DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2017/31

Component A: PEXMOD Starting Point Report

Tectonic set-up and structural evolution in and around the Song Hong Basin: Linking Paleogene rifting and inversion in the northern Song Hong and Beibuwan basins, Vietnam, with left-lateral motion on the Ailao Shan-Red River Shear Zone

Michael B.W. Fyhn & GEUS/VPI ENRECA Research Team

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G E U S

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Tectonic Set-up and Structural Evolution in and around the Song Hong Basin: *Linking Paleogene rifting and inversion in the northern Song Hong and Beibuwan basins, Vietnam, with left-lateral motion on the Ailao Shan-Red River Shear Zone*

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REPORT BACKGROUND AND ACKNOWLEDGEMENTS

This comprehensive review of the structural evolution within the northern Song Hong and Beibuwan basins, offshore Vietnam and the discussion of its linkage to major structural events in the region represents our "tectonic starting point" at the initiation of the PEXMOD Project.

The report summarizes the geoscientific results and knowledge harvested to date through the implementation of the ENRECA Research Capacity Building project. The project, titled **Integrated Analysis and Modeling of Geological Basins in Vietnam and an Assessment of their Hydrocarbon Potential,** facilitated a long-term research cooperation between the "twinning" research institutes of Vietnam Petroleum Institute (VPI) and the Geological Survey of Denmark and Greenland (GEUS). Hanoi University of Mining and Geology (HUMG), Hanoi University of Science (HUS) and the Department of Geography & Geology, University of Copenhagen (DGG/KU) were also involved in the academic aspects of the ENRECA Project. The project was carried out in the period January 2001 to December 2015 funded by DANIDA's Council for Development Research (FFU).

Over the years, the ENRECA Research Group, within the cooperating institutes and universities, has received valuable administrative and geoscientific support from a large number of individuals at VPI, PetroVietnam, CCOP, HUMG, DGG/KU and GEUS. We thank all colleagues and friends at these institutes for their contributions, encouragement and support.

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Various Vietnamese authorities, including the Ministry of Planning and Investment (MPI) and the Vietnamese Embassy in Copenhagen, are thanked for their valuable advice and administrative support provided to the ENRECA Research Group during the initiation and implementation of the co-operating activities.

Finally, the Royal Danish Embassies in Hanoi and Bangkok, DANIDA's Fellowship Centre (DFC) and DANIDA's Council for Development Research (FFU) are thanked for their continuous financial support and advice that contributed greatly to the success of the ENRECA Project.

EXECUTIVE SUMMARY

Extrusion tectonics forced by plate collisions shape continents not only through lateral terrain displacement and mountain building, but also through massive rifting and basin development. The rift system underneath the Gulf of Tonkin, Vietnam, constitutes a world-class example of how extrusion tectonics drives continental rifting and transtensional basin development.

Rifting, and the Song Hong and Beibuwan basin evolution, are compared with the development of the Ailao Shan-Red River Shear Zone (ASRRSZ) that accommodated the extrusion of Indochina forced by the Indian-Eurasia collision. Rifting occurred during later Eocene-Late Oligocene time forced by ASRRSZ left-lateral shearing. Latest Oligocene-earliest Miocene transpression and inversion brought rifting to a halt, after which left-lateral shearing decreased.

Paleogene rift systems extended along the trail of the ASRRSZ now outlined by lower to mid-crustal metamorphic core complexes. Most of these rift systems were probably inverted and removed during the latest Oligocene-earliest Mio-

cene, however. The metamorphic core complexes are suggested to represent the lower to mid-crustal roots of these transtensional rifts exhumed during basin inversion.

Rift termination in the northern Gulf of Tonkin and exhumation of the metamorphic core complexes coincided with cessation of Paleogene rifting along the western South China Sea and a common causal mechanism is speculated.

INTRODUCTION

Escape tectonism, although controversial, has been suggested to account for as much as 30–40% of the overall deformation associated with the Indian-Eurasian collision and has been proposed as driving mechanism for rifting and basin formation in SE Asia (Tapponnier et al 1982; 1986; Leloup et al., 1995; 2001; Replumaz and Tapponnier, 2003). During the collision, continental fragments located east and northeast of the Indian indenter were squeezed up to several hundred kilometers away from the suture along major lateral shear zones. The ASRRSZ delineates the largest of these shear zones stretching from eastern Tibet to the Gulf of Tonkin where it continues offshore along the north and central Vietnamese margin (Fig. 1). Even so, the geological history of the shear zone is far from understood. Recent discussions of the ASRRSZ concern four major aspects: 1) The timing of motion, 2) the crustal architecture of the shear zone, 3) the amount of lateral offset, and consequently, 4) the regional plate tectonic implications of the shear zone.

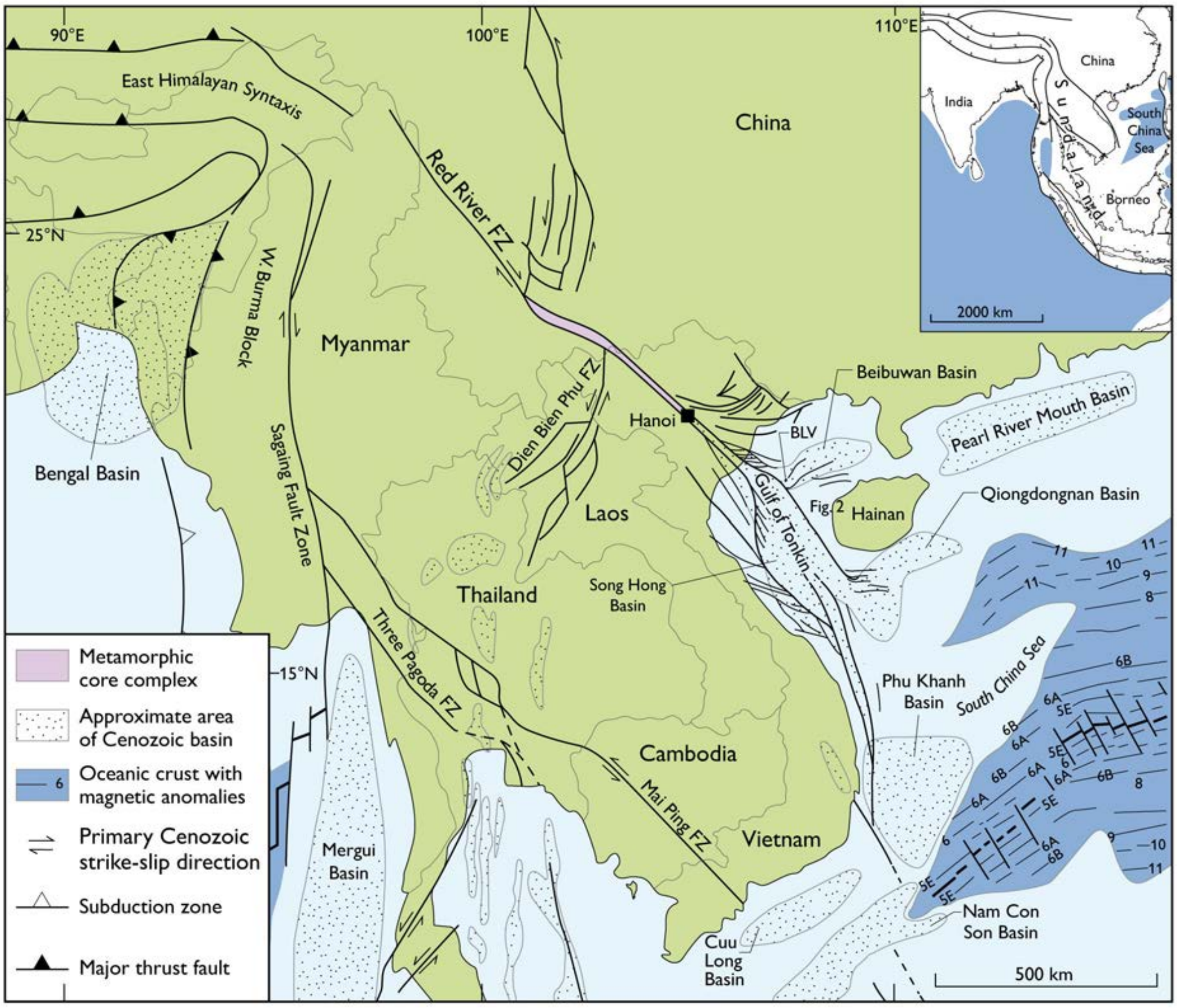


Figure 1. *Simplified structural outline of Cenozoic basins and selected fault zones on- and offshore Indochina and southernmost China modified after Fyhn and Phach (2015) and references therein. Small insert map illustrates the main structural framework in greater East Asia. Box indicates the location of the study area and figure 2. AS=Ailao Shan metamorphic core complex, BLV=Bach Long Vi Island, CBB= Cao Bang Basin, CLT= Cua Luc Trough, CTF= Cao Bang-Tien Yen Fault, DNCV=Dai Nui Con Voi metamorphic core complex, Diancang Shan metamorphic core complex, EVBFZ=East Vietnam Boundary Fault Zone, MPSZ=Mai Ping Shear Zone, NDB= Nha Duong Basin, TPSZ=Three Pagodas Shear Zone, Xuelong Shan metamorphic core complex.*

According to classic escape tectonic models, strike-slip motion from the ASRRSZ continued into the South China Sea realm where lateral motions where taken up by rift-system fault splays from central transform zones (Tapponnier et al., 1982; 1986). Other models down-tone the importance of escape tectonism (Hall, 2002; Morley, 2002; 2013; Pubbellier and Morley 2014). According to these models, the escape of the Indochina Block relative to the South China Block was modest, and most left-lateral motion across the ASRRSZ was accom-

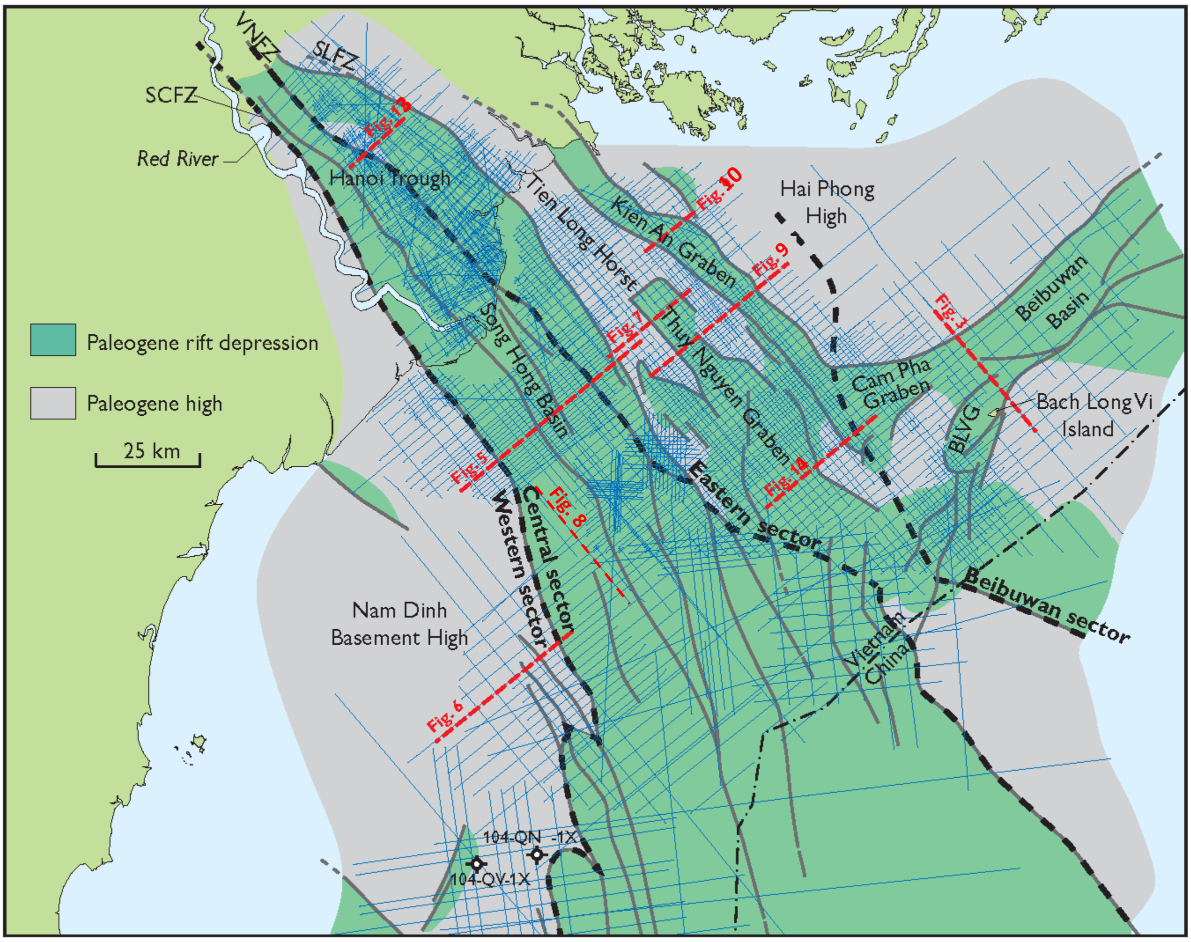


Figure 2. *Structural outline of the northern Song Hong Basin and the western Beibuwan Basin emphasizing the main Paleogene faults, rift depressions and structural highs. Blue lines delineate the available 2-D seismic database with red lines indicating the position of documented seismic examples. BLVG=Bach long Vi Graben, CFZ=Chay Fault Zone, SLFZ=Song Lo Fault Zone, VNFZ=Vinh Ninh Fault Zone.*

modated within deformation along the fault zone onshore (e.g. Hall, 2002). Accordingly, understanding Indochina's extrusion is fundamental to any plate tectonic restoration of SE Asia.

