Journal of Structural Geology 31 (2009) 1540–1555

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Geometry of an oblique thrust fault zone in a deepwater fold belt from 3D seismic data

Chris Morley [a,b,*]

[a] Baan Yosawaadi, Soi Ari, Phahonyohothin, Bangkok, Thailand

[b] Department of Petroleum Geoscience, Universiti Brunei Darussalam, Tunku Link, Bandar Seri Begawan, Brunei Darussalam 10900, Thailand

ARTICLE INFO

Article history:
Received 29 June 2008
Received in revised form
23 August 2009
Accepted 30 August 2009
Available online 17 September 2009

Keywords:
Deepwater
Thrust
Oblique fault
Fold
Normal fault

ABSTRACT

Growth of a 12 km long, deepwater anticline during the late Pliocene–Recent is documented from 3D seismic reflection data across NW Borneo. The fold is part of a train of folds formed along the slope at the distal margin of the Baram Delta Province. Growth of the anticline involved fold lateral propagation and linkage of two thrusts formed in the anticline forelimb as either break thrusts or as imbricates ramping up from a master detachment (at ~3 km depth). For the southwestern anticline, the northern tip of the NE–SW striking, SE-dipping thrust passes into an E–W striking oblique termination, which lies in the linkage zone between the two anticlines. The thrust termination is characterised by the following changes passing east towards the fault tip: 1) the fault zone dips steeply to the south, then 2) passes to a vertical segment (inferred to have oblique motion), and 3) furthest east the fault dips northwards with an extensional component of displacement. The fault zone terminates in a transtensional graben. This graben does not fit with a simple pull-apart geometry or simple oblique ramp geometry. In the future if the thrust faults propagate together and link this oblique fault zone may develop into an oblique ramp that acts as a transfer zone between the faults. However at present the oblique fault zone appears to be a region of 3D strain, where deformation at the fault tip, and the gravity effects of plunging folds have affected the shallow, weak sediments and given rise to a complex thrust termination at a early stage of thrust and fold development. The oblique structure may have developed in response to strains imposed by the encroachment of the fold and thrust belt on an uplifted basement or volcanic high that forms a pronounced topographic feature across a narrow part of the thrust front, 14 km NW of the most external (oceanward) fold.

1. Introduction

Lateral and oblique ramps in thrust faults are a common feature of compressional belts (e.g. Rich, 1934; Dahlstrom, 1970; Goldburg, 1984; Couzens and Dunne, 1994; Castonguay and Price, 1995; Apotria, 1995; Holl and Anastasio, 1995; Fermor, 1999; Rowan and Linares, 2000; Soto et al., 2002). However, the range of natural possible oblique ramp or other oblique fault geometries in three dimensions is poorly known (Wilkerson et al., 2002). To properly image oblique structures requires 3D seismic data, which is only rarely acquired in typical onshore fold and thrust belts. Consequently the geometries of lateral and oblique structures in thrust belts are known in most detail from analogue modelling (e.g. Apotria et al., 1992; Wilkerson et al., 1992; Dubey, 1997; Schreurs et al., 2002; Soto et al., 2002). This paper describes an example of an oblique fault system associated with an anticline (IX) in a deepwater fold and thrust belt from offshore Brunei Darussalam (Figs. 1 and 2).

2. Geological background and tectonic history

The NW margin of Borneo has been extensively explored for hydrocarbons, and as a result the shelf and upper slope areas of Brunei, Sabah and Sarawak are well known from drilling and seismic reflection data. Several books summarising the data have been published (James, 1984; Sandal, 1996; Petronas, 1999). Prior to the Miocene northern Borneo was largely submerged, and is thought to have occupied a position in the upper plate of a subduction zone, whose associated accretionary prism is represented by the folded and thrusted deepwater Rajang and Crocker Formations that outcrop in NW Borneo (Figs. 3 and 4; James, 1984; Lambiase et al., 2007). The proto-South China Seas oceanic crust is thought to have formed the lower plate, which was subducted to the SE beneath Borneo (e.g. Hazebroek and Tan, 1993; Hall, 2002).

