Contraction and extension in northern Borneo driven by subduction rollback

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Abstract

During the Paleogene the Proto-South China Sea was subducted beneath northern Borneo. Subduction ended with Early Miocene collision of the Dangerous Grounds/Reed Bank/North Palawan block and the Sabah–Cagayan Arc. Much of northern Borneo then became emergent forming the Top Crocker Unconformity. Later in the Early Miocene subsidence resumed. It is proposed that northward subduction of the Celebes Sea initiated formation of the Sulu Sea backarc basin, followed by subduction rollback to the SE. This formed a volcanic arc, which emerged briefly above sea level and collapsed in the Middle Miocene. As rollback continued the Sulu Arc was active during Middle and Late Miocene between Sabah and the Philippines. Rollback drove extension in northern Borneo and Palawan, accompanied by elevation of mountains, crustal melting, and deformation offshore. There were two important extensional episodes. The first at about 16 Ma is marked by the Deep Regional Unconformity, and the second at about 10 Ma produced the Shallow Regional Unconformity. Both episodes caused exhumation of deep crust, probably on low angle detachments, and were followed by granite magmatism. The NW Borneo–Palawan Trough and offshore Sabah fold and thrust belt are often interpreted as features resulting from collision, regional compression or subduction. However, there is no seismicity, dipping slab or volcanicity indicating subduction, nor obvious causes of compression. The trough developed after the Middle Miocene and is not the position of the Paleogene trench nor the site of Neogene subduction. Inboard of the trough is a thick sediment wedge composed of an external fold and thrust belt and internal extensional zone with structures broadly parallel to the trough. The trough is interpreted as a flexural response to gravity-driven deformation of the sediment wedge, caused by uplift on land that resulted from extension, with a contribution of deep crustal flow.

1. Introduction

Northern Borneo is situated relatively far from the subduction boundaries that surround SE Asia, in a region commonly considered part of the Eurasian Plate, or within a SE Asian Plate (McCaffrey, 1996) or Sundaland Block (Simons et al., 1999) that is moving slowly with respect to Eurasia. It is a region of relatively little seismicity (Fig. 1), no significant volcanic activity, and apparently low but variable rates of present-day crustal movements relative to Eurasia measured by GPS (Simons et al., 2007). Yet close to the coast of Sabah in northern Borneo is the highest mountain in SE Asia, the 4100 m high Mount Kinabalu, at the northern end of the Crocker Range, which is a Late Miocene granite (Jacobson, 1970; Cottam et al., 2010), and offshore to the northwest of Sabah a wide fold and thrust belt between the coast and the deep NW Borneo Trough. The trough is south of the oceanic crust of the South China Sea and its extended southern continental margin of Reed Bank and the Dangerous Grounds (Fig. 2). The cause of the northern Borneo offshore fold and thrust belt, and the elevation of the Crocker Range and Mount Kinabalu on land, remain the subject of disagreement and much discussion.

Haile (1973) first recognised the role of subduction in the history of northern Borneo, and Hamilton (1979) interpreted the NW Borneo–Palawan Trough as an extinct subduction trench. It is generally agreed that there was subduction of the Proto-South China Sea beneath northern Borneo during the Paleogene. Subduction of the Proto-South China Sea terminated in the Early Miocene after collision of the extended South China continental margin crust/North Palawan block with the active continental margin of Sabah and the Cagayan Arc (Holloway, 1982; Rangin et al., 1990; Tan and Lamy, 1990; Hinz et al., 1991; Hall, 1996; Hutchison et al., 2000; Hall and Wilson, 2000). Oceanic spreading in the South China Sea ceased in the Early or Middle Miocene (Taylor and Hayes, 1983; Briais et al., 1993; Barckhausen and Roeser, 2004). At about the same time there was deformation and uplift of the Crocker Group sediments on Sabah. The exact ages of these events are uncertain but deformation on land in Palawan and Sabah are often...
considered to be related, and major unconformities offshore such as the well-known Deep Regional Unconformity (DRU) of Middle Miocene age (Bol and van Hoorn, 1980; Levell, 1987; Hutchison, 2004, 2005), are commonly linked to the collision and cessation of South China Sea spreading.

However, even if these events are connected, the present-day wide offshore fold and thrust belt, much of the elevation of the Crocker Range, and the uplift and exhumation of the Mount Kinabalu granite, result from Neogene deformation that post-dates the Early Miocene collision. What is their cause? Numerous authors have provided models for the tectonic development of Sabah. Explanations fall into a number of broad categories. Many authors suggest the NW Borneo Trough was an active subduction trench and subduction has continued until the Late Neogene or present-day (Tongkul, 1991; Simons et al., 2007); from this viewpoint the offshore fold belt is an accretionary complex. Those who reject Neogene subduction argue that the offshore deformation is the result of regional compressional events with thrusting resulting in a foreland fold and thrust belt (Bol and van Hoorn, 1980; Hinz et al., 1989; Tan and Lamy, 1990; Hazebroek and Tan, 1993; Morley, 2007; Cullen, 2010) perhaps linked to subduction of attenuated continental crust or gravity tectonics. Others interpret the offshore deformation as largely gravity-driven but still suggest the elevation on land that is driving the offshore deformation results from regional compression (Hesse et al., 2009; Gartrell et al., 2011). Several authors (e.g. Ingram et al., 2004; Morley et al., 2008; Hesse et al., 2009, 2010; King et al., 2010) interpret deformation, shortening magnitudes, stress orientations, GPS observations (Simons et al., 2007) and recent seismicity to indicate a role for tectonic stresses which they attribute to subduction, ongoing convergence of blocks or plates, inheritance from former subduction or far-field stresses.