The Song Hong Basin (or Yinggehai Basin) bridges the onshore ASRRSZ with the offshore rift-system and thus holds essential clues illuminating the magnitude, style and timing of SE Asian escape tectonism. The Song Hong Basin is the largest basin along the western South China Sea margin stretching from north of Hanoi underneath the Red River Delta (Song Hong Delta) and into the Gulf of

Tonkin (Fig. 1). Situated at the extension of the onshore ASRRSZ, the formation of the Song Hong Basin is often considered to be linked with Cenozoic continental-scale left-lateral motion taking place across the shear zone (Rangin et al., 1995; Sun et al., 2004; Clift and Sun, 2006; Zhu et al., 2009). The Paleogene rift system flooring the basin is little studied, however, but holds vital information to unraveling the tectonic history of the ASRRSZ.

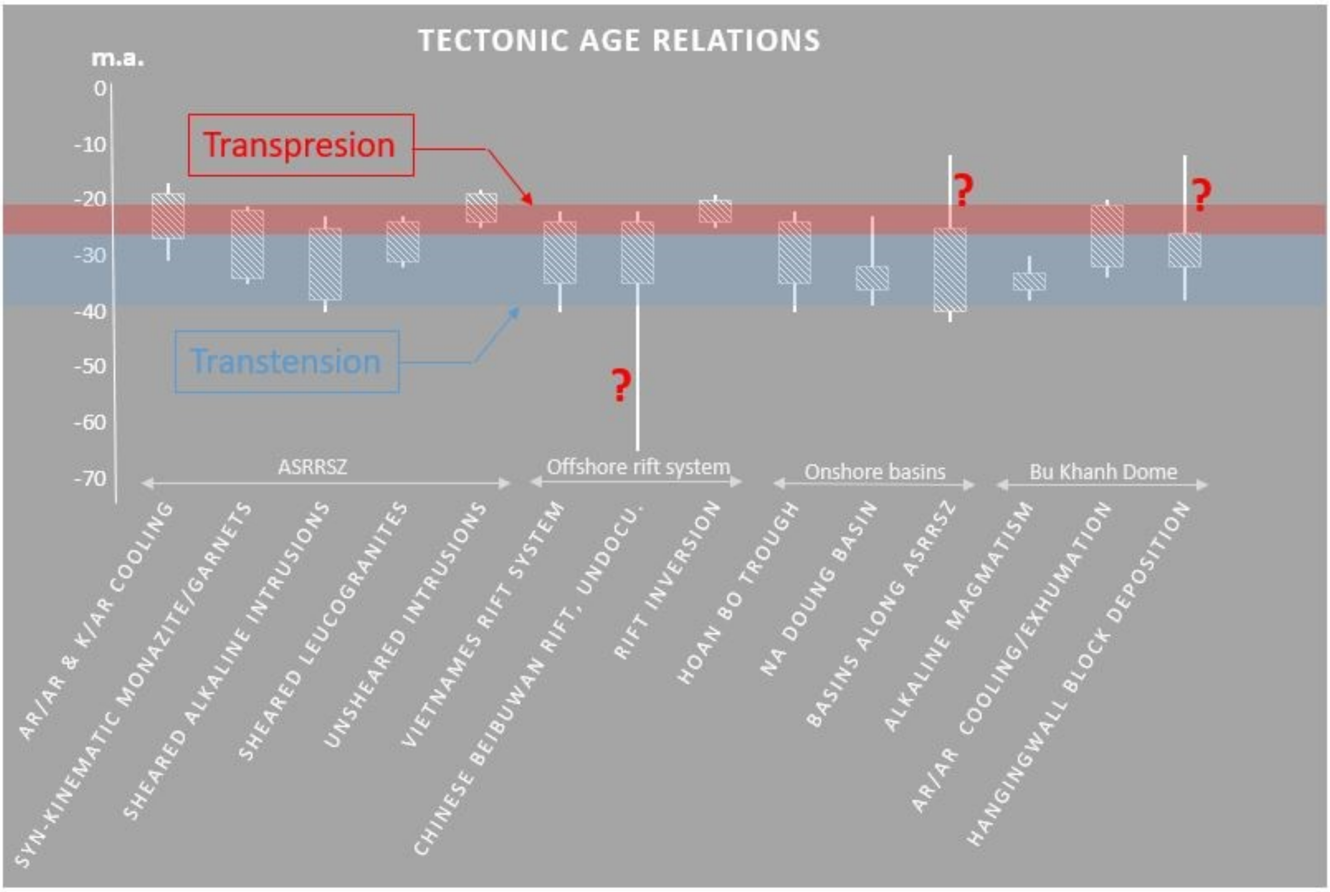
Based on a dense 2-D seismic grid covering the northern Song Hong Basin tied to exploration wells, the Paleogene syn-rift system of the greater northern Song Hong Basin has been mapped and analyzed (Fig. 2). By integrating the Paleogene basin development with stratigraphic information from coeval rift-systems exposed onshore and on Bach Long Vi Island and thermochronologic evidence from onshore, the timing of rifting is evaluated and a model connecting Eocene–Oligocene rifting, formation of metamorphic core complexes and large-scale left-lateral strike-slip faulting across the ASRRSZ is proposed.

GEOLOGICAL SETTING

Ailao Shan-Red River Shear Zone

The ASRRSZ is outlined by a prominent relief and by discontinuous metamorphic core complexes (Tapponier et al., 1990; Leloup et al., 1995; Burchfield et al., 2008; Searle et al., 2010). The core complexes are confined by faults that accommodated moderate right-lateral slip induced by eastward escape of the South China Block relative to Indochina during Late Neogene time (Allen et al., 1984; Rangin et al., 1995; Replumaz et al., 2001; Schoenbohm et al., 2006; Trinh et al., 2012; To et al., 2013; Zuchiewicz et al., 2013; Fyhn and Phach, 2015). Earlier, the shear zone took up left-lateral shearing in response to the southeastward escape of Indochina relative to South China (Tapponnier et al., 1986; Leloup et al., 1995; 2001).

The ASRRSZ metamorphic core complexes were exhumed from lower to mid-crustal levels and preserve evidence for massive ductile left-lateral shearing (Tapponnier et al., 1990; Leloup et al., 1995; 2001a; Jolivet et al., 2001; Anczkiewicz et al., 2007; Burchfield et al., 2008; Searle et al., 2010; Palin et al., 2013). Thermochronology of the metamorphic core complexes has been widely used to constrain the timing of left-lateral displacement (Schärer et al., 1990; 1994; Tapponnier et al., 1990; Harrison et al., 1992; Leloup et al., 1995; 2001; Nam et al., 1998; Wang et al., 1998; 2000; Zang and Schärer, 1999; Gilley et al., 2003; Liang et al., 2007; Sassier et al., 2009; Searle et al., 2010; Cao et al., 2011a; Li et al., 2014a; Liu et al., 2012; Tang et al., 2013). None-the-less, great controversy concerning the age of left-lateral motion remains. $^{40}Ar/^{39}Ar$- and K/Ar-ages were interpreted to record mid-Oligocene to Early Miocene cooling and left-lateral motion across the ASRRSZ (Table 1) (Leloup et al., 1995; 2001; Nam et al., 1998). Th/Pb-ages of monazite inclusions in garnets ranging from 21 to 34 My were interpreted to indicate garnet growth syn-kinematic to left-lateral displacement (Gilley et al., 2003). In addition, sheared and un-sheared alkaline and leucocratic granites within and along the metamorphic core complexes ranging from 22 to 36 My in age were interpreted to have formed simultane-



Tabel 1: *Age relation between associated tectonic events. Scale in million years ago (m.a). Qeustion marks denote suspect suggested ages of tectonic events.*

ous to left-lateral shearing (Schärer et al., 1990; 1994; Leloup et al., 1995; 2001; Liang et al., 2007; Sassier et al., 2009). Searle (2006) on the other hand suggested that most of these granites pre-date left-lateral shearing and thus provide little constraint on the age of shearing. Subsequent analyses of granite dykes within the metamorphic core complex document intrusion ages in between 38 and 21 My (Table 1) (Searle et al., 2010; Cao et al., 2011a; Tang et al., 2013; Li et al., 2014a; Zang et al., 2014; Liu et al., 2015a; Liu et al., 2015b). Earliest Miocene intrusions are not, or only slightly, deformed compared to the pervasively left-laterally sheared metamorphic core complex host rocks. This suggest that left-lateral ductile shearing were mostly restricted to the Paleogene, whereas more moderate, brittle Neogene left-lateral deformation took place as the core complexes cooled during uplift and exhumation (Table 1) (Searle et al., 2010; Cao et al., 2011a; Tang et al., 2013; Li et al., 2014a).

On the other hand, Late Eocene and Early Oligocene granite dykes are highly sheared comparable to the mylonitic host rocks within the metamorphic core complex and were suggested to predate left-lateral shearing (Searle et al., 2010; Cao et al., 2011a; Tang et al., 2013; Li et al., 2014a). Instead, these dykes were attributed to another undescribed magmatic and high-grade metamorphic event also responsible for the coeval monazite and zircon ages in the core complex gneisses (Searle et al., 2010; Cao et al., 2011a; Palin et al., 2013; Tang et al., 2013; Li et al., 2014a).

However, distinguishing between pre- and early syn-kinematic magmatic intrusions and metamorphism is highly intricate due to the high strain rate of the shear zone and may be impossible. In the Ailao Shan metamorphic core complex, Sassier et al., (2009) noted that dykes with strain rates exceeding 10 tend to be sub-parallel with the left-lateral ductile fabric in the surrounding gneisses. Distinguishing the differential strain rates more exactly for these high-strain dykes was not feasible based on outcrops. Strain rates exceeding 30 have been measured from the ASRRSZ (Lacassin et al., 1993) and very high strain rates is expected within the shear zone in general since left-lateral offset across the ASRRSZ are considered to be measured in hundreds of kilometers (e.g. Tapponnier et al., 1990; Leloup et al., 2001; Hall, 2002; Morley, 2002; Burchfield et al., 2008).

A pure-shear, high-temperature mineral fabric within Ailao Shan and Dai Nui Con Voi gneisses and granites was interpreted by Liu et al. (2011) and taken in support of a metamorphic event pre-dating left-lateral shearing. In addition, Liu et al. (2011) identified a simple shear, low-temperature mineral fabric interpreted to have formed subsequently during left-lateral deformation. In contrast, Leloup et al. (1995) only interpreted mineral fabrics consistent with pervasive left-lateral shearing.

Oligocene cooling and exhumation of the metamorphic core complexes is suggested by the change from ductile to brittle deformation and retrograde metamorphism constrained by thermochronology (Schärer et al., 1990; 1994; Tapponnier et al., 1990; Leloup et al., 1995, 2001; Nam et al., 1998; Wang et al., 1998, 2000; Zhang and Schärer, 1999; Gilley et al., 2003; Viola and Anczkiewicz, 2008 Cao et al., 2011a; Palin et al., 2013; Tang et al., 2013; Li et al., 2014a). Particular rapid cooling occurred during latest Oligocene to earliest Miocene time (Table 1) (Wang et al., 2000; Leloup et al., 2001, Cao et al., 2011b). Different exhumation models of the Ailao Shan and Dai Nui Con Voi metamorphic core complexes exist. Ductile stretching lineation across all ASRRSZ metamorphic core complexes and a foliation fabric delineating an antiform across the Dai Nui Con Voi complex were suggested to imply left-lateral transtension-related exhumation (Jolivet et al., 2001; Anczkiewicz et al., 2007). On the other hand, brittle contractional deformation within and along the ASRRSZ, and the exhumation of lower crustal rocks, were interpreted in favor of transpresional exhumation of the core complexes (Leloup et al., 2001; Schoenbohm et al 2005; Searle, 2006; Searle et al., 2010).

Offshore Cenozoic Rift Basins

The Gulf of Tonkin is underlain by the interconnected Beibuwan, Song Hong and Qiongdongnan basins (Fig. 1). The basins formed through Paleogene rifting followed by Late Cenozoic thermal sagging (Rangin et al., 1995; Nielsen et al., 1999; Sun et al., 2004; Andersen et al., 2005; Zhu et al., 2009; Chen et al., 2013; Huang et al., 2013; Zhang et al., 2013; Zhao et al., 2015). In addition, the northern Song Hong Basin, including the onshore Hanoi Trough and the southwestern Beibuwan Basin have been affected by various Neogene phases of extension and inversion with the most recent inversion continuing to the present in the area around the Bach Long Vi Island (Rangin et al., 1995; Fyhn and Phach, 2015) (Figs 2, 3).

