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The recent convergence on the NW Borneo Wedge—a crustal-scale gravity gliding evidenced from GPS

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SUMMARY

The existence of an active compression on the frontal fold-and-thrust belt (FTB) of the NW Borneo Wedge is a long debate. Because of the absence of seismicity, the frontal FTB is traditionally considered as inactive and generally attributed to the thin-skin gravity-driven Baram Basin. However, there are some signs of convergence and compression (GPS velocities and horizontal stress field measured from borehole analysis) do exist between the NW Borneo area and Sunda Plate (Dangerous-Grounds). Revisited GPS data, combined with a rigorous structural study of the NW Borneo Wedge suggest that the recent compression recorded on the frontal FTB is the result of a crustal-scale gravity-driven mechanism, the orogenic collapse of the NW Borneo in the Sabah–northern Sarawak area since 1.9 Myr. These results provide a new understanding of the recent behaviour of the NW Borneo Wedge which can be included in a continuum of the wedge history.

Key words: Intraplate processes; Dynamics: gravity and tectonics; Asia.

1 INTRODUCTION

The presence or absence of an active lithospheric convergence on the frontal NW Borneo fold belt has been the subject of a long debate. Important petroleum exploration and structural studies of the Brunei margin (James 1984; Sandal 1996) demonstrated active shortening in the deep-offshore Brunei. Since then, the NW Borneo fold-and-thrust belt (FTB) has been attributed to the gravity-driven basin associated to the Champion and Baram deltas (Sandal 1996). This hypothesis was supported by the absence of seismicity on the NW Borneo margin.

More recent work (Hesse *et al.* 2009; Morley *et al.* 2011; Sapin *et al.* in press) showed that the Champion-Baram Basin was emplaced on an active margin. However, this lithospheric convergence, although structurally well described, was poorly constrained in terms of ages. In the meantime, GPS studies, reported in Socquet *et al.* (2006a,b) and Simons *et al.* (2007) show a small but significant convergence of $\sim$5 mm yr^{-1} between NW Borneo and the Sunda Plate (Fig. 1). This convergence is diffuse and not related to any identified active fault in the area.

Socquet *et al.* attributed this convergence to the punching of the Sundaland Plate by the Sulu Spur. Most part of the intense shortening between Sula and Sundaland ($\sim$30 mm yr^{-1}) being accommodated by subduction in the southern Celebes Sea and by crustal compressive belt in the Makassar Strait (Pubellier *et al.* 2000). A small part of it is transmitted inland (Hermawan *et al.* in press). Simons *et al.* (2007) proposed another mechanism where this convergence corresponds to deformation transmitted from the south Philippine and the Moluccas converging area through the Celebes Sea.

Recent GPS studies in the Makassar Straight area show that the residual convergence coming from the south Philippine and Moluccas area is accommodated in the easternmost area of the Borneo Island, around the Mangkalihat Peninsula (Hermawan *et al.* in press). This finding is compatible with deformation of the Celebes Sea oceanic floor (Pubellier *et al.* 2000), and seems to support the original mechanism suggested by Socquet *et al.* (2006b). Recent structural studies done on the NW Borneo Wedge (Sapin *et al.* in press), supported by the GPS velocities recorded, permits reconsideration of the motion of the NW Borneo in the geodynamic setting of what appears to be a dead accretionary wedge (Hutchison 1996).

2 NW BORNEO GPS MOTION

Seven stations have been recorded in the north of Borneo (Table 1, Fig. 2). The GPS velocities recorded on the northern NW Borneo coast (MIRI, LABU, KINA) have a direction which differs by 30° from the ones predicted by the Sundaland motion (in a fixed Sundaland frame) at their location (Fig. 2). On the other side, on the NE coast of Borneo, TABA/TABX velocities also differ from the rigid block prediction (Fig. 2). Therefore, instead of using the

