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The deep-water fold-and-thrust belt offshore NW Borneo: Gravity-driven versus basement-driven shortening

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ABSTRACT

The deep-water region offshore NW Borneo is an active fold-and-thrust belt that hosts a significant number of proven hydrocarbon accumulations. In the past, two mechanisms have been discussed as primary control for Neogene to Holocene folding and thrusting in this deep-water province: (1) basement-driven crustal shortening and (2) gravity-related delta tectonics. In this study, new, balanced interpretations of regional, crustal-scale, depth-migrated, two-dimensional (2-D), multichannel seismic-reflection profiles are presented that provide for the first time quantitative data on tectonic shortening throughout the entire deep-water fold-and-thrust belt of NW Borneo. We use our tectonic restorations to compare the amount of deep-water shortening on the NW Borneo slope to the amount of extension across the NW Borneo shelf. A key result of this balancing study is the observation that Pliocene to Holocene gravity-driven shortening decreases from south to north, while the total amount of shortening increases slightly to the north. Consequently, the amount of purely basement-driven compression along NW Borneo is strongly inferred to increase toward the north. Because most of the shortening is late Pliocene and younger, we interpret the tectonic shortening to be ongoing.

INTRODUCTION

The continental shelf and slope areas of NW Borneo (Fig. 1) are well known from drilling and seismic-reflection data (e.g., James, 1984; Levell, 1987; Hinz et al., 1989; Sandal, 1996; Petronas, 1999; Ingram et al., 2004; Morley, 2007; Gee et al., 2007; Franke et al., 2008). The NW Borneo shelf mainly consists of middle Miocene to recent prograding shallow-marine clastic sediments that locally attain thicknesses of over 10 km (Fig. 2). The shelf units are commonly deformed and exhibit extensional and compressional structural features including kilometer-scale synsediimentary normal faults (growth faults), shale diapers, and inversion-related anticlines (e.g., James, 1984; Sandal, 1996; Van Rensbergen et al., 1999; Imber et al., 2003; Morley et al., 2003). The continental slope of NW Borneo is underlain by a large, basinward-thinning, middle Miocene to Holocene deep-water clastic wedge that is deformed by numerous compositional folds and thrusts (Figs. 2B, 3, and 4). Despite significant research and exploration efforts in deep-water NW Borneo in recent years, there are still questions concerning the controlling mechanisms of deep-water folding and thrusting. Based on regional two-dimensional (2-D) seismic-reflection data, Hinz et al. (1989) interpreted the deep-water tectonics offshore NW Borneo as reflecting a continent-continent collision, and they inferred regional compression to have induced major thrusting that continues until today. In contrast, for example, Hazebroek and Tan (1993) drew...
Figure 2. (A) Structural map showing key tectonic elements of NW Borneo and the location of the seismic data presented in this paper. Bathymetric contours offshore are drawn at 500 m intervals. Bold black line indicates location of cross-section A–A’. High-velocity body indicated by gray color is discussed in Franke et al. (2008). (B) Regional geological cross section across NW Borneo along line A–A’. The section is based on offshore seismic-reflection data (Sandal, 1996; Van Rensbergen and Morley, 2000), onshore seismic-reflection and well data (Back et al., 2008), geological maps (Sandal, 1996; Back et al., 2001, 2005), and models for the tectonic development of northern Borneo (e.g., James, 1984; Morley et al., 2003; Morley and Back, 2008).
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attention to the similarities of structures in their “Outboard Belt” with thrusts at the toe of the Niger Delta, suggesting that deep-water folding and thrusting offshore NW Borneo primarily developed in response to gravitational delta tectonics. Between these two end-member interpretations (basement-driven versus gravity-driven), Ingram et al. (2004), for example, proposed a compressional regime for deep-water NW Borneo dominated by crustal shortening in the range of 4 cm/yr until recent times (sensu Hinz et al., 1989) and a small contribution by gravity-related deltaic toe thrusting (sensu Hazebroek and Tan, 1993).