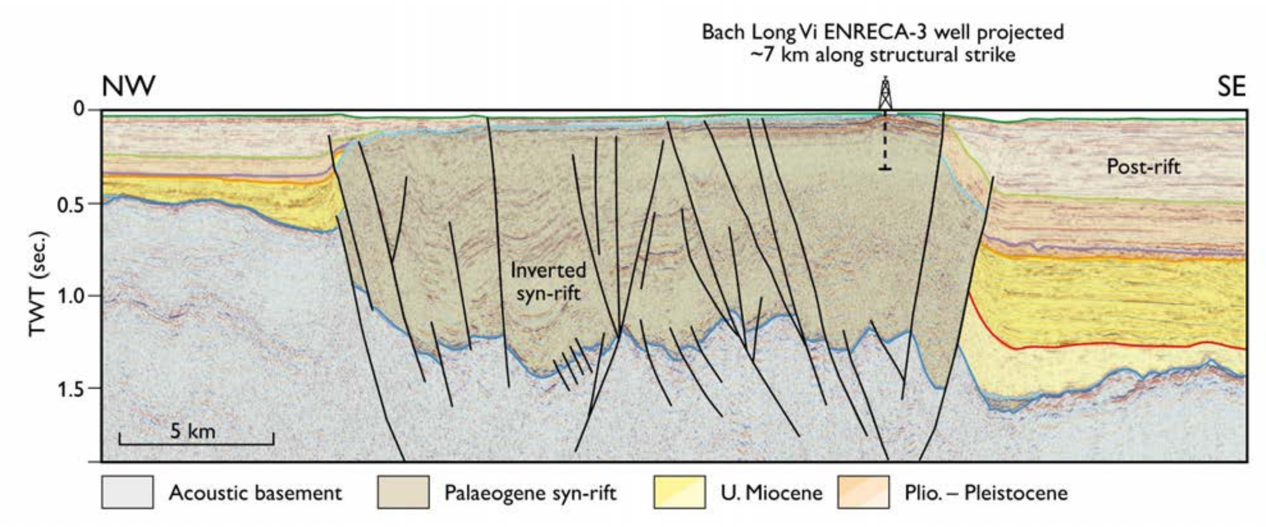


__Figure 3.__ Seismic transect across the Bach Long Vi inversion trend. The Paleogene graben underlying the Bach Long Vi Island has been nearly completely inverted throughout the Late Neogene. The EN-RECA-3 stratigraphic core well drilled on the island treated in the text is projected onto the transect. Location shown in Fig. 2.

Rifting in the Song Hong and the Qiongdongnan basins are generally considered as Eocene and Oligocene in age (Table 1) (Huyen et al., 2005; Clift and Sun, 2006; Zhu et al., 2009; Zhang et al., 2013). In contrast, published stratigraphic charts of the Beibuwan Basin portray rifting commencing already during Early Paleocene time and continuing throughout the Eocene and Oligocene (Huang et al., 2013).

The Paleogene syn-rift successions in the three basins are non-marine comprising alluvial and lacustrine siliciclastic deposits. In the Chinese part of the Beibuwan Basin, organic rich lacustrine mudstones of the Liushagang Formation are thickly developed. According to published stratigraphic charts of the basin these source rocks are entirely Eocene in age and are overlain by the Oligocene Weizhou Formation entirely comprising alluvial and shallow lacustrine deposits with little organic content (Huang et al., 2017).

On Bach Long Vi Island, located in the Vietnamese part of the basin few kilometers from Chinese territory (Fig. 2), a more than 500 m thick deep-lacustrine succession was recently documented (Fig. 3) (Petersen et al., 2014; Hovikoski et al., 2016). Similar to the Liushagang Formation, the Vietnamese mudstones are characterized by their very high organic content, but in contrast to the Chinese source rocks, the mudstones from Bach Long Vi Island were tentatively dated as Upper Oligocene based on identification of a sparse microflora consisting mainly of long range spores and pollens attributed to the *F. Verrutricolporites Pachydermus* subzone of the *Florschuetzia Trilobata* biozone (Upper Oligocene) in addition to freshwater dinoflagellates (Tuyen, 2013; Petersen et al., 2014).

The lacustrine succession on Bach Long Vi Island was previously considered to be Neogene in age based on macro floral fossils (Ky, 2001), but the more recent ages are substantiated by seismic data along the island that document the strata to be part of an inverted Paleogene graben (Fig. 3) (Fyhn et al., 2012; Petersen et al., 2014; Fyhn and Phach, 2015).

Offshore in the northern Song Hong Basin, a distinct unconformity caps the Paleogene syn-rift (Rangin et al., 1995). Late Oligocene nanofossils were reported from the overlying section, which made Rangin et al. (1995) interpret the unconformity as mid-Oligocene in age, and thus bracketing the age of the syn-rift to in between the Paleocene/Eocene and the mid-Oligocene. Rangin et al. (1995) further interpreted the unconformity as a break-up unconformity associated with the incipient opening of the South China Sea. Since then, the Dinh Cao Formation subcropping the unconformity has been documented to include Upper Oligocene strata and the Phong Chau Formation immediately overlying the unconformity has been more firmly dated as Lower Miocene based on both planktonic foraminifers, nanofossils and palynology (Bat et al., 2009). This instead documents a near-top Oligocene age of the unconformity (Table 1). A near-top Oligocene unconformity also delineates the top of the syn-rift in the Beibuwan Basin (Huang et al., 2013; 2017). Farther south along the western South China Sea margin, rifting also widely terminated close to the Oligocene–Miocene transition, in places also marked by distinct unconformities (Chen et al., 1993; Ginger et al., 1993; Matthews et al., 1997; Lee et al., 2001; Fyhn et al., 2009a; b; 2010; 2013; Burton and Wood, 2010).

northern reaches of the ASRRSZ (Table 1) (Schoenbohm et al., 2005). Some of these Chinese basins are intruded by sub-volcanic granite stocks, one of which yielded a Late Eocene age (35.0 +/- 01.1 Ma) (Schärer et al., 1994), corroborating the pre-Neogene age of these basins. Similar to the other Paleogene basins, the depressions along the Ailao Shan and Dai Nui Con Voi metamorphic core complexes are filled by fluvial sandstones, conglomerate and subordinate fine-grained lacustrine deposits interpreted as syn-rift sediments (Wysocka and Swierczewska, 2003; 2005; 2010). The Cenozoic sediments along the Ailao Shan and Dai Nui Con Voi complex thus appear much coarser grained than the Miocene section in the neighboring Hanoi Trough that delineates the onshore part of the Song Hong Basin, and does not contain marine interludes in contrast to the deltaic-dominated Miocene in the Hanoi Trough (Bat et al., 2009; Tri and Khuc, 2011). The conglomerates in these depressions reportedly do not contain clasts derived from the adjacent metamorphic core complex (Schoenbohm et al., 2005; Wysocka and Swierczewska, 2010), which may indicate exhumation of the Dai Nui Con Voi metamorphic core complex subsequent to deposition if this can be verified .

Bu Khang Metamorphic Dome

The Bu Khang metamorphic dome situated roughly 200 km south of the ASRRSZ is a metamorphic core complex exhumed by NW–SE-striking extensional detachment faulting (Figs 1, 4) (Jolivet et al., 1999). $^{40}Ar/^{39}Ar$-dating document latest Eocene to earliest Miocene (36–21 Ma) cooling bracketing the age of

Onshore Cenozoic Rift Basins

Onshore northern Vietnam the Hoanh Bo Trough and the Na Duong and Cao Bang basins delineate restricted pods of Paleogene alluvial and lacustrine deposits (Fig. 4). Similar to the Bach Long Vi Island, these basins were initially mapped as Neogene in age based on macro floral fossils (Thuy, 2001; Luong, 2001). More recent work based on palynology and macro fauna has documented their Paleogene age (Petersen et al., 2001; Bat et al., 2009; Böhme et al., 2011; 2013; Tri and Khuc, 2011). The Na Duong and Cao Bang basins are small left-lateral pull-apart basins located along the Cao Bang-Tien Yen Fault that strikes parallel to the larger ASRRSZ (Pubellier et al., 2003) (Fig. 1). A rich vertebrate fauna from the lowermost part of the Na Duong Basin suggest a Late Barthonian or Priabonian age (39–35 Ma) for the lower part of the basin (Table 1) (Böhme et al., 2013).

The Ailao Shan and Dai Nui Con Voi metamorphic core complex along the ASRRSZ are bracketed in between elongate Cenozoic basins with up to kilometers thick deposits (Wysocka and Swierczewska, 2003; 2005; 2010; Schoenbohm et al., 2005). The basins situated in Vietnam and southern China were initially mapped as Neogene based on their macro flora (Ky, 2005)**.** More recent palynological investigations document a Paleogene age for at least part of their infill comparable to the syn-rift in the offshore basins, however (Cuong et al., 2001; Schoenbohm et al., 2005; Tri and Khuc, 2011). This revised age fits well with the Eocene age of comparable Chinese basins next to the central and faulting (Table 1). Comparable to along the ASRRSZ, Late Oligocene alkaline granites intrude the metamorphic core complex. Nagy et al. (2000) speculated that lithospheric thinning related to the extensional detachment faulting could have caused the magmatism. The fault zone confining the Bu Khang dome strikes parallel to Paleogene rift faults along the western flank of the Song Hong Basin. Extensional detachment faulting and exhumation of the metamorphic dome was therefore interpreted to be associated with rifting in the Song Hong Basin (Jolivet et al. 1999). The down-faulted hangingwall block northeast of the metamorphic dome is covered by Paleozoic matasediments and Mesozoic sediments, but the hangingwall block east of the dome also holds up to more than 500 m of Cenozoic coarse-grained deposits comparable to syn-rift deposits in the Na Duong Basin. These deposits were initially interpreted as Neogene in age based on their macro flora (Bach and Quan, 1996). More recently, the sediments were reinterpreted to be Eocene(?) and Oligocene–Lower Neogene in age (Table 1) (Tri and Khuc, 2011). Deposition thus coincides with extensional detachment faulting and could be considered as remnant syn-rift sediments similar to the Cenozoic strata along the ASRRSZ and farther north.

DATA

The current study is based on approximately 20,000 km industrial 2-D seismic data made available to the ENRECA research group during the 20 years of project collaboration. The seismic was acquired on- and offshore during different surveys through a 30 year long period from the mid-1970es. Acquisition equipment and methods together with data processing techniques therefore vary considerably. Hence, data quality fluctuates. The onshore area is covered by approximately 5500 km of seismic with data quality in the investigated interval ranging from poor (c. 20%) to good (c. 40%). The offshore area is covered by almost 15,000 km of seismic data with a quality ranging from good (c. 25%) to very good (c. 75%). The dense data coverage allows for a detailed structural mapping and a high stratigraphic resolution. Seismic recording time lies in between 4–8 sec Two-Way-Time (TWT). Onshore recording generally terminates around 4 sec TWT, whereas offshore recording lengths are mostly around 6 sec TWT and up to 8 sec TWT for regional surveys enabling deeper imaging.

Seismic data was made available to this study by Vietnam Petroleum Institute (VPI) together with stratigraphic information from confidential exploration wells. A 500 m Paleogene section was drilled and fully cored by GEUS and VPI on Bach Long Vi Island (Petersen et al., 2014). The core is stored at VPI's core repository in Hanoi and has been analysed in the Geological Survey of Greenland and Denmark's and VPI's laboratories.

Seismic data was correlated to exploration wells to obtain chronostratigraphic control. The limited number of wells drilled into the syn-rift interval and the non-marine nature of the succession restricts the biostratigraphic resolution of the Paleogene syn-rift.

PALEOGENE STRUCTURAL DEVELOPMENT

Paleogene Rifting

Major NW-striking extensional faults stretch along the axis of the central northern Song Hong Basin and delineate a major Paleogene syn-rift depocenter (Fig. 4). Of these faults, the Vinh Ninh and Song Chay faults lie in direct continuation of the brittle Red River and Song Chay faults that flank the Day Nui Con Voi metamorphic core complex. The overall deformational pattern is complicated by Late Neogene inversion in between especially the Vinh Ninh and the Song Chay faults (Fig. 5). Farther south, Neogene inversion fades.

The central part of the Song Hong Basin broadens southeastward. In the northwest, the narrow central depression of the Song Hong Basin is limited to a roughly 10 km broad belt in between the Vinh Ninh and the Song Chay faults. Farthest southeast, the basin center exceeds 80 km in width (Fig. 4). The basin broadening reflects left-steps in the NW–SE-striking faults that borders the eastern basin margin. On the southwestern flank of the basin, imbricate extensional faults with a 10°–20° counterclockwise angle to the Song Chay Fault contribute to the southeastward depocenter broadening (Fig. 4).

Along the flanks of the Song Hong Basin and towards the Beibuwan Basin, the base of the Cenozoic is marked by a strong "hard-kick" reflector. The pre-Cenozoic is acoustically transparent across much of the northern Nam Dinh Basement High located at the western flank of the Song Hong Basin. In addition, subtle stratigraphic sub-Cenozoic reflectors and mounded features often cored by a chaotic reflection pattern can be distinguished especially in the

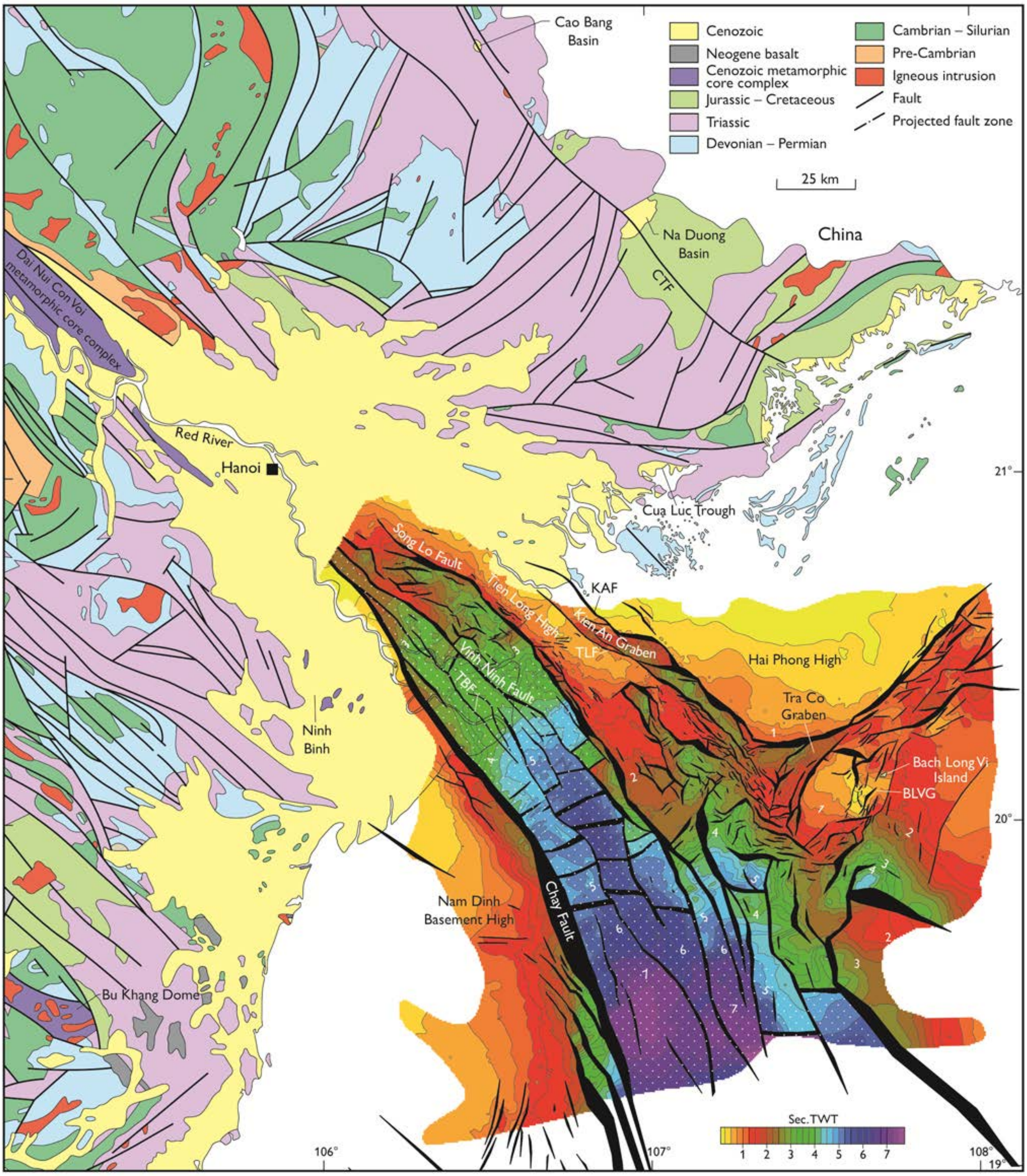


__Figure 4.__ Seismic time-structure map to the base of the Cenozoic superimposed on onshore geology modified after Tien (1991). Dotted area denotes where systematic picking of the base of the Cenozoic is mostly hampered by the deep burial depth, Neogene deformation and coal seams dampening deep seismic imaging. Instead, the mapped surface here denotes the base of the deepest regionally recognizable Paleogene section. The structures where similarly mapped at this interval. The central Song Hong Basin lies in direct continuation of the Dai Nui Con Voi metamorphic core complex delineating the ASRRFZ in northern Vietnam. BLVG=Bach Long Vi Graben, CTF=Cao Bang-Tien Yen Fault, KAF=Kien An fault, TBF=Thai Binh Fault, TLF=Tien Long Fault. Labelling of isochron curves in seconds TWT.

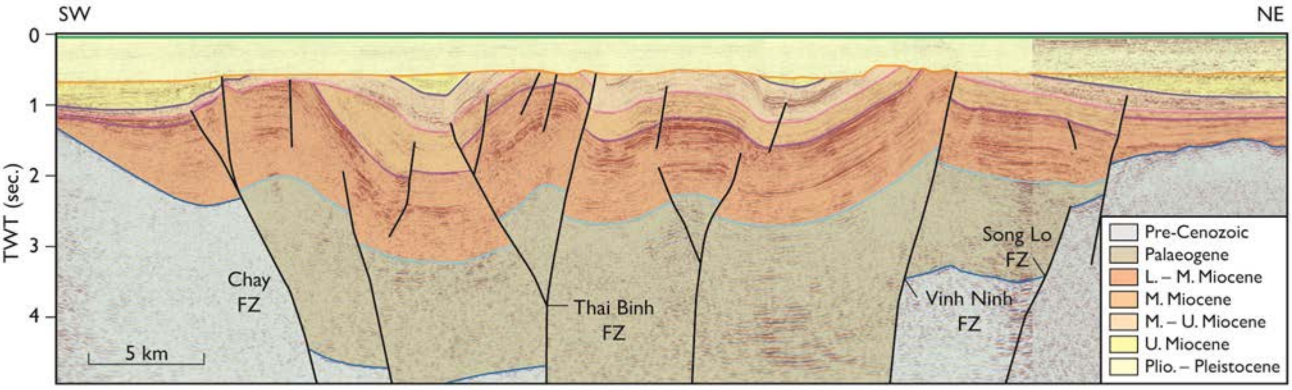


Figure 5. *Seismic transect across the northern Song Hong Basin illustrating the deep Paleogene rift and the strong Middle–Late Miocene inversion affecting the central part of the basin. Deep erosion along part of the near-base Pliocene unconformity caps folds and faults. Middle to lower Upper Miocene NW–SE-striking transpressional faults reactivate former transtensional faults. E–W-striking extensional faults continue into the lower Upper Miocene together with the transpressional structures. Location shown in Fig. 2.*

southwest. The mounded facies was documented as karstified Paleozoic carbonates in the 104-QV-1X exploration well (Figs 2, 6). Few wells have been drilled into the pre-Cenozoic on the northwestern margin. Apart from Paleozoic carbonates, granitic basement has been intersected in the 104-QN-1X well. Onshore near Ninh Binh (Fig. 4), small hills of high-grade mylonites rise in between recent alluvium in the Red River Delta approximately 15 km west of the Song Chay Fault that confine the northwestern flank of the Song Hong Basin (Fig. 4). The mylonites show Late Oligocene biotite $^{40}Ar/^{39}Ar$-ages and Leloup et al. (2001) interpreted them to have formed in relation to left-lateral shearing along the ASRRSZ.

On the eastern basin flank, distinctly reflected pre-Cenozoic stratigraphy generally underlie the top of the pre-Cenozoic. The pre-Cenozoic is in some areas outlined by mounded features with strong internal reflectivity documented as karstified Devonian–Permian carbonates in wells (Fig. 7). The thickness of the Upper Paleozoic carbonates is mainly controlled by erosion along the base of the Cenozoic and is often thickly preserved. The carbonates are in places unconformably overlain by a thick pre-Cenozoic succession with lower internal reflection amplitudes and with a smoother subcrop surface towards the base-Cenozoic compared to the Devonian–Permian carbonates (Fig. 7). The interval probably correspond to Mesozoic siliciclastic deposits outcropping regionally onshore (Fig. 4). The Upper Paleozoic rests on a succession with a more subtle seismic reflectivity probably corresponding to the Middle and Lower Paleozoic siliciclastics and metasediments that floor Upper Paleozoic carbonates onshore.

In the central northern Song Hong Basin, the base-Cenozoic surface is deeply down-faulted across the Vinh Ninh, Song Lo and Song Chay faults. Between the Vinh Ninh and Song Chay faults, exact picking of the base of the Cenozoic is hampered by the great basin depth, Neogene inversional deformation and the presence of thick, Lower Neogene coal seams that dampen the acoustic energy transmitted into the Paleogene section in the landward part of the basin. In-

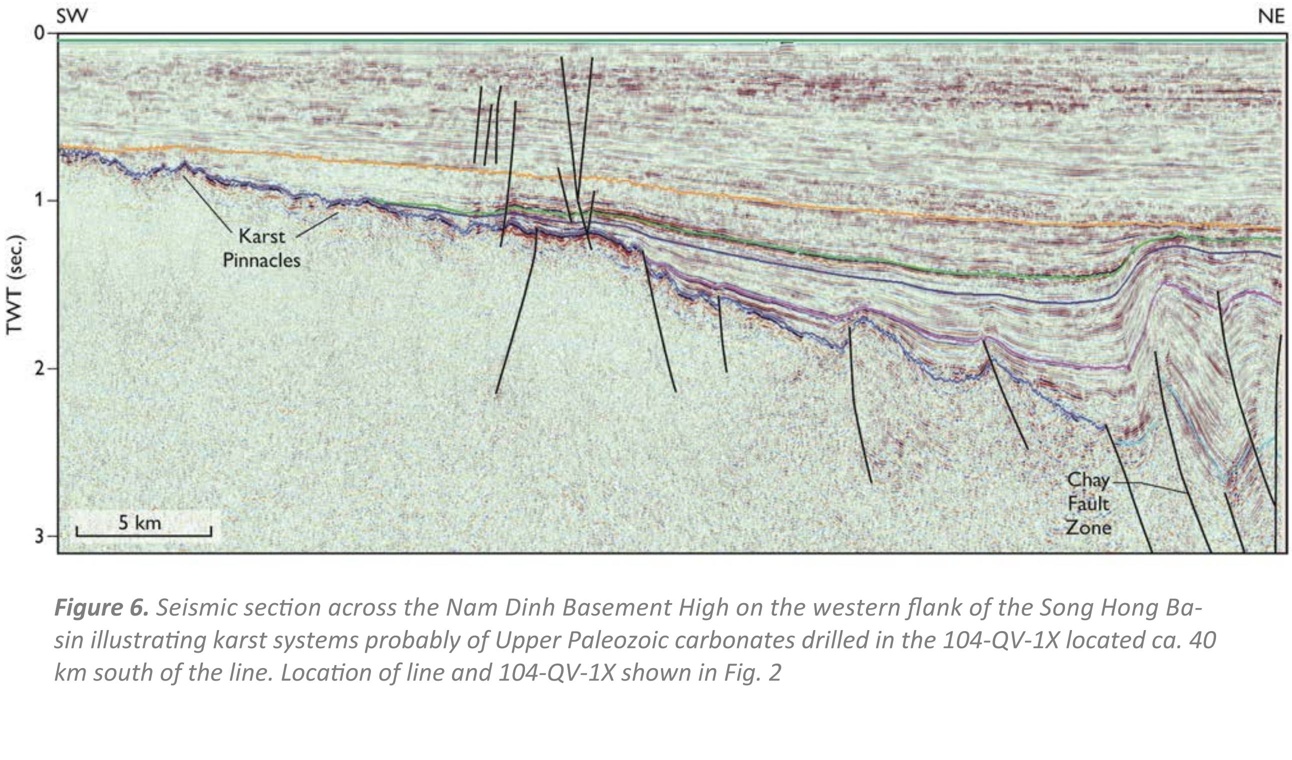


Figure 6. *Seismic section across the Nam Dinh Basement High on the western flank of the Song Hong Basin illustrating karst systems probably of Upper Paleozoic carbonates drilled in the 104-QV-1X located ca. 40 km south of the line. Location of line and 104-QV-1X shown in Fig. 2*

stead, the lowermost recognizable Paleogene reflectors where picked to provide a minimum basin depth in this area and fault outlines were mapped based on intra-Paleogene fault trends. The basin depth of the central Song Hong Basin decreases from more than 7 s. TWT in the southeast to a little more than 2 s. TWT farthest northwest (Fig. 4). The central basin fill is offset and deformed by long NW-Se striking faults and folds. In between the Vinh Ninh and the Song Chay faults, the Thai Binh Fault Zone delineates a through-going fracture zone in the northern central Song Hong Basin (Figs 4, 5). The fault zone is traceable within the Lower Miocene and Upper Paleogene section and must be rooted in the basement, but the fault root is concealed underneath the thick Cenozoic overburden. In addition, roughly E–W-striking extensional faults offset strata in

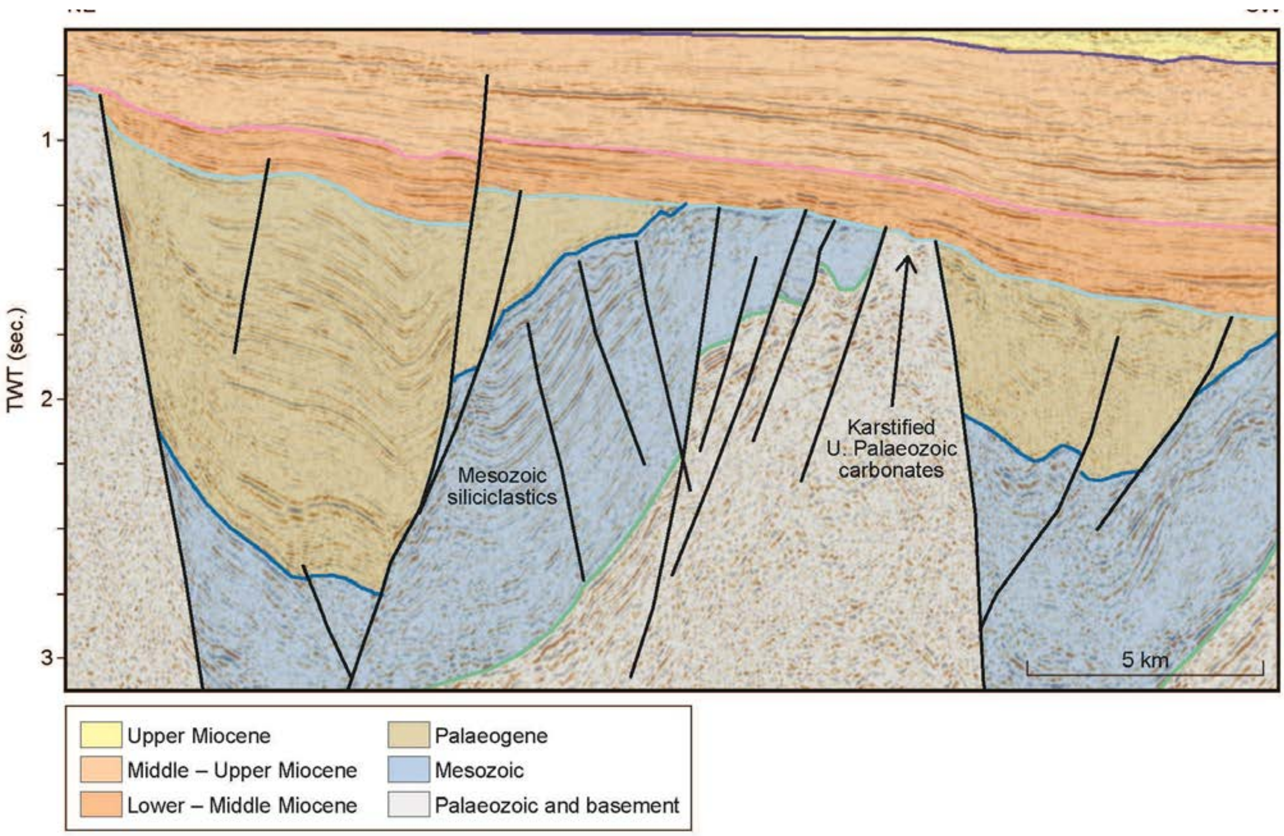


Figure 7. *Seismic transect illustrating karstified Upper Paleozoic carbonates subcropping the Cenozoic. Younger deposits probably of Mesozoic age also subcrop the Cenozoic, but often distinguish from karstified carbonates by their smoother subcropping relief and internal reflection pattern.*

the basin center, but the deeper extent of these faults is unconstrained by the seismic data due to the great basin depth (Fig. 8). The great burial depth similarly hampers the level of detail for which these faults can be mapped with the current seismic database.

The base of the Cenozoic across the Nam Dinh Basement High is inclined towards the basin in the northeast (Fig. 4). The surface is sporadically faulted especially along the basin confining margin, but is mostly buried only by Neogene deposits except for a few isolated minor, possibly Paleogene grabens (Fig. 2). The scarcity of Paleogene syn-rift deposits on the western margin of the Song Hong Basin suggests that this area behaved as an uplifted rift shoulder flanking the main basin.

In contrast, the base of the Cenozoic along the northeastern margin of the Song Hong Basin (eastern sector, Fig. 2) is strongly rifted with horst structures and grabens and half-grabens filled by thick Paleogene alluvial and lacustrine deposits intersected in wells (Fig. 9). NW–SE-striking faults prevail at the northeastern margin, but E–W-, N–S- and NE–SW-striking extensional faults also exist (Fig. 4). Across part of the northeastern basin flank, the syn-rift system is separated from syn-rift deposits in the central Song Hong Basin by the Tien Long Horst (Fig. 4). Farther southeast, the syn-rift depocenters of the central Song Hong Basin (central sector of Fig. 2) and of the northeastern margin (eastern sector of Fig. 2) are connected. The basin flank rift system is bound by the Hai Phong High that only experienced little Cenozoic rifting and probably behaved as an uplifted rift shoulder during the Paleogene. Palynological evidence from exploration wells places the syn-rift succession in the *Florschuetzia Trilobata* zone with the upper part confined to the *Verrutricolporites Pachydermus* subzone suggesting an Early to Late Oligocene age (Tham and Quang, 2013). Eocene palynomorphs are reported from the oldest part of the syn-rift encountered in exploration wells in the Song Hong Basin (Tri and Khuc, 2011). Differentiation between Eocene and Oligocene deposits is notoriously difficult and *Magnastriatites Howardi* and *Crassoretitriletes Nanhaiensis* palynomorphs from sediments situated immediately above pre-Cenozoic strata suggest an age no older than roughly Upper Eocene (Tham, 2009).

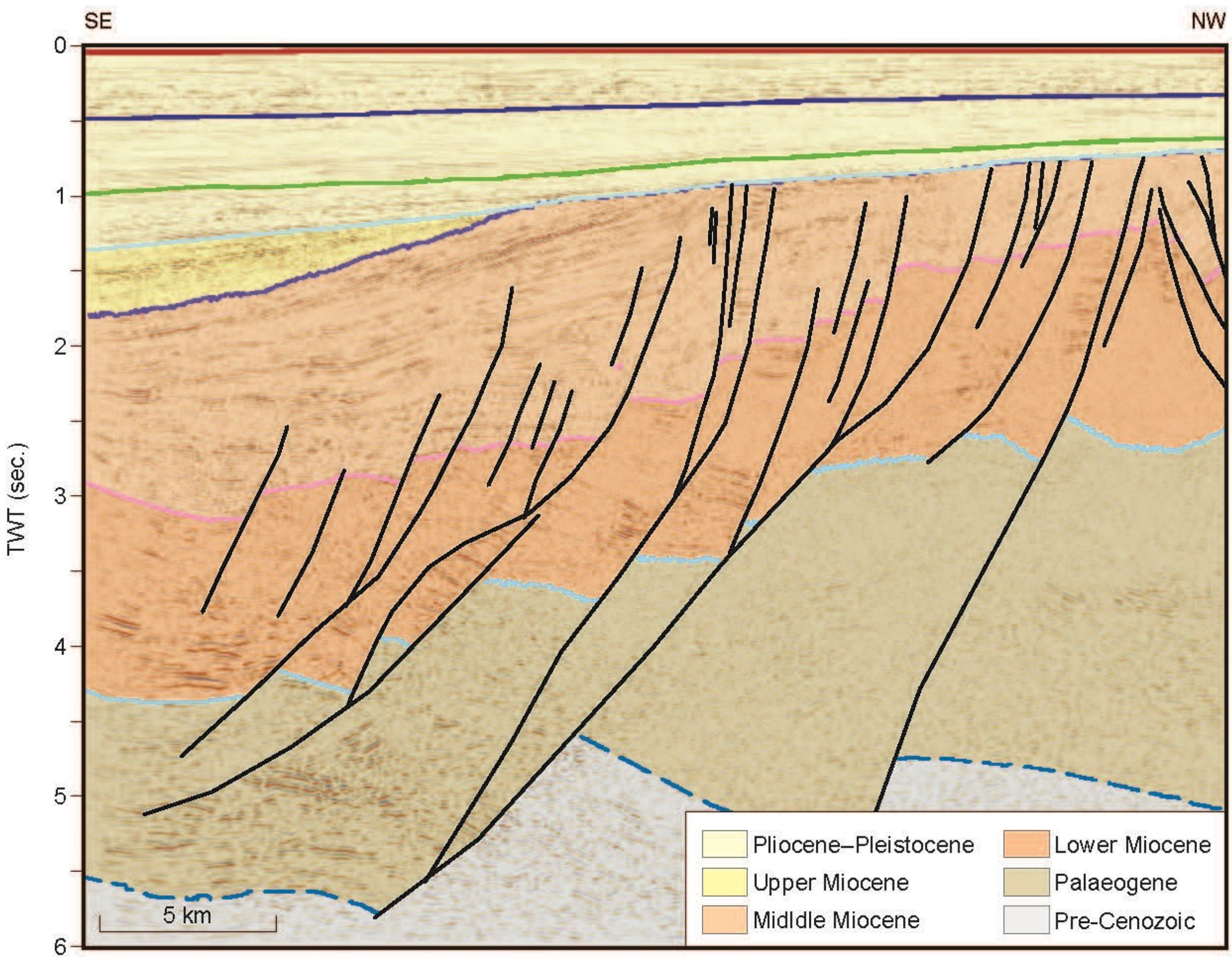


Figure 8. Seismic transect showing roughly E-W striking faults over the central part of the Song Hong Basin. The faults intersect both the top and the base of the Paleogene resulting from both Paleogene movements and Neogene reactivation.

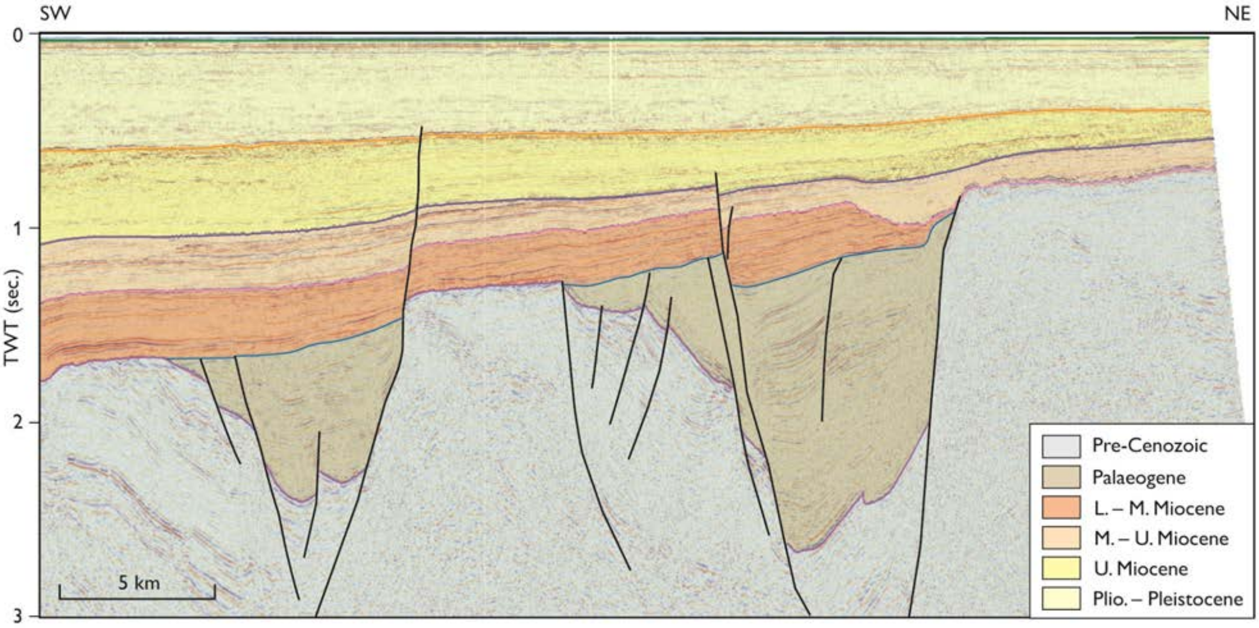


Figure 9. *Seismic transect illustrating the Paleogene graben and horst configuration characterizing the northeastern margin of the Song Hong Basin. Location shown in Fig. 2.*

The Beibuwan Basin is directly connected with the eastern sector of the Song Hong Basin through fault splays from the NW-trending Kien An Graben and splays from the rift system south of the Bach Long Vi Island (Figs 2, 4). The Kien An Graben is delineated by the Kien An and the Tien Lang faults that are steep to sub-vertical along longer stretches. A distinct succession of continuous, high-amplitude, low-frequency reflectors is thickly developed at a left-step in the graben (Figs 10, 11). Away from the fault left-step, the seismic facies changes due to decreasing reflector amplitudes and continuities and increasing frequencies. The Kien An Fault splays towards the northeast delineating the edge of the Cam Pha Graben and the southwesternmost part of the Beibuwan Basin (Fig. 4). The Paleogene stratigraphy can be tied from grabens along the northeastern flank of the Song Hong Basin and into the westernmost Beibuwan Basin (western Beibuwan sector of Fig. 2) . Similarly, the syn-rift stratigraphy can be tied from the Song Hong Basin flank in the south to the southwesternmost Beibuwan Basin in the Bach Long Vi Graben. No sign of a deeper and older

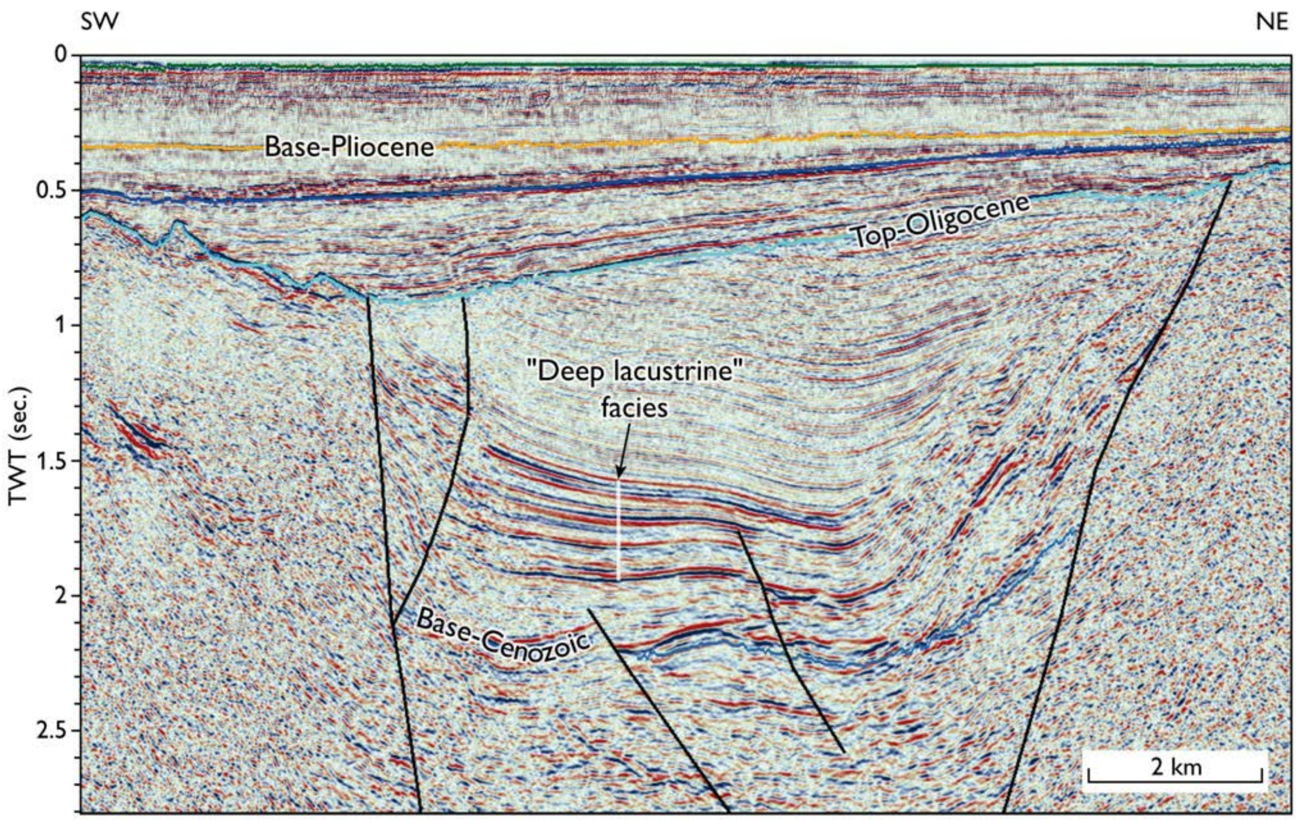


Figure 10. Seismic transect across a releasing bend in the Kien An Graben illustrating a thickly de-veloped succession of strong, continuous and low-frequency reflectors typical for carbonaceous deep-lacustrine deposits. Location shown in Figs 2 and 10.

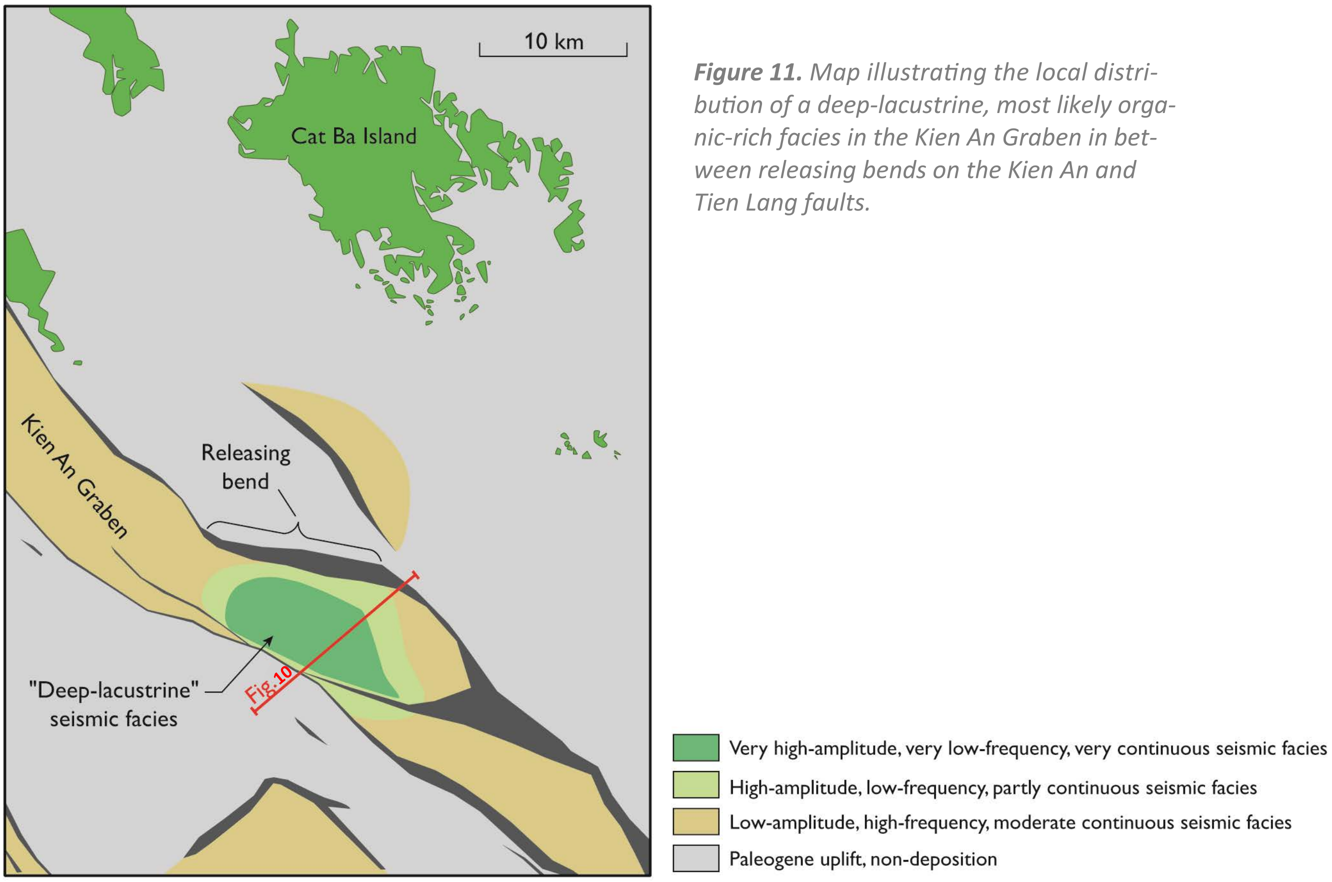


Figure 11. Map illustrating the local distribution of a deep-lacustrine, most likely organic-rich facies in the Kien An Graben in between releasing bends on the Kien An and Tien Lang faults.

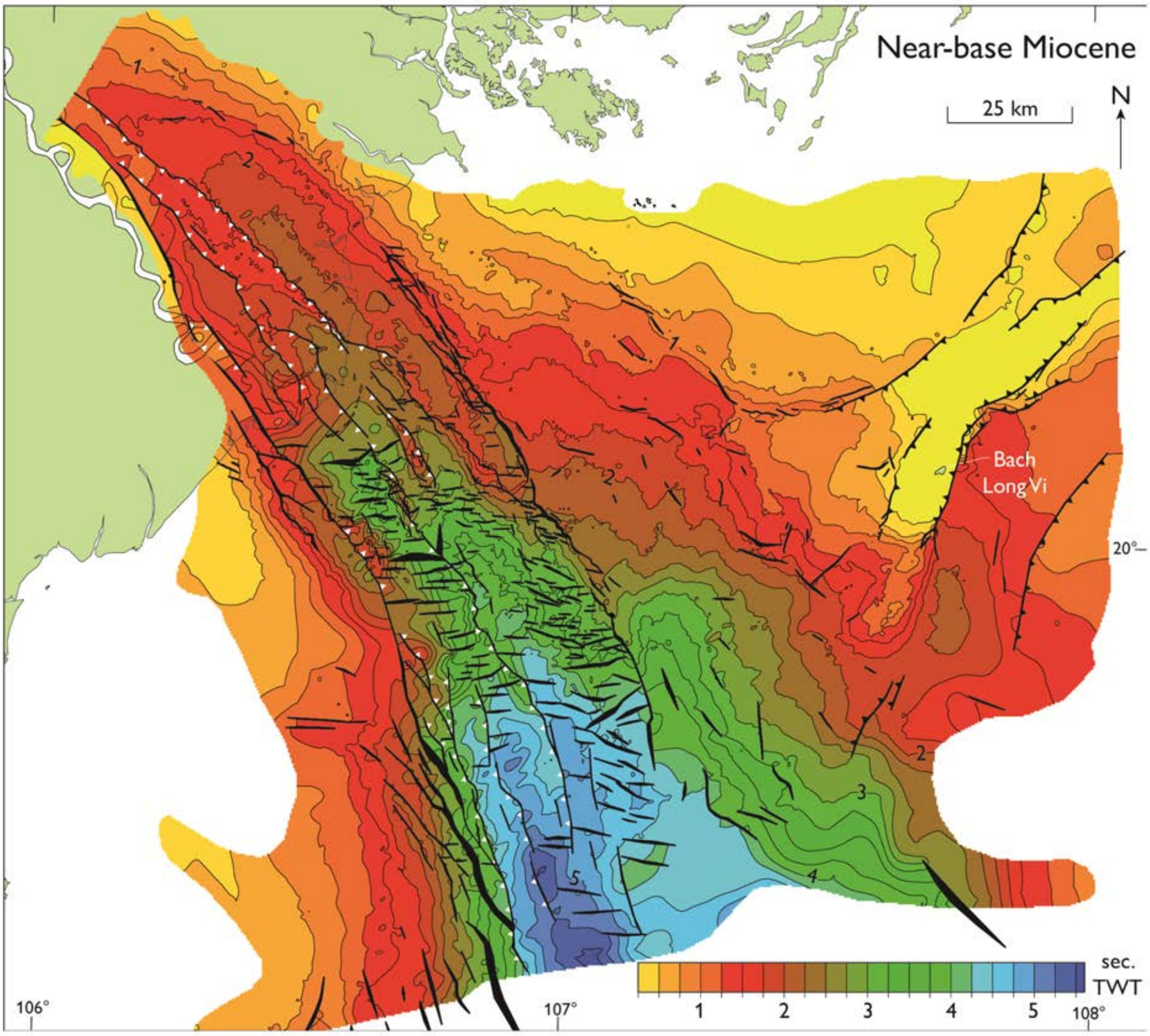


Figure 12. *Time-structure map to near the base of the Neogene corresponding to the end-Oligocene inversional unconformity well-developed along the flanks of the Song Hong Basin. Neogene deformation was an order of magnitude less than the Paleogene (e.g. compare with base-Cenozoic map on Fig. 4).*

Paleogene succession has been observed in the Beibuwan Basin compared to in the Song Hong Basin. Deformation associated with strong Neogene inversion in the southwestern Beibuwan Basin hampers direct seismic correlation in between the Song Hong- and the central Beibuwan Basin. Neogene inversion becomes more gentle northeast of Bach Long Vi Island.

Paleogene fault heaves and the general deformation of Paleogene syn-rift deposits strongly exceeds Neogene faulting and deformation illustrating that Paleogene structuring by far exceeded the subsequent Neogene (e.g. compare

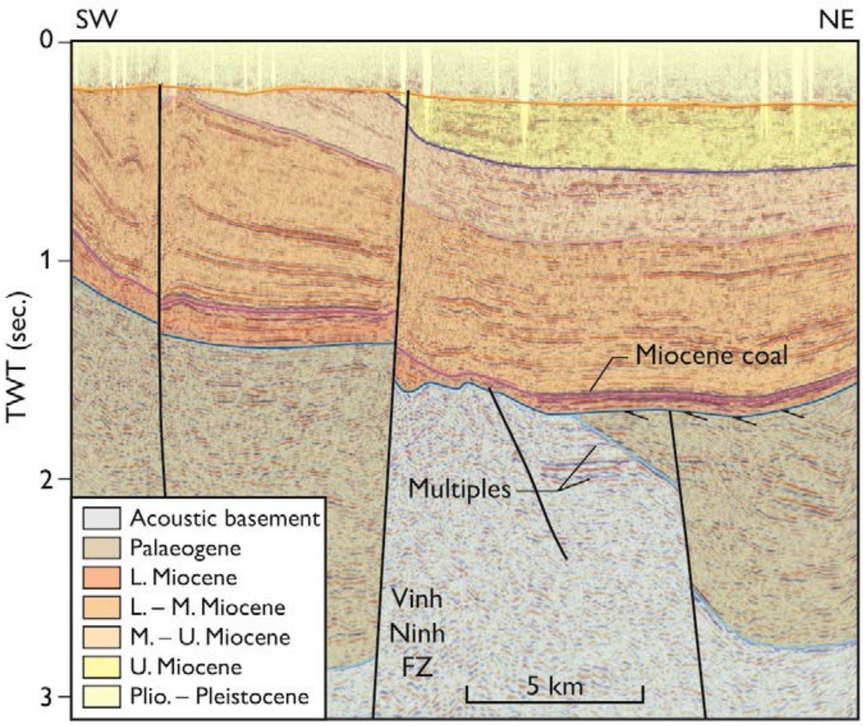


Figure 13 *Seismic transect across the onshore part of the Song Hong Basin. The inver-ted Paleogene graben and horst system continues on-shore under-neath the Red River Delta. Thickly de-veloped Neogene coals produ-ce strong multiples and redu-ce the energy trans-mitted into the Paleogene succession and thus lowers the deep seis-mic reso-lution. Location shown in Fig. 2.*

Fig. 4 with Fig. 12). Mainly near Bach Long Vi Island, Neogene inversion com-pletely invert the Paleogene rift (Fig. 3).

The Neogene thickness decreases northwestward along the basin axis in the northern Song Hong Basin causing the Paleogene to become shallower seated in the basin center (Fig. 12). Similarly, the pre-Cenozoic in between the Vinh Ninh and the Song Lo faults gradually becomes shallower seated towards the onshore. Underneath the Red River delta plain in between the Vinh Ninh and the Song Lo faults, a number of large Paleogene rift structures exist comparable to those along the offshore northeastern Song Hong Basin margin (Fig. 13). Thick Neogene coal seams restricts detailed imaging of these underlying struc-tures on the available seismic data. Vertical offset across the Song Lo Fault de-crease towards the northwest and the fault dies out (Fig. 4).

End-Oligocene Inversion.

The Oligocene is capped by a prominent erosional, inversion-related unconformity especially well-developed along the northeastern flank of the Song Hong Basin on- and offshore. On hangingwall blocks, increasing erosion depth towards former Paleogene extensional faults is common, thus denoting compressional reactivation and hangingwall uplift (Fig. 14). In some places, a section corresponding to more than 1 s. TWT of syn-rift strata appears to have been removed and a peneplain developed prior to Neogene burial indicating protracted uplift and erosion. Strong inversion and erosion took place along both NW–SE- and N–S- and NE–SW-striking faults (Fig. 15). In the Vietnamese part of the Beibuwan Basin, inversion continues to the present, which complicates distinguishing between end-Oligocene and younger inversion. Equivalently strong inversion along E–W-striking rift faults is not observed.

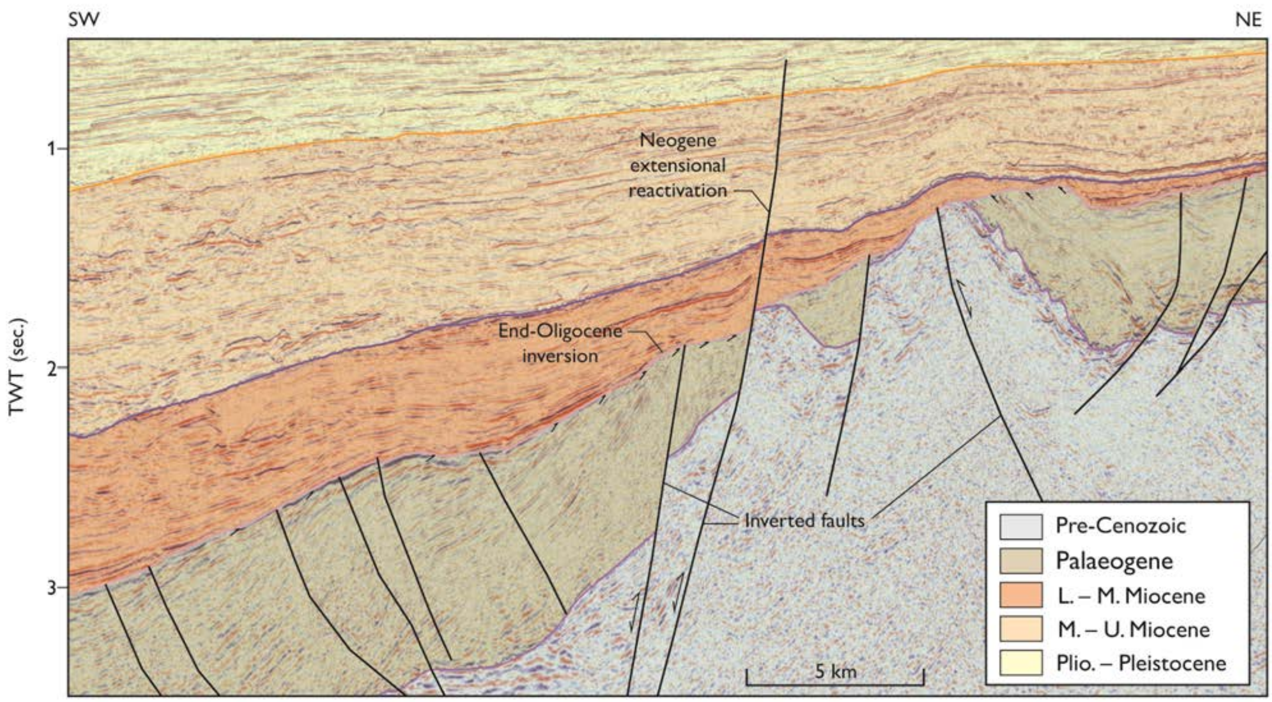


Figure 14. *Seismic transect illustrating the effects of the end-Oligocene inversion. Inversion resulted in uplift and tructation of Paleogene strata especially along former Paleogene extensional faults. Some of these faults were reactivated by modest extension during the Miocene. Location shown in Fig. 2.*

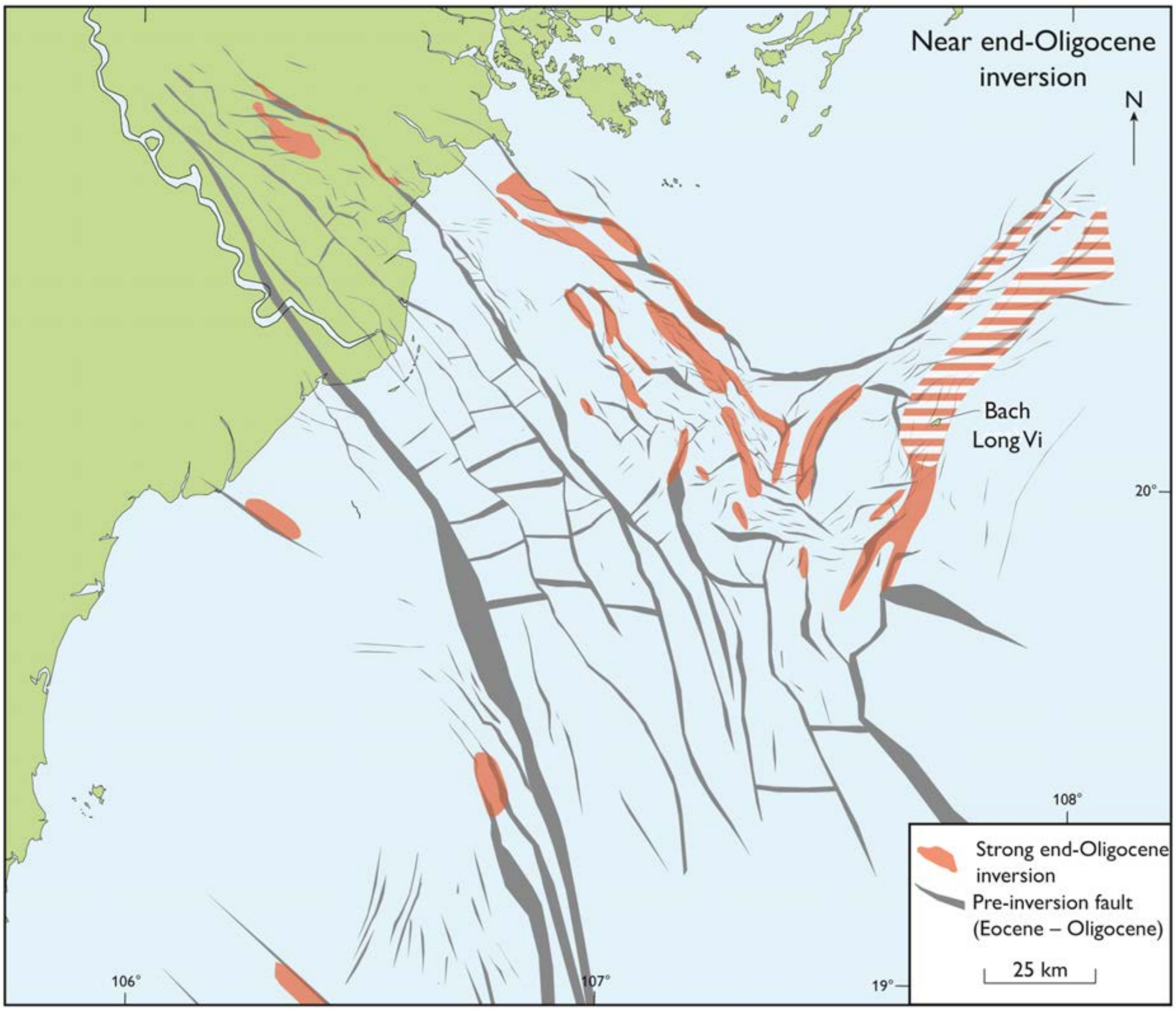


Figure 15. *Delineation of major end-Oligocene inversion zones. Hatched area denotes area where inversion continues to the present. Distinguishing between end-Oligocene inversion and subsequent deformation is not possible in these areas.*

Modest extensional offsets up to a few hundred milliseconds TWT of the inversion unconformity and the Lower and Middle Miocene section across NW-striking, former Oligocene inverted faults are common (Fig. 14). This suggests resumption of mild extension during the Early Miocene along the basin flank.

Signs of end-Oligocene inversion are sporadic on the western margin of the Song Hong Basin where Paleogene rift depressions are scarce (Figs 2, 15). In the offshore central part of the Song Hong Basin, the Oligocene–Miocene transition is generally deeply buried and contorted by Miocene deformation. Towards the basin center, top-Oligocene erosion decreases and the boundary becomes more conform compared to along the flanks. In the basin center, indications of end-Oligocene inversion-related reflector truncation near NW–SE-striking faults are less conspicuous and have not been observed along E–W-trending faults. This suggests modest end-Oligocene erosion in the seaward central part of the northern Song Hong Basin compared to along the basin flanks. This probably reflects strong end-Oligocene compactional and thermal subsidence and/or the presence of considerable accommodation space across the basin center immediately prior to inversion (e.g. a deep lake/eustarine environment). This may have counterbalanced the end-Oligocene inversion uplift and minimized erosion across the offshore basin center.

Onshore, the Oligocene–Miocene transition is situated underneath thick Miocene coal seams that hamper unambiguous deep seismic imaging. It is therefore not clear if the transition is nearly conformable or unconformable in the onshore central part of the basin between the Song Chay and Vinh Ninh faults. An unconformable relation certainly exists onshore outside the central part of the basin (Fig. 13).

The end-Oligocene surface is offset by E–W-striking listrict normal faults and by NW–SE-striking extensional and compressional faults that reactivate Paleogene structures (Figs 5, 8, 12). These faults strongly influence Miocene thicknesses in the central basin.

In the central basin and along the basin flanks, the inversion unconformity is covered by Lower Miocene strata. The age of the sediments onlapping the unconformity decreases away from the Song Hong Basin depocenter. In the southwestern part of the Beibuwan Basin around Bach Long Vi Island that experienced a more protracted inversion history (Fyhn and Phach, 2015), the unconformity is buried mainly underneath Upper Miocene and younger strata. Around the Bach Long Vi Island, the top of the Paleogene is even exposed at the seafloor and crop out on the island or is covered only by a thin drape of Pleistocene–Holocene deposits.

Strike-slip and Slip Sense Indicators

The Song Hong Basin lies in direct extension of the ASRRSZ and was therefore proposed to have formed in response to left-lateral pull-apart rifting (Rangin et al., 1995; Clift and Sun. 2006; Sun et al., 2003; 2004; Zhu et al., 2009). A systematic investigation of strike-slip and shear sense indicators in the area remains, however, and the inferred genetic relation between the ASRRSZ and the Song Hong Basin is based virtually on the location of the Song Hong Basin relative to the ASRRSZ. Morley (2013) therefore suggested left-lateral motion recorded within the ASRRSZ onshore to mostly predate the Song Hong Basin, and consequently ruled out a left-lateral transtension or pull-apart mechanism behind rifting and basin formation.

The detailed structural mapping presented in this study substantiate that the fault system within the central part of the Song Hong Basin outlines the direct continuation of the ASRRSZ represented by the Dai Nui Con Voi metamorphic core complex on Fig. 4. The basinal faults continue the structural trend outlined by the ASRRSZ, and the remarkable continuity and linearity of the faults in the basin center is compatible with major strike-slip faulting (Fig. 4). The Thai Binh Fault located along the basin axis in the central part of the basin resembles a cross basin strike-slip fault zone, which tends to develop in transtensional pull-apart basins when significant lateral offset takes place (Wu et al., 2009)

The distinctly left-stepping fault trend along the eastern basin margin is consistent with left-lateral shearing across the basin axis (Fig. 16). On the south-western flank of the basin, the imbricated extensional faults with a counter-clockwise angle of 10°–20° to the Song Chay Fault are compatible with major left-lateral Riedel shears (e.g. Sylvester, 1988). The roughly E–W-trending faults in the basin center linking the major NW-striking faults are interpreted as ex-

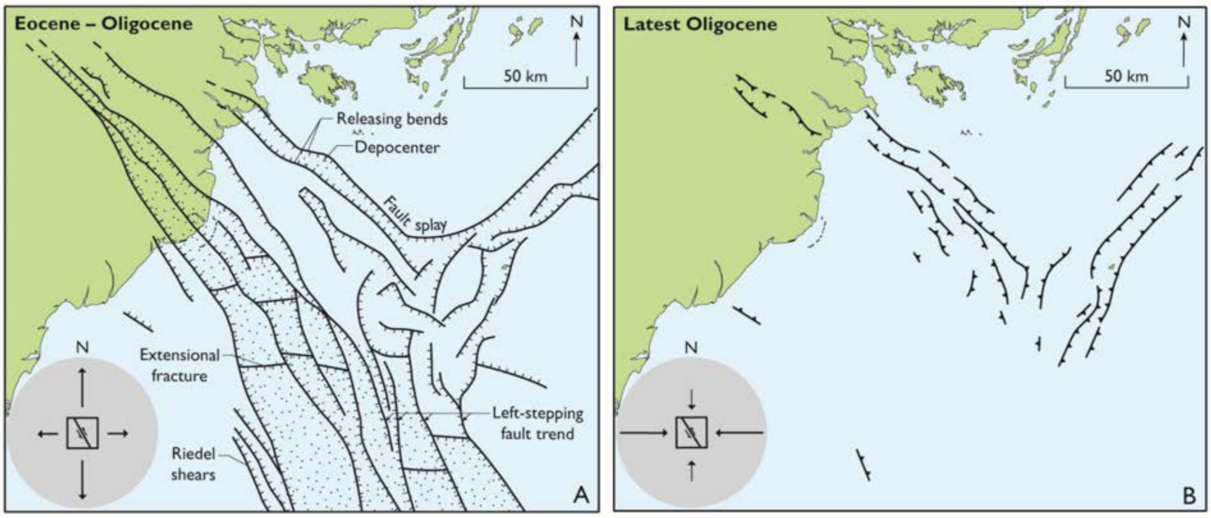


__Figure 16.__ Reconstruction of the evolving stress pattern around the northern Song Hong Basin with fault-trends active during the sub-periods indicated. A) During the later Eocene and Oligocene, NW-, NE-, E- and N-striking faults all accommodated extension. Riedel shears counter clockwise to the main NW-fault trend, extensional left-steps in the basin confining NW-striking faults, E–W-striking extensional fractures and left-stepping releasing bends suggest a left-lateral sense of shearing across NW-striking faults. Together with other extensional fault trends, this suggests a dominance of roughly N–S-extension together with subordinate E–W-extension characterizing the regional stress regime during the latter Eocene and Oligocene. B) During the latest Oligocene and earliest Miocene, compressional inversion across NW-, NE- and N-striking faults and the relatively modest inversion taking place across E-striking faults suggest a stress regime dominated by roughly E–W-compression and possibly subordinate N–S-compression. The stress pattern of both periods suggests left-lateral motion across the Song Hong Basin axis.

tensional fractures induced by left-lateral shearing across the NW-striking faults along the basin axis.

Faults along the northeastern basin flank are less continuous compared to the basin faults, but may also have had a lateral component. The distinct succession of continuous, high-amplitude, low-frequency reflectors thickly developed at a left-step in the Kien An Graben is typical for organic-rich, deep-lacustrine mudstone-dominated successions interspersed with other “harder” lithologies giving rise to the strong and continuous reflectors (Figs 10, 11) (Andersen et al., 2005; Fyhn et al., 2009b; Huan et al., 2013). The seismic amplitude and continuity decrease and frequencies increase away from the left-stepping fault zone is compatible with fluvial and shallower lacustrine deposits. This pattern probably reflects particularly fast subsidence at the fault left-step, promoting deep-lacustrine deposition in the local subsidence center. In left-lateral regimes, fault left-steps tend to behave as releasing bends causing rapid subsidence, which would explain the observed local seismic facies pattern.

The Paleogene rift geometry in the greater north Song Hong Basin area is dominated by NW–SE-, NE–SW- and E–W-striking extensional faults, but a smaller number of roughly N–S-striking extensional faults also occur along the basin flanks. Major, roughly N–S-trending extension are compatible with massive extension across NW–SE-, NE–SW- and E–W-striking faults. At the same time, the smaller number of roughly N–S-striking extensional faults suggests a secondary E–W-trending extensional component (Fig. 16a). This stress pattern is compatible with left-lateral transtension along NW–SE-striking fault lineament.

The end-Oligocene inversion documents a change in stress pattern. Strong inversion took place across especially NW–SE-, N–S- and NE–SW striking faults. In contrast, more modest inversion affected E–W-striking faults in the eastern and the Beibuwan sectors. This deformation pattern fits with dominating E–W-trending compression, possibly in combination with modest N–S-trending compression (Fig. 16b). This indicates a change from left-lateral transtension to left-lateral transpression across NW–SE-striking faults in the Song Hong Basin towards the end of the Oligocene.

DISCUSSION

Age of Regional Rifting

Palynostratigraphy suggests an Oligocene age for most of the offshore syn-rift, but rifting probably initiated already during the later Eocene. This is compatible with the ages of the onshore rifts in the region obtained most recently (Böhme et al., 2013). The top of the Paleogene syn-rift succession in the central Song Hong Basin shallows along the basin axis to the northwest. This could indicate that the Paleogene was originally interconnected with the coeval basins outcropping along the Dai Nui Con Voi metamorphic core complex (Fig. 4). Pleistocene sediments cover the upper reaches of the Song Hong Delta and conceal any preserved parts of this connection, however.

Paleogene palynostratigraphy from the northwestern margin of the South China Sea is only loosely tied to the well-established marine biostratigraphic and other chronostratigraphic frameworks. It is uncertain if the applied palyno zonation brackets well-constrained, super-regionally correlateable depositional periods or if it also partly reflects more local paleoclimatic fluctuations (Morley, 2014). This calls for caution when evaluating the Paleogene chronostratigraphy based on palynomorphs alone.

The Na Duong Basin delineating a small left-lateral pull-apart basin seems genetically related to the Song Hong Basin and contains palynological assemblages compatible with the Paleogene of the Song Hong Basin (Fig. 4) (Pubellier et al., 2003; Böhme et al., 2011). The Late Barthonian or Priabonian age (39–35 Ma) of the lowermost part of the Na Duong Basin determined based on a rich vertebrate fauna (Böhme et al., 2013) suggests latest Middle or Late Eocene pull-apart initiation.

Late Eocene rifting is also recorded within the Bu Khang Dome on the southwestern flank of the Song Hong Basin (Jolivet et al., 1999). This suggests a late Middle or Late Eocene onset of basin formation around the Song Hong Basin.

Most syn-rift sediments both outcropping onshore and deeply buried in the Song Hong Basin are interpreted as Oligocene based on palynostratigraphy (Bat et al., 2009; Tri and Khuc, 2011). This is consistent with rift-related exhumation of the Bu Khang Dome continuing throughout the Oligocene (Jolivet et al., 1999).

Rifting in the Beibuwan Basin is generally indicated as Paleocene to Oligocene in age, having occurred throughout a roughly 40 My long period (e.g. Huang et al., 2013; 2017; Liu et al., 2014), but convincing argumentation for this age assignment remains to be presented. In contrast, rifting in the neighboring Vietnamese basins probably occurred in between late Middle/Late Eocene and the Oligocene corresponding to a roughly 16–12 My long period.

The interpreted seismic stratigraphy indicates syn-rift deposition taking place simultaneously in the Beibuwan sector and the Song Hong basin sectors, however (Fig. 2). No observations of a deep (Paleocene–Eocene) syn-rift succession separated unconformably from a younger syn-rift interval (upper Middle/Upper Eocene –Oligocene) have been made in support of diachronic rifting.

In the Chinese part of the Beibuwan Basin, the thickly developed organic-rich lacustrine mudstones in the Liushagang Formation described as Eocene contrasts to the entirely lean Weizhou Formation labelled as Oligocene (Huang et al., 2013; Liu et al., 2014). The more than 500 m thick organic-rich, lacustrine succession drilled on the Vietnamese Bach Long Vi Island located in the Beibuwan sector only few tens of kilometers from the Chinese-Vietnamese territorial boundary is highly comparable to the Chinese Liushagang Formation (Fig. 2) (Petersen et al., 2014; Huang et al., 2013; 2017; Liu et al., 2014) and most likely represents more or less the same stratigraphic interval. However, palynostratigraphy attributes the cored Vietnamese section to the *Verrutricolporites Pachydermus* subzone of the *Florschuetzia Trilobata* zone suggesting a middle to Late Oligocene age (Tuyen et al., 2013). Together with the seismic stratigraphy interpreted in this study, this argues for a common late Middle/Late Eocene through Oligocene age of the syn-rift successions in both the northern Song Hong and the Beibuwan basins.

The Early Miocene age of the oldest part of the post-rift succession suggests that rifting probably terminated during the latest Oligocene and certainly no later than the earliest Miocene (Bat et al., 2009). This brackets rifting in the area to in between late Middle/Late Eocene and Late Oligocene/earliest Miocene.

Linking Basin Formation and the ASRRSZ

The aligned trend of the ASRRSZ and the Song Hong Basin have been used as an indicator for a genetic relationship between left-lateral shearing and basin formation (Tapponnier et al., 1986; Sun et al., 2004; Clift and Sun, 2006; Zhu et al., 2009). The kinematic indicators revealed by the structural style of the northern Song Hong Basin confirms that Paleogene rifting in the Song Hong Basin occurred in response to left-lateral movement along the ASRRSZ and its offshore extension. The kinematic indicators are compatible with the Song Hong Basin having formed by a pure pull-apart- or transtensional pull-apart mechanism, the latter being characterized by slightly oblique motion relative to the principal displacement zone (Wu et al., 2009).

Paleogene rifting characterize the primary deformation period in the northern Song Hong Basin succeeded by more modest Neogene deformation. The late Middle/Late Eocene through Oligocene/earliest Miocene age of rifting is overlapping with the age of left-lateral shearing suggested by thermochronology of the metamorphic core complexes within the ASRRSZ (Table 1). Indications of substantial slow-down of lateral shearing towards the end of the Oligocene are in line with coeval termination of rifting in the northern Song Hong Basin. Whether left-lateral shearing along the ASRRSZ commenced after the Early Oligocene or already during Middle or Late Eocene time is a matter of debate. Advocates for a mid-Oligocene or later initiation of shearing interpret Late Eocene –Early Oligocene intrusions and metamorphism along and within the ASRRSZ to be pre-kinematic in nature (Chung et al., 1997; Searle, 2006; Searle et al., 2010). The oldest Paleogene potassic alkaline intrusions and extrusives are interpreted to have resulted from lithospheric mantle delamination and intraplate extension (Chung et al., 1997; Searle, 2006; Liang et al., 2007). In contrast, Searle et al. (2010) suggested these rocks to represent arc-related magmatism pre-dating left-lateral shearing. Schärer et al. (1994), Zang and Schärer (1999), Leloup et al. (2001) and Liang et al. (2007) interpreted a close link between the Eocene–Early Oