Vietnamese sedimentary basins: geological evolution and petroleum potential

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A number of sedimentary basins of various ages are located on- and offshore Vietnam (Fig. 1). Some of them have significant petroleum resources and have thus attracted interest from industry and academia (Rangin *et al.* 1995; Matthews *et al.* 1997; Lee & Watkins 1998; Lee *et al.* 2001). Moreover, Vietnam is located in a position central to the understanding of the geological development of South-East Asia (Hall & Morley 2004). The structural style and the stratigraphy of the Vietnamese basins thus provide a valuable record about the development of South-East Asia throughout the Phanerozoic and the subsequent Eocene as well as younger deformation associated with the collision and indentation of India into Eurasia and the opening of the South China Sea (Fyhn *et al.* 2009a, 2010a).

The Geological Survey of Denmark and Greenland has worked in Vietnam since 1995 to assess the geology and petroleum potential of the Vietnamese basins. Since 2002 the work has been carried out in cooperation with the Department of Geography and Geology, University of Copenhagen, as part of the ENRECA project (Enhancement of Research Capacity in Developing Countries). An integrated part of the project is its training of Vietnamese MSc and PhD students incorporating both training courses at the Department of Geography and Geology and courses held in Vietnam. So far, 10 MSc and 4 PhD students have completed their training under the auspices of the ENRECA project and another 10 are expected to complete their education within the next phase of the project.

The ENRECA project has already completed two phases and a third and final phase has recently started. The initial phase focused on the Phu Khanh and the Song Hong Basins located in the South China Sea offshore north and central Vietnam and the smaller onshore Song Ba Trough (Fig. 1; Bojesen-Koefoed *et al.* 2005; Nielsen *et al.* 2007; Fyhn *et al.* 2009a, b, c). During the second ENRECA phase, completed in 2009, attention shifted towards the Malay – Tho Chu and Phu Quoc basins located in the Gulf of Thailand, SSW of Vietnam (Petersen *et al.* 2009, in press; Fyhn *et al.* 2010a, b). The Phu Quoc Basin continues onshore to the north to form part of the mountainous area between Vietnam and Cambodia. In the recently started third phase of the project, the focus remains on the Phu Quoc Basin in addition to a revisit to the Song Hong Basin on the north Vietnamese margin and onshore beneath the Song Hong (Red River) delta.

The Phu Quoc Basin

The Phu Quoc Basin stretches in a 100–150 km broad belt from the central part of the Gulf of Thailand *c.* 500 km northwards to central Cambodia. The basin is Late Jurassic to Cretaceous in age but is one of the least explored basins in the region and remains to be drilled offshore (Fyhn *et al.* 2010a). In order to assess the geological evolution and the petroleum potential of the basin, regional seismic analyses of the Vietnamese part of the basin were carried out in combination with drilling of the fully cored, 500 m deep ENRECA-2 well on the Phu Quoc island. Data from the ENRECA-2 well were complemented by data from outcrop studies on Phu Quoc and in Cambodia.

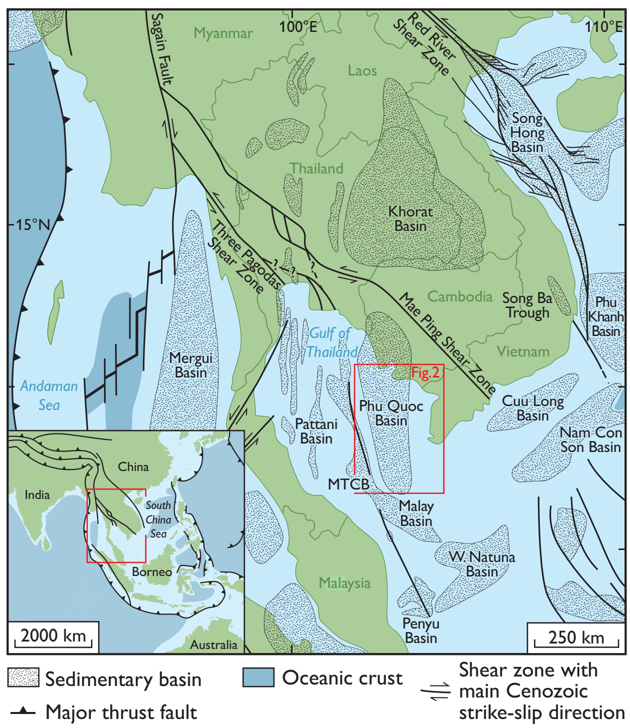


Fig. 1. Map of South-East Asia showing the locations of sedimentary basins and areas underlain by oceanic crust. Strike-slip arrows illustrate the prevailing Eocene–Recent offset directions. **MTCB**: Malay – Tho Chu Basin. The inset map shows a simplified structural outline of the region. Modified from Fyhn *et al.* (2010b).