This paper presents new, balanced interpretations of regional, crustal-scale, depth-migrated 2-D multichannel seismic-reflection profiles (Fig. 2) covering large parts of the NW Borneo deep-water fold-and-thrust belt between Brunei Darussalam to the south and the Malaysian-Philippines border to the north, locally supported by published 2-D and 3-D industry seismic and well data. A stepwise retrodeformation of thrusts and folds provides incremental measurements of tectonic shortening for the time between the Miocene and present-day in deepwater NW Borneo. We use the tectonic restoration results primarily for a comparison between deep-water compression and shelfal extension, which enables us to separate the contribution of shallow, gravity-driven shortening from the amount of total shortening of the deep-water fold-and-thrust belt.

GEOLOGICAL FRAMEWORK

The principal features of the geological evolution of northern Borneo are summarized in Hinz et al. (1989), Hutchison (1996a, 1996b), Milsom et al. (1997), Petronas (1999), Hutchison et al. (2000), Hall and Wilson (2000), Morley et al. (2003), Morley and Back (2008), and Hall et al. (2008). Northern and Central Borneo were built from the Mesozoic to Holocene, and they record a complex plate tectonic history involving oceanic and continental crust. Today, NW Borneo is a mountainous region exposing Cretaceous–Eocene deep-water clastic deposits that are thrust, folded, and locally metamorphosed to phyllites (Crocker and Rajang Groups exposed in the Crocker Mountain Range; for detailed description, see Hutchison, 1996a, 1996b), and Eocene to Lower Miocene sand-rich turbidites (Crocker Formation; for a detailed description, see Van Hattum et al., 2006). These Crocker sediments are thought to represent deep-water units in or adjacent to an accretionary prism. Several authors have proposed that NW Borneo is underlain largely by Mesozoic ophiolitic rocks (e.g., Hutchison, 1996a; Hall and Wilson, 2000), particularly due to the presence of the Telupid ophiolite of central Sabah (see, e.g., Hutchison, 1996a; his Figure 5.18; Morley and Back, 2008).

During Oligocene–early Miocene times, the South China Sea was opened by seafloor spreading. Seafloor-spreading anomalies in the South China Sea oceanic basin range from magnetic anomaly 11 (ca. 32 Ma) to anomaly 5c (ca. 16 Ma; Taylor and Hayes, 1980; Brias et al., 1993), with a southward ridge jump at anomaly 7/6b (ca. 27 Ma; Brias et al., 1993). The end of the seafloor spreading occurred at 20.5 Ma (magnetic anomaly 6A1; Barckhausen and Roeser, 2004). With the opening of the South China Sea, the thinned continental crust of the Dangerous Grounds region was rifted away from the southern margin of China (e.g., Holloway, 1981; Hinz and Schlüter, 1985; Taylor and Hayes, 1983; Brias et al., 1993). On the southeastern side of the Dangerous Grounds, Hinz and Schlüter (1985) interpreted an older region of oceanic crust, the proto–South China Sea.

During the Paleogene, this proto–South China Sea closed, most likely due to a SE-directed subduction beneath NW Borneo. Following complete subduction of the proto–South China Sea oceanic crust, continental crust of the Dangerous Grounds region was partially subducted beneath the Crocker Formation basin of NW Borneo in the latest early Miocene before its buoyancy locked the system (James, 1984; Levell, 1987; Hazebroek and Tan, 1993; Hutchison, 1996a, 1996b; Sandal, 1996; Hall, 1996; Milsom et al., 1997). Subsequently, northern Borneo experienced significant compressional deformation, as documented onshore in folded sedimentary units of late early Miocene to middle Miocene ages (e.g., Sandal, 1996; Morley et al., 2003; Back et al., 2001, 2005, 2008), as well as offshore in folded and thrustsed middle Miocene to present-day shelf and slope sequences (e.g., Levell, 1987; Hazebroek and Tan, 1993; Hutchison, 1996a, 1996b; Sandal, 1996; Hall, 1996; Milsom et al., 1997). On the shallow NW Borneo shelf, late Neogene compression coincided with the development of major synsedimentary normal faults in the up to 10-km-thick late Neogene deltaic overburden (Fig. 2B). This “thin-skinned” extensional deformation was superimposed on deep-seated compressional structures and generated, particularly in the southern part of the NW Borneo shelf, a multitude of complex tectonic features that resulted in the reactivation of major thrusts as normal faults and the inversion of synsedimentary normal faults (Morley et al., 2003). The complex interference of extensional and compressional features ceased in the vicinity of the shelf break, beyond which a purely compressional fold-and-thrust belt developed (Figs. 2B, 3, and 4). Recent tectonic deformation in the deep-water thrust belt is documented by the prominent seafloor expression of several thrust hanging-wall fault bend folds, where the youngest structures form at the thin, distal part of the sediment wedge near the NW Borneo Trough (Figs. 3 and 4; Ingram et al., 2004; Morley, 2007; Gee et al., 2007).