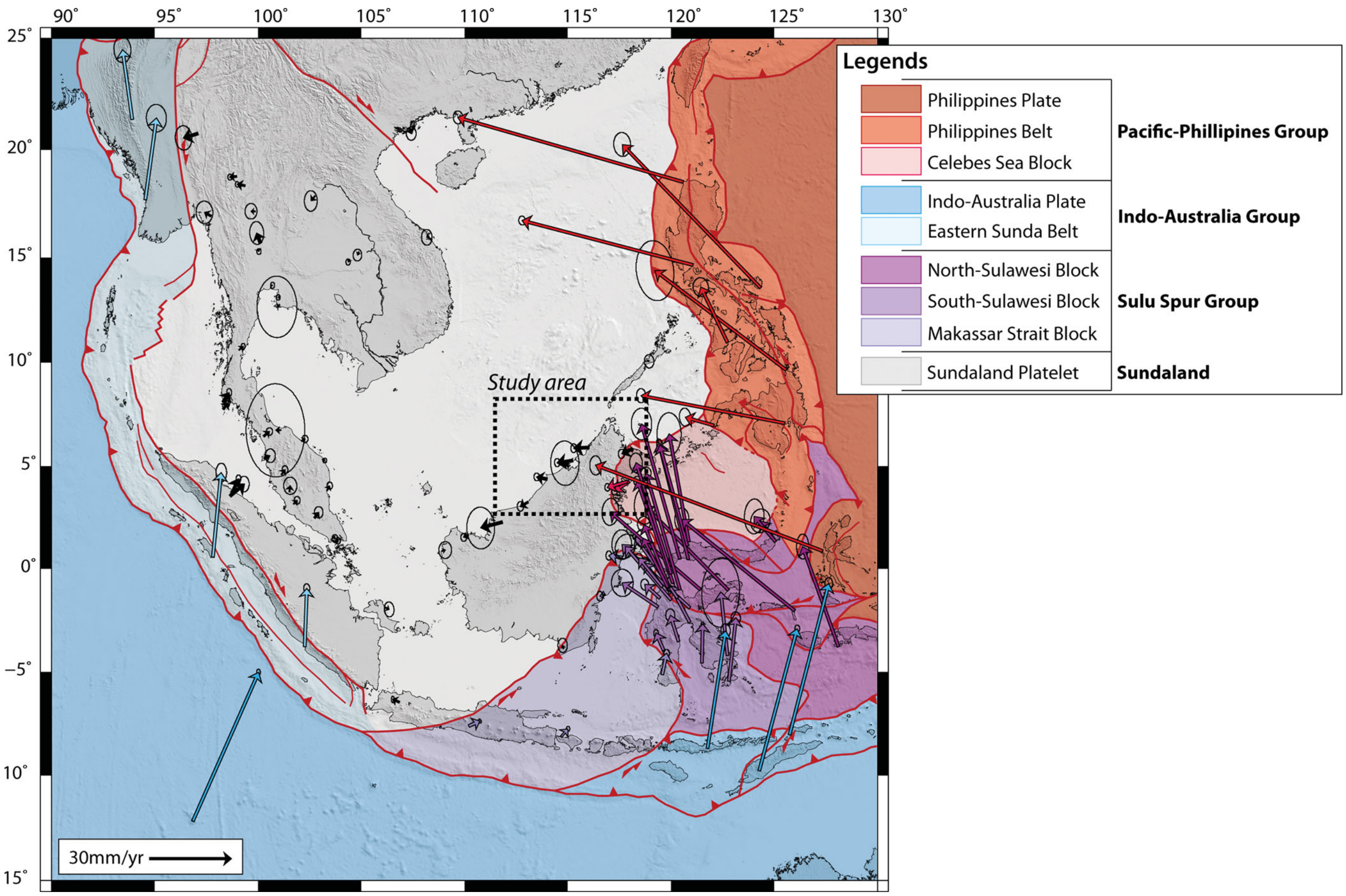


Figure 1. Sundaland geodynamic settings (GPS data are from Simons *et al.* 2007). GPS velocities are given in a fixed Sundaland reference frame. The Sunda Plate is a large area with little deformation despite the very important stresses on its borders. The Borneo area slow movement may be influenced by the important movement in the South Sulawesi, the north Sulawesi and the south Philippines.

Table 1. Velocities on the NW Borneo area. All velocities are given in mm yr^{-1}. The latitude and longitude are in degrees. The bold face stations are the one located on the northern area of the NW Borneo Wedge.

	Position		Velocity/Sunda (ITRF2000)		Velocity/NW Borneo		Uncertainties		
Site	Lon.	Lat.	V_lon	V_lat	V_lon	V_lat	σ_lon	σ_lat	Corr.
KINA	**116.039**	**5.905**	**24.59**	**−12.6**	**−1.895**	**1.285**	**0.42**	**0.66**	**0.02**
LABU	**115.245**	**5.283**	**24.38**	**−12.89**	**−2.105**	**0.995**	**0.4**	**0.61**	**−0.027**
MIRI	**114.002**	**4.372**	**25.99**	**−10.79**	**−0.495**	**3.095**	**0.41**	**0.58**	**−0.029**
BINT	113.067	3.262	26.69	−12.85	0.205	1.035	0.47	0.71	−0.022
SAND	118.121	5.842	26.28	−14.92	−0.205	−1.035	0.47	0.69	0.014
TAWX	117.882	4.263	22.44	−15.21	−4.045	−1.325	0.37	0.56	−0.053
TAWA	117.979	4.251	24.31	−16.51	−2.175	−2.625	0.4	0.62	−0.019

Sundaland platelet average motion (defined in earlier works using some of these points), we redefined a local reference frame using only SAND and BINT, supposedly not affected by the deformation of the NW Borneo area (Fig. 2). Despite the presence of little seismicity between these two stations the fact they are consistent with one other station on Borneo (KUCH; Simons *et al.* 2007; Fig. 1) made our choice of a "Borneo Unit" consistent.

Though there are few stations, in a local NW Borneo reference frame, it is possible to distinguish three main GPS motion units (Fig. 2): (1) the fixed Borneo Unit (BINT and SAND); (2) the Celebes Sea Unit (residual convergence coming from the south Philippines and the Moluccas area affecting TAWA and TAWX); (3) the NW Borneo coastal Unit (MIRI, LABU, KINA) showing a general slow motion of ∼3 mm yr^{-1} to the NW, away from Borneo mainland.

