PERGAMON

Journal of Structural Geology 25 (2003) 1147–1169

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Characteristics of repeated, detached, Miocene–Pliocene tectonic inversion events, in a large delta province on an active margin, Brunei Darussalam, Borneo

C.K. Morley[a,*], S. Back[a], P. Van Rensbergen[b], P. Crevello[c], J.J. Lambiase[a]

[a]*Department of Petroleum Geoscience, University of Brunei Darussalam, Bandar Seri Begawan, 2028, Negara Brunei Darussalam*
[b]*Renard Centre of Marine Geology, Universiteit Gent, Krijgslaan 281-S8, 9000 Gent, Belgium*
[c]*Sublot 1032/lot 2123 Jln. Murina 2/ Pujut 2B, Miri, 98000, Sarawak, Malaysia*

Received 1 March 2001; accepted 1 August 2002

Abstract

The Baram Delta province evolved during the Middle Miocene to present day from a foreland basin to a shelf margin. Episodic folding events affected the region, causing uplift of the hinterland, delta progradation, and inversion of gravity-related faults. Existing models place the N–S- and NE–SW-trending folds in a strike-slip transpressional setting. New geological mapping and re-interpretation of existing data suggest the region is better understood as the development of a west-verging thrust belt in a Middle Miocene foreland basin (filled by sandstones and shales of the Belait and Setap Formations), with key major folds (Jerudong and Belait anticlines, Belait syncline) forming during the Middle Miocene as fault bend and fault propagation folds. The deformation style is complicated by the predominantly shaley Middle Miocene–Pliocene Setap Formation becoming thicker and more overpressured from south to north. Onshore where the Setap Formation is thin or absent, the Belait formation is attached to the underlying Lower Miocene and older sequences. Offshore and in a narrow onshore strip the overpressured Setap Formation causes deformation in the Beltait Formation to be detached from the underlying Cretaceous–Tertiary accretionary prism 'basement'. The detached style exhibits considerable structural complexity, including lift-off folds, growth faults, shale diapirs and pipes. Onshore thrust and inversion features are dominantly N–S-trending and began activity in the Middle Miocene; deformation is probably associated with an E–W maximum horizontal stress direction. In the Late Miocene (around 7.5 Ma; Watters et al., 1999) NE–SW striking inversion folds developed, located mostly over early counter-regional faults and associated reactive diapirs. Folds verge towards the NW when underlain by counter regional faults, and towards the S or SE when underlain by regional faults. Folds and diapirs along N–S trends were also reactivated. Continuation of this deformation into the Pliocene is largely confined to the offshore area. Onshore the N–S structures (no detachment) were not reactivated during the Pliocene.

Keywords: Tectonic inversion events; Delta province; Active margin

1. Introduction

The prolific hydrocarbon province of the Baram and Champion deltas in Brunei Darussalam and neighbouring regions of Sabah and Sarawak on the island of Borneo is formed in Middle Miocene–Recent deltaic sedimentary rocks (Fig. 1). While many of the structural features are typical of gravity tectonics in large deltas (growth faults, shale diapirs, toe thrusts, e.g. James, 1984; Sandal, 1996; Figs. 1 and 2), the structures have been commonly modified by the growth of compressional or strike-slip related folds and thrusts (Bol and van Hoorn, 1980; James, 1984; Levell, 1987; Bait and Banda, 1994; Sandal, 1996; Morley et al., 1998). Most large delta provinces described in the literature are developed on passive margins (e.g. Mississippi, Nile, Niger deltas). The Baram Delta province is different as it has developed on a tectonically active margin. Another example is the Kutei Basin in eastern Borneo (Ferguson and McClay, 1997; McClay et al., 2000).

This paper describes examples of a poorly documented class of inversion structures: positive inversion of gravity structures. The most widely described class of positive inversion are rifts, where most inverted normal faults pass

---

[*] Corresponding author.
E-mail address: chrissmorley@yahoo.co.uk (C.K. Morley).

0191-8141/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0191-8141(02)00130-X

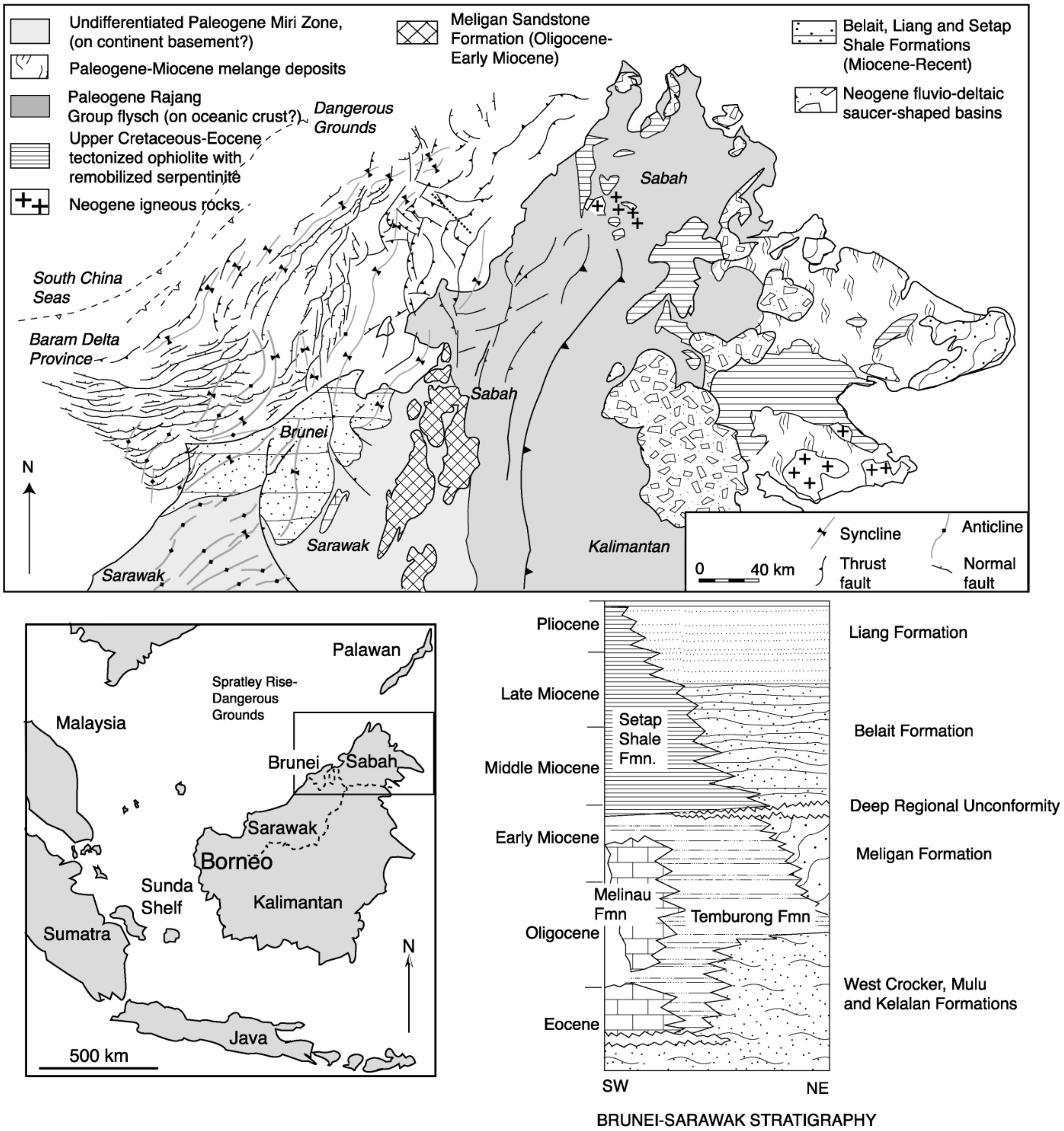


Fig. 1. Regional geological map of Northern Borneo. Compiled and slightly modified from Hutchison (1996a) and Sandal (1996). Stratigraphic column for the Tertiary of Brunei and Sarawak modified from Sandal (1996).

into basement. Conversely normal faults in large deltas pass into detachments within the sedimentary section. The latter are frequently associated with thick, overpressured mobile shale units and shale diapirs. Consequently, in deltas the thick overpressured shale unit will result in decoupling of basement faults from the deltaic fault system (e.g. Levell, 1987; McClay et al., 2000). Brunei Darusslam offers a rare chance to see good exposures of inverted deltaic normal faults onshore, representative of deformation deep in the section, and extensive coverage of the shallower part of the section offshore due to oil exploration and the extensive acquisition of 2D and 3D seismic reflection data. The overpressured Middle Miocene–Pliocene shaley Setap Formation, which gives rise to the deltaic gravity tectonics, is found in outcrop, onshore Brunei and underlies the entire offshore area of Brunei Darussalam.

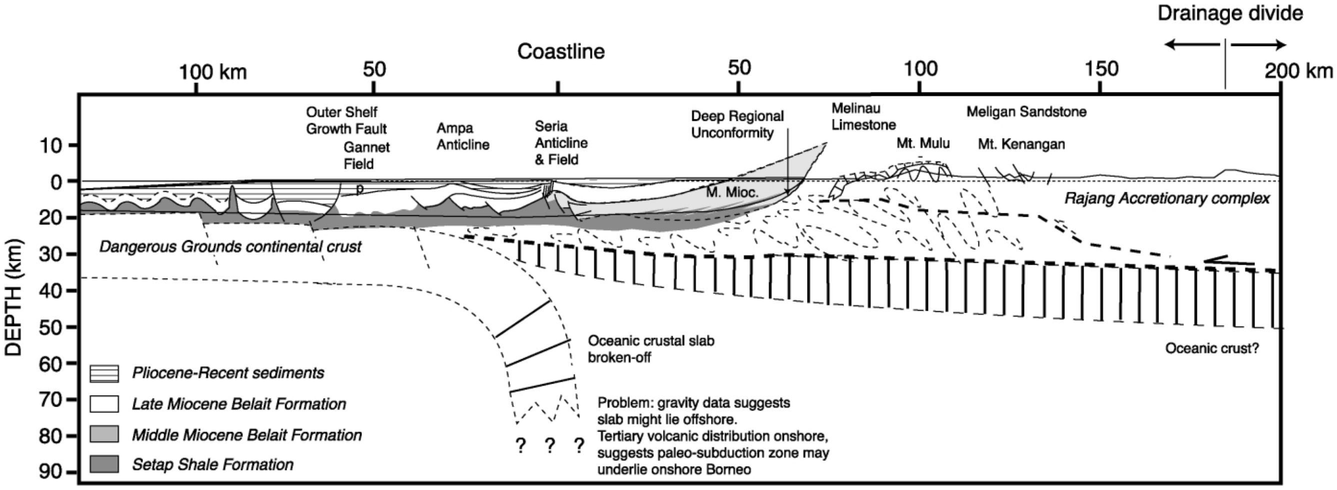


Fig. 2. Regional geological cross-section through Brunei and Sarawak. The section is based on offshore seismic reflection data (Sandal, 1996), onshore geological maps (Wilford, 1960), and models for the tectonic development of northern Borneo from James (1984) and Hutchison (1996a,b) and our own geological fieldwork in Brunei.

One problem with understanding the structural evolution of Brunei from the middle Miocene onwards is reconciling how predominantly N–S-trending folds and faults onshore relate to the mixed NE–SW- and N–S-trending growth faults, folds and shale diapirs offshore. The second problem is whether the major N–S trends are related to strike-slip deformation or a late phase of thrusting associated with the development of an accretionary prism. The kinematics of these fault zones have not previously been investigated from outcrop. This paper describes the evidence for the sense of motion and timing of displacement on N–S-trending faults in Brunei. These faults provide insight into the deeper tectonics, which drive inversion structures found offshore.

2. Regional geological setting

The oldest rocks along the NW margin of Borneo comprise a large Upper Cretaceous–Eocene belt of strongly folded and thrust deep marine clastics called the Rajang Group Flysch Belt (reviewed by Hutchison, 1996b; Fig. 1). Fragments of ophiolites overlie or are thrust within the Rajang Group. The Rajang Group may have been deposited on both continental and oceanic or island-arc type crust (Hutchison, 1996a,b). Passing to the NW the age-equivalent rocks to the Rajang Group in Brunei Darussalam and western Sabah and Sarawak are of generally shallower marine origin, and comprise the Miri Zone. The south-eastern passive margin of the fragment, which contained the Rajang Group was subjected to folding and thrusting first in an accretionary prism setting associated with a SW-dipping subduction zone (late Cretaceous–Oligocene), followed by west to northwest-directed obduction of oceanic crust during the late Oligocene–Early Miocene (Hutchison, 1996a,b). Following complete subduction of the proto-South China Sea oceanic crust (Hall, 1996), during the Early Miocene, the Dangerous Grounds continental fragment, which lay northwest of Borneo, entered and jammed a SE-dipping subduction zone beneath the NW Borneo margin, which led to folding and thrusting of the Miri zone during the Miocene–Pliocene (James, 1984; Hutchison, 1996b; Sandal, 1996; Fig. 2). East and southeast of Borneo, during the Miocene, continental fragments began to accrete to form Sulawesi, and the Australian continent began to impinge on the Sundaland block (e.g. Hall, 1996). Consequently there is no shortage of tectonic events that could cause inversion in the sedimentary basins of northern Borneo during the Miocene–Recent.

Oligocene–Middle Miocene times represent the transitional period where deposition shifted from being largely internal to what is now the landmass of Borneo, to the margins of the landmass. Crustal shortening, jamming of the S- to SE-dipping subduction zone by thinned continental crust, and isostacy caused emergence of central and northern Borneo during the Middle and late Miocene (Levell, 1987; Hutchison, 1996b; Hutchison et al., 2000). The Deep Regional Unconformity (DRU), which marks this transition, lies between the Middle Miocene and underlying Late Eocene–Early Miocene sequences (Levell, 1987). The DRU is characterised by uplift of the present day inner shelf area from a deep marine to shallow marine/terrestrial environment, while further offshore, deposition remained continuous through the Early and Middle Miocene. Erosion of the rising landmass generated extensive delta-dominated sedimentary basins around the fringes of the island along the NW, NE and SE margins (e.g. Hamilton, 1976). The offshore propagation of structures and growth of the island forced rapid progradation of deltaic sediments, and resulted in uplift and erosion of earlier sedimentry sequences (Sandal, 1996).