SEISMIC DATA

Acquisition and Processing

The data used in this study are regional 2-D multichannel seismic-reflection profiles acquired by the Federal Institute for Geosciences and Natural Resources (BGR) in 1986 (survey details in Hinz et al., 1989) and various published seismic profiles. The BGR86 multichannel seismic-reflection data set has a total length of 3129 km along 27 lines. Seven representative multichannel seismic-reflection profiles (Fig. 2A) with a total length of 1762 km (lines BGR86–12 to BGR86–24) were selected for reprocessing and depth migration, including trace editing, band-pass filtering, prestack predictive deconvolution, and amplitude recovery. In a second step, detailed stacking velocity analyses were carried out on average every 1.5 km. The prestack procedure was finalized by a multiple suppression, in which a radon velocity filter combined with an inner trace mute provided sufficient results. After normal-move-out (NMO)-correction, the seismic data were stacked. The velocity field for the depth migration was estimated by a step by step approach based on the stacking velocities determined by semblance analysis. This velocity information was converted into interval velocities using a smoothed-gradient algorithm. The final depth-migration algorithm used was an implicit finite-difference (FD) migration code. FD time migration was run for quality control of the poststack depth migration. Figure 3 shows a representative depth-migrated section across the northern part of the NW Borneo continental margin (line BGR86–12), extending from the Sabah shelf into the NW Borneo Trough. Figure 4 illustrates the typical seismic-reflection signature of the central to southern portion of offshore NW Borneo (line BGR86–20).

Seismic Interpretation

The study area is characterized by a wide variety of slope geometries and structural styles (Figs. 3 and 4). The north portion (lines BGR86–12, BGR86–14) exhibits a multitude of steep, southeast-dipping thrust-related fold anticlines, of which the youngest, most westward-located anticlines exhibit a clear seafloor expression. The
Figure 3. Depth-migrated seismic section BGR86–12 (locations of all seismic lines are shown on Fig. 2) and line drawing showing the main tectonic features of the northern zone of the study area (3x vertical exaggeration). The seismic section crosses the shelf, the slope, and the NW Borneo Trough. To the SE of the NW Borneo Trough, up to 15 NE-SW–trending fault-related folds are imaged. At the landward edge of the section, a high-velocity body masks the seismic signals of the underlying strata. Different grayscale indicate seismic units SeiS-A, SeiS-B, SeiS-C, SeiS-D, and SeiS-E. Marker horizons separating the seismic units are labeled horizon 1 to horizon 5. Horizon 1, interpreted as a detachment, dips between 2° below the shelf to 7° below the thrust front (average dip 3.8°).
Figure 4. Depth-migrated seismic section BGR86–20 and line drawing showing the main tectonic features of the central and southern zone of the study area (3x vertical exaggeration). The seismic line crosses the shelf, the slope, and the NW Borneo Trough. The NW Borneo deep-water fold-and-thrust belt consists of eight major NE-SW–trending fault-related folds. Grayscales and horizons are as in Figure 3. Horizon 1, the detachment, dips between 2° below the shelf and 6° below the thrust front (average dip 3.5°); these values are only slightly steeper than those proposed for offshore northern Brunei (Morley 2007).
In the immediate vicinity of the fault zones, which are also atypical for diapirs. Therefore, we believe that the narrow zones of chaotic reflectivity more likely represent steep faults.