It is difficult to identify the limits of these three units. In contrast with the Celebes Sea Block where several well-known active structures in the Dent and Semporna areas with present-day seismicity may define its boundaries (Ego *et al.* 2006; Hermawan *et al.* in press), the boundaries of the NW Borneo coastal unit are not yet identified. In particular, the presence of the superficial gravity-driven system of the Baram Delta masks the northwestern boundary of this unit.

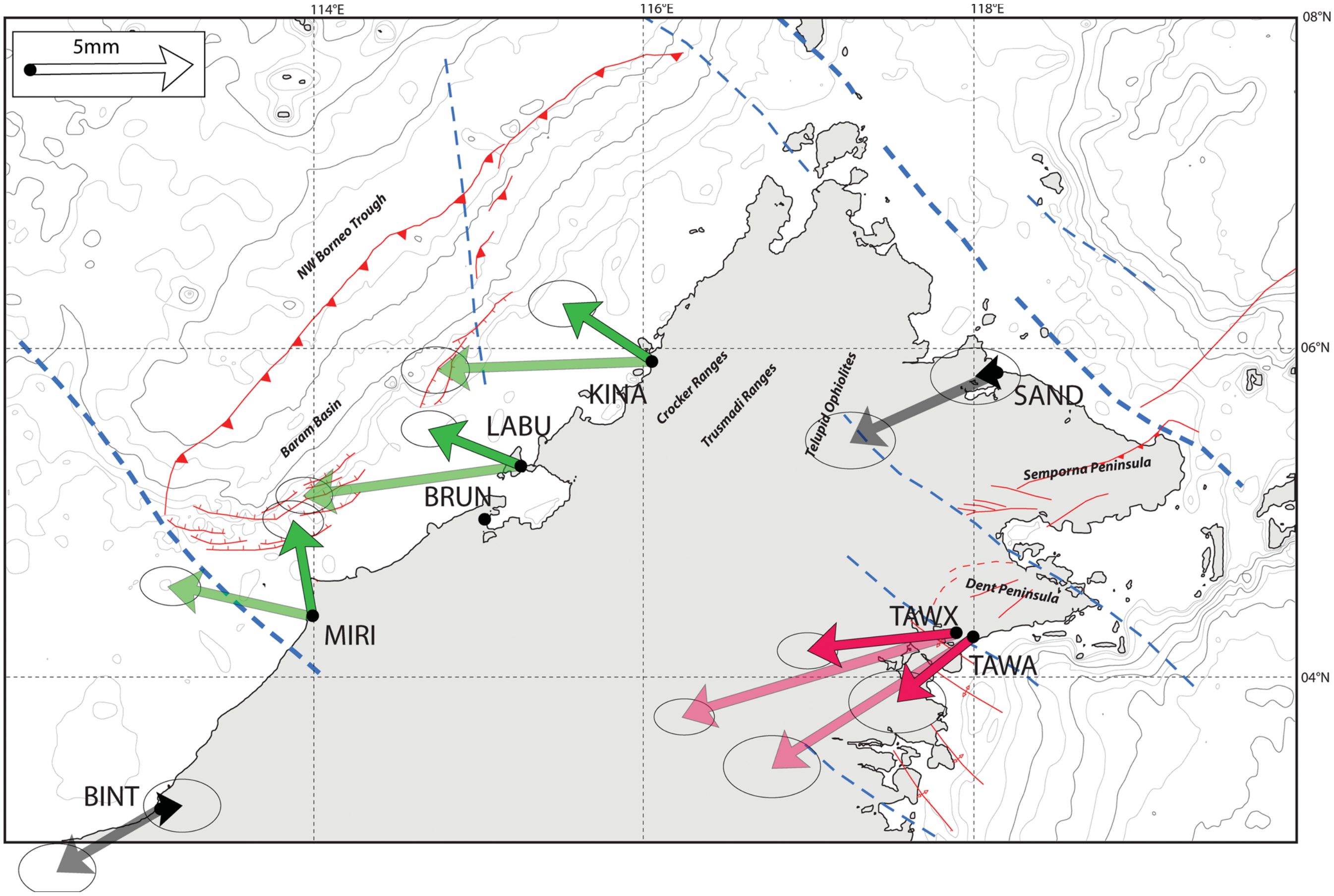


Figure 2. NW Borneo GPS motion and structural scheme (from Ego *et al.* 2006). In a fixed Sundaland reference frame (transparent arrows), the motion of the three stations on the northwestern coast of Borneo (MIRI, LABU, KINA) is quite coherent with the overall motion. However, in a fixed NW Borneo reference frame (BINT and SAND stations are fixed; opaque arrows), the stations on the Brunei–Sabah coast have a slow motion to the NW, disconnected of any large convergence area (Celebes Sea, TAWA and TAWX stations).

3 THE STRUCTURAL BOUNDARIES OF THE NW BORNEO COASTAL UNIT: COMPRESSION IN THE NW BORNEO SHELF AND TROUGH AND POSSIBLE EXTENSION IN THE HINTERLAND

To understand the motion of the NW Borneo coastal unit, we have to characterize its boundaries whether they are extensive, compressive and/or strike-slipping and weather they are localized or diffuse.