I suggest there is no plate convergence in the NW Borneo–Palawan region and that most Neogene deformation is a result of episodes of extension, not compression. Extension caused subsidence and elevation in different places, was accompanied by magmatism, and mobility of the deeper crust and topographically-induced stresses can account for the deformation that continues at present.

2. Present setting

The area around northern Borneo up to the western Philippines and northern Sulawesi is largely free of seismicity (Engdahl et al., 1998). All hypocentres close to Borneo have depths less than 50 km and a majority are shallower than 30 km (Fig. 1). The events
there for which there are moment tensor solutions show an inconsistent pattern (Simons et al., 2007). In the SE, beneath the Celebes Sea and Mangkalihat peninsula, most solutions indicate NE–SW compression, whereas those further north, mainly beneath the northeast Sabah coast and the Sulu Sea, suggest predominantly NW–SE extension and some strike-slip movements.

GPS observations (Simons et al., 2007) indicate active deformation of northern Borneo with small displacements relative to Sundaland and southern Borneo, suggesting broadly SW-directed movements up to 8 mm/yr. They must record surface motions but there is reason to doubt that the GPS measurements record the motions of lithospheric or crustal blocks. Firstly, the motions are different from those indicated by earthquake solutions. Secondly, the orientation of GPS vectors is different from those expected based on the orientation of structures offshore (e.g. Hazebroek and Tan, 1993; Hutchison, 2005; Hesse et al., 2009;
Thirdly, almost all the GPS stations are close to the coast in areas likely to be underlain by weak sedimentary rocks or unconsolidated sediments; thus some of the measurements could simply reflect surface movements related to gravity-driven moments for which there is clear evidence offshore (e.g. McGilvery and Cook, 2003; Morley, 2009).

There are no active volcanoes in Sabah. In south Sabah there are remnants of small Quaternary volcanic cones in the Tawau area and Semporna peninsula (Kirk, 1968), and there are small islands in Darvel Bay that probably represent Plio–Pleistocene volcanic centres. These are all close to the southwestern end of the inactive Sulu volcanic arc that links Sabah to Mindanao at the south side of the Sulu Sea (Fig. 2). Geochemical evidence suggests that the Plio–Pleistocene volcanic rocks do not record active subduction, but have an ocean-island basalt (OIB) character that reflects upwelling of OIB melts in the upper mantle into lithospheric thin spots produced during Miocene subduction (Macpherson et al., 2010).

3. Sabah geology and fold and thrust belts

The geology of northern Borneo is described in numerous papers and only a brief summary is given here based on earlier work which is well reviewed by Hutchison (2005).

3.1. Pre-Neogene

Sabah has a basement of Mesozoic igneous and metamorphic rocks overlain by a Cenozoic sedimentary cover (Figs. 3 and 4).
The basement includes basic igneous rocks, variably serpentinitised peridotites and Triassic to Cretaceous rocks described as crystalline basement (Reinhard and Wenk, 1951; Kirk, 1968; Leong, 1974). The latter resemble deformed ophiolitic rocks intruded by arc plutonic rocks and have been suggested to represent a Mesozoic intra-oceanic arc (Hall and Wilson, 2000). The peridotites have been interpreted as part of a Cretaceous ophiolite (Hutchison, 2005) that is mainly Middle Jurassic to Early Cretaceous (c. 160–75 Ma) and was emplaced in the Late Cretaceous or Early Paleogene (Newton-Smith, 1967; Omang and Barber, 1996). Unusual peridotites exposed close to Mount Kinabalu have been interpreted to represent sub-continental mantle (Imai and Ozawa, 1991). In Sarawak (e.g. Tate, 1991; Tate and Hon, 1991) the basement includes isolated occurrences of metamorphic rocks that are undated but usually considered to be Carboniferous or older, Permo-Carboniferous limestones, and volcanic and sedimentary rocks of Triassic and Jurassic age.

In southern Sarawak there are widespread terrestrial to marginal marine sedimentary rocks of Late Cretaceous to Eocene age. Elsewhere in Sarawak and Sabah the Mesozoic and older basement rocks are overlain or in faulted contact with a sequence of predominantly deep-water turbidites and related deposits of the Upper Cretaceous to Eocene Rajang Group. In Sabah deep-water Eocene to Lower Miocene Trusmadi and Crocker Formations (Collenette, 1985) the basement includes isolated occurrences of metamorphic rocks that are undated but usually considered to be Carboniferous or older, Permo-Carboniferous limestones, and volcanic and sedimentary rocks of Triassic and Jurassic age.

Fig. 4. Simplified geological maps of Sabah and Palawan based on Lim and Heng (1985), Almasco et al. (2000), Mines and Geoscience Bureau, Philippines (2011) and Suggate (2011). The location of the section of Fig. 5 is shown.
1965; van Hattum et al., 2006) were deposited during subduction of the Proto-South China Sea beneath northern Sarawak, Sabah and the Cagayan Arc, southeast of Palawan and were later deformed as a fold and thrust belt (Taylor and Hayes, 1983; Rangin and Silver, 1991; Tongkul, 1991, 1994; Hall, 1996; Hall and Wilson, 2000; Hutchison et al., 2000).