We have divided the sedimentary column into five seismic units (SeiS-A to SeiS-E, from old to young) that are separated by five horizons (1—the basal detachment to 5—the present-day seafloor) of high reflectivity and lateral continuity (e.g., Figs. 3 and 4). Following the interpretation of Hinz et al. (1989), we assume a late Pliocene to recent age for stratigraphic unit SeiS-E, an early Pliocene age for stratigraphic unit SeiS-D, a possible latest Miocene age for stratigraphic unit SeiS-C, and an early Miocene age for stratigraphic unit SeiS-B. Marker horizon 1 is the acoustic basement forming the basal detachment surface and is mapped at depths of 5 (NW) to 13 km (SE). The associated reflectivity is positive, of high continuity, and shows prominent amplitudes, particularly in depths <7 km (Figs. 3 and 4). The acoustic substratum (unit SeiS-A) below horizon 1 is characterized by a complex system of horsts, tilted blocks, grabens, and half grabens within and westward of the NW Borneo Trough. The grabens either show onlap fill with laterally continuous, parallel to subparallel reflections of moderate to high amplitudes, or a complex, nearly transparent fill pattern (Figs. 3 and 4). The horst structures are commonly overlain by laterally continuous, parallel to subparallel reflectors with high amplitudes. The seismic response of horizon 1 and the underlying unit SeiS-A deteriorates with increasing depth toward the eastern part of the study area (Figs. 3 and 4), and only segments of it exist below 9 km depth.

Horizon 2 is a positive reflector, of high continuity, mapped at depths of 3 km to 8 km. This reflection forms the top of unit SeiS-B, which is characterized by laterally continuous, mainly subparallel to parallel reflectors of low to moderate amplitudes (Figs. 3 and 4). In the western part of the study area, package SeiS-B onlaps onto and terminates against horizon 1.

Horizon 3 is a continuous reflector that shows a medium- to high-amplitude peak located at depths of 2–5 km. Horizon 3 is the top of the seismic unit SeiS-C, a unit characterized by laterally continuous, subparallel to parallel reflections of low to medium amplitudes in the NW Borneo Trough, and by higher amplitudes and a wider reflector spacing on the NW Borneo slope (Fig. 4). Throughout the survey area, unit SeiS-C shows an upward increase in amplitude and frequency.

Horizon 4 is a positive reflector, of high continuity, located in depths of 4 km near the NW Borneo Trough and 1.8 km near the shelf edge. Horizon 4 defines the top of the seismic sequence SeiS-D, a unit characterized by parallel to divergent reflections of moderate to high amplitudes, moderate to high frequency, and high lateral reflectivity continuity (Figs. 3 and 4). Internally, unit SeiS-D exhibits alternating intervals of moderate amplitudes and lower frequency and high-amplitude zones with dense reflector spacing (Fig. 5A).

The present-day seafloor (horizon 5) varies in depth between 2.8 km in the NW Borneo Trough and <100 m in the shelf regions. Horizon 5 defines the top of unit SeiS-E, a unit characterized by parallel, subparallel, chaotic and divergent reflections of moderate to high amplitude with variable frequencies and high reflection continuity (Figs. 3 and 4). Figure 5A shows the typical facies pattern of this seismic unit: the backlimbs of the thrust anticlines preserve growth strata with parallel, subparallel, and divergent reflectors of medium to high amplitude and reflector spacing. These stratified units are commonly interbedded with chaotic seismic facies that may represent slump mass accumulations (Fig. 5B). The latter may have been derived from the unstable, oversteepened forelimb of the landward-located thrust anticline (see also McGilvery and Cook, 2003; Gee et al., 2007). Another prominent feature within unit SeiS-E is the widespread occurrence of a strong bottom-simulating reflector (BSR) with a clear amplitude-reversal in comparison to the seafloor reflection (Figs. 5A and 5B). The BSR is most distinct at the tops of the thrust anticlines at 250–300 m below seafloor.

Structural Restoration

In order to evaluate the validity of the seismic-based structural and stratigraphic interpretation, reconstruction of the tectonic evolution of the NW Borneo deep-water fold-and-thrust belt between the deposition of units SeiS-A and SeiS-E, and measure deformation associated with deep-water folding and thrusting, a series of 2-D tectonic restorations (unit per unit, from young to old) was carried out on seismic lines BGR86–12, BGR86–14, BGR86–18, BGR86–20, BGR86–22, and BGR86–24 (for locations, see Fig. 2A). Line BGR86–16 was excluded from structural restoration due to limited data quality. On all other lines, the retrodeformation work included (1) the fault-by-fault restoration of thrust displacement, (2) fold-by-fold unfolding, (3) unit-wide decompaction, and (4) unit-wide isostatic correction. It was assumed that there was no movement of material into or out of the individual section planes.