3.1 Compression in the NW Borneo Wedge: localization and timing

The compression in the NW Borneo Trough is well known thanks to extensive petroleum exploration and recent structural/geodynamic studies (Hesse *et al.* 2009; King *et al.* 2010a,b; Sapin *et al.* 2011, in press). Recent petroleum exploration in the deep-offshore domain permits accurate dating thanks to seismic-wells calibration of the geological layers.

Because of the presence of the large gravity-driven system of the Baram Delta, the offshore NW Borneo area can be divided into two zones (Fig. 3):

1. Brunei/North Sarawak area (Baram gravity-driven system): the frontal wedge presents a continuous deformation from the Late Miocene to Present (Hesse *et al.* 2009; Morley 2009; King *et al.* 2010a,b; Sapin *et al.* 2011, in press; Fig. 3c). This frontal compression is associated to and compensates the extension on the distal shelf area (Hesse *et al.* 2009; King *et al.* 2010a). However, there is still a compressive stress-field evidenced by borehole analysis (King *et al.* 2010b) in the coastal area. It is recorded on several structures such as the Seria and Ampa inverted normal faults and the Champion structure (James 1984; Sandal 1996; Morley *et al.* 2011; Sapin *et al.* in press);

2. Sabah area: the frontal wedge presents a discontinuous deformation. From the Middle Miocene to the Pliocene (∼3.6 Myr), the wedge shows a typical stacking of thrust-sheets. It is followed by a tectonic quiescence from 3.6 to 1.9 Myr. The compression resumed at the end of the Pleistocene (∼1.9 Myr) and is localized on the most frontal part of the wedge (Fig. 3).

Between these two zones, the compression is possibly expressed on transverse structures mainly localized on a large NS transfer zones in the prolongation of the Brunei Bay and Labuan Island (Fig. 2). This change of structural style along the NW Borneo thrust belt has also been shown by Hesse *et al.* (2009) and Cullen (2010).

From these observations, we may characterize the northwestern border of the NW Borneo coastal block as compressive, the deformation being diffuse in the south and localized in the north.