Onshore in Brunei and Sarawak, the DRU separates

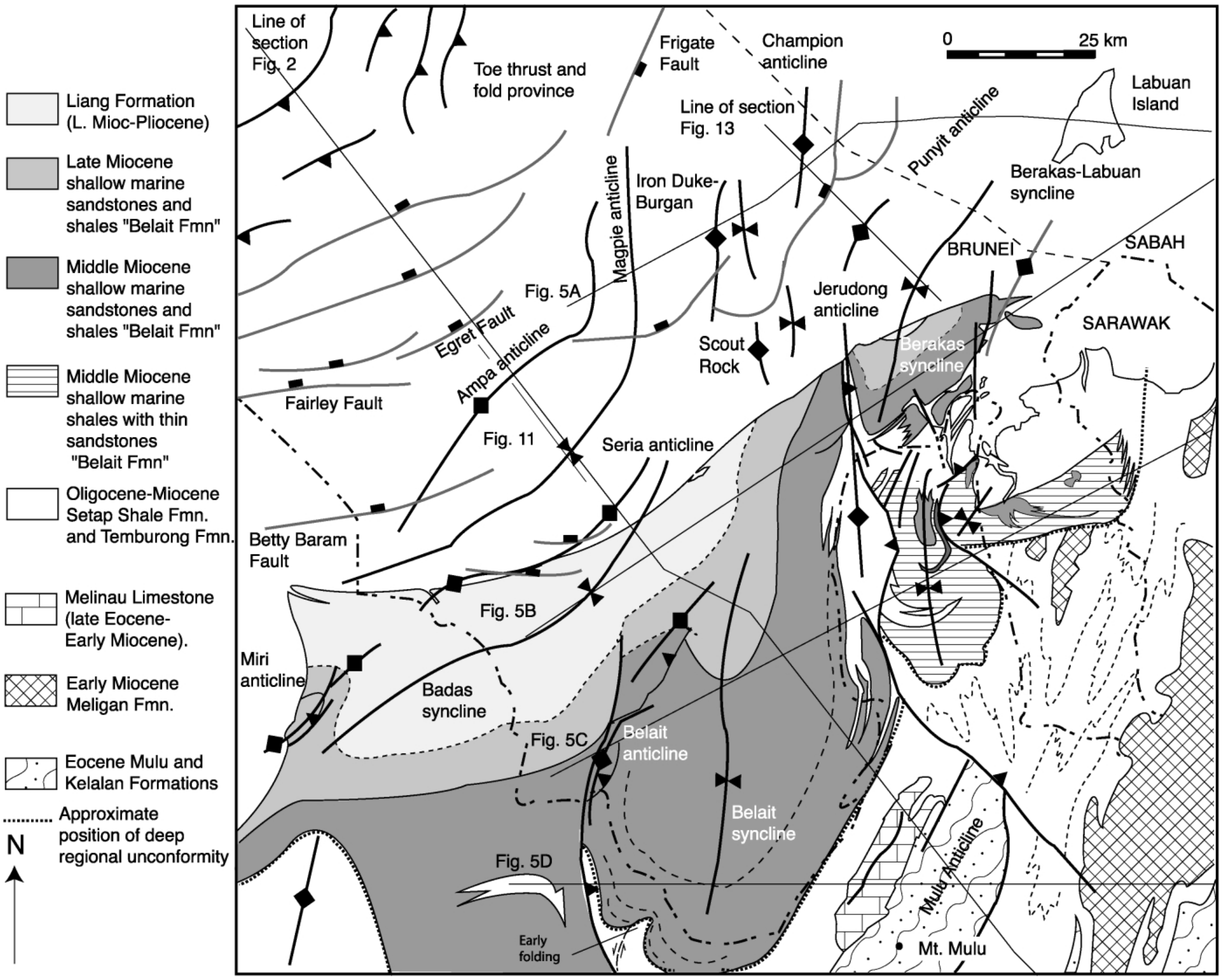


Fig. 3. Geological map of Brunei and adjacent areas of Sarawak (modified and updated from Wilford, 1960; James, 1984). For stratigraphic column see Fig. 1.

different structural styles. Underlying the DRU are Eocene–Early Miocene section 'basement' rocks (i.e. well lithified, to slightly metamorphosed sedimentary rocks, strongly folded and faulted) while overlying the DRU are poorly lithified, Middle Miocene and younger, deltatic sequences of the Baram basin deformed by broader wavelength, more open folds (James, 1984; Fig. 3).

Over most of onshore and offshore Brunei the DRU is overlain by the Setap Formation, which is a loose stratigraphic term that describes all shelfal to deep water shale sequences of Middle Miocene–Pliocene age (Fig. 1). A significant part of the Setap Formation is thought to be overpressured, undercompacted and mobile, it is the unit that acts as the source of shale diapirs, and the detachment zone for growth faults. It can be several kilometres thick and served to detach basement-involved structures from the deltaic sequences. The Middle–Late Miocene shallow marine, more sand-prone 'delta' related sequence, which is the more proximal, time equivalent of the Setap Formation, is known by two names: the Belait and Miri Formations (Sandal, 1996). However, there is no practical distinction between the two formations so the term Belait Formation is used ubiquitously here. The deltas evolved whilst episodic compression affected the margin, which led to a complex interplay between predominantly extensional gravity-related structures of the delta and collision-related basement structures (e.g Bol and van Hoorn, 1980; Levell, 1987; Sandal, 1996).

3. Structural evolution of Brunei Darussalam and adjacent areas of Sarawak

The onshore geology of Brunei Darussalam is dominated by two, large, broad synclines, called the Belait and Berakas synclines, and two narrower, tighter anticlines, which strike N–S, called the Jerudong and Belait anticlines (James, 1984; Fig. 3). Offshore growth faults and anticlines strike NE–SW and N–S (Sandal, 1996). It is generally thought that the N–S trends are influenced by 'basement'-related

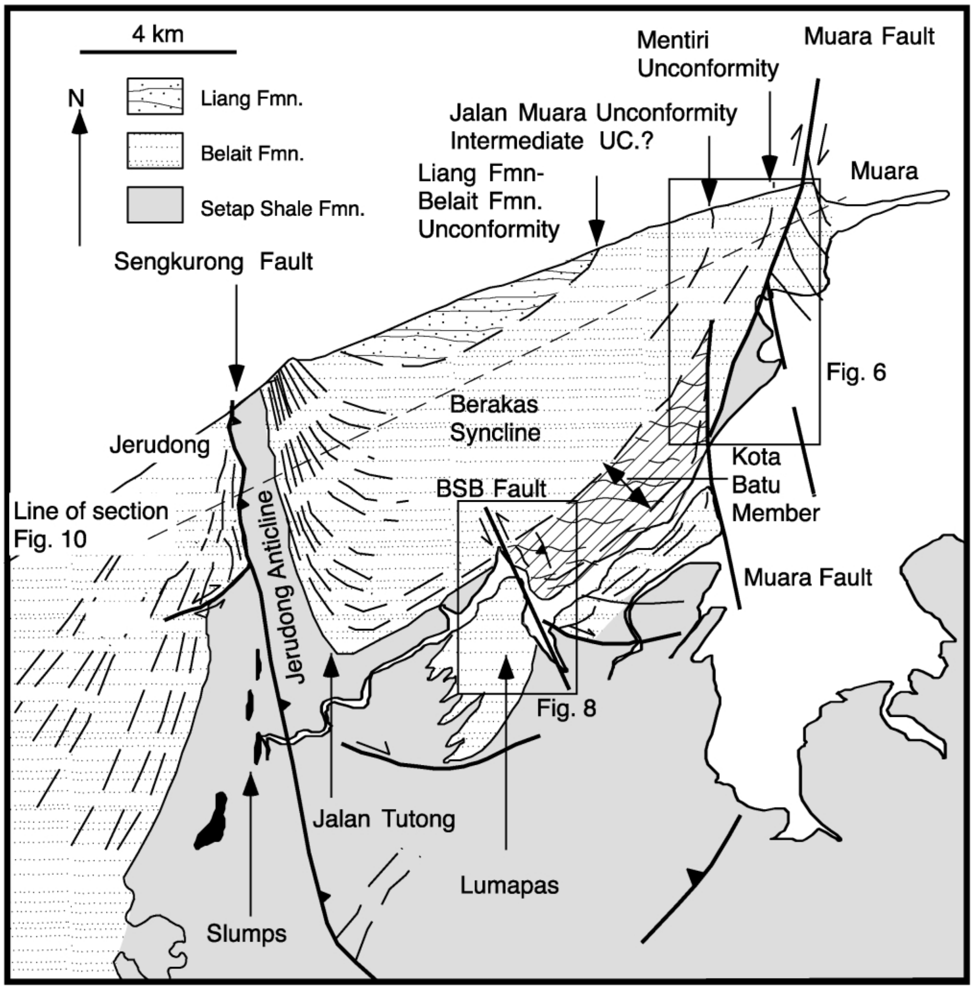


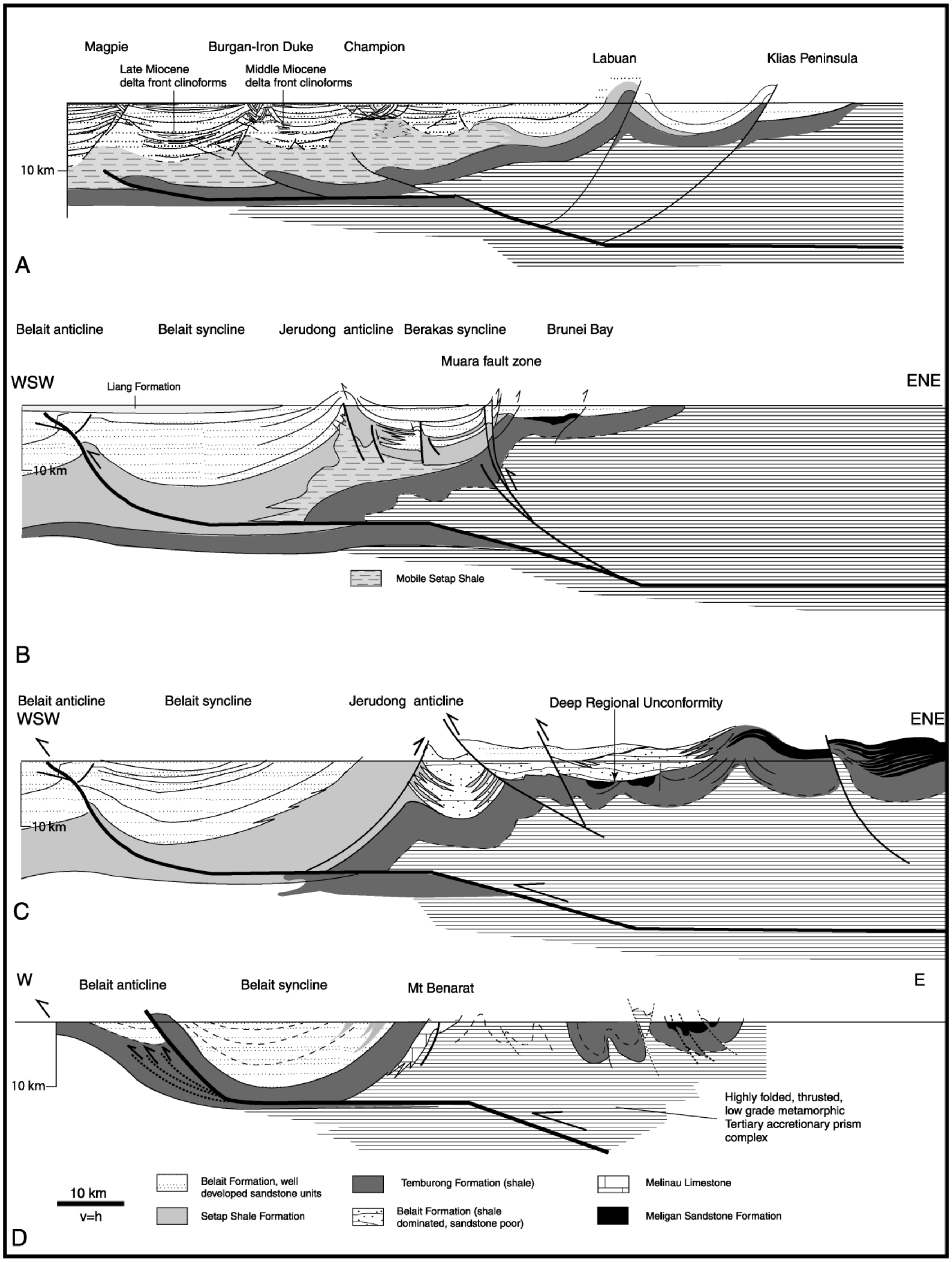
Fig. 4. Map of the main geological features of the Berakas syncline (see Fig. 3 for location). BSB = Bandar Seri Begawan.

structures, whilst the NE–SW trend reflects gravity driven deformation perpendicular to the depositional strike of deltas filling the Baram basin (Sandal, 1996). This section discusses evidence for the type and timing of deformation along the onland N–S-trending structures.

3.1. Belait syncline, Belait and Jerudong anticlines

The Belait syncline is bound to the west and east by the Belait and Jerudong anticlines, respectively. A key to understanding the Miocene–Recent evolution of the region is determining how these anticlines developed. The Belait and Jerudong anticlines are considered by some workers to be manifestations of strike-slip fault blocks moving in basement (e.g. Levell, 1987; Sandal, 1996); however, no previous attempt has been made to construct deep crustal sections to make sense of the structural configuration. There is, however, considerable basic geological information available (wells, seismic lines, down plunge projections from geological maps; e.g. Wilford, 1960; James, 1984; Sandal, 1996) that helps constrain the deep geometry of the major folds.