For fault restoration, we used a trishear algorithm (sensu Erslev, 1991), in which fault displacement was accommodated by heterogeneous shear in a triangular zone radiating from the fault
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After each step of restoring a hanging-wall horizon cutoff to its position before faulting, remnant folding of the target horizon was balanced using flexural slip sensu Griffiths et al. (2002; see Fig. 6B). This two-step fault-restoration and unfolding approach was carried out systematically within each stratigraphic unit starting at the deep-water deformation front and progressively moving landward. Fault displacement, throw, heave, fold-related shortening, and total shortening were measured incrementally along each section. Complete fault restoration and unfolding within each stratigraphic unit were followed by a sectionwide decompaction sensu Sclater and Christie (1980) and an isostatic correction sensu Burov and Diament (1992).

Figure 7 is a representative example of the unit-per-unit restoration of the NW Borneo deep-water fold-and-thrust belt based on the retrodeformation of seismic line BGR86–24. Figure 8 summarizes the restoration results of all balanced sections of this study and documents total shortening of each section as well as incremental shortening during times of development of stratigraphic units SeiS-B, SeiS-C, and SeiS-D. The total shortening values measured across the ~120-km-wide study area range from 8 to 13 km per section (Fig. 8). Low total shortening is observed in the very north (8 km; line BGR86–12) and very south of the study area (10 km; line BGR86–24). From south to north, total shortening increases from 10 km (line BGR86–24) to a maximum of 13 km at line BGR86–22. Shortening decreases 20–40 km northward to 12 km (lines BGR86–20 and BGR86–18). At line BGR86–14, total shortening was determined to be 10.5 km, before reaching a minimum of 8 km at line BGR86–12. If broken into incremental steps, the spatial distribution of shortening remains nonuniform, but shortening increases through time (Fig. 8).

Compression versus Extension

The results of the fault restoration and unfolding of six shelf-to-basin transects across the NW Borneo deep-water fold-and-thrust belt offshore Sabah indicate a significant regional
Step 2 - unfolding (flexural slip)

Step 1 - removing fault displacement (trishear - downdip movement)

Step 3 - removal of the complete restored unit / decompaction / isostatic correction

Figure 7. Representative example of a tectonic restoration (deep-water section BGR86–24 and interpretation). (A) The present-day geological situation with an 86 km distance between the deep-water deformation front (pin 1 at the upper tip of the youngest thrust fault) and the present-day shelf edge (pin 2). (B) Interpreted section BGR86–24 after complete fault restoration and unfolding of the top of unit SeiS-D, including decompaction and isostatic correction. Fault restoration and unfolding have restored the distance between pins 1 and 2 (91.5 km; 5.5 km of shortening). (C) Section BGR86–24 after retrodeformation, decompaction, and isostatic correction of the top of unit SeiS-C; restored cross-section length between pins 1 and 2 is 93.5 km. (D) Interpreted section BGR86–24 after tectonic balancing, decompaction, and isostatic correction of the top of unit SeiS-B, finally restoring the cross section to a length of around 96 km between pins 1 and 2 (2.5 km of shortening, for a total of 10 km of shortening). The change in basement dip (top unit SeiS-A) between A and D is a result of the sequential isostatic compensation after each restoration step. The location of seismic line BGR86–24 is indicated on Figure 2.