3.2. Neogene

In the Early Miocene the attenuated South China continental margin, variously referred to as the North Palawan or Dangerous Grounds-Reed Bank Block, collided with northern Borneo and the Cagayan Arc, terminating subduction, an event which Hutchison (1996) named the Sabah Orogeny. It deformed and elevated much of Sabah, and probably Palawan, and produced a major regional unconformity (Fig. 3), the Top Crocker Unconformity (TCU of van Hattum et al., 2006), now often called the Base Miocene Unconformity (BMU) by oil companies (e.g. Gartrell et al., 2011) and others (Jackson et al., 2009). The TCU is older (Hall et al., 2008) than the Deep Regional Unconformity (DRU) in offshore Sabah (BoI and van Hoorn, 1980; Levell, 1987) and its approximate equivalent, the Middle Miocene Unconformity (MMU), in offshore Sarawak (Petronas, 1999). Levell (1987) recognised this older unconformity on land in Sarawak and Sabah, and observed it is an angular unconformity at the base of the shallow water Meligian Formation, but considered the DRU to be more likely related to the end of subduction because it was more extensive, an interpretation advocated by some later authors (e.g. Clift et al., 2008). I consider the TCU to mark the end of subduction and collision because on land shallow water deposits rest with a major angular discordance on deformed deep water rocks, and suggest that offshore this unconformity may have been removed by tectonism or erosion associated with the DRU. It is likely that both unconformities are diachronous, but their approximate ages are 20–19 Ma for the TCU (Levell, 1987; Balaguru and Nichols, 2004), and 16–15 Ma for the DRU (Hutchison, 2005; Gartrell et al., 2011).

The collision caused emergence of much of Sabah and the present central highlands of northern Borneo, with folding and thrusting of both basement and cover. However, by the end of the Early Miocene much of present-day Sabah was below or close to sea level (Noad, 1998; Balaguru et al., 2003; Hall et al., 2008) with probably a low elevated range of hills at the position of the Crocker Mountains. Because there are few Neogene rocks in western Sabah this is uncertain, but in Brunei and Sarawak Neogene rocks are preserved and the shelf edge moved broadly northwestwards from the Middle Miocene onwards (e.g. Sandal, 1996; Hazebroek and Tan, 1993; Hutchison, 2005; Cullen, 2010), suggesting a gradual rise and widening of the Crocker Mountains during the Middle and Late Miocene. To the west of the shelf edge in offshore Brunei and Sabah, and north of the West Baram Line, is a thick Middle Miocene to Recent deep-water clastic wedge that thins northwards. This is deformed by folds and thrusts to form a wide and active fold and thrust belt between the coast and the NW Borneo Trough (Tan and Lamy, 1990; Hazebroek and Tan, 1993; Hinz et al., 1989; McGilvery and Cook, 2003; Morley et al., 2003; Ingram et al., 2004; Franke et al., 2008, 2011; Morley and Leong, 2008; Hesse et al., 2009; Gartrell et al., 2011).

To the east of the Crocker Mountains during the Middle and Late Miocene there was subsidence and deposition of a thick succession of fluvi-marine deposits (Noad, 1998; Balaguru et al., 2003; Balaguru and Nichols, 2004) in the Central Sabah Basin (Hutchison, 1992) whose remnants are now found in the circular basins of eastern Sabah (Tija et al., 1990; Tongkul, 1993; Clemen, 1996; Balaguru et al., 2003; Tongkul and Chang, 2003).

While sediments were being deposited in the Central Sabah Basin and offshore to the west of Sabah in the Middle and Late Miocene, there was important igneous activity in the region. The Sulu Sea was opening, and the Sulu volcanic arc formed above a northwest-dipping subduction zone on its south side (Hall and Wilson, 2000; Hall, 2002; Chiang, 2002). The Sulu arc can be traced on land into the Semporna and Dent peninsulas of south Sabah. In the centre of the Crocker Mountains the Kinabalu granite was intruded between 8 and 7 Ma (Cottam et al., 2010). Low temperature thermochronology (Cottam et al., in press) suggests the granite was intruded into mountainous terrain indicating that the Crocker Range existed at this time but based on the inferred positions of the NW Sabah shelf edge, and the distribution of sedimentary rocks in the circular basins, it must have been much narrower than today (Hall and Nichols, 2002; Morley and Back, 2008).

Sabah became fully emergent only at the end of the Miocene or Early Pliocene (Colletnet, 1963; Balaguru et al., 2003; Tongkul and Chang, 2003; Morley and Back, 2008). The glaciated summit plateaus and Pleistocene glacial tills (Colletnet, 1958) of the Kinabalu area, and similar deposits near to Mount Tambuyukon, indicate that the summits of Kinabalu, Tambuyukon and possibly Trusmadi, were significantly higher than other parts of the Crocker Range by the Pleistocene.