The folds are primarily developed in the Setap Shale and Belait Formations. Along the eastern flank of the Belait Syncline the earliest Middle Miocene section is a sequence of west-dipping shelfal deposits, up to about 12 km thick (Figs. 3 and 4). Their outcrop pattern shows strongly prograding clinoforms marked by rapid lateral transitions from tidal-lower shoreface sandstones and shales of the Belait Formation into shelfal mudstones containing slumps (Setap Shale). The sequence stratigraphy of the Middle Miocene reveals the following evolution of basin setting (Back et al., 2001). (1) The early part of the Middle Miocene basin fill has sequence stacking patterns consistent with rapid subsidence and more aggradational patterns that could fit with subsidence in a foredeep basin. (2) The upper part of the Middle Miocene basin fill shows more strongly progradational sequences with detached sandstones in a shelfal environment, indicating a major change in basin configuration. This reorganisation is probably related to uplift south of the Belait syncline and growth of N–S-trending compressional features within the Belait foredeep. Much of the Belait Formation onshore is not cut by any significant growth faults, nor is folded by diapirs. It appears


Magpie
Burgan-Iron Duke
Champion
Labuan
Klias Peninsula
Late Miocene delta front clinoforms
Middle Miocene delta front clinoforms
10 km
A
Belait anticline
Belait syncline
Jerudong anticline
Berakas syncline
Brunei Bay
Muara fault zone
WSW
ENE
Liang Formation
10 km
Mobile Setap Shale
B
Belait anticline
Belait syncline
Jerudong anticline
Deep Regional Unconformity
WSW
ENE
10 km
C
W
Belait anticline
Belait syncline
Mt Benarat
E
10 km
Highly folded, thrusted, low grade metamorphic Tertiary accretionary prism complex
10 km
v=h
Belait Formation, well developed sandstone units
Setap Shale Formation
Temburong Formation (shale)
Belait Formation (shale dominated, sandstone poor)
Melinau Limestone
Meligan Sandstone Formation
D

that the initial progradation of the Belait Formation occurred across a relatively stable substratum that did not respond significantly to differential loading. Only near the present day coastline did the underlying marine shales exhibit instability typical of undercompacted–overpressured sequences. This is due in part to the increasing thickness of the Setap Shales from zero to several kilometres passing offshore, in a SE to NW direction.

The Jerudong anticline developed during deposition of the Middle and Late Miocene Belait formation as indicated by progressive rotation and thinning of the sedimentary rocks towards the anticline (e.g. Wilford, 1960, and variants of the map in James (1984) and Sandal (1996); Fig. 4). New geological mapping has established that while the effects of fold growth can be seen in stratal patterns (progressively steepening dips, onlaps, some abrupt increase in dip across short distances), the folding apparently had little effect on distribution of sedimentary facies, and all deposition occurred in a shallow shelf-tidal setting. An important west-dipping thrust (Sengkurong Fault) emplaced west-dipping Setap Formation in the hanging wall over east-dipping Belait Formation in the footwall.

Published cross-sections through the Belait anticline (James, 1984; Sandal, 1996) show the overall geometry is of a fault tip fold above an east-dipping footwall ramp, with a number of accompanying back-thrusts (Fig. 5). The older terms for fault tip and ramp anticlines are used here because the folds with their progressive rotation of layers do not appear to fit the growth criteria for fault bend- and fault propagation-folds (e.g. Suppe, 1983). The Belait anticline is the westernmost fold, and it began to grow in the Beltait Formation slightly later in the Middle Miocene than the Jerudong anticline (in-sequence thrusting). However, minor folding affects the lower part of the Belait Formation between the Belait anticline and the Jerudong anticline and hence appears contemporaneous with the Jerudong anticline. The Belait anticline marks the thrust front. In the footwall of the Belait thrust lie NE–SW-trending folds within shales comprising the Miri zone (Fig. 1); these folds represent early Tertiary accretionary prism deformation that pre-dates the development of Middle Miocene N–S-striking structures.

Fig. 5 is an attempt to place the Belait and Jerudong anticlines within a structural framework. The cross-sections presented are constrained by the map of Wilford (1960), and by exploration data (Sandal, 1996). Although not a unique solution, the sections demonstrate that the Jerudong anticline, Belait syncline and anticline can fit a ramp–flat thrust model very well and consistently. The western limb of the Jerudong anticline is particularly well-developed as the forelimb of a frontal ramp anticline (Rich, 1934). One complexity to section construction is the lateral facies changes between the Belait Formation and Setap Formation. The central and southern sections (Fig. 5), show the Belait and Setap Formations are attached to the underlying units. In the northermost section, part of the Setap Formation around the Jerudong anticline–Berakas syncline area has become mobile, giving rise to growth faults and shale diapirs. Consequently some of the deformation in the Belait Formation is detached from deformation in basement. However, the effects of the large-scale passive ramp folds are still apparent as well. This interaction of detached and basement structure is best exposed in the Berakas syncline described below.

3.2. Berakas syncline

The Berakas syncline lies in northeastern Brunei (Fig. 4). The oldest units (Middle Miocene) are found in the southeastern region (Lumapas area), and they progressively young to the NW, the youngest section being the Late Miocene–Pliocene Liang Formation found near the coastline (Fig. 3). Dip values also progressively change from 60–80° in Lumapas to 10–15° near the coast, indicating rotation during syn-tectonic sedimentation. There is no significant repetition of the section by thrusting. From the base of the Lumapas section to the coast is a distance of 22 km, the section is approximately 12.5 km thick, with the Middle Miocene accounting for 11 + km thickness. The simple structure of much of the Berakas syncline is interrupted in three areas by N–S-trending anticlines and faults that grew episodically and affected sedimentation patterns. These areas are the northern Jerudong anticline, the Bandar Seri Begawan (BSB) fault and the Muara fault system (Fig. 4) described below.

3.3. Muara fault zone

The Muara fault zone is one of the important N–S- to

Fig. 5. Three sections across the onshore area of Brunei, based on the geological map of Wilford (1960), and modifications to the map by the authors, and Sandal (1996); see Fig. 3 for locations. Sections illustrate the way in which Middle Miocene N–S-striking thrusts have interacted with the Middle Miocene–Recent deltaic sequences (Belait and Setap Formations). The ramp-flat geometry within the Paleogene–Early Miocene 'basement' is highly speculative, but consistently fits the data. (A) Detached style, offshore Brunei (based on seismic reflection data for the post-Setap Formation section, and projection of the onshore structural style for the deep section). Most of the Setap Formation is inferred to be overpressured and mobile, under the main Middle Miocene–Recent depocentres. Passing eastwards the Setap Formation thins, and loses its mobile characteristics. (B) Transitional detached, northern section. Near the coast the Setap Shale is thick enough under the Jerudong anticline–Belait syncline to cause the lower part of the Setap Formation to be mobile and permit some detachment of underlying and overlying units. Rotated early normal faults and shale intrusions are present in the cores of the Jerudong anticline. (C) Central section. A very thick fore deep sequence filled by Belait and Setap Formation is deformed along with basement. (D) Southern section, attached folding. A thin or absent Setap Formation permits deformation in the Belati Formation to be coupled with the accretionary prism basement.

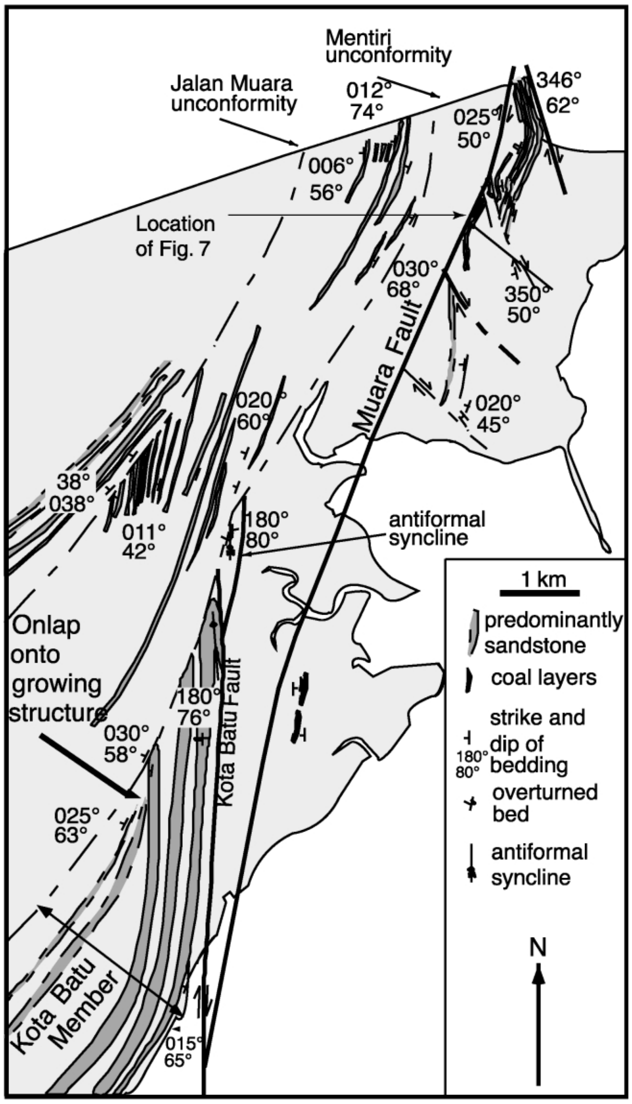


Fig. 6. Geological map of the Muara fault zone. Stippled units are predominantly tidal–lower shoreface sandstones with lesser amounts of shales; unpatterned areas are marine shales with lesser amounts of sandstones. The western splay (Kota Batu fault) of the Muara fault zone terminates at an unconformity relatively low in the section, suggesting the main Muara fault was active later than the Kota Batu splay.

NNE–SSW-striking fault zone that dissect the NW Borneo margin. The structural style and amount of displacement associated with these fault zones is poorly known. The fault zone is a composite of several faults that bound the eastern margin of the Berakas syncline. The fault zone is characterised by:

1. A N–S lineament formed by the abrupt termination of hilly topography against a flat plain.
2. On the western side of the N–S lineament the strike of bedding swings from NE–SW to N–S, and dips increase from 50–60° to vertical and even overturned passing eastwards towards the inferred fault zone (Fig. 6). Channelised sandstones with interbedded coals displaying variable but low-angled dips (up to 30°) are found east of the fault zone lineament.
3. In places N–S-trending anticlines are present. One refolded fold with an antiformal syncline geometry was found associated with the western fault branch (Fig. 6). Unconformities indicate the western branch is the oldest fault strand (Fig. 6). The antiformal syncline is probably caused by back-rotation of the older fault zone in the hanging wall of a transpressional fold associated with the (younger) eastern fault branch.

The Kota Batu Member represents the sedimentary section formed between the BSB fault and Muara faults when they were both active; anticlines associated with the faults developed on both margins of a sub-basin (Fig. 4). The Kota Batu member displays onlaps and progressive decreases in dip onto the anticlines (Wilford, 1960). An angular unconformity defines the termination of activity of the western strand of the Muara fault zones during the Middle Miocene (Fig. 6). The Kota Batu Member contains considerably more coal layers and coaly shales and is more sand-prone than units to the west of the BSB fault, which have a slightly stronger marine character. The differences are subtle since lower shoreface-tidal deposits are characteristic of both areas, but suggest that the area of the Kota Batu Member remained slightly shallower than the equivalent units to the west. These could reflect differences in sediment supply, tectonically controlled subsidence, or structural controls on drainage patterns.

There is one good exposure of the eastern branch of the Muara fault zone in a building site. There the fault zone is composed of fault slices that cause abrupt changes in dip of fault blocks, overall the faults trend NNE–SSW to NE–SW, and a mixture of high-angle normal faults, and high and low-angle thrust faults are present. Lithological variations have caused considerable local complexity within the fault zone such as smaller faults passing into local detachments, and disharmonic folding. Despite local complexity a larger-scale fault zone geometry can be discerned (Fig. 7): the western side of the fault zone is bounded by an east to ESE-verging, tight anticline; the building site exposures lie mainly within a complex syncline east of the anticline, and are bounded by east to southeast verging oblique (left lateral?) high and low angle thrusts on the eastern margin. The predominance of close to dip-slip displacements on the (few) striated fault surfaces visible suggest that although the fault zone is oblique slip, dip-slip motions are probably more significant than strike-slip motion.