Figure 6. Schematic illustration of the structural restoration approach of this study. (A) Representative interpretation of a fault-related fold. Dashed circles mark the fault-horizon intersections on footwall and hanging-wall sides. (B) Section after fault restoration balancing displacement of top horizon. (C) Flexural-slip unfolding of top horizon. Underlying surfaces are carried with the top surface along the same movement vectors as it is deformed with the flexural-slip algorithm. (D) Target fold after removal of restored sedimentary unit followed by decompaction and isostatic correction.
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BGR86-24 - Southern Zone

Cross section length 86 km (Pin 1 to Pin 2)

Cross section length 91.5 km (Pin 1 to Pin 2)

Cross section length 93.5 km (Pin 1 to Pin 2)

Cross section length 96 km (Pin 1 to Pin 2)
variation in both total crustal shortening as well as incremental crustal shortening through time. We consider the observed shortening variations between the individual transects to be valid, although absolute shortening values might carry an error of up to 15%, taking into account seismic-processing uncertainties (i.e., depth migration), horizon-interpretation errors (i.e., across-fault correlation), or uncertainties during restoration (included in Fig. 8). A comparison of our interpretations with published data of deep-water Sabah (Hinz et al., 1989; Petronas, 1999; Ingram et al., 2004) and adjacent areas of Brunei Darussalam (Sandal, 1996; Van Rensburg and Morley, 2000; Saller and Blake, 2003; Morley, 2007; Morley and Back, 2008; Gee et al., 2007) documents that our fault and horizon interpretations fit well into the margin-scale geological framework. Based on our stratigraphic subdivision, we calculated a rather uniform shortening of ±3 km in late Miocene and early Pliocene times. Since the late Pliocene, the study area has undergone a major shortening of 4–8 km, where the maximum shortening is located in the central part of the study area between lines BGR86–22 and BGR86–18. Despite a large Pliocene to Holocene sediment influx from the shelf to the continental slope (Sandal, 1996; Petronas, 1999; Van Rensburg and Morley, 2000), the stepped topography of the fold belt is not leveled-out on the moderate seafloor (Figs. 3 and 4; also see detailed 3-D seafloor images of Morley [2007]; Gee et al. [2007]), indicating that many folds and faults in the study area are active today.

The increase in crustal shortening from the Pliocene until today might be interpreted as gravity-driven shortening related to major Pliocene shelfal growth. To test this hypothesis, we compiled published seismic data from the Sabah shelf (e.g., Bol and Van Hoorn, 1980; Levell, 1987; Hazebroek and Tan, 1993; Petronas, 1999; Ingram et al., 2004), Brunei shelf (e.g., Sandal, 1996; Watters et al., 1999; Van Rensburg and Morley, 2000; Imber et al., 2003; Morley et al., 2003; Saller and Blake, 2003), and deep-water Brunei (Morley, 2007; Morley and Back, 2008; Gee et al., 2007). This data set documents large-scale compressional and extensional features affecting the Pliocene to present-day basin fill offshore NW Borneo (Fig. 9). The measurements of post-Miocene fault heaves (20 sections) and fold-related shortening (six sections) in nearshore northern Sabah and onshore Brunei limit NW-SE-directed extension on the NW Borneo shelf to a maximum of 6 km offshore Brunei Bay, decreasing northward to <1 km offshore Kota Kinabalu. In contrast, the post-Miocene shelfal compression along NW Borneo shows an opposite trend: the maximum of fold-related shortening is found in nearshore Sabah north of Gordon-Klias (Fig. 9B), whereas Pliocene shortening on the Brunei shelf is limited to a few inversion features of limited extent (Morley et al., 2003).

Figure 10 is a synoptic plot of Pliocene to present-day deep-water, outer shelf, and nearshore shortening (Fig. 10A) and extension estimates (Fig. 10B) of this study between offshore Brunei Darussalam and the Gaya Hitam area offshore Sabah (Fig. 9). In the very south of the study area (south of line BGR86–24), there is an overall balance between deep-water compression and shelfal extension, indicating that gravity-driven processes could be the primary control for deep-water shortening. However, shelfal extension significantly decreases north of line BGR86–24, causing an imbalance between shallow-water extension and deep-water compression. We interpret the shortening surplus in this part of the study area as an indication of northward-increasing Pliocene to present basement-driven compression (Fig. 10C).

The interpreted decrease in basement-driven compression between lines BGR86–18 and BGR86–12 possibly reflects the lack of neotectonic data from nearshore and onshore Sabah around Kota Kinabalu (Fig. 9), or incomplete fault balancing below the high-velocity body of seismic line BGR86–12 (Fig. 3).