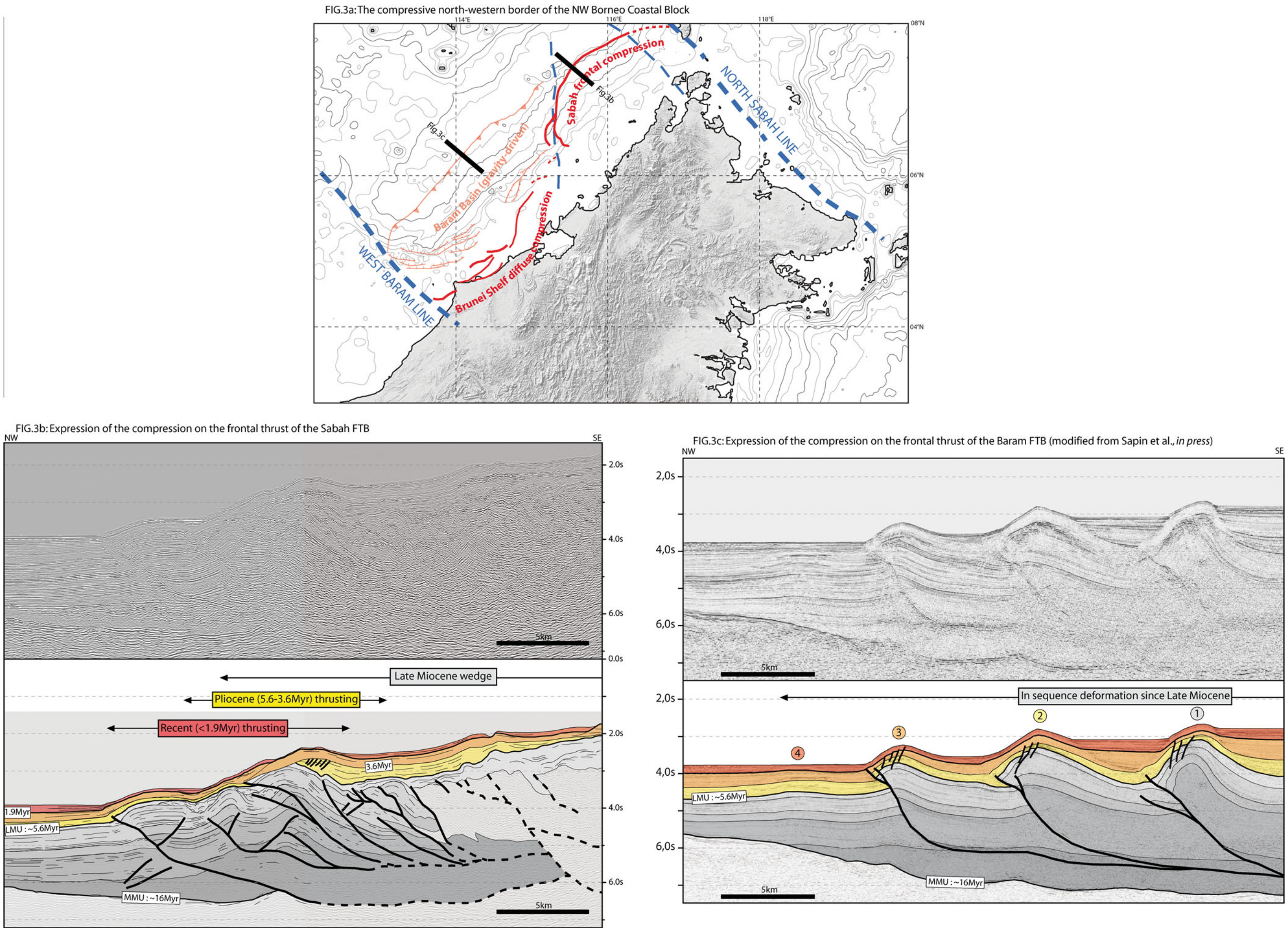


Figure 3. Recent frontal compression in Sabah. In the Brunei area, borehole analysis (King *et al.* 2010b) evidenced an active compression on the Brunei Shelf. In Sabah, the frontal wedge registered a continuous compression from the Late Eocene to the beginning of the Pliocene. At −3.6 Myr, the compression stopped and was sealed by pelagic sediments. The compression resumes recently (−1.9 Myr) on the most frontal thrust.

3.2 Extension in the NW Borneo Wedge: expression and localization

Contrarily to the compression, the extension is difficult to observe because of the absence of data in a poorly accessible region cover by forest. No large-scale detachment or large normal fault was observed; however, we can observe signs of extension in the hinterland at different scales (Fig. 4). In Brunei and northern Sarawak, none of these signs have been observed or interpreted, but the area have been intensely deformed by the subduction of a crustal salient (Sapin *et al.* 2011) and the coastal area has no pronounced topography.

(1) Seismicity and focal mechanism: two earthquakes with extensive focal mechanism have been recorded in the NW Borneo hinterland in front of the NW Borneo Wedge suture (Telupid ophiolites).

(2) In some areas, such as the Trusmadi Ranges, DEM topography suggests the existence of lens shape normal faults, globally oriented NE–SW and dipping NW, cutting through the antiformal structure of the ranges.

These few evidences show that the extension is likely diffused and in consequence, difficult to observe. However, it seems to be recent and still active as shown by the seismicity.

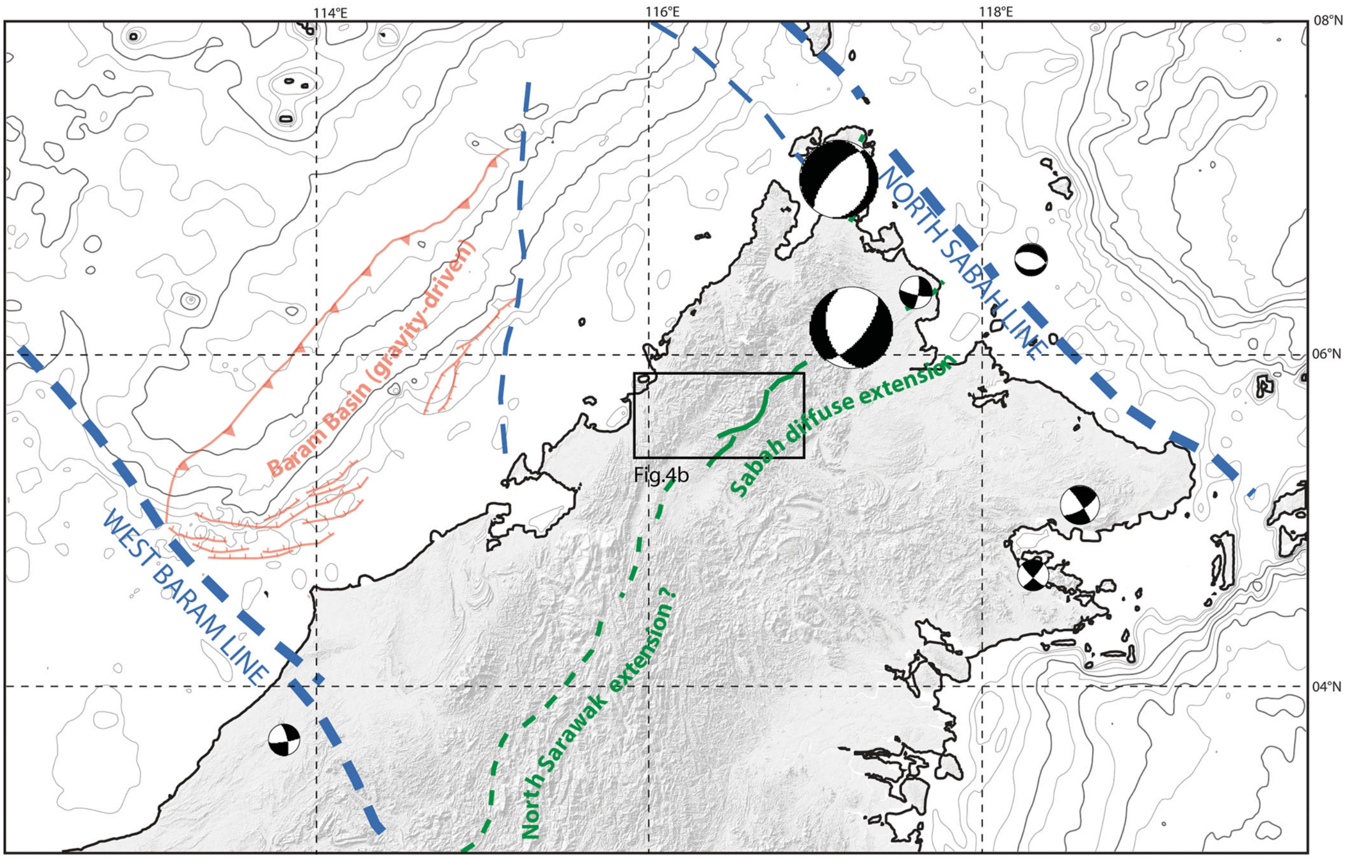
4 DISCUSSION: OROGENIC COLLAPSE LENS OF THE NW BORNEO WEDGE

GPS vectors, in a fixed NW Borneo reference frame, show that the NW Borneo coastal area moves independently from the rest of the Borneo Island towards the NW at a slow motion of $\sim$3 mm yr^{-1}. This NW Borneo Coastal Unit is limited by (Figs 3–5):

(1) In the NW: a compressive zone, localized in Sabah on the most frontal thrust on the Sabah FTB, and along several near-shore inversion structures in the Baram Deltaic Province (former gravity-driven listric normal faults);

(2) In the SE: an extensive zone, whose location is suggested in Sabah by weak field observations and seismicity and remains unknown in Brunei/North Sarawak area;

(3) In the NE and SW, strike-slip structures (right lateral in the NE and left lateral in the SW) may limit the NW Borneo coastal block. They are not observed on the field neither on seismic data but the two earthquakes recorded in these areas are consistent with this hypothesis. The strike-slip structures are possibly located on major deep crustal transfer zones, such as the West Baram Line and the North Sabah Line.



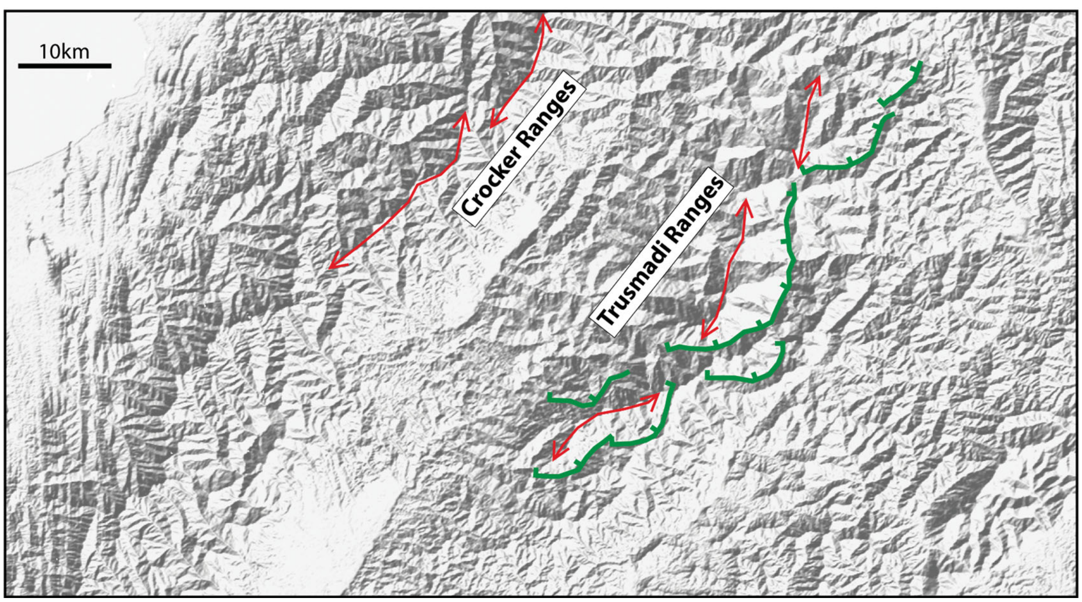


Figure 4. Diffuse extension expressed in the NW Borneo Wedge. The signs of extension in the NW Borneo Highlands are discrete and highly interpretative. The extension seems to be diffuse and distributed on several small structures.

The motion and associated structures of the NW Borneo coastal block allow proposing a model of gravity sliding lens. Its size indicates that it is of crustal scale and may be linked to large-scale mechanisms. A possible interpretation of these results is to consider this gravity-sliding as a consequence of the collapse of the NW Borneo orogenic belt. As the whole area was previously structured by the accretion of the NW Borneo Wedge, it is likely that this gravity-driven lens only affect the accreted sediments. This collapse began approximately 2 Myr ago as recorded on seismic lines and is still active nowadays.