3.4. Lumapas area—Bandar Seri Begawan fault

The NNW–SSE-trending Bandar Seri Begawan (BSB) fault runs through the centre of Bandar Seri Begawan, affects the course of Sungai (estuary) Brunei, and bounds the eastern side of the Lumapas outcrops (Fig. 8). The most obvious effects of the fault zone are the large-scale drag of

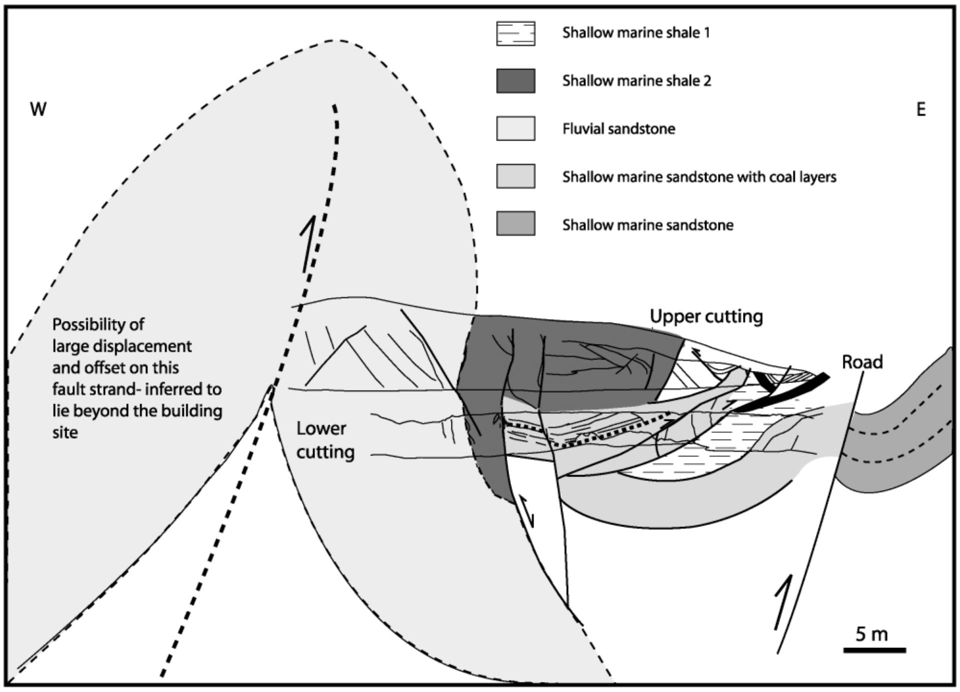


Fig. 7. Detail of the Muara fault zone, from a building site on Jalan Kaanan. See Fig. 5 for location.

bedding from the regional 030° to 040° strikes to more N–S orientations (Fig. 8), which indicates a sinistral sense of displacement, at least for the later fault movements. In the eastern Lumapas outcrops motion on the fault has caused local overturning of the strata. The upper part of the BSB Fault terminates in the Kota Batu Member (Fig. 4), where cessation of fault activity is marked by a local angular unconformity (Fig. 8).

The Lumapas area provides important information about the early history of the fault zone. In beds adjacent to the fault zone, drag folds and rotated normal faults are present (Fig. 9). The orientation of the normal faults corrected for later bedding rotations is NW–SE to N–S. This orientation is sub-parallel to the BSB fault and suggests an early period of extensional displacement on the fault zone.

Also present in the lower part of the Lumapas section are west- to northwest-verging folds and thrusts. The overall 020° to 040° strike of bedding is commonly disrupted by folds associated with early rotated thrust faults (Fig. 9). In one section there is a normal fault, that was later partially inverted as a thrust (Fig. 9). The upper part of the section at Lumapas does not display evidence for this style of folding and thrusting, which suggests contractional deformation occurred during the early Middle Miocene. The folds tend to display steeply plunging hinge lines (Fig. 9) that resulted from rotation by later folding on the southern ENE–WSW-trending limb of the Berakas syncline.

3.5. Northern Jerudong anticline

Up to about 16 km inland from the coast, the map pattern of the Jerudong anticline shows the fold is noticeably narrower and tighter than to the south (Fig. 3). The western core of the anticline displays vertical bedding and contains numerous rotated normal faults (original strike E–W to NE–SW) and shale dykes related to Middle Miocene deltaic gravity tectonics (Morley et al., 1998; Figs. 5 and 10). The northern part of the Jerudong anticline is probably located on the site of an older reactive shale diapir associated with E–W-striking normal faults. Shale dykes were intruded into the rocks forming the anticline core both prior folding (Middle Miocene), and at the end of folding (Pliocene–Recent; Morley et al., 1998). The early shale intrusions are associated with the initial sedimentary loading of the Setap Shales by the prograding Belait Formation, and occurred along with the formation of growth faults. The late shale intrusions probably occurred as a result of a drop in horizontal stresses following the termination of folding after compression had forced an increase in pore fluid pressure (Morley et al., 1998). The northern narrowing and tightness of the Jerudong anticline coupled with evidence for shale intrusions suggests a northwards change from the attached style of deformation to a lift-off structure facilitated by the presence of mobile shales below the anticline (Fig. 5).

3.6. A strike-section through the Berakas syncline

In Fig. 10, the Belait Formation is shown decoupled in some way (seismic lines do not image the section below the Belait Formation) from the underlying accretionary prism ‘basement’ of early Miocene and older sedimentary rocks, by the overpressured, undercompacted Middle Miocene Setap shales. One possible solution for the structural

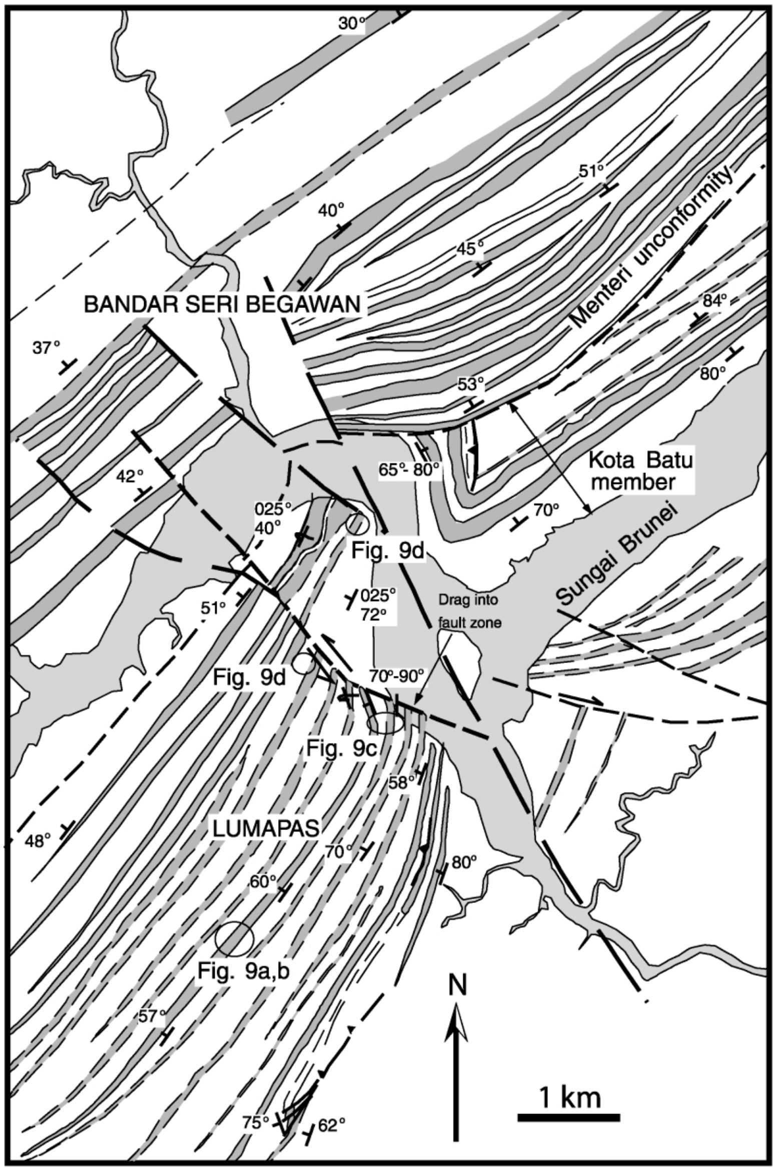


Fig. 8. Geological map of the Lumapas–Bandar Seri Begawan area, illustrating the effect of the Bandar Seri Begawan fault zone on the stratigraphy of the Belait Formation. Stippled units are predominantly tidal–lower shoreface sandstones with lesser amounts of shales; unpatterned areas are marine shales with lesser amounts of sandstones.

geometry is illustrated in Fig. 5. Folds affecting the Berakas syncline are related to the BSB and Muara faults structures are most intensely developed deep in the section and become simpler passing up-section.

4. ENE–WSW- to NE–SW-trending inversion structures

N–S contractional and NE–SW gravity tectonics structural trends are superimposed in a NE–SW-trending belt along the coast line that extends about 30 km offshore, and 25 km onshore. This zone is a region with a complex Middle Miocene–Recent structural evolution where contractional features grew within deltaic deposits and delta-related structures. Some of the contractional features follow NE–SW trends (Miri, Seria and Ampa anticlines), while others (e.g. Magpie trend, Iron Duke, Bugan) trend approximately N–S (Fig. 3). The Ampa and Seria anticlines are located over old NE–SW-trending counter-regional faults and associated reactive diapirs (e.g. Sandal, 1996; Van Rensbergen et al., 1999; Watters et al., 1999; Figs. 2 and 11). The NE–SW-trending fold structures lie mostly offshore or in the subsurface and are imaged on 2D and 3D seismic reflection data. They include the Ampa, Punyit, and Seria anticlines. One NE–SW-trending structure known from the surface is the Miri Anticline (Fig. 3). The Ampa anticline terminates to the SW in the NNE–SSW-trending SW Ampa anticline, and passes to the NE into the N–S-trending Magpie anticline (Fig. 12).

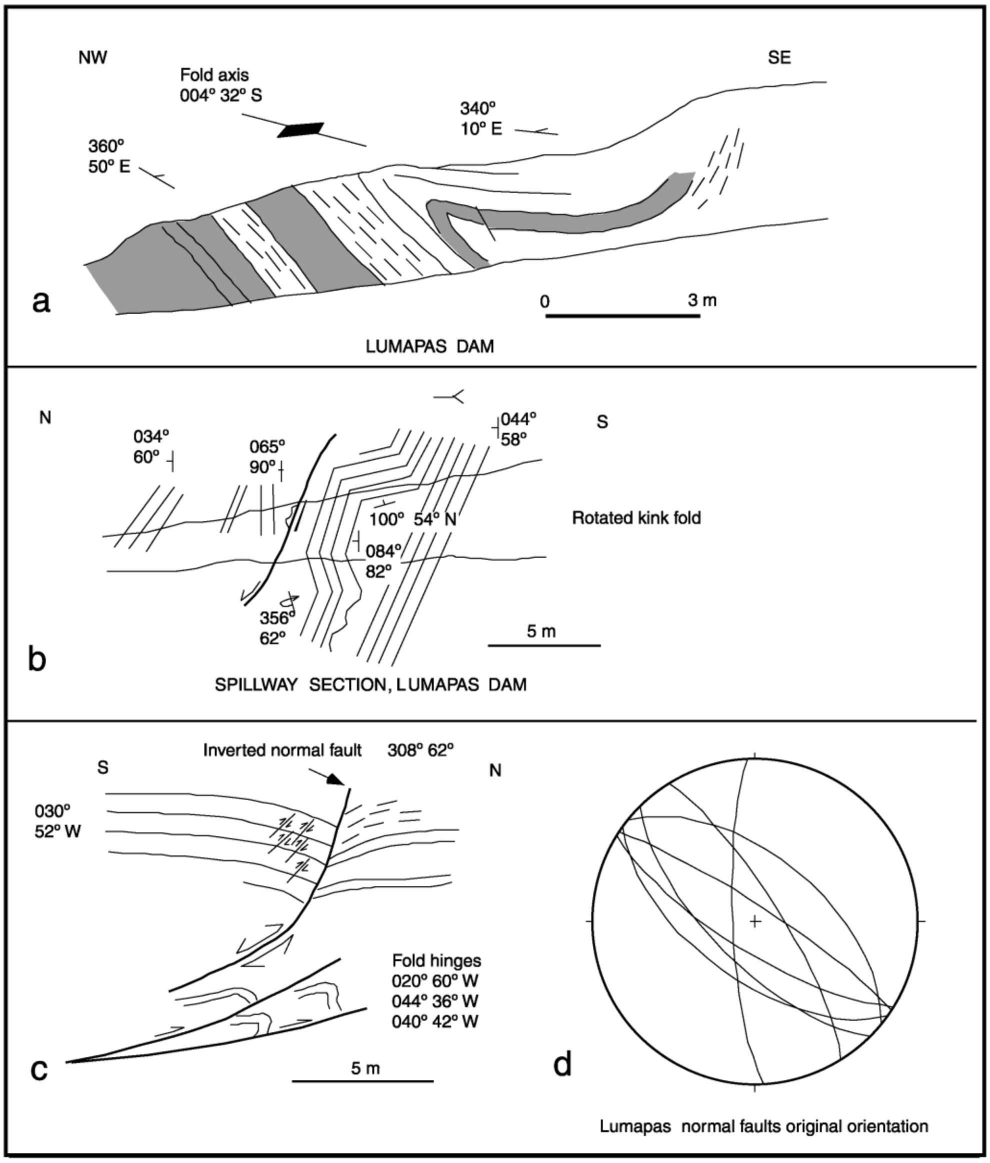


Fig. 9. Examples of outcrop-scale structures from the Lumapas Examples folds from the lower part of the section indicates at least one phase of compression/transpression associated with the BSB fault. Stereonet of normal faults orientations corrected for horizontal bedding. The NW–SE orientation is sub-parallel to the BSB fault and is an unusual orientation for faults in the area (they predominantly trend NE–SW). The orientation suggests the BSB fault zone underwent at least one stage of extensional–transtensional displacement. Inversion of some normal faults indicates a later stage of compression/transpression. See Fig. 5 for locations.

The fold structures are characterised by a simple, shallow asymmetric fold geometry. Commonly small displacement, predominantly regional (offshore-dipping) or conjugate normal faults sets are developed on the forelimb (Fig. 11). There is a progressive decrease in reflection dips within the Late Miocene–Pliocene section passing upwards towards the seafloor, accompanied by thinning of the strata towards the fold crest. These relationships indicate late growth of the anticlines. For the Seria field the main timing of uplift was from 7.5 to 4 Ma, and uplift of the crest is estimated to be 850 m (Watters et al., 1999). Passing deeper, below the fold, syn-kinematic strata form a number of overstepping packages, which generally thicken offshore. The deepest of these offshore thickening wedges terminate at counter regional faults underlying the fold (Sandal, 1996; Van Rensbergen et al., 1999; Watters et al., 1999). The most landward counter regional faults ceased moving first, and there is a general younging of counter regional fault initiation and termination passing offshore, typical of prograding deltaic sequences. The counter regional faults have, in places, given rise to reactive and active shale diapirs (Van Rensbergen et al., 1999). The folds are nucleated around these shale diapir cores. Some pipe-like intrusive features of mobile shales and gas-rich fluids appear to have intruded inversion anticlines just after folding ceased (Van Rensbergen et al., 1999).