**DISCUSSION**

The structural interpretation and restoration approach in this paper tries to account for and separate the processes that have influenced the geometry and evolution of the deep-water fold-and-thrust belt offshore NW Borneo. The following arguments support an interpretation of the fold-and-thrust system as being at least partly controlled by active basement-driven shortening. (1) The fault-related folds of the present-day deep-water thrust front show a seabed expression, documenting that deformation is still ongoing today. (2) Our restoration work resolves a twofold trend of shortening along the >250-km-long deep-water-margin segment stud-
Figure 9. (A) Location map showing all deep-water, outer-shelf, nearshore, and onshore seismic sections (dashed lines indicate published data) used in this study for measuring late Pliocene to present-day shortening and extension. Numbers on map refer to locations and data sources provided below. (B) Comparison of late Pliocene to recent deep-water shortening values (calculated for unit Seis-D) of this study with published data. The southern part of the study area offshore Brunei Bay shows an approximate balance between shelfal extension and deep-water compression, whereas the northern study area is characterized by waning extension values and dominant compression. GF—growth fault.
Figure 10. Late Pliocene to Holocene deep-water shortening values and shelfal extension estimates: (A) Deep-water shortening values offshore Sabah (this study) and from published data of deep-water Brunei Darussalam (Sandal, 1996; Van Rensbergen and Morley, 2000; Morley, 2007; Gee et al., 2007; Morley and Back, 2008). (B) Shelfal extension measured on 20 published seismic sections (section locations and references are shown on Fig. 9). (C) Shortening surplus calculated from balancing deep-water shortening and shelf extension. The apparent decrease of the shortening surplus in the very north of the study area possibly results from insufficient information on Pliocene to Holocene folding and thrusting in nearshore and onshore Sabah.

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ied for Pliocene to recent times: in the very south of the study area offshore Brunei, deep-water shortening equals estimates of shelfal extension (Fig. 10). This suggests that shelfal growth might act as an important control for gravity-driven, shallow-seated, overburden-restricted shortening of the deep-water fold-and-thrust belt. In contrast, further north offshore Sabah, deep-water shortening cannot be balanced by shelfal extension. The observed tectonic imbalance between the shallow-water and deep-water provinces indicates the presence of an excess shortening that is best explained by basement involvement. (3) Figure 11 provides an isopach map of the Pliocene to recent sediment fill of the greater study area between offshore Brunei, deep-water shortening cannot be balanced by shelfal extension. The observed tectonic imbalance between the shallow-water and deep-water provinces indicates the presence of an excess shortening that is best explained by basement involvement. (3) Figure 11 provides an isopach map of the Pliocene to recent sediment fill of the greater study area offshore Brunei (Morley and Back, 2008) and deep-water Sabah (this study). The distribution of modern sediment shows a maximum of over 6000 m in the very south of the study area immediately beyond the shelf break offshore Brunei, while the Sabah slope is characterized by Pliocene to recent sediment fill not exceeding 4000 m. This sediment distribution suggests that gravity-driven, overburden-controlled processes should decline toward the north of the study area. However, our structural interpretation documents a northward increase in the frequency of folds and faults (see Figs. 3, 4, and 11). In the northernmost part of the study area, the intense deformation observed may be related to the impact of the high-velocity body interpreted by Franke et al. (2008) as a rigid obstacle that restricted deformation to the distal slope portion of the NW Borneo fold-and-thrust belt. (4) Previous studies have documented Pliocene to recent inversion of older fault systems as well as folding both onshore Borneo and on the inner NW Borneo shelf; this deformation has been attributed to plate-margin stress, consistent with a tectonically active margin (Morley et al., 2003; Morley, 2007; Back et al. 2008).

We feel that these observations support our interpretation of active basement involvement for crustal shortening of the NW Borneo deep-water fold-and-thrust belt in recent times. However, in the southern part of the greater study area, gravity-related delta tectonics may have played a significant role in the balance and can explain the deep-water folds and thrusts. This is not the case in the northern part of the study area, where shelfal extension strongly declines, causing a significant increase in calculated basement-driven compression (Fig. 10). Given the uncertainties of this study, it is difficult to judge whether the measured basement-driven compression gradually increases northward, or if there is an abrupt increase north of line BGR86–24.