The hypothesis of a collapse of the NW Borneo Wedge have been also proposed by Hall (2011) as a reaction of a possible significant

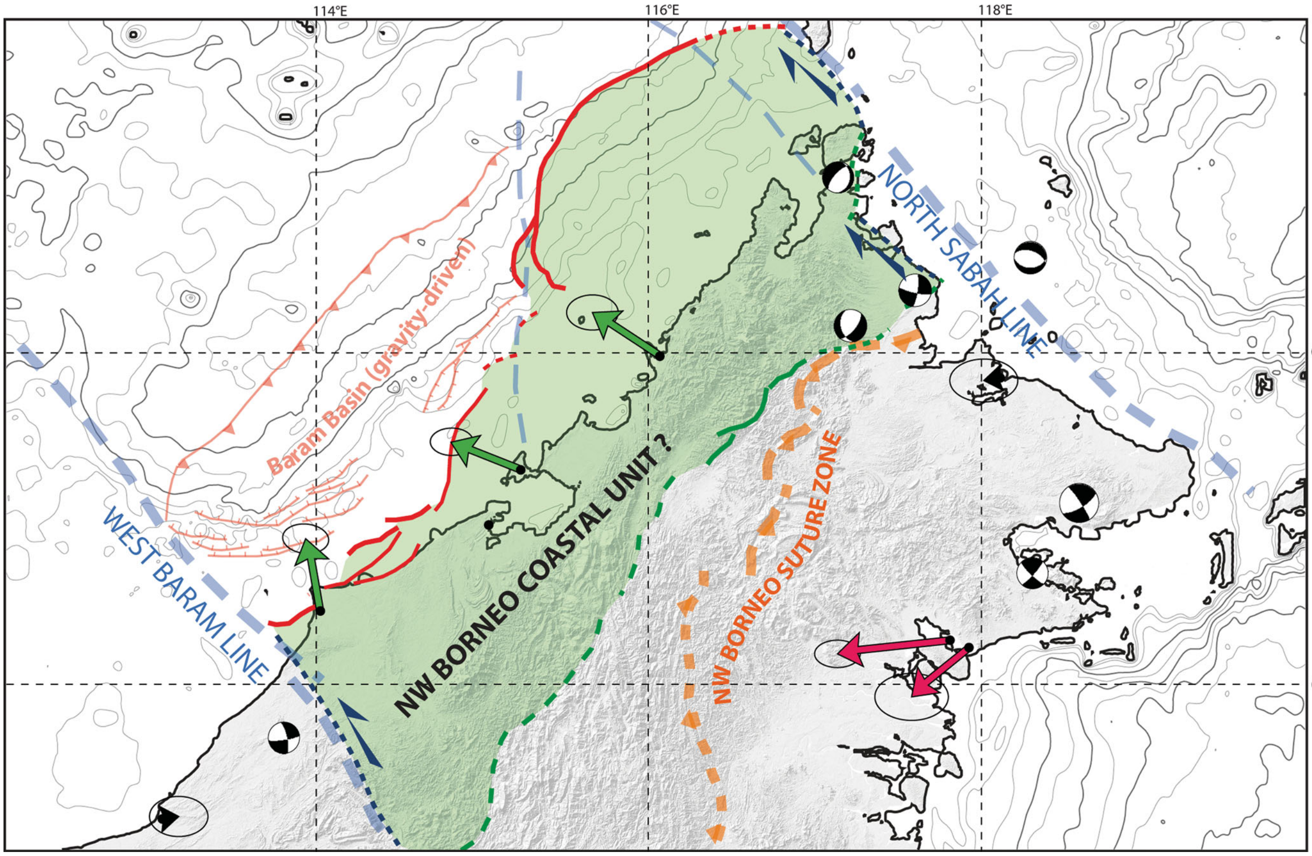


Figure 5. The NW Borneo coastal block, an independent gravity sliding lens. Structures and GPS velocities show that the sliding is towards the NW, from the NW Borneo hinterland to the NW Borneo Trough.

Lower Crust flow beneath the Crocker/Trusmadi ranges evidenced by the rise of the Mount Kinabalu. In this point of view, the beginning of the collapse is estimated in the Late Miocene (8–5 Myr). However, the author does not propose any direct evidences to support his hypothesis and mechanism.

However, this collapse may be a response to the large uplifts that have affected the NW Borneo Wedge during the collision (Fig. 6):

- The first uplift mechanism is the beginning of the continental subduction by the Middle Miocene (Hutchison 1996). The wedge balanced the increase of the friction on the basal decollement by large uplifts;
- The second uplift mechanism is a slab break-off. Recorded thanks to geochemistry analyses (Prouteau *et al.* 2001) and seismic tomography (Rangin *et al.* 1999) and fission tracks results (Hutchison 2005). This mechanism, dated of the Late Miocene (Prouteau *et al.* 2001; Hutchison 2005; Morley & Back 2008), generally induces large global uplifts of the belt (Ben-Avraham *et al.* 1981).

Affected by both mechanisms, the northern area of the NW Borneo Wedge seems to have been uplifted of several kilometres (5–7 km; Hutchison 2005) during the last 10 Myr as suggested by the raise of the Mount Kinabalu (Vogt & Flower 1989; Swauger *et al.* 2000; Chiang 2002) and fission tracks studies in the Crocker Ranges area (Hutchison 2005). The collapse seems to have begun very recently, around 1.9 Myr ago (seismic-well correlation), after the lithospheric convergence ceased at 3.6 Myr.

5 CONCLUSION

GPS velocities recorded on the northern NW Borneo coast, previously considered odd in the absence of active convergence, can be attributed to a recent gravity sliding of the NW Borneo Wedge towards the NW evidencing the hypothesis proposed by Hall (2011). This motion of the NW Borneo coastal block is supported by geological observations both on 2-D seismic lines and field. Seismic lines show also that this movement is recent, less than 2 Myr and is still active nowadays as evidenced by some seismicity and the GPS velocities themselves.

This gravity sliding of the NW Borneo coastal block interpreted as a collapse of the NW Borneo Wedge towards the NW following the end of the convergence. The convergence has been active since the Mid Eocene evolving from an oceanic subduction to a continental collision (∼16 Myr) and seemed to end in the Pliocene (∼3.6 Myr) as evidenced in Sabah (part 2.1).

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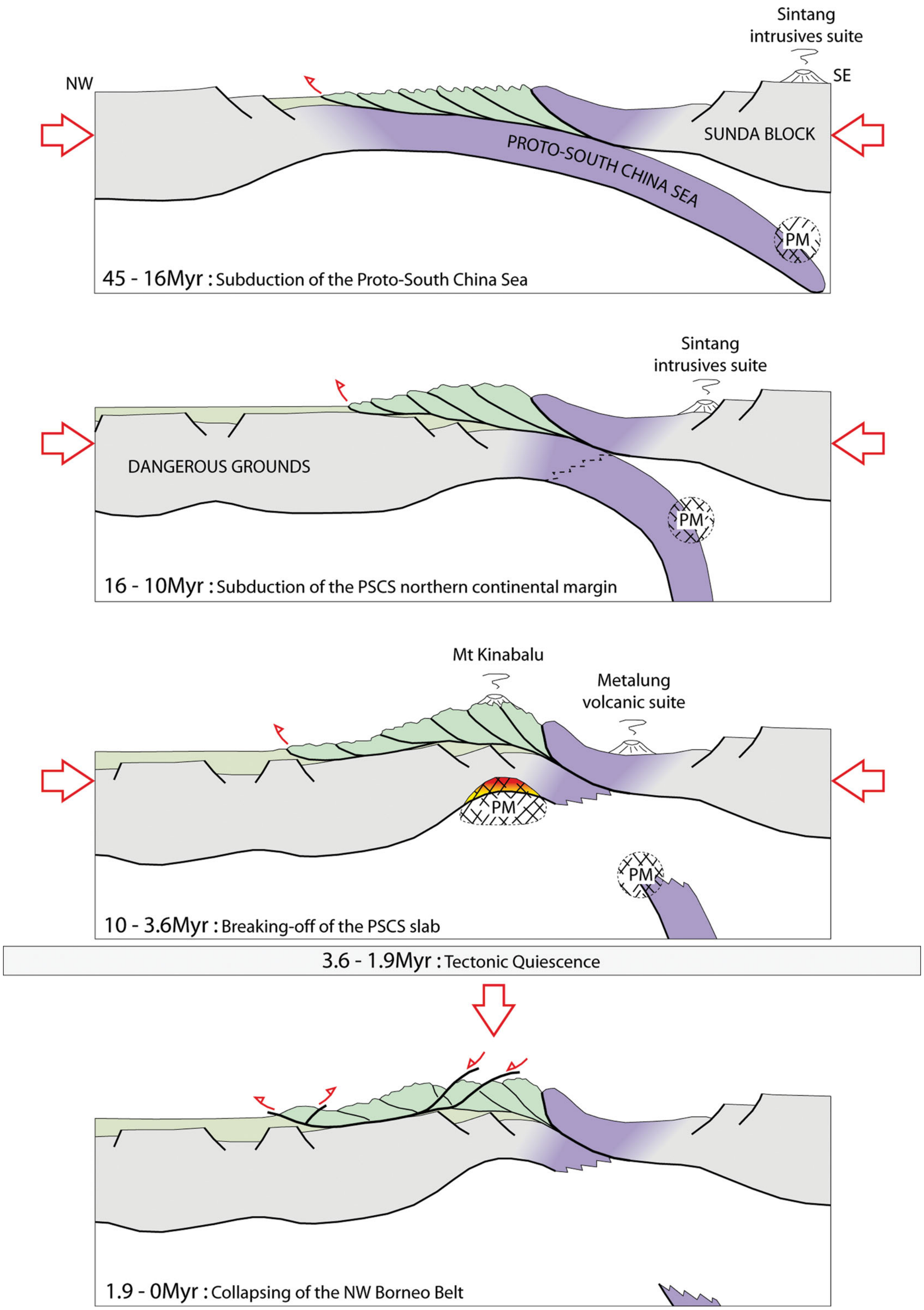

Figure 6. Geodynamic evolution of the NW Borneo Wedge: from oceanic subduction to post-collison collapse. The NW Borneo subduction began in Mid-Eocene (emplacement of the East Crocker Formation). The northern margin of the Proto-South China Sea entered the subduction zone during the Mid-Miocene (16–10 Myr) leading to the surrection of the Crocker and Trusmadi Ranges (Tongkul 1997; Hutchison 2005). The continental subduction continued until 3.6 Myr, as the subduction slab was breaking of (record of Adakitic Volcanism, Prouteau *et al.* 2001). During the last 2 Myr, the compression resuming in the frontal area of the NW Borneo Wedge may be to the orogenic collapse of the belt.

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