The forelimbs of the folds tend to be a complex of conjugate normal faults, rotated by varying amounts by folding,

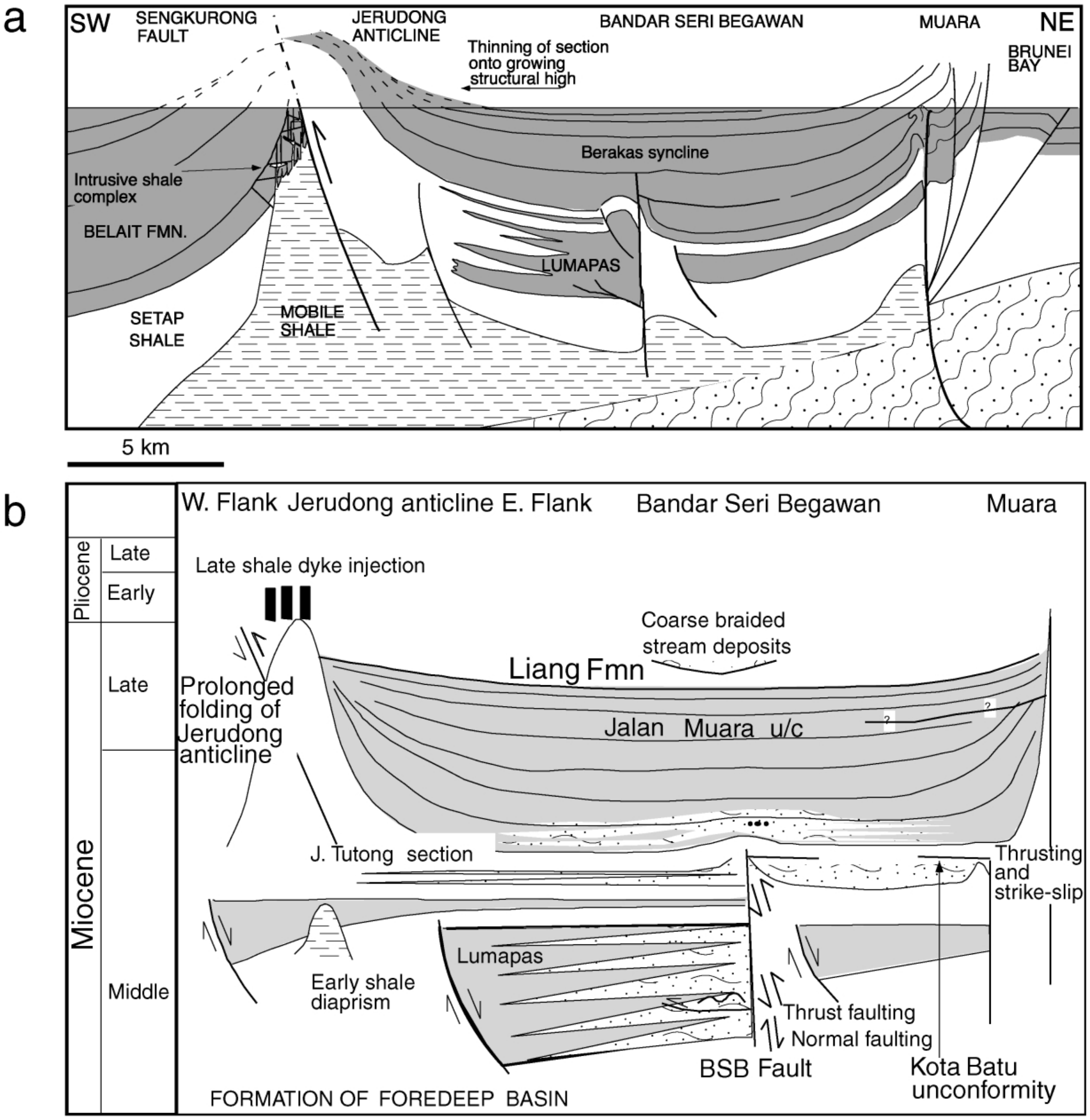
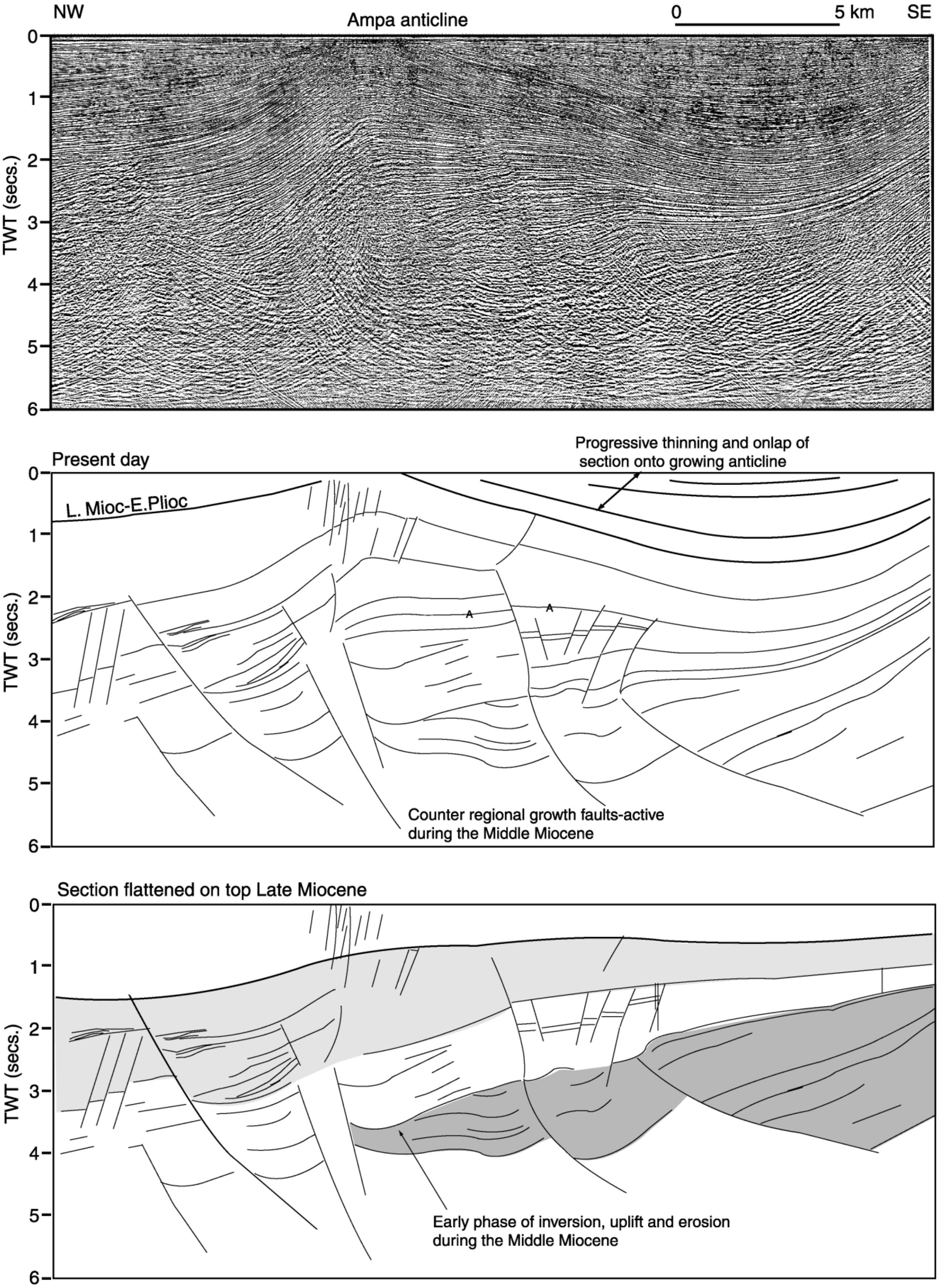


Fig. 10. (a) NE–SW cross-section through the onshore Berakas syncline illustrating the relationships between the three main N–S structures (Jerudong anticline, BSB fault zone and Muara fault zone) discussed in this paper. (b) Timing of structural development in the Berakas syncline based on data discussed in this paper.

dependent upon their time of formation and location (Sandal, 1996). Less frequently occurring reverse faults are also present. Fault strike is variable between E–W and NE∇SW and the resulting fault network is complex in three dimensions.

The Champion field area is the complex offshore extension of the Jerudong anticline (Figs. 13 and 14). Progressive restoration of a NW–SE cross-section through the Champion area based on a regional 2D seismic line shows that during the Middle Miocene–Pliocene extensional gravity-driven structures have alternated with contractional/inversion tectonics as the deltaic depocentres migrated progressively offshore, and became inverted in the nearshore (Fig. 14).

Outcrops provide some details about the nature of the inverted faults. The Miri anticline described by Bait and Banda (1994) is cut by a number of NE–SW to ENE–WSW striking normal faults (Fig. 15). At outcrop most normal faults show no indication of inversion, but a few small thrust faults with centimetres to tens of centimetres displacement are present; two minor inverted normal faults and one major inverted normal fault have been identified (Fig. 16). The major inverted (regional) fault (Canada Hills fault) lies on the SSE side of the Miri anticline, and verges to the SSE (Fig. 15). Evidence for the inversion comes from multiple sources as follows:



Ampa anticline

Present day

Progressive thinning and onlap of section onto growing anticline

Counter regional growth faults-active during the Middle Miocene

Section flattened on top Late Miocene

Early phase of inversion, uplift and erosion during the Middle Miocene

Fig. 11. Seismic section through the NE–SW-trending Ampa anticline illustrating the location of an inversion anticline over older NE–SW-striking counter regional faults. See Fig. 3 for location.

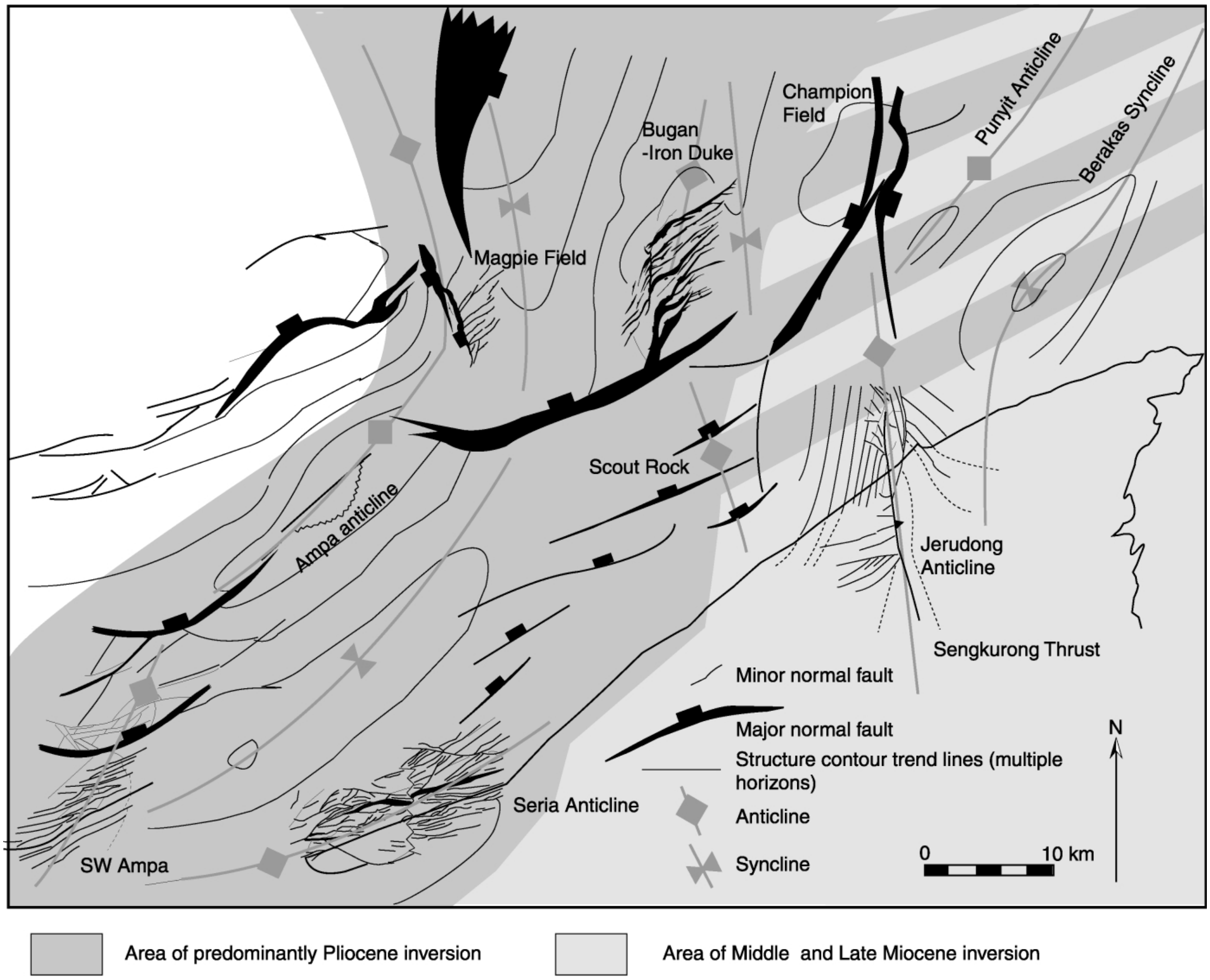
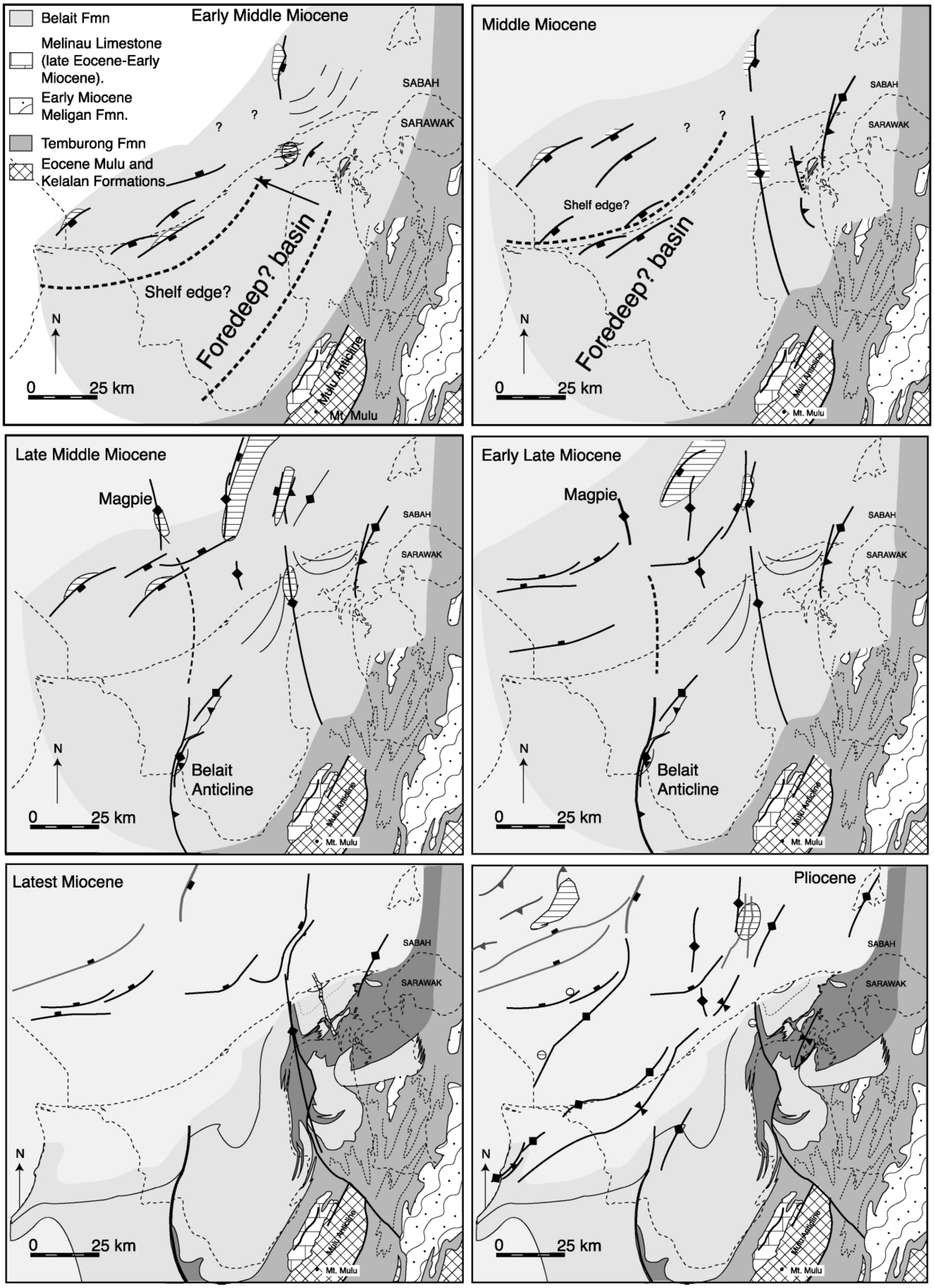


Fig. 12. Subsurface maps based on seismic data of the Magpie and Iron Duke fields, illustrating the fault patterns associated with N–S-trending anticlines. Modified from James (1984) and Sandal (1996).

1. Fault orientation. Where exposed the inverted fault is a high-angled fault dipping 55–60°, striking 045°. Minor normal faults in the same section strike between 044 and 054° and dip between 45 and 60°.
2. Kinematic indicators. Minor cataclastic zones display mixed normal and reverse offsets. The fault zone is much wider (up to 3 m), cataclasis zones are thicker (up to 10 cm), and more intensely deformed than nearby extensional fault zones of similar displacement magnitude. Brecciated zones are present in some inverted fault zones, and are never seen in the more numerous normal fault zones. These characteristics suggest strain hardening during inversion, which is to be expected considering the non-ideal orientation for thrust reactivation of steeply dipping normal faults with respect to the (inferred) sub-horizontal maximum principal stress direction required for inversion (e.g. Sibson, 1995). Rotation and folding of units within the fault zone is inconsistent for normal fault drag, but consistent with a reverse sense of motion. Low-angled footwall splays and imbricates in the hanging wall section show reverse motion.
3. Location. The fault lies on the gently dipping backlimb (6–12° NW), only 10–20 m north of the Miri anticline fold axis. Crossing the fold axis to the forelimb bedding dips range from 70° SSE to locally overturned (Fig. 15).

Fig. 13. Maps illustrating the evolution of structures from the Middle Miocene–Pliocene, for Brunei and adjacent areas of Sabah and Sarawak. Some offshore fault trends for the Middle Miocene are schematically illustrated only. The restorations are based on surface data discussed in this paper, and offshore seismic data. Horizontal striped area = shale diapir.


Belait Fmn
Melinau Limestone (late Eocene-Early Miocene).
Early Miocene Meligan Fmn.
Temburong Fmn
Eocene Mulu and Kelalan Formations
Early Middle Miocene
Middle Miocene
Late Middle Miocene
Early Late Miocene
Latest Miocene
Pliocene
SABAH
SARAWAK
Shelf edge?
Foredeep? basin
Magpie
Belait Anticline
Mulu Anticline
Mt. Mulu
N
0
25 km
?

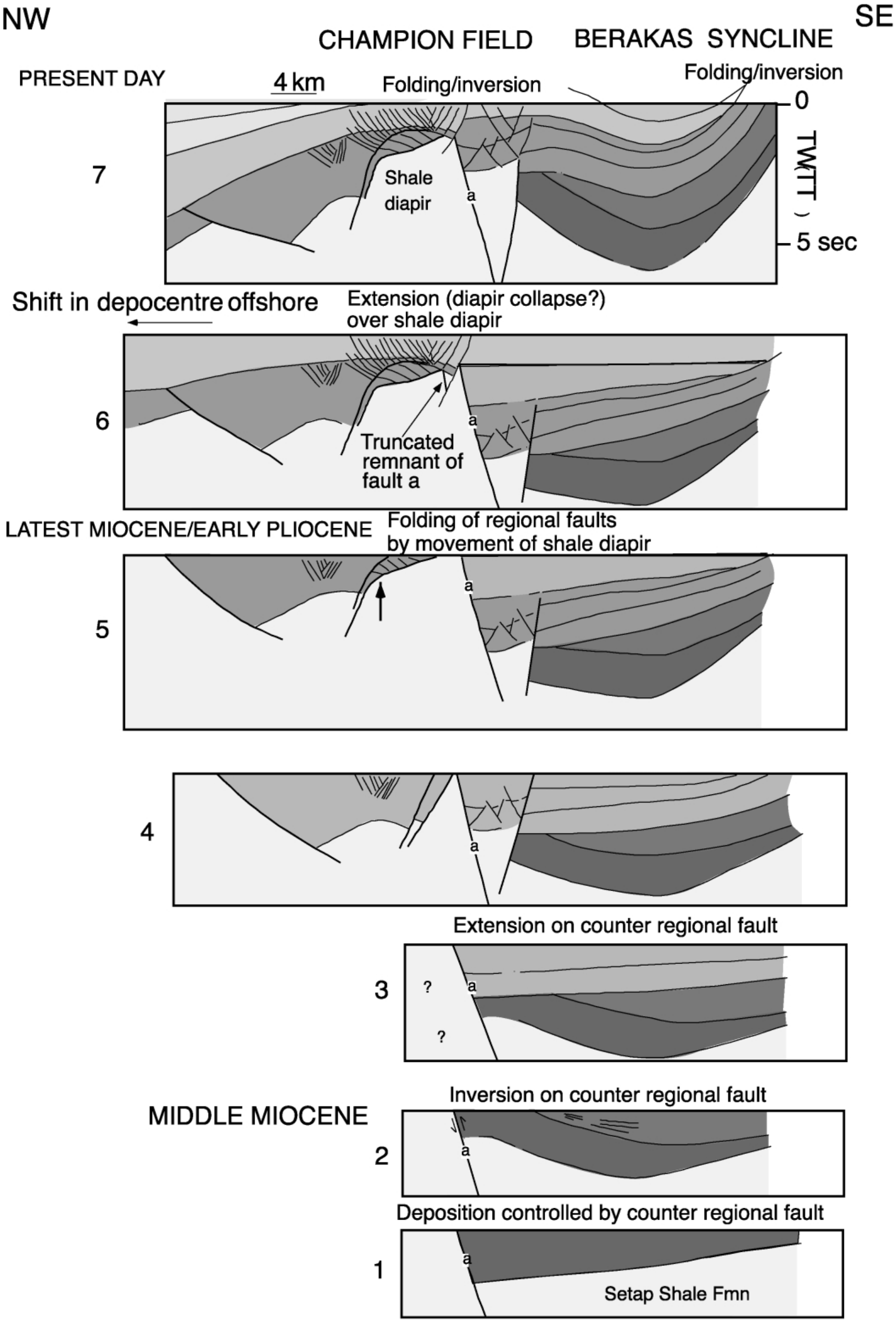


Fig. 14. Sequential evolution of the offshore Berakas syncline–Champion Field area based on a regional seismic reflection line. Stages in this figure are tied into the map view evolution in Fig. 13.

The inverted structures around the Miri anticline conform well with inferences made about inversion fault behaviour from sandbox models and fault mechanics models that high-angle normal faults are unsuitable for reactivation as thrusts (e.g. Eisenstadt and Withjack, 1995; Sibson, 1995). Of 28 normal faults examined in the Miri outcrops, only three have been inverted. In the Jerudong anticline only two out of 32 faults show signs of inversion. Hence inversion of normal faults is very selective. Where normal faults are inverted, numerous low-angle thrust faults splay from them.

The Miri oilfield is a series of small, compartmentalised

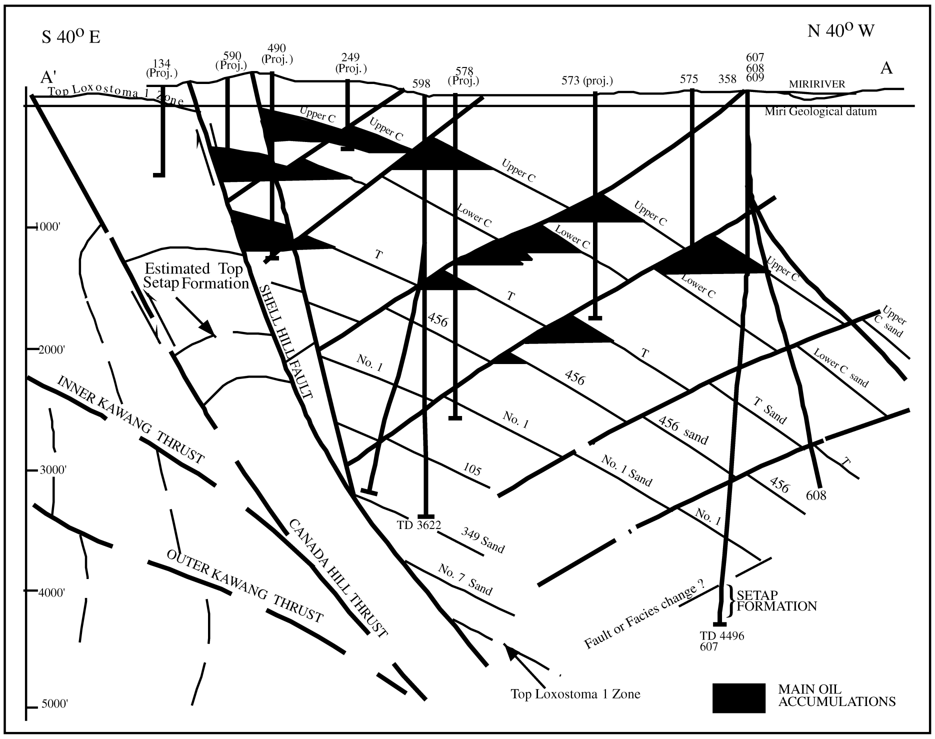


Fig. 15. Geological cross-section of the Miri anticline after Bait and Banda (1994).

traps bounded on at least one side by normal faults (Fig. 15). Offset oil–water contacts on sandstones juxtaposed across the normal faults indicate sealing faults are an important aspect of the structural traps. It is noticeable that the main inverted normal fault (Canada Hills thrust) does not trap any hydrocarbons, which suggests inversion does not promote fault seal or was active during hydrocarbon migration. It is also further evidence that the majority of the normal faults were unaffected by inversion-related reactivation (assuming that inversion would destroy the fault seal).