4. Problems

The Neogene to Recent deformation offshore, and the elevation of the present Crocker Mountains has been interpreted mainly in terms of convergence and compression. Hamilton’s (1979) suggestion that the NW Borneo Trough was a trench has been accepted by many authors who interpret Neogene subduction to have continued to the present (e.g. Simons et al., 2007; Sapin et al., 2011), implying the offshore fold and thrust belt is an accretionary prism related to convergence between the Dangerous Grounds and Sabah, even though Hamilton suggested the ‘trench’ was extinct. Hinz et al. (1989) interpreted the offshore fold and thrust belt as reflecting a continent–continent collision, and they inferred regional compression to have induced major thrusting that has continued until today, a commonly held view (e.g. Ingram et al., 2004; Gartrell et al., 2011). In contrast, the fold and thrust belt has been interpreted as a mainly gravity-driven phenomenon (e.g. Hazebroek and Tan, 1993), analogous to the deep-water fold and thrust belt of the Niger Delta (cf. Corredor et al., 2005). Hesse et al. (2009) have shown that the amount of contraction in the outboard fold belt is not fully matched by the amount of extension in the inboard region offshore and concluded that there must be a component of tectonic shortening that increases northwards, and others have suggested the gravity-driven deformation is ultimately linked to regional compression (e.g. Morley, 2007; Gartrell et al., 2011). However, there are many problems with regional compressional hypotheses.

4.1. Sulu Sea spreading

Hutchison (1992) drew attention to the location, age and significance of the Sulu Sea and the importance of extension from the late Early Miocene. The ocean drilling program (ODP) drilled three Sulu Sea sites and Site 768 in the centre of the SE Sulu basin (Fig. 2) provided the most complete section (Silver et al., 1991). There is a basaltic basement dated at 18.8 Ma, with a thin clay cover interpreted as deposited below the CCD, suggested to be oceanic crust (Silver and Rangin, 1991). This is overlain by volcanic rocks and volcanioclastic sediments, interpreted as deposited in a subaerial or shallow marine setting, in turn overlain by brown claystones typical of pelagic sedimentation below the CCD of late Early to early Middle Miocene age (Nichols et al., 1990). The site is now at a water depth of 4385 m. Seismic lines (Rangin, 1989; Rangin
and Silver, 1991) indicate the entire sequence is cut by extensional faults associated with rifting. This sequence indicates extension had begun by about 19 Ma, producing oceanic crust, with a volcanic arc sequence constructed on top of the basement which became emergent, and later the entire arc sequence subsided to pelagic depths by about 15–14 Ma. Using backstripping and decomposition techniques for Site 768 Huang et al. (1991) highlighted high rates of basement subsidence in the Sulu Sea between 19–17.7 Ma and 10.7–10 Ma. In passing it is worth noting that the SE basin of the Sulu Sea is often described as oceanic crust, but only at Site 768 was basaltic crust encountered at the base of the section, and this is overlain by a volcanic sequence with arc-like character. At both the other drilled sites in the Sulu Sea, at depths between 2856 and 3645 m, the oldest rocks drilled are probable late Early Miocene volcaniclastic rocks, considered to have been deposited at depths no greater than 1000 m (Nichols et al., 1990) and suggested to have been erupted from a subaerial or shallow marine vent. Middle Miocene faunas in claystones indicate rapid and significant early Middle Miocene subsidence. Thus, the parts of the deep SE Sulu Sea basin that have been drilled appear to be an extended and subsided volcanic arc built on oceanic crust, rather than normal oceanic crust.

Before the ODP drilling Rangin (1989) suggested the Sulu Sea was a backarc basin formed above a northwest-dipping slab due to subduction of the Celebes Sea and he also drew attention to later Neogene episodes of extension on Sabah interpreted to be related to this subduction. After ODP drilling, Rangin and Silver (1991) preferred a model in which the Sulu Sea formed behind a southeast-dipping slab related to subduction of the Proto-South China Sea. Hutchison (1992) remarked that the arc–trench system of the Sulu arc had migrated southeastwards, in what today would be described as a rollback setting. Geochemical data (Chiang, 2002) and other arguments (Hall and Wilson, 2000) also favour Rangin’s (1989) original suggestion of northward subduction of the Celebes Sea to form the Sulu Arc, post-dating collision of the Reed Bank block with the Cagayan volcanic arc and elevation of Palawan.

4.2. Sediments from Palawan in Early Miocene

Sediment provenance studies also favour collision in Palawan in the Early Miocene before formation of the Sulu Sea. At the northernmost tip of Sabah the Lower Miocene Kudat Formation shallow marine sandstones rest unconformably on deformed Crocker Group rocks above the TCU. The Kudat Formation has a lower member with an unusual heavy mineral assemblage that includes abundant garnet, kyanite and zircon (van Hattum, 2005; van Hattum et al., in press). Kyanite is unknown from potential sources on Borneo, but is found on Palawan (Encarnación et al., 1995) and garnets are well matched to sources on Palawan (Suggate, 2011; Suggate and Hall, in press). Zircons also indicate a Palawan provenance. In contrast, the upper member of the Kudat Formation suggests derivation almost entirely from central Borneo. These data indicate elevation of Palawan, interpreted to be the result of Early Miocene collision of the North Palawan block, resulting in south-flowing rivers that carried sediment into shallow marine areas of northern Sabah. The supply of sediment from Palawan to Sabah was very short-lived and the termination of this supply is suggested here to mark the beginning of extension leading to formation of the Sulu Sea by about 19 Ma.

4.3. Unusual position of Kinabalu, Tambuyukon, Trusmadi

The mountains of western Sabah, the Crocker Range, strike broadly N to NNE in what is known as the NW Borneo trend (Bol and van Hoorn, 1980; Hinz et al., 1989; Hazenbroek and Tan, 1993). This trend is oblique to the NW Borneo Trough and parallel to the strike of the Crocker Formation (Tongkul, 1990, 1991) in the Early Miocene collisional fold and thrust belt. The fold belt changes orientation abruptly through 90° at the position of Mt Kinabalu and its strike in northernmost Sabah is parallel to the E to ESE Sulu trend (Fig. 2).

Normally the highest parts of a mountain range are found at its centre, but the highest peaks of the Crocker Range, Mounts Kinabalu, Tambuyukon and Trusmadi (Fig. 4), are close to its northernmost end. The mountain range is thus longitudinally highly asymmetrical. The highest peaks are less than 150 km from the coast of the Sulu Sea, and 250 km to the NE water depths exceed two kilometres, whereas the mountain belt descends gently to the SSW over a distance of more than 750 km. These peaks expose rocks from relatively deep in the crust, including low to medium grade metamorphic phyllites and schists at Trusmadi, peridotites at Kinabalu and Tambuyukon, and the well-known granite intrusion at Kinabalu.

If, however, it is assumed that the NW Sulu Sea basin is an extended part of the mountain belt, and the Palawan segment of the mountain range is restored, the longitudinal symmetry is that expected of other mountain belts. This interpretation implies that the extension post-dates the Early Miocene, as expected from the ages of volcanic rocks drilled in the Sulu Sea.

4.4. Movement of shelf edge

In Brunei and offshore Sabah, the position of the shelf edge at different times can be identified (Hazenbroek and Tan, 1993; Sandal, 1996) showing that it moved seaward during the last 15 million years. This indicates that the Crocker Ranges were narrower about 15 million years ago, and have widened gradually with time. Rice-Oxley (1991) and Hutchison (2005) show a similar pattern for offshore Sabah, confirmed by Cullen (2010). In offshore Brunei and NW Sabah Morley et al. (2008) noted that inversion, thrusting and uplift of the present-day onshore area and inner shelf occurred during the Middle Miocene to Pliocene, while a deepwater fold and thrust belt developed during the latest Miocene to Holocene. There was a seaward shift of deformation with time consistent with the movement of the shelf edge. This pattern is apparently consistent with a developing fold and thrust belt driven by regional compression, but is inconsistent with the history of eastern Sabah.

4.5. Neogene sedimentation in eastern Sabah

After collision in the Early Miocene there was a brief period of erosion (van Hattum et al., 2006, in press; Hall et al., 2008) which formed the TCU on land and offshore. However, soon after the emergence of much of present-day Sabah, the situation changed again. Although a narrow band of mountains probably remained along the present spine of the Crocker Ranges, the areas to the west and east subsided below sea level and sedimentation resumed. West of the Crocker Ranges there was deposition of thick sediments, initially in what are now deltas and coastal plains of Brunei and Sabah, and later in offshore areas, by rivers flowing to the west or northwest.

In eastern Sabah there was a wide Central Basin east of the Crocker Range (Hutchison, 1992; Noad, 1998; Balaguru et al., 2003; Tongkul and Chang, 2003; Balaguru and Nichols, 2004). Most of the lower Middle to Upper Miocene sediment fed into this basin and carried to the Sulu Sea came from the Borneo interior. River and shallow marine sediments are now preserved in a number of structures described as circular basins, which are deformed remnants of the much larger basin supplied by a large river system, flowing broadly northeast, which deposited sand and mud in a river, delta and coastal plain complex. This subsidence provided accommodation space for the accumulation of several kilometres
of Neogene sediment, variously estimated on land to be more than 6 km (Balaguru and Nichols, 2004), more than 7.5 km (Tongkul and Chang, 2003), or more than 18 km (Collettette, 1965), and offshore in the Sandakan Basin to be 15 km thick (Graves and Swauger, 1997). It occurred at the same time as extension in the Sulu Sea, and is generally considered to be related to the extension (Hutchison, 1992; Tongkul, 1993). Extension and subsidence are difficult to reconcile with suggestions of long-term Neogene regional compression in Sabah, sometimes linked to even larger scale regional causes such as collision in Sulawesi (e.g. Cullen, 2010).

4.6. Sulu Sea fold and thrust belt

It is now commonly accepted that some of the offshore deformation of NW Borneo can be attributed to shallow gravitational processes. Nonetheless, several authors have highlighted differences between the NW Borneo margin and other well-known gravity-driven offshore fold and thrust belts such as the Niger Delta (e.g. Morley et al., 2008; Hesse et al., 2009; King et al., 2010) based on differences in modern stress patterns, and the observation that in parts of the deepwater fold and thrust belt there is more contraction than extension in the Neogene sedimentary section. This has been used to suggest that there is broadly NW–SE regional compression which may be the result of subduction, convergence of blocks or plates, or far-field stresses, such as India–Asia collision or deformation in Sulawesi. Little is published concerning the offshore area to the NE of Sabah at the margins of the Sulu Sea, yet on land the structural grain is completely different from west Sabah (Fig. 2), changing from N to NNE (NW Borneo trend) to E to ESE (Sulu trend) (Bol and van Hoorn, 1980; Hinz et al., 1989; Hazebroek and Tan, 1993; Tongkul, 1991, 1994). There is some information offshore from the Sandakan basin obtained during hydrocarbon exploration but structures and stratigraphy are not yet documented in detail; the few published data show thrusts on one seismic line which includes structures described as toe-of-slope compressional folds (Graves and Swauger, 1997) at the basinward end of a thick sedimentary section (Wong, 1993). Offshore fold axes and thrusts are apparently broadly parallel to the Sulu trend.