Figure 1 shows that Borneo is located in the tectonically active South China Sea region close to major plate boundaries. However, the role of Borneo in the large-scale plate-tectonic context of SE Asia both in the past and in the present is still under discussion (e.g., Replumaz et al., 2004; Pubellier et al., 2004; Hall et al., 2008). A range of modern studies based on global positioning system (GPS) measurements (e.g., Chamot-Rooke and Le Pichon, 1999; Rangin et al., 1999; Simons et al., 2007; see Fig. 12) proposes recent westward movement of NW Borneo with respect to the Sundaland block (Fig. 1). The GPS vectors of these studies converge on similar values for different stations in North Borneo (Figs. 12A and 12B) but represent only 10 yr worth of observations in comparison to the restoration of 3 m.y. of basement-driven contraction presented in this paper (Fig. 12C). The results of our tectonic reconstruction document that pure basement-related shortening (Fig. 10) is concentrated in the northern part of our study area at rates...
Figure 11. Isopach map of the Pliocene to Holocene sediment fill between offshore Brunei (Morley and Back, 2008) and deep-water Sabah (this study). Offshore Brunei exhibits a maximum thickness of 6 km. The thickness of this sedimentary unit decreases to the north, with a maximum of 4 km offshore Sabah. This northward decrease in thickness coincides with a northward increase of fold and fault frequency between offshore Brunei and offshore northern Sabah. BSB—Bandar Seri Begawan.

Figure 12. Global positioning system (GPS)–based movement vectors of NW Borneo with respect to the Sundaland block (Fig. 1) and measurements of basement-driven deep-water-shortening (this study). (A) Movement vector after Rangin et al. (1999) suggesting a WNW-directed motion of northern Borneo of ~10 mm/yr with respect to a “Sunda plate” that is interpreted to be accommodated by crustal shortening in a “North Borneo Trench.” (B) Movement vectors of NW Borneo after Simons et al. (2007), proposing a general westward motion of NW Borneo between 3 and 6 mm/yr with a significant amount of shortening that is interpreted to be accommodated in an active “NW Borneo Trench.” (C) Long-term deep-water-shortening values calculated in this study suggesting a general northwestward-directed compression between 1 and 5 km in 3 m.y. (0.3–1.6 mm/yr).
between 1 and 5 km per 3 m.y., equivalent to a long-term shortening rate of 0.3–1.6 mm/yr. This rate is less than that predicted by modern GPS monitoring (Fig. 12). Our study indicates a SE–NW–directed compression perpendicular to the main fold-and-thrust trend, whereas the land-based short-term GPS vectors are either ESE–WNW (Rangin et al., 1999) or E–W (Simons et al., 2007). Although the different motion predictions (Fig. 12) are difficult to compare with respect to scale and methodology, all models predict present-day tectonic activity in NW Borneo.

**CONCLUSIONS**

The deep-water portion of NW Borneo has been structurally balanced and restored in order to investigate the controlling mechanisms of deep-water folding and thrusting. Key results of this tectonic reconstruction are:

1. Total crustal shortening measured along six shelf-to-basin transects across the NW Borneo deep-water fold-and-thrust belt ranges from 8 to 13 km. These values represent the sum of shortening calculated for three incremental time steps, late Pliocene to recent (5–7 km per section), early Pliocene to late Pliocene (2–4 km per section), and latest Miocene to early Pliocene (1–3 km per section). Our data indicate that total shortening generally increases through time. The seafloor expression of active folds indicates significant recent tectonic activity of deep-water faults and folds.

2. When analyzed against shelf extension, the NW Borneo deep-water fold-and-thrust belt exhibits a twofold trend of shortening along the >250 km portion studied: in the south (offshore Brunei Darussalam and southern Sabah), Pliocene to recent deep-water shortening equals shelf extension, and in the north (offshore northern Brunei Darussalam, deep-water shortening exceeds shelfal and-thrust belt. In contrast, offshore northern Malaysia, deep-water shortening of the fold-and-thrust belt: Marine and Petroleum Geology, v. 21, p. 629–6328, doi: 10.1016/S0191-8141(02)00034-2.

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