5. Oblique offshore structures

A number of discontinuous NNW–SSE to NNE–SSW trending folds are present offshore (Magpie, SW Ampa, Bugan-Iron Duke, Scout Rock, and Champion anticlines). Seismic mapping indicates these structures tend to be crossed by dense arrays of conjugate normal faults that strike NE–SW, oblique to the fold axis (Fig. 12). Hence typical growth fault trends are superimposed on oblique trending folds. In the SW Ampa field, a deep, NE–SW-trending major counter regional fault is present, but apparently failed to influence the strike of the NNE–NNW-trending fold axis. The Magpie Anticline strikes NNW–SSE, verges to the west, and is cut by a large NNW–SSE fold axis-parallel normal fault system and by NE–SW-striking faults (Sandal, 1996; Fig. 12). At the fold core lies a mobile shale ridge, 20 km long, 5 km wide. Most of the folding is of mid-Pliocene age, but thinning of Late Miocene reservoir sands onto a syn-sedimentary structural high suggests that earlier deformation also affected the structure (Sandal, 1996). The Bugan-Iron Duke anticline displays similar features to the Magpie anticline, it verges westwards, and the fold axis is affected by complicated arrays of conjugate normal faults, which display NE–SW and N–S strikes. The N–S striking fault segments follow the axis of the underlying mobile shale ridge, while the NE–SW strikes follow the regional gravity tectonics trends. Some faults planes display vertical changes in strike, tending towards a more N–S strike at depth, and a NE–SW strike higher in the section. Fig. 5 presents a cross-section through the offshore area, the upper part of the section, above the Setap Formation is based on seismic reflection data. The lower part of the section projects the structural style from onshore, and shows the thrust belt interpretation remains possible in the detached tectonics environment offshore. As thrust folds grew at depth, N–S-striking normal faults above the overpressured shales may have developed in response to gravity sliding off the forelimbs of growing basement folds.

6. Discussion

A schematic summary of the structural evolution of inverted counter-regional fault depocentres is given in Fig. 16. The Seria anticline marks the first effects of gravity structures within the foredeep basin at a location sufficiently

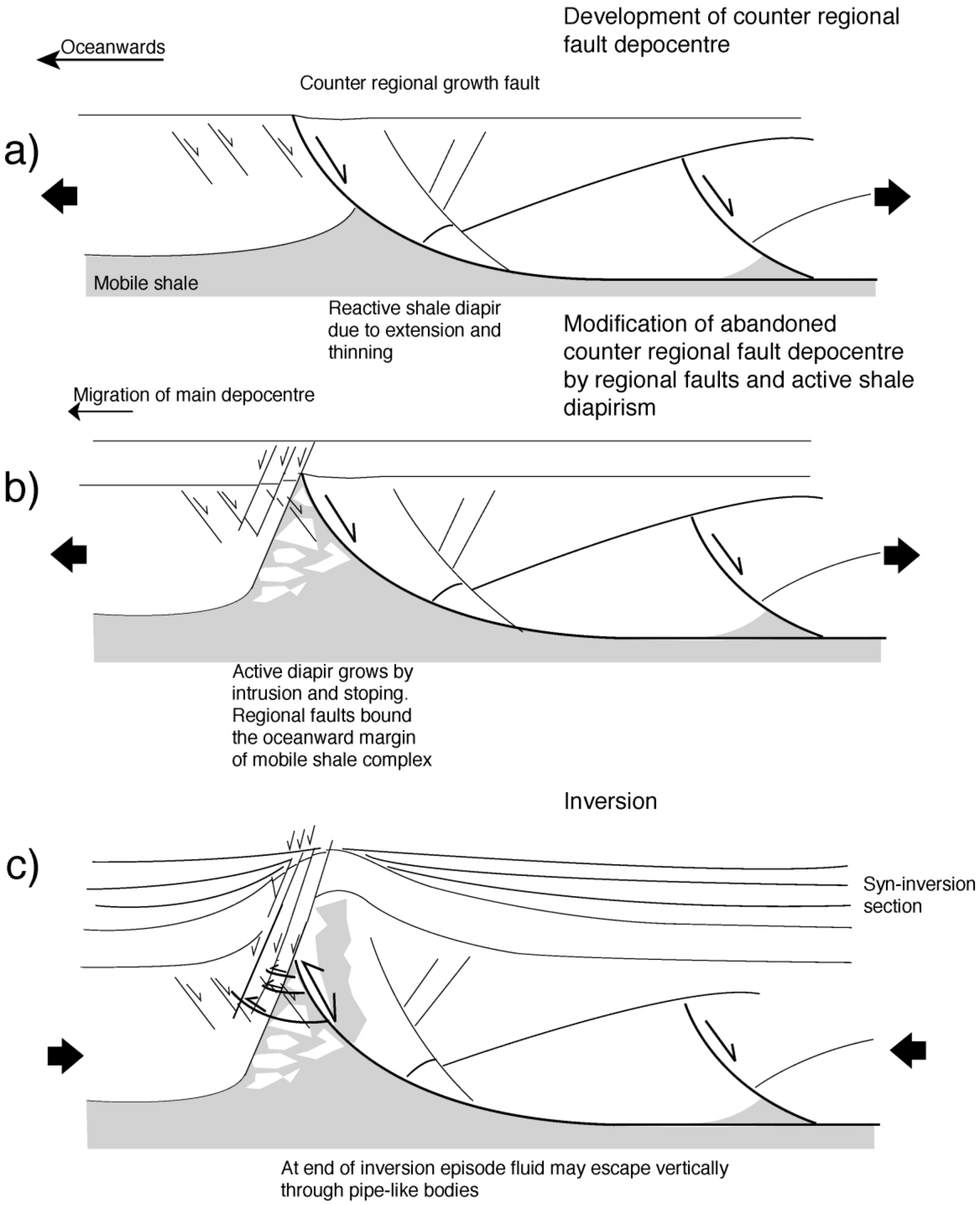


Fig. 16. Schematic evolution of a NE–SW-striking inversion anticline over a counter-regional fault depocentre associated with the offshore area where a detached style of deformation is dominant. Based on the Seria, Miri and Ampa anticlines.

distal within the foredeep basin that the Middle Miocene is a predominantly shale-prone sequence (Sandal, 1996; Fig. 2). Large counter regional faults are commonly the dominant early major growth faults found in large deltas (Morley and Guerin, 1996), and NW Borneo is no exception (e.g. Sandal, 1996; Van Rensbergen et al., 1999; Figs. 2 and 11). A series of oceanward-propagating counter-regional faults and/or expulsion synclines can be seen associated with depocentres younging from the Middle to Late Miocene, progressing from the Seria to the Ampa anticlines (Fig. 2; Van Rensbergen and Morley, 2000). Capping the counter-regional faults is a section that does not expand significantly into major depocentres (due to progradation of the depocentres further offshore), it is affected by relatively small regional faults (Fig. 16). Active growth of the diapir by intrusion and stoping partially replaces the stratified units, in a triangular zone bounded by divergent regional and counter regional faults (e.g. Morley et al., 1998; Van

Rensbergen et al., 1999). Compression or transpression caused inversion of selected faults and folding. The fold axis underlies the footwall area of the counter regional faults and it appears that the folds nucleated at the sites of reactive shale diapirs in the footwalls of the counter regional faults; a relationship noted earlier by Harper (1975) for the Seria anticline (also see Watters et al., 1999). The folds verge towards the NW, and are underlain by large counter regional fault depocentres. Early normal faults (predominantly counter regional faults) have been rotated during Late Miocene and Pliocene folding. Superimposed on the folds are late regional normal faults located at the fold crest and forelimb. Selective reactivation of the normal faults by reverse or strike-slip motions has been reported in Sandal (1996).

Counter-regional faults are inverted because they are the most common, large fault system found onshore and near-offshore. Where regional faults are present, such as the Miri anticline, they too are inverted.

Deposition of thick deltaic sediments on an active margin has resulted in a complex interplay between gravity-related structures and a growing fold and thrust belt. Previously the evolution of the margin has been explained as mostly due to strike-slip reactivation of basement wrench faults (Levell, 1987; Sandal, 1996). However, evidence for important strike slip motion is debatable.

Sinistral offset of sedimentary facies along N–S trends has been cited as evidence for large displacements (Hazebroek and Tan, 1993). However, this evidence is problematic because across the Sengkurong–Morris fault line the 11 and 12 Ma shelf edges show less ‘sinistral’ offset than the younger 8.5 Ma shelf edge (Sandal, 1996). It would be unlikely for a strike-slip fault to display its greatest offset on the youngest marker. The alternative explanation is that syn-depositional structural control on bathymetric highs and lows strongly influenced the location of sedimentary facies.

Field evidence for significant strike-slip offset on important N–S trends is lacking. Data from the Jerudong anticline shows little evidence for any strike-slip faulting (Morley et al., 1998). The Muara and BSB fault zones show evidence for a mixed contractional/transpressional and transtensional/extensional history and at least show for some episodes a sinistral component of displacement. However, vertical motions appear to have dominated over horizontal motions.

Here it is suggested that the NNW–SSE to NNE–SSW oblique trends are better understood when considered as largely thrust-related features, which display different structural geometries depending upon the degree to which decoupling from basement, of the section overlying the Setap Formation, has occurred (Fig. 5). In Fig. 5 the basement thrust is simplified to represent a ramp flat geometry. The basement structure is a deformed accretionary prism complex that must thin and terminate northwards, to be replaced across a suture by thinned continental crust of the Dangerous Grounds passive margin (Fig. 2). Hence lateral variations and pre-existing structures are likely to cause complex thrust geometries at depth that presently cannot be determined. However, it is the nature of the decoupling, not the deep thrust geometry that is the emphasis here.

Onshore the Belait Formation is mostly coupled to the underlying accretionary prism ‘basement’; passing offshore it becomes increasingly more detached (Figs. 5 and 13), resulting in a considerable change in structural style along the axis of major N–S structures such as the Jerudong anticline. The attached style of deformation (onshore Brunei) displays N–S to NE–SW-striking folds, which are most commonly associated with major west-verging thrusts. Folding lasted from the Middle to Late Miocene. Relatively tight folds affect a very thick sedimentary sequence (in excess of 12 km), but are essentially fault tip and frontal ramp folds (Fig. 5).

The transitional detached style of deformation (north-eastern onshore Brunei–Berakas syncline) is characterised by E–W- to NE–SW-striking early growth faults and shale intrusions, which are rotated by Middle–Late Miocene folding. Generally the normal faults are not inverted. Folds are associated with N–S-striking thrusts in their core. Post-folding shale intrusions affect the Jerudong anticline. Along some N–S fault zones (e.g. BSB fault zone) there is evidence for transtensional and transpressional phases of deformation.

The offshore detached style is characterised by NNW–SSE to NNE–SSW-striking folds oblique to the margin. They are inferred to be associated with thrust-related folds at depth, similar to those seen onshore (Fig. 5). The thrusts are not well imaged on seismic data. The upper levels of the folds that are imaged show NE–SW- and N–S-striking conjugate extensional faults and some faults with oblique motion. The faults are at various stages of rotation due to folding. The strike of individual normal faults may vary from NE–SW to N–S with depth. The folds tend to verge westwards. Lower sedimentary packages may expand towards normal faults located on the forelimb of the folds. High in the section sedimentary packages thin onto the crests the folds indicating syn-depositional folding.

NE–SW-striking folds have the following characteristics. They are best developed in areas where the Setap Formation causes detached deformation. They developed either on accretionary prism basement that lies beyond the Miocene thrust front or on Dangerous Grounds thinned passive continental margin basement. Inversion folds are most commonly located over early NE–SW-striking counter-regional faults and associated reactive diapirs (Seria, Ampa, SW Ampa, Punyit anticlines). Late Miocene–Pliocene anticlines change vergence depending upon whether regional (verge onshore) or counter regional faults (verge offshore) are inverted. Complex arrays of conjugate normal and oblique-slip faults offset the region around the fold axis. Outcrop and seismic show most normal faults ($>90\%$) display no evidence of inversion. Important

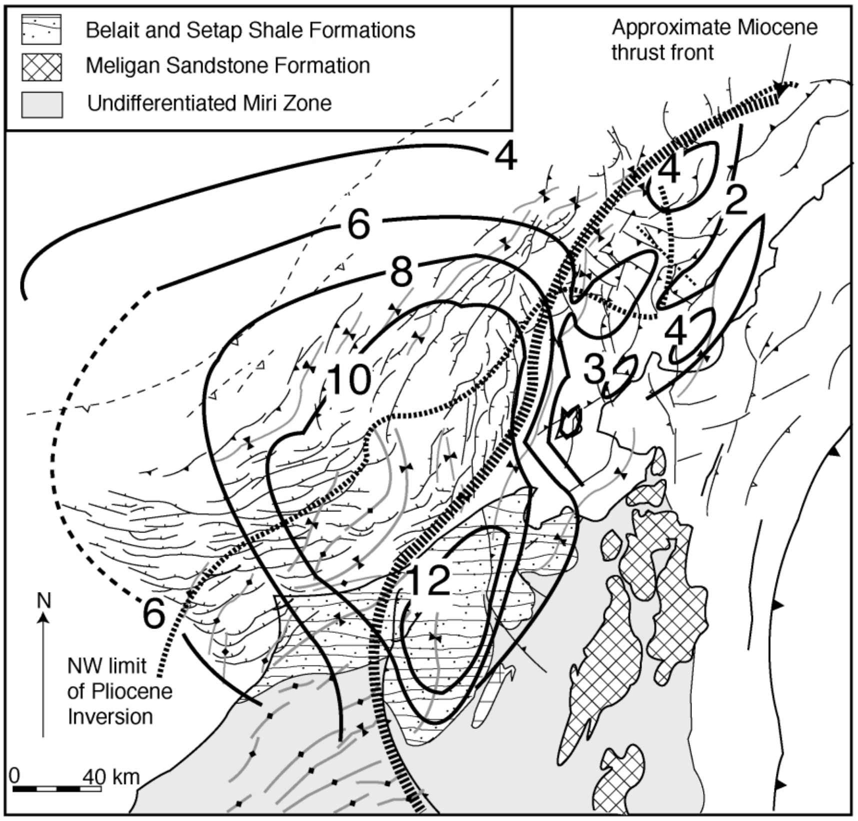


Fig. 17. Regional geological map of NW Borneo (extracted from Fig. 1) with isopach map for the Middle Miocene–Recent section (contours in kilometres) superimposed. Approximate western to northern limits of the Middle Miocene thrust front and Pliocene inversion front are also shown. These limits are derived from data in Levell (1987), Sandal (1996) and unpublished data. Note the isopach thick is very much focused on Brunei. The onshore 12 km isopach thick is related to the Middle Miocene Belait and Setap Formations, while offshore the isopach thick is related to the same formations but of Middle Miocene–Recent age. The shift in depocentre location marks uplift due to shortening and isostacy.

inverted normal faults lie close to the fold forelimb. Minor low-angled thrust faults are found in areas where normal faults have been inverted, they occur most frequent in the steeply dipping forelimb (Fig. 15). Possibly the NE trend at the northern end of the Limbang syncline, and the Belait anticline are associated with the Late Miocene–Pliocene folding.