The key point is that the Sandakan basin and Sulu Sea margins are generally ignored in discussion of regional compression yet the orientation of structures appears completely inconsistent with the direction of stresses required to produce the offshore fold and thrust belt of NW Sabah and Brunei. The suggested microplates (e.g. Simons et al., 2007) based on GPS observations, and the deformation history and structural trends in eastern Sabah (Balaguru, 2001; Balaguru et al., 2003; Tongkul and Chang, 2003) are similarly incompatible. The few authors that include the Sulu trend (e.g. Rangin et al., 1990; Tongkul, 1991; Ingram et al., 2004) show the supposed subduction system bending at right angles round northern Borneo, suggesting a major reorientation of regional stresses, or link the NW Borneo Trough to strike-slip faults, implying that the apparent continuity of the NW Borneo and Palawan Troughs is coincidental.

4.7. The NW Borneo Trough and Palawan Trough

Hutchison (2010) provided a review of previous interpretations of the NW Borneo and Palawan Troughs to which he added new information based on seismic lines from oil companies and data acquired during Malaysian Law of the Sea investigations. On seismic lines perpendicular to the Borneo margin the trough and fold and thrust belt resemble a subduction trench and accretionary complex. However, there is no seismicity below or landward of the trough such as might be associated with a subducting slab, although deformation of the seabed above the fold and thrust belt indicates active deformation (e.g. McGilvery and Cook, 2003; Morley, 2007, 2009; Clift et al., 2008). Hesse et al. (2009) have shown that the contraction in the outboard fold belt is largely balanced by extension in the inboard shelf region, but concluded that there was an excess of shortening in the northern part of their studied area, west of Mount Kinabalu, which they interpret to require base ment-driven compression.

Published seismic studies show evidence of repeated failures of the shelf edge and movement into deep water of mass transport complexes (e.g. McGilvery and Cook, 2003; Morley and Leong, 2008; Morley, 2009) which were then folded. Multiple episodes of folding (Morley et al., 2003; Ingram et al., 2004; Gartrell et al., 2011) indicate contraction of the fold and thrust belt offshore but do they require regional compression to drive this? Since much of the contractual deformation recorded in Brunei and offshore must have occurred while east Sabah was subsiding to form the Central Basin, now preserved as remnants in the circular basins, regional compression is incompatible with regional extension suggested above to be the cause of this subsidence.

Hall (2011) suggested the imbalance measured by Hesse et al. (2009) could be accounted for by including extension on land and observed that the deepest part of the trough is immediately NW of the highest point on land, Mount Kinabalu. This interpretation suggests a link between rapid and young uplift on land, evidenced by exhumation of the 7–8 Ma Kinabalu granite now exposed at 4 km above sea level and the surrounding Crocker Range, and subsidence offshore. From this it follows that the offshore fold and thrust belt, and major shelf failures producing huge deep water mass transport complexes, are the result of uplift and extensional faulting on land.

At its SW end the trough ends abruptly at the West Baram Line (Fig. 2). This is not an active fault (cf. Ingram et al., 2004), nor a fault active during the Neogene (cf. Clift et al., 2008), as it has no expression in the Neogene section on seismic lines offshore, nor on high resolution SRTM or ASTER imagery of Borneo on which post-Eocene structures can be traced along the fold belt on land without offset.

The trough is here interpreted as a flexural depression due to loading by the fold and thrust belt onto the thinned continental crust of the Dangerous Grounds and is associated with a flexural bulge in the Dangerous Grounds west of the trough. This interpretation is supported by the presence of elevated features within the NW Borneo Trough at water depths up to 3 km which are capped by carbonates and pinnacle reefs, indicating major subsidence. Some of these are draped by sediments whereas others have no sediment cover and are surrounded by flat lying sediments in the wide trough. Unfortunately, none of these features are dated, but some features capped by carbonate pinacles (see Fig. 10 in Hutchison, 2010) imply a phase of rapid subsidence from close to sea level to water depths of more than 1.7 km, and the complete absence of any sedimentary cover suggests this was relatively recent.

The NW Palawan margin has been described in a number of publications (Holloway, 1982; Hinz and Schlüter, 1985; Hinz et al., 1985, 1991). Sections from the Sulu Sea to Reed Bank by Rangin and Silver (1991) interpret it as an imbricated accretionary thrust zone, with an overthrust ophiolite rooted in the Sulu Sea obducted before collision of the Cagayan arc and the Reed Bank microcontinent in the Early–Middle Miocene. However, the southern edge of the Palawan Trough is not a thrust front (Hinz et al., 1985), as would be expected for a subduction zone, or by comparison with the NW Borneo Trough. The northern continuation of the Palawan Trough is a broad deep water area separating Reed Bank from Palawan and the Calamian Islands. Relatively poor quality vintage seismic lines in this area appear to show a rifted section recording separation of a microcontinental block from South China in the Eocene (Hinz et al., 1985, 1991; Morado and Poblete, 1997).
Recent high quality data (Franke et al., 2011) show there is a complex wide continent–ocean transition which was part of the South China Sea continental margin that was hyper-extended before collision in Palawan. There is no indication of thrusting at the site of the trough. Thrusting is observed only close to Palawan. Industry seismic lines (Forbes et al., 2011) show the rifted sequence is apparently unaffected by younger deformation although there is a thrusted package higher in the section.

4.8. Granite magmatism

Two small granite bodies are known from the axis of the NE–SW oriented elevated region running from Sabah to Palawan. The Capoas granite of Palawan is dated as 14–13 Ma (Encarnación and Mukasa, 1997; Suggate et al., in press) and the Kinabalu granite of Sabah as 8–7 Ma (Cottam et al., 2010). Both contain zircons that indicate a contribution to the melt of old continental crust interpreted in both cases to be South China extended continental crust underthrust during the Early Miocene collision (Fig. 4). Encarnación and Mukasa (1997) described the Capoas granite as ‘anorogenic’ and interpreted it to be the result of partial melting of South China crust in a setting unrelated to subduction or collision. Cottam et al. (2010) argued that the Kinabalu granite cannot be related to subduction. I suggest both are the products of extensional thinning of the crust during the Neogene as explained below.

4.9. Thinned crust beneath the offshore fold belt

Northwest of the Crocker Range is the very thick Neogene sediment wedge, including the offshore fold and thrust belt. Milsom et al. (1997) interpreted crustal thinning beneath the NW Borneo Trough, based on gravity data, which they assumed must pre-date Neogene basin formation. Recent studies based on seismic refraction and gravity data (Fig. 5) show the maximum thinning of continental crust beneath the sediment wedge (Franke et al., 2008; C. Foss, pers. comm., 2008). This is a surprising observation since the crust would be expected to be relatively thick in this region as a result of thickening during the Early Miocene collision of the Dangerous Grounds microcontinental block and the Sabah active continental margin (e.g. Hall and Wilson, 2000; Hutchison et al., 2000; Morley et al., 2011). If subduction had continued during the Neogene with underthrusting of the thinned Dangerous Grounds continental crust, this would also lead to thickening, as would basement involvement in the fold and thrust belt interpreted by many authors (e.g. Bol and van Hoorn, 1980; Gartrell et al., 2011; Morley et al., 2011; Sapin et al., 2011). I suggest thinning observed beneath the thickest part of the Neogene clastic wedge requires either extensional faulting or crustal flow (Hall, 2011; Morley et al., 2011) of the continental crust below the offshore fold and thrust belt.

5. Alternative explanation

Although the Early Miocene deformation in Sabah is well explained by collision resulting from subduction and convergence of extended South China Sea continental crust of the Dangerous Grounds/Reed Bank/North Palawan block with the NE–SW oriented Sabah–Cagayan Arc active margin, the younger fold and thrust belt deformation offshore is much more difficult to reconcile with such an interpretation. I therefore suggest an interpretation of the geology and tectonics in terms of extension (Fig. 5). A possible scenario is as follows (Fig. 6).

During the Palogene the Proto-South China Sea was subducted beneath northern Borneo (Fig. 6A). Subduction ended with Early Miocene collision of the Dangerous Grounds/Reed Bank/North Palawan block and the Sabah–Cagayan Arc. Collision caused folding and thrusting of Sabah and Palawan during the Sabah orogeny of Hutchison (1996). This produced the widespread TCU and elevated much of the region of present onshore Sabah and Palawan above sea level. This unconformity is Early Miocene in age, c. 20 Ma, and is older than the DRU or MMU. In Sabah the collision juxtaposed and probably tectonically intercalated ophiolitic rocks that had formed parts of the Sabah basement, the Crystalline Basement, some of which may be part of the underthrust South China Sea continental crust, and deep water sedimentary rocks of the Rajang Group and Crocker Group (Fig. 5). In Palawan, the ophiolites probably include oceanic and arc rocks added to the South China Sea continental margin in the Late Cretaceous, as well as Eocene ocean crust or serpentinitised peridotites of the extended Dangerous Grounds/Reed Bank/North Palawan block, and they are intercalated with pre-Mesozoic granites and Mesozoic sedimentary rocks during collision with the Cagayan Arc. The Palawan part of the orogenic belt was much wider than Palawan today (Fig. 6B) and sediment from it was transported south to the Kudat Formation of northern Sabah (van Hattum et al., in press; Suggate and Hall, in press).

Rifting began before 19 Ma, assuming that the oldest rocks drilled in the Sulu Sea were erupted at an oceanic spreading centre in a backarc basin. This was driven by northwestward subduction of the Celebes Sea, which then formed the proto-Sulu Arc volcanic arc that emerged rapidly above sea level, as indicated by ODP drilling. However, by about 15–14 Ma, based on drilling at Site 768, the volcanic rocks were below the CCD. I suggest this marks a period of rapid trench rollback to the SE, identified by Hutchison.
The arc activity was at the SW end of the Sulu Arc and was certainly widespread in the Middle and Late Miocene. This indicates arc activity in the Semporna area (1968; Haile et al., 1965; Rangin et al., 1990; Bellon and Rangin, 1991; Swauger et al., 1995) and in the Central Basin of eastern Sabah (Kirk, 1962, 1968; Rangin et al., 1990; Bellon and Rangin, 1995; Rossetti et al., 2000; Dini et al., 2002, 2009).