Alluvial sandstones with an average of *c.* 10% rhyolite-dominated lithic fragments make up the greater part of the up to *c.* 4 km thick sediments filling the Phu Quoc Basin. Only a few, minor, shallow marine sandstone beds have been encountered in the terrestrially dominated succession. The sandstone-dominated succession is intercalated with subordinate alluvial plain and lacustrine silt- and mudstone intervals. Coal fragments are abundant at specific stratigraphic levels but do not contribute to any source potential.

The thicknesses of the deposits are not affected by syn-sedimentary faulting, but gradually increase towards the east, where a coeval, Jurassic–Cretaceous, magmatic arc parallels the eastern basin flank (Fig. 2). This is compatible with a retroarc–foreland basin setting associated with the growth of the magmatic arc located east of the basin that also served as a primary source of sediments for the basin. A distinct basin inversion is indicated by a prominent angular unconformity that caps the Mesozoic basin fill and is associated with spectacular thrust faulting and folding (Fig. 3). The structural complexity increases towards the deeply eroded and hitherto undescribed fold belts that confine the basin to the east and west. The stratigraphic level of erosion increases towards these orogenic belts. Palaeozoic and Lower Mesozoic igneous and sedimentary rocks therefore crop out on small islands and onshore, or subcrop towards the base of the Cenozoic within the Kampot Fold Belt flanking the basin to the east. The inversion unconformity is underlain by Lower Cretaceous deposits and overlain by Middle Eocene and younger deposits, which provide only modest information on the age of the orogenic event. In order to constrain the age of inversion more precisely, apatite fission track analysis (AFTA) was carried out on rock samples from the Kampot Fold Belt collected on islands and in mainland Vietnam. The AFTA samples demonstrate a distinct cooling event that affected the region during the period from Late Paleocene to Early Eocene (Fyhn *et al.* 2010a). The cooling corresponds to uplift and denudation of the area in response to the thrust faulting and basin inversion and thus confines the age of the orogenic event controlling the deformation.

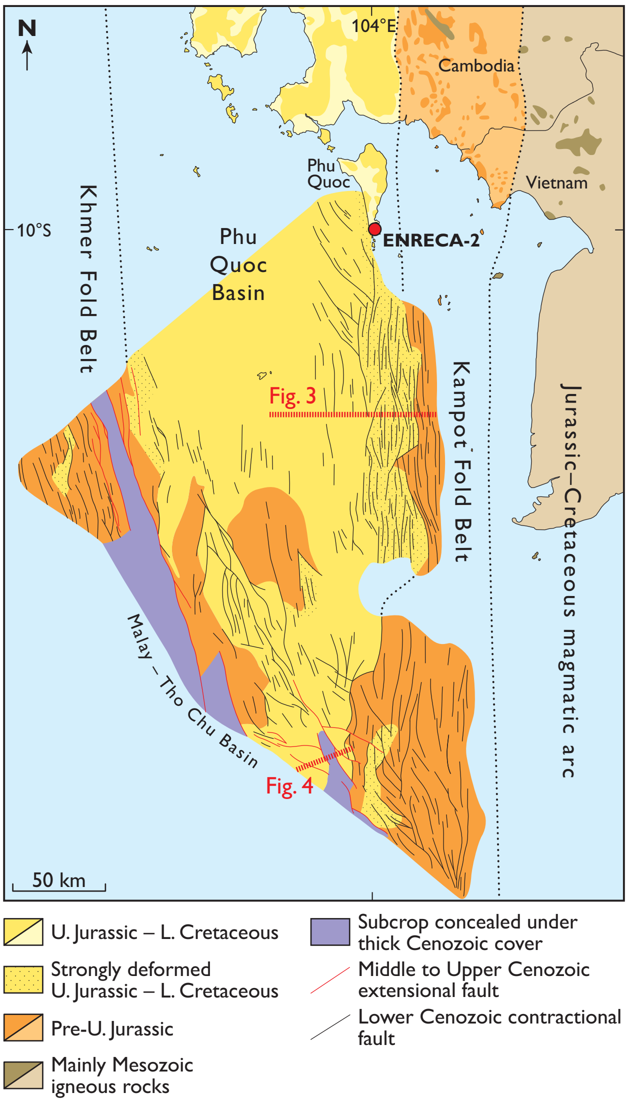
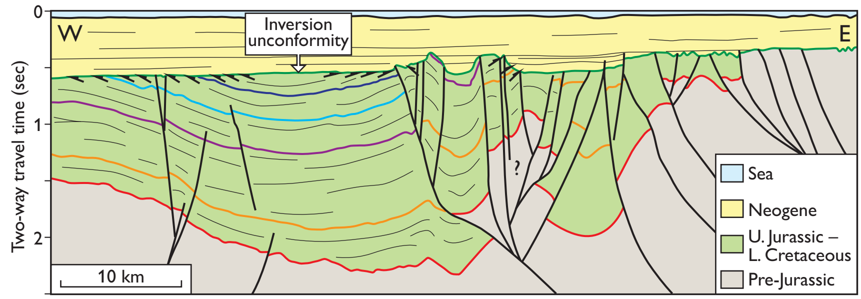


Fig. 2. Subcrop map towards the base Cenozoic top / Mesozoic unconformity outlining the southern part of the Phu Quoc Basin. Fold belts confine the basin to the east and west. Onshore pre-Quaternary outcrops are indicated, outlining the onshore continuation of the Phu Quoc Basin, the Kampot Fold Belt and the SE Indochina Jurassic–Cretaceous magmatic arc. For location see Fig. 1. Modified from Fyhn *et al.* (2010a).

The Malay – Tho Chu Basin

The Malay – Tho Chu Basin constitutes the Vietnamese north-eastern part of the Malay Basin that was initiated somewhere between the Middle and Late Eocene (Fyhn *et al.* 2010b). The Malay – Tho Chu Basin is situated in the central part of the Gulf of Thailand and is therefore superimposed on the southernmost part of the Phu Quoc Basin. Rifting in the area took place between Middle?–Late Eocene and Oligocene time and resulted in the creation of a series of deep grabens filled by continental to shallow marine deposits (Fig. 4; Fyhn *et al.* 2010b). A set of NNW-trending rifts are the dominating structures in the area; they are often distinguished from other, WNW-trending rifts by their downwards steepening, their great depth and their linearity. The NNW-trending rifts seem to have accommodated left-lateral transtension. Large-scale Eocene–Oligocene rifting associated with strike-slip faulting in the region is viewed as a response to the Indian–Eurasian collision that forced the neighbouring parts of South-East Asia away from the collision zone through a series of lateral shear zones (e.g. Tapponnier *et al.* 1986; Fyhn *et al.* 2009a, 2010b), although

Fig. 3. Offshore stratigraphic profile across the Phu Quoc Basin. Jurassic–Cretaceous subsidence was most intense simultaneous with the magmatic arc developing to the east. A prominent inversion unconformity separates the Mesozoic thrust-faulted strata from the truncating unconformity of the base of the Neogene deposits. Modified from Fyhn *et al.* (2010a).



other theories exist (Morley 2002; Hall & Morley 2004; Watkinson *et al.* 2008; Hall 2009). Around the onset of the Miocene, rifting declined and thermal sagging came to dominate throughout the Neogene. This resulted in broadening of the subsiding area and increasing marine influence. Deltaic and shallow marine siliciclastics therefore prevail in the Neogene succession of the basin.

Petroleum exploration in the Malay – Tho Chu Basin began during the early 1970s, encouraged by successful exploration immediately south of Vietnamese territory. The first well was drilled in 1994. Since then, significant gas, condensate and oil discoveries have been made in several wells drilled in this basin, but only a few discoveries are as yet considered commercial. A re-evaluation of the existing exploration strategies is therefore desirable in order to optimise and focus future exploration. Exploration has mainly aimed at Early to Middle Miocene fluviodeltaic sand reservoirs with Late Neogene structural trapping mechanisms. Potential source rocks have been interpreted as alginite-bearing lacustrine shales and humic coals situated in the Palaeogene synrift and in the lowermost post-rift sections.