The N–S basement trends are probably thrusts associated with Middle Miocene–Late Miocene E–W compression. During the Late Miocene the maximum principal stress probably rotated to a more NW–SE direction similar to the modern Sh1 orientation (Sh = horizontal principal stress, Sv = vertical principal stress). This rotation may reflect changing regional stress regimes as obduction of the Darvel Bay ophiolite ceased, and continued deformation resulted from the final stages of the Dangerous Grounds continental crust underthrusting the Rajang–Crocker accretionary complex and complex plate interactions.

In Sabah the timing and location of folding and faulting has changed with time, which is explained as varying activity on different underlying basement fault blocks (Bol and van Hoorn, 1980; Levell, 1987). In this paper it is suggested that for Brunei in the Middle Miocene N–S-trending folds and thrusts were initiated, and that later, particularly in the Pliocene, NE–SW-trending folds were dominant with some reactivation of N–S features. An example that displays this particularly well is the onshore Middle Miocene N–S-trending Belait anticline, which is unconformably overlain by the Late Miocene–Pliocene Liang Formation, which is folded by the NE–SW-trending Badas syncline and Miri anticline (Fig. 3). It is suggested here that for lower levels in the sedimentary pile approximately E–W-trending Middle–Late Miocene Sh1, Sv3 was replaced by NW–SE-trending Sh1, Sv2 or Sv3 in the Pliocene.

The modern state of stress tends to be complex in a detached environment (Bell, 1996). Tingay et al. (2002) show how the vertical change in the state of stress is associated with changes in pore fluid pressure and change from stresses typical for gravity tectonics (extension) in the upper parts of wells, to stresses typical for contractional or strike-slip deformation in the lower parts, so that today Sh1 is oriented NW–SE, approximately perpendicular to the coastline and the inferred strike-slip shear couple (Watters et al., 1999; Tingay et al., 2002). This implies that contraction, rather than strike-slip, dominated the development of at least the younger structures. The modern stress orientation seems compatible with the Pliocene inversion structures. Consequently in this study the ENE–WSW to NE–SW fold trends are interpreted to be non-basement related detached trends following predominantly Middle Miocene regional and counter-regional growth faults and associated reactive diapirs. The regional structural geometry as illustrated in Fig. 5 fits very well with thrusting exerting the primary control. Any local strike-slip motions occur within the large-scale fold and thrust framework. In particular decoupling above the Setap Formation may permit local strike-slip faults to develop.

Fig. 17 shows that the major Middle Miocene–Recent depocentre has remained focused in the offshore and onshore areas of Brunei where sediments reach thicknesses of 10–12 km. In Sabah thicknesses in excess of 4 km are rarely attained (e.g. Mazlan Madon et al., 1999). This reflects the configuration of drainage patterns in the hinterland and the location of the Miocene thrust fronts. In the early Middle Miocene, onshore sedimentation marked by the 12 km isopach occurred in an undeformed, shallow marine foreland setting. The main surface expression of thrusting and folding must have lain to the east and southeast. In Sabah, however, it would appear that thrusting had already affected the present day shelf region (Levell, 1987). Thrusting propagated to the west in Brunei during the Middle Miocene, deformed the foredeep basin, generated the Belait and Berakas synclines, and progressively forced the depocentre offshore. Foreland propagation of compressional/transpressional deformation is pronounced in the southern half of Fig. 2 and absent in the northern half.

The timing of deformation described above is similar to that determined for the Kutai basin on the eastern Borneo margin where McClay et al. (2000) noted that contractional reactivation of growth faults associated with compressional stresses occurred after 14 Ma, with particularly pronounced phases of contraction occurring after 10 and 5.5 Ma. They also concluded on the basis of sandbox experiments using a variety of structural styles (inverted rifts, inverted growth faults, strike-slip) that contractional inversion of growth faults best matched the observed geology. However, there is less development of oblique structures in the Kutai Basin compared with the Baram Basin.

The structural evolution of Brunei during the Middle Miocene–Recent comprises the following key elements (Fig. 13):

1. Development of a foreland basin up to 12 km thick during the Middle Miocene. NW of the foreland basin lay a sediment-starved deep marine basin (Hutchison, 1996a) that was later filled by prograding sediments from the Baram and Champion deltas.
2. Progradation of the Middle Miocene section occurred first over a stable substratum, then as the delta complex prograded further to the NE a mobile shale substratum was encountered and gravity features (growth faults, diapirs, toe thrusts) developed. The growth faults strike predominantly NE–SW, although other orientations are also present, including E–W and N–S.
3. During the Middle Miocene an arcuate thrust belt comprising N–S- to NE–SW-trending folds and thrusts propagated into the foredeep basin. The Jerudong and Belait anticlines, Muara and BSB fault zones appear to have undergone prolonged growth during the late Middle Miocene and Upper Miocene, as indicated by sedimentary thinning, onlaps and progressive changes in dip (Figs. 5 and 10). Offshore the effects of this early deformation phase are more subtle than onshore.
4. Commencing around 7.5 Ma (Watters et al., 1999), Late Miocene–Pliocene folding along NE–SW-trending anticlines, and some N–S-trending segments occurred predominantly along the modern coastline and offshore area (Figs. 5 and 13). These folds are more widespread offshore than the Middle Miocene folds. Folds are located over reactive shale diapirs associated with counter-regional faults (Ampa, Seria and Champion anticlines; Figs. 11 and 14), regional faults (Miri anticline), and segments of N–S trends (Iron Duke-Bugan; Magpie; Scout Rock) (Fig. 3). Most of the onshore N–S-striking, attached fold and fault zones appear to have been inactive during this phase (Figs. 5 and 13). However onshore the NE–SW-striking Badas syncline was superimposed on the older N–S-striking Belait anticline trend. Enhanced fluid movement and shale injection at the end of a phase of inversion occurred, and gave rise to the development of pipe-like shale intrusions up to 1 km in diameter (Van Rensbergen et al., 1999; Figs. 13 and 16).

7. Conclusions

The evolution of deformation in Brunei and Sarawak is significant for understanding the regional tectonics of NW Borneo, and for providing a general model for how detached inversion structures can occur within gravity related structures of deltas on active margins. The model proposed is similar to that developed for the Kutai basin on the eastern margin of Borneo (Ferguson and McClay, 1997; McClay et al., 2000), who also emphasis the importance of distinguishing attached and detached structures. This paper adds geological detail about the timing of structures, impact of shale intrusions, basement type, and effects of variable thickness mobile shale on deformation style. The similar timing of inversion events in the Kutai and Baram basins (middle Miocene, late Miocene, Pliocene), suggests important regional stress affected the whole of northern Borneo.

The model for the development of folds on the deltaic margin stresses:

1. The development of a N–S-striking, west-propagating Middle–Late Miocene fold and thrust belt (E–W Sh1?).
2. Changes in deformation style related to increasing detachment of the Middle Miocene–Recent section from basement passing in a northerly direction, due to depositional thickening of the overpressured Setap Formation.
3. Interaction of detached, predominantly NE–SW-striking structures and attached NNW–SSE- to NNE–SSW-striking structures.
4. The importance of large, Middle–Late Miocene counter regional and regional growth faults in controlling the location of Pliocene inversion anticlines (NW–SE Sh1?).
5. Phases of reactive diapirism associated with gravity extensional tectonics and forceful shale intrusions, especially pipes following or during episodes of inversion.
6. Evolution from a foreland basin to a growth fault margin with time.
7. The regional thrust belt configuration created a drainage pattern that resulted in a remarkably persistent depocentre thick centred on the onshore and offshore Brunei area (when compared with adjacent areas of the margin).

Acknowledgements

This paper is partly a summary of work that has involved numerous M.Sc. student projects conducted at the University of Brunei Darussalam, for many of the projects Brunei Shell provided subsurface data. T. Dooley and two anonymous reviewers are thanked for making very constructive reviews of earlier versions of this manuscript.

References

Back, S., Morley, C.K., Simmons, M.D., Lambiase, J.J., 2001. Depositional environment and sequence stratigraphy of Miocene deltaic cycles exposed along the Jerudong anticline, Brunei Darussalam. Journal of Sedimentary Research 71, 915–923.

Bait, B., Banda, R.M., 1994. Tertiary basins of North Sarawak Malaysia: a field excursion in the Tatau–Bintulu and Miri areas. AAPG International Conference and Exhibition, 21–24 August 1994.

Bell, J.S., 1996. In situ stresses in sedimentary rocks (part 2): applications of stress measurements. Geoscience Canada 23, 135–153.

Bol, A.J., van Hoorn, B., 1980. Structural styles in Western Sabah offshore. Geological Society of Malaysia Bulletin 12, 1–16.

Eisenstadt, G., Withjack, M.O., 1995. Estimating inversion: results from clay models. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion. Geological Society of London, Special Publication 88, pp. 119–136.

Ferguson, A., McClay, K., 1997. Structural modelling within the Sanga Sanga PSC, Kutei Basin, Kalimantan: its application to paleochannel orientation studies and timing of hydrocarbon entrapment. Proceedings of the Petroleum Systems of SE Asia and Australasian Conference, May 1997, Indonesia Petroleum Association, pp. 727–749.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geological Society of London, Special Publication 106, pp. 203–224.

Harper, G.C., 1975. The discovery and development of the Seria oilfield. Penerbitan Khas Bil, 10, Muzium Brunei, Bandar Seri Begawan, Brunei, 99pp.

Hazebroek, H.P., Tan, D.N.K., 1993. Tertiary tectonic evolution of the NW Sabah continental margin. Geological Society of Malaysia Bulletin 33, 195–210.

Hutchison, C.H., 1996a. South-East Asian Oil, Gas, Coal and Mineral Deposits, Oxford University Press, 368pp.

Hutchison, C.H., 1996. The 'Rajang accretionary prism' and 'Lupar Line' problem of Borneo. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geological Society of London, Special Publication 106, pp. 247–261.

Hutchison, C.H., Bergman, S.C., Swauger, D.A., Graves, J.E., 2000. A Miocene collisional belt in north Borneo: uplift mechanism and isostatic adjustment qualified by thermochronology. Journal of the Geological Society of London 157, 783–794.

James, D.M.D., 1984. The Geology and Hydrocarbon Resources of Negara Brunei Darussalam. Special Publication, Muzium Brunei and Brunei Shell Petroleum Company Berhad.

Levell, B.K., 1987. The nature and significance of regional unconformities in the hydrocarbon-bearing Neogene sequences offshore West Sabah. Geological Society of Malaysia Bulletin 21, 55–90.

Mazlan Madon, Bin Hj., Meng, L.K., Anuar, A., 1999. Sabah Basin. In: Anonymous, (Ed.), The Petroleum Geology and Resources of Malaysia, Petronas, Kuala Lumpur, pp. 501–542.

McClay, K., Dooley, T., Ferguson, A., Poblet, J., 2000. Tectonic evolution of the Sanga Sanga block, Mahakam Delta, Kalimantan, Indonesia. AAPG Bulletin 84, 765–786.

Morley, C.K., Guerin, G., 1996. Comparison of gravity-driven deformation styles and behaviour associated with mobile shales and salt. Tectonics 15, 1154–1170.

Morley, C.K., Crevello, P., Zulkifli, A., 1998. Shale tectonics-deformation associated with active diapirism: the Jerudong Anticline, Brunei Darussalam. Journal of the Geological Society of London 155, 475–490.

Rich, J.L., 1934. Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust block, Virginia, Kentucky and Tennessee. AAPG Bulletin 18, 1584–1596.

Sandal, S.T., 1996. The Geology and Hydrocarbon Resources of Negara Brunei Darussalam (1996 revision). Brunei Shell Petroleum Company/Brunei Museum, Syabas Bandar Seri Begawan, Brunei Darussalam, 243pp.

Sibson, R.H., 1995. Selective fault reactivation during basin inversion: potential for fluid redistribution through fault-valve action. In: Buchanan, J.G., Buchanan, P.G. (Eds.), Basin Inversion, Geological Society of London Special Publication 88, pp. 3–19.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding. American Journal of Science 283, 684–721.

Tingay, M.R.P., Hillis, R.R., Morley, C.K., Swarbrick, R.E., Okpere, E.C., 2002. Pore pressure-stress coupling in the Baram Basin, Brunei Darussalam, implications for shale mobilisation. Special Publication of the Geological Society, in press.

Van Rensbergen, P., Morley, C.K., 2000. 3D seismic study of a shale expulsion syncline at the base of the Champion delta, offshore Brunei and its implications for the early structural evolution of large delta systems. Marine and Petroleum Geology 17, 861–872.

Van Rensbergen, P., Morley, C.K., Ang, D.W., Hoan, T.Q., Lam, N.T., 1999. Structural evolution of shale diapirs from reactive rise to mud volcanism: 3D seismic data from the Baram delta, offshore Brunei Darussalam. Journal of the Geological Society of London 156, 633–650.

Watters, D.G., Maskall, R.C., Warrilow, I.M., Liew, V., 1999. A sleeping giant awakened: further development of the Seria Field, Brunei Darussalam, after almost 70 years of production. Petroleum Geoscience 5, 147–159.

Wilford, G.E., 1960. The geology and mineral resources of Brunei and adjacent parts of Sarawak with description of Seria and Miri oilfields. Memoir 10 the Geological Survey Department, British Territories in Borneo, 2nd edition, Brunei State, 319pp.