Extension is suggested to have occurred on low angle detachments (which may be observed in Palawan – M.A. Forster, pers. comm., 2011) exhuming the stacked thrust complex of ophiolites, continental basement and Mesozoic sediments, and caused the first episode of granite magmatism that formed the Capoas granite at c. 15 Ma. The Capoas (and Kinabalu) granite are suggested to resemble those of the western Mediterranean, such as those in Elba and Corsica, which are associated with Tyrrenhian Sea extension and subduction rollback (e.g. Jolivet et al., 1994, 1998; Daniel and Jolivet, 1995; Rossetti et al., 2000; Dini et al., 2002, 2009).

The Palawan extension was much greater than that of Sabah where the early extension phase that began before 19 Ma was marked by widespread subsidence and deposition of sediments in the Central Basin of eastern Sabah (Fig. 5), with crustal thinning but no oceanic crust formation and limited arc volcanism. Stratigraphy and K–Ar dating of volcanic rocks on Sabah (Kirk, 1962, 1968; Haile et al., 1965; Rangin et al., 1990; Bellon and Rangin, 1991; Swauger et al., 1995) indicate arc activity in the Semporna and Dent peninsulas of Sabah may be as old as Early Miocene and was certainly widespread in the Middle and Late Miocene. This arc activity was at the SW end of the Sulu Arc.

Models of core complexes and low angle detachments (Davis and Coney, 1979; Lister and Davis, 1989; Arca et al., 2010) show extension is accompanied by both subsidence and uplift in different parts of the system. The widening of the elevated region in NW Borneo, indicated by the migration of the shelf edge, is suggested to reflect uplift related to extension. There could also be a contribution to uplift by deep crustal flow in response to sediment loading (Morley and Westaway, 2006; Hall, 2011), and by laccolithic granite intrusions, both ultimately products of extension driven by subduction rollback (Fig. 5).

I suggest there was another phase of extension, presumably correlated with rollback, at about 11–10 Ma. This is correlated with an increased rate of basement subsidence at this time recorded by ODP drilling at Site 768, and the Intermediate Unconformity (Bol and van Hoorn, 1980; Levell, 1987) and/or the Shallow Regional Unconformity. This phase of extension was also followed by granite magmatism about 2 million years later, this time in the Kinabalu area. I suggest the laccolith-like form of the Kinabalu intrusion (Cottam et al., 2010) exploited extensional detachments marked in the Kinabalu and Tambuyukon areas by extensional areas of partially serpentinised peridotites (Fig. 5). In this model (Fig. 5) the crustal thickness beneath Kinabalu and Telupid is approximately 5–10 km less than that estimated by Holt (1998) based on the assumption that the ultrabasic rocks in the upper crust are significantly denser than the average crustal density of 2.67 Mg/m³ he used. In Palawan this phase of extension may be marked by gravity-driven thrust sheets that have moved northwards into deeper water above the undeformed older rifted section (Holloway, 1982; Hinz et al., 1991; Forbes et al., 2011).

In Sabah it appears that subduction of the Celebes Sea ceased at the end of the Miocene (Chiang, 2002), and there was a change in the Pliocene to basaltic magmatism with an ocean island character (Macpherson et al., 2010). This implies a major change in the character of the mantle beneath the region which could mark slab break-off or possible delamination of a lithospheric root beneath the Crocker Range centred on Kinabalu. Either could explain the upper mantle high velocity anomaly below Sabah centred at depths of about 250 km on some P wave tomographic models (Bijwaard et al., 1998). Slab break-off would explain the absence in P-wave tomographic models of any sign of a slab beneath the Sulu arc, and the geochemical character of volcanism. Slab break-off or delamination would also explain the widespread uplift of the whole of Sabah since the Early Pliocene. I suggest the Pliocene to Recent uplift of the Crocker Range and the exceptional elevation of Mount Kinabalu is the cause of recent deformation offshore, and the movements recorded by GPS measurements. These reflect...
radial movements of the upper crust, which are largely gravity-driven, away from a centre at the position of Mount Kinabalu.

6. Conclusions

If NW Borneo is considered on its own an explanation for Neo-
gene deformation in terms of regional compression seems plausible, but when examined in a wider context it is impossible to reconcile with evidence for major extension in the South Pala-
w–Sulu Sea region, and the record of sedimentation in eastern Sabah. Hypotheses of Neogene subduction from the NW Borneo trough ignore the absence of seismicity and volcanism, and lack of evidence from seismicity and tomography for a subducted slab beneath the region.

An alternative explanation in which extension played a major role can account for many of the discrepancies. The history of research shows that there are many regions where the conventional wisdom of regional compression has been replaced by interpretations involving extensional faulting and core complexes, but even in well-exposed areas, such as the western United States, it has taken many years of painstaking observations to convince doubters. This will undoubtedly be the case in the rainforest and inaccessible mountains and valleys of northern Borneo. However, detailed dating of structures and fabrics on land may be possible, and consideration of the offshore sedimentation record and links to events on land may provide the evidence needed to test these suggestions. It is interesting to note that some of these ideas are to be found in Charles Hutchinson’s 1992 paper on the Sulu Sea, although I suspect that he may not have agreed with the way I have reconstructed them.

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