The few potential source-rock levels penetrated by wells have shown remarkably low vitrinite reflectance (VR) values compared to VR values obtained from overlying Neogene coals (data presented in Petersen *et al.* 2009). The maturity trends of such VR data sets are not well constrained as they produce suspiciously low thermal maturity gradients. However, suppressed VR values may occur in algenite-rich rocks. VR suppression is therefore particularly common in lacustrine shales with high HI (hydrogen index) values. The fluorescence alteration of multiple macerals (FAMM) technique is an accurate method to determine thermal maturity in rocks including those containing vitrinite with suppressed and enhanced VR values (Willkins *et al.* 1992). By combining conventional VR measurements and the FAMM technique a revised, higher and more reliable thermal maturity gradient has been established (Petersen *et al.* 2009). 2-D modelling of the maturation history of the basin was carried out based on the revised thermal maturity gradient, detailed seismic mapping, borehole information and new custom kinetics for petroleum generation; the latter was determined from lacustrine source rock samples and a terrestrially influenced mudstone collected from wells (Petersen *et al.* in press).

Maturation modelling indicates that most of the syn-rift succession in the Vietnamese Malay Basin is located in, or has passed through, the main oil and gas windows. Carbonaceous

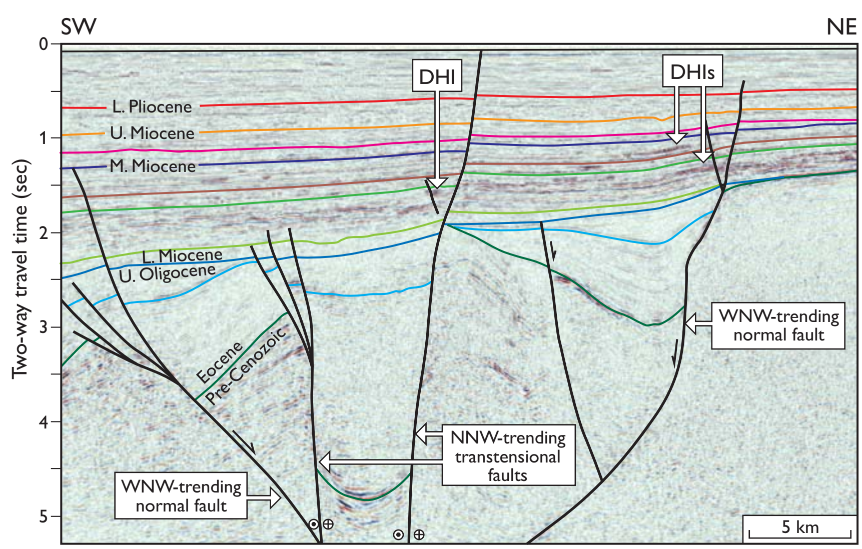


Fig. 4. Seismic transect across a NNW-trending Palaeogene graben bounded by steep transtensional faults and half grabens confined by more gently dipping WNW-trending normal faults that link up with the steep faults at depth. Deposition broadened across basement highs following the Palaeogene synrift period due to regional thermal sagging. DHIs (direct hydrocarbon indicators) within the Miocene succession are frequently associated with structural traps formed during the Late Neogene. Modified from Fyhn *et al.* (2010b).

syn-rift deposits have therefore undergone adequate maturation and may have produced and expelled significant quantities of hydrocarbons. The oldest deposits in the deepest part of syn-rift depressions entered the oil window during the Palaeogene syn-rift period but the main oil generation generally took place during Early and Middle Miocene times. 2-D modelling of the hydrocarbon generation therefore indicates that the main risks in the tested play types are (1) the timing of petroleum generation relative to trap formation completed in the Late Neogene, (2) the pervasive faulting, which may have complicated petroleum migration to the structures and breached charged traps and (3) the distribution and amount of matured source rocks in smaller grabens. Based on the above-mentioned criteria and the presence of direct hydrocarbon indicators (DHI), an untested alternative play type is proposed relying on syn-rift sandstones located up-dip from and near source-rock intervals with Palaeogene structural and stratigraphic trapping mechanisms that did not experience subsequent Neogene deformation.

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