* Tel.: +66 02 538 4624.
E-mail address: chrissmorley@gmail.com

0191-8141/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2009.08.015

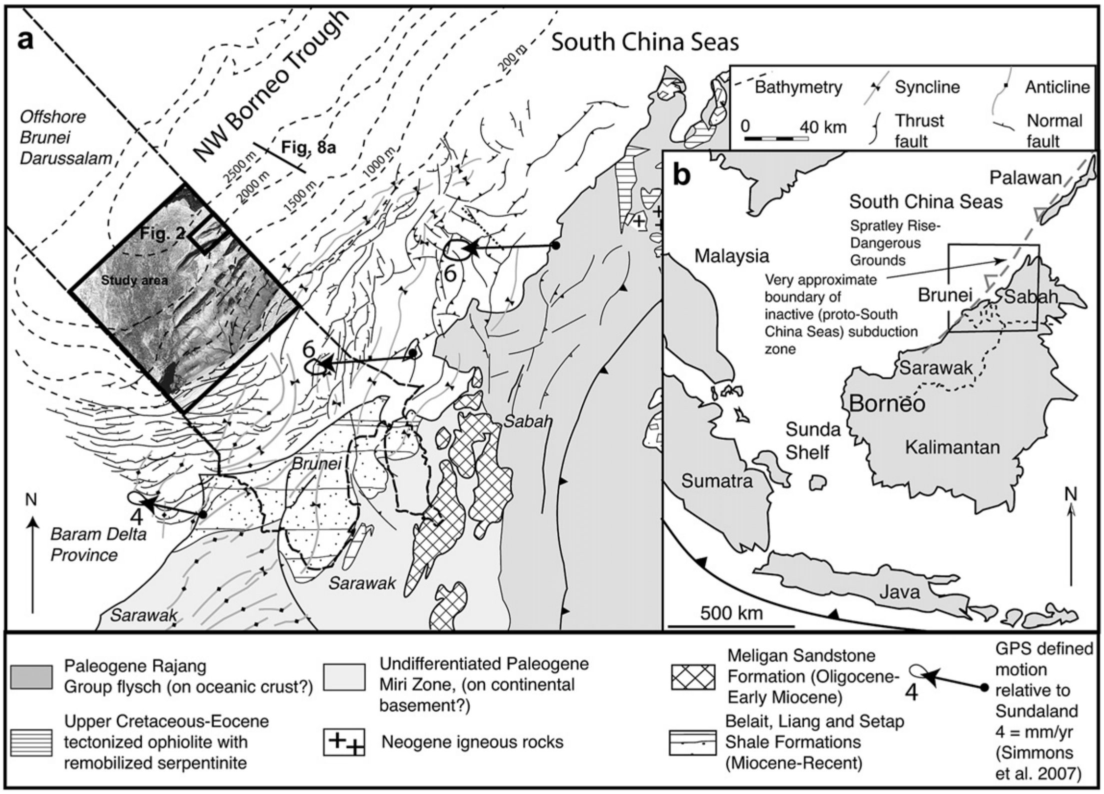

Fig. 1. a) Map of NW Borneo showing location of the NW Borneo trough and study area, offshore Brunei Darussalam. b) SE Asia location map. Modified from Morley and Back (2008).

The deepwater sequences were uplifted during the Miocene, when the relatively buoyant, thinned continental crust of the Dangerous Grounds Crust entered and jammed the subduction zone (e.g. Levell, 1987; Hutchison et al., 2000). Consequently Borneo became uplifted and eroded, and shed huge quantities of sediment onto the margin of the island during the Miocene–Holocene (Hall and Nichols, 2002; Morley and Back, 2008). As a result of uplift and high rates of sediment supply, the Miocene–Holocene shelf of NW Borneo in general, and Brunei in particular is dominated by prograding shallow marine sequences of Middle Miocene–Recent age, which in places attain thicknesses in excess of 10 km. The Miocene–Holocene depocentre in Brunei is known as the Baram Deltaic Province; it is deformed by growth faults, shale diapirs, folds, thrusts and inversion-related anticlines (Morley et al., 2003, 2008). Gravity-driven deformation has occurred by rapid progradation of sand and shale dominated deltaic sequences comprising the Belait and Liang Formations, over a thick marine shale sequence (Setap Formation; Fig. 3). The Setap Formation is composed of overpressured, mobile shales that have flowed and deformed in response to sediment loading by the Belait and Liang Formations.

The general structural evolution of the delta is marked by progradation of growth faults from the onshore area during the Middle Miocene, towards the offshore with time. At the present day, the most active growth faulting occurs around the outer shelf-uppermost slope (Figs. 4 and 5). The Baram Deltaic Province is not a classic passive margin delta because it has been subject to thrusting, folding and inversion of growth faults in the proximal part of the province from the late Middle Miocene to the early Pliocene (Sandal, 1996; Morley et al., 2003, 2008; Figs. 4 and 5).

At the offshore (distal) end of the deltaic province is another fold and thrust province located on the slope in the deepwater equivalents of the extensively drilled Baram Delta Province Middle Miocene–Recent shelfal sequences (Fig. 4). The slope dips between one and three degrees into the deepest region of the South China Seas: the Northwest Borneo trough. 2D seismic data have shown the NW Borneo trough marks the site of inactive subduction where thinned continental crust of the Dangerous Grounds block entered the subduction zone (Levell, 1987; Hall, 1996). The existence of the fold-thrust belt has been established by sparse industrial and academic 2D seismic lines (James, 1984; Hinz and Schluter, 1985; Hinz et al., 1989; Sandal, 1996; Schluter et al., 1996; Pin and Hailing, 2004). The 2D seismic data shows an extensive train of folds spaced between 5 and 15 km apart affects the slope, and generally verge offshore. They are predominantly folds associated with imbricate thrusts that sole out at depth into one or more detachments (e.g. Franke et al., 2008; Hesse et al., 2008). The thrust belt has a classic taper geometry, with the basal decollement dipping shelfward. At the shelf-slope break the detachment probably lies at a sub-seafloor depth of about 10 km, while at the thrust front the depth is about 3 km (Morley, 2007a).

The present-day fold-thrust belt is largely of latest Miocene–Recent age (Sandal, 1996; Ingram et al., 2004). Deformation is unrelated to past subduction of oceanic crust. The active folds trend NE–SW, parallel to the old subduction zone and the ancient subduction zone appears to have continued to act as a major zone of weakness in the crust (Hall and Morley, 2004). GPS data shows that northern Borneo is moving west at about 4–6 mm/yr with respect to Sundaland (i.e. Palawan, South Borneo, Peninsula Malaysia and Indochina; Simmons et al., 2007)). This motion is oblique to the NE–SW striking folds of the continental slope and oblique to the modern maximum horizontal stress direction (NW–SE) determined for the shelf immediately adjacent to the GPS points (Tingay et al., 2005; King et al., 2009). The stress tensor for the deepwater area is a combination of gravity-driven deformation