of outcropping Oligocene–Lower Miocene section, which is included in the Hamilton (1979) map but excluded from our isopach map. (2) In Figure 4b, the Neogene depocentre along NW Borneo is concentrated immediately offshore Brunei, whereas in the Hamilton (1979) map the depocentre contours are similar through Sabah (Fig. 4a), and expand to the SW towards Sarawak. Today we know the Middle Miocene–Recent section thins to the SW across the West Baram line into the Luconia Platform of Sarawak (Fig. 1), where the maximum Middle Miocene–Recent sediment thickness is about 2–3 km (e.g. Epting 1980; Mat-Zin & Tucker 1999). The thinning coincides with the abrupt termination of delta-related growth faults (Sandal 1996; Fig. 1). NE of Brunei the isopach thinning towards Sabah is more transitional, but throughout Sabah the Middle Miocene–Recent section rarely attains thicknesses greater than 4 km (e.g. Bol & van Hoorn 1980; Levell 1987; Petronas 1999). The basin isopach in Figure 4b makes the Baram Deltaic Province look much more like the other basins in northern Borneo, which are all roughly oval or round, localized point-source depocentres (e.g. Hutchison 1996). (3) Possibly the greatest potential source of sediment volume errors in the Hamilton (1979) map is the very large, deep basinal area offshore Sarawak (Fig. 4a), which may not be as extensive as mapped. Out of a total sediment volume for Borneo of 3.4×10^6 km^3, the Sarawak basin has a volume of 1.6×10^6 km^3 (Hall & Nichols 2002). However, regional 2D lines across the Sarawak basin do indicate the presence of a large, deep basin of possibly Oligocene age (see, e.g. Hutchison 1996). We lack the data to be able to properly evaluate this aspect of the Hamilton (1979) map.

Regarding the sediment restoration to the source area, Hall & Nichols (2002) looked at the problem of restoring all Neogene sediment back onto Borneo with a uniform thickness (tabular profile). The uniform linear nature of the Sabah depocentre shown by Hamilton (1979) lent itself to restoration of sediment to the adjacent highlands in a similar fashion. However, the present study shows the Baram Deltaic Province depocentre focused in a laterally (NE–SW) limited area in comparison with the drainage area. Hence, in addition to the proportionally different sediment volumes compared with Hall & Nichols (2002), we restore sediment back onto a proportionally larger percentage of the drainage area. Modern studies of eroded topography in tectonically active settings support the assumption of increasing erosion with altitude, which justifies the use of a prismatic, not tabular restoration profile (e.g. Montgomery & Brandon 2002; von Blanckenburg *et al.* 2004). However, if a prismatic profile was applied to the Hall & Nichols (2002) sediment volume estimate, then the Neogene exhumation along the centre of Borneo would average about 13 km, which seems too large. Some of this excess exhumation could be possibly mitigated by searching for volume errors in the Hamilton (1979) map. However, if Hall & Nichols (2002) are approximately (±25%) correct in their volume estimates, then we need to better understand how and where to restore that sediment volume. For example, is there a significant non-Borneo (e.g. Malay Peninsula) source to the Sarawak basin, as proposed for the Palaeogene by Hutchison (1996)? Or could southern Borneo have been a primary source area for sediment during the late Palaeogene and early Neogene? To address these questions it would be necessary to conduct similar studies to the volumetric estimation and restoration approach of this paper for the other circum-Borneo basins.

Because of the potentially large-scale impact on climate of the growth of mountain belts, many linked climate and tectonic studies have focused on the Asian region, particularly on the Himalayas and the Tibetan Plateau (e.g. Kutzbach *et al*. 1989; Molnar & England 1990; Raymo & Ruddiman 1992; Burbank *et al*. 1993; Molnar *et al*. 1993; Einsele *et al*. 1996; Métevier *et al*. 1999; Clark *et al*. 2003, 2004; Clift 2006; Rowley & Currie 2006). Similar to this NW Borneo case study, some studies have assessed deposition in the sedimentary basins fringing the Himalayas, particularly those basins associated with the deltas of large rivers where sediment arriving from the Tibetan Plateau is being deposited (e.g. Bengal Basin, Gulf of Martaban, Gulf of Tonkin; see Métevier *et al*. 1999; Clift 2006; Clift & Sun 2006). Generally, it is assumed that slower rates of sedimentation equate with less erosion and less exhumation in the sediment source area. In turn, this may be related to climate change or a change in rate of surface uplift. For dramatic changes in sedimentation rate this will probably be the case. However, this NW Borneo case study documents that other factors also need to be considered, in particular changes in the sediment source area with time as a result of shortening or extension, emergence of a region above sea level, changes in sediment-preservation potential with time, or, although not applied in this study, the effects of river capture *sensu* Clark *et al*. (2004).

In this study, the Middle Miocene sedimentary volume is smaller than the Late Miocene and Pliocene–Recent volumes (Table 1). Consequently, the Middle Miocene might be inferred to be the time of slowest erosion in the sediment source area.

However, if palaeoenvironmental changes affecting the land–sea distribution and source area are considered (parameters a_1, a_2 and a_3; Table 1), the Middle Miocene source area exhibits the highest exhumation rate of the periods studied (Table 2). Although these differences are comparatively small, the approximations do indicate that caution is needed when inferring hinterland rates of uplift–erosion or tectonic activity solely from sediment rates obtained from a basin, without considering how the eroded sediments restore back onto the sediment source area.

A study of sedimentation in basins of northern SE Asia, related to drainage from the Tibetan Plateau (Clift 2006), showed that the icehouse climate imposed by Plio-Pleistocene glaciation was not the sole factor in an increase in sedimentation that was previously proposed (Métevier *et al*. 1999). According to Clift (2006), rapid erosion occurred during the Early–Middle Miocene (24–11 Ma) prior to glaciation, suggesting as a trigger mechanism the effects of rock uplift and increasing precipitation related to monsoon strengthening. The application of the restoration method discussed in this paper to the northern SE Asia setting would raise the following questions about the size of the drainage area with respect to the sediment volume for any stage in time. (1) Did any large-scale shortening of the source area (i.e. Tibetan Plateau) result in a net decrease in drainage area with time? (2) Did Late Miocene to Recent extension in the plateau (Blisniuk *et al*. 2001) affect sediment delivery? (3) Did drainage capture result in increases and decreases in the area of single drainage basins with time (*sensu* Clark *et al*. 2004)? Another factor that also needs to be considered is how uplift beyond the main mountain belt and closer to the depositional areas may distort inferences made about the geological history of the sediment source system (Hall & Morley 2004).

Today, Borneo straddles the equator, and lies below the landmasses affected by the monsoon, which was also the case during the Miocene (Moss & Wilson 1998). Hence, the climate effects discussed by Métevier *et al*. (1999) and Clift (2006) for varying sedimentation budget in the Himalayas would seem unlikely to have affected Borneo. In this respect our results indicate approximately steady-state tectonic and climatic conditions for the last 17 Ma, accompanied by relatively high, sustained erosion rates. Hewawasam *et al*. (2003) and von Blanckenburg (2005) showed that the topographically high, but tectonically quiescent region of Sri Lanka had overall low erosion rates, suggesting that active tectonic uplift, not only relief, is necessary for high, sustained erosion rates. In turn, the relatively constant and high amount of erosion calculated in the present study can be seen as indicating a fairly constant and continuous uplift rate for the sediment source area, requiring one or more mechanisms for continuous uplift from the latest Early Miocene until today.

Simple isostatic rebound as a result of Late Oligocene buoyant rebound of partially subducted continental crust (e.g. Hutchison 2004) would produce a marked early uplift pulse that decayed exponentially with time. This rebound was probably a factor in producing probably somewhat higher early erosion rates during formation of the deep regional unconformity, but cannot explain the stable Neogene uplift and erosion pattern monitored in this study. Hall & Morley (2004) suggested that mantle-driven uplift possibly related to delamination of a lithospheric blob during crustal thickening might be the primary driving mechanism. Alternatively, slab detachment appears to be a process that could explain the continuous exhumation determined in the present study. Modelling of slab detachment predicts large amounts of uplift in elastic models (*c*. 6 km, Buiter *et al*. 2002), and much less uplift in viscous models (*c*. 1.4 km, not taking into account erosion and sedimentation; Gerya *et al*. 2004). Topography is predicted to develop in a zone about 300 km wide, with a fairly constant uplift rate being sustained over a time range of the order of 20 Ma (Gerya *et al*. 2004). Although the models of Buiter *et al*. (2002) and Gerya *et al*. (2004) explore basic rheological cases, and more sophisticated viscous–elastic–plastic models are needed to realistically model uplift, these models at least suggest that the topography of NW Borneo is of the right dimensions and duration to be explained by slab detachment. Lateral variations in detachment style and timing may also help explain lateral variations in subsidence and topography along the NW Borneo margin (e.g. the younging of uplift to the NE with time).

Conclusions

Hall & Nichols (2002) used a regional approach to highlight the importance of understanding how the large volumes of sediment on the Borneo margin can be restored back to the hinterland. Not surprisingly, the present, more detailed study has highlighted some broad similarities to and some significant differences from their pioneering work. Understanding these differences would require work in the future that better quantifies sediment age and volume offshore, definition of the location and shape of sediment source areas for single basins, and well-constrained models for how to distribute the restored section across the palaeo-sediment source areas.

The key focus of this study is the estimation of the Miocene to Recent exhumation of the NW Borneo margin by applying a novel mass-balancing approach that not only restored volumes of eroded sediment back onto the hinterland of Borneo, but also accounted for palaeoenvironmental changes in the sediment source area with time. Incorporation of parameters such as (1) varying width of drainage areas as a result of shoreline progradation, (2) syn-erosional tectonic shortening, (3) changes in the amount of uplifted areas, (4) variation in sediment density with time, (5) incomplete preservation of eroded rock volume, and (6) the degree to which the basin is an open system into end-member calculations allowed by restoration indicates that the NW Borneo hinterland uplift was probably greatest in the middle Miocene (*c*. 300 m Ma^{-1}), and has slightly diminished during the late Miocene and Pliocene (*c*. 290 m Ma^{-1}). There are differences in the ranking of the times of largest sediment volume (1, Late Miocene; 2, Pliocene; 3, Middle Miocene) and times of greatest hinterland uplift (1, Middle Miocene; 2, Late Miocene; 3, Pliocene). Our results show that if palaeoenvironmental changes affecting the land–sea distribution and source area are considered, estimated exhumation rates for sediment source areas can differ significantly from those in sink-to-source restorations omitting palaeoenvironmental change. Although for NW Borneo these differences are not large, the approximations do indicate that caution is needed when inferring hinterland rates of exhumation or tectonic activity solely from sediment rates obtained from a basin, without considering how the eroded sediments restore back onto a dynamically changing source area.

Although perhaps fortuitous uncertainties exist in the data, the estimated regional exhumation of this study is of similar magnitude, if not identical, to independent exhumation data derived from fission-track analysis (Swauger *et al*. 1995; Hutchison *et al*. 2000), vitrinite reflectance studies (Hutchison *et al*. 2002), combined analyses of uranium series, electron spin resonance and palaeomagnetic dating (Farrant *et al*. 1995), and sediment-load analysis of the modern Baram River (Staub & Esterle 1994). Integration of these diverse approaches suggests that NW Borneo has been characterized since Miocene times by a strong coupling between constant exhumation of low-grade metamorphic basement in the hinterland, constantly high sedimentation rates offshore, and effective erosion and basinward material transport that ultimately provides a counter-scenario to that of orogenic belts characterized by extensional collapse and unroofing of high-grade metamorphic terrane. Slab detachment *sensu* Gerya *et al*. (2004) appears to be a viable mechanism to explain the sustained exhumation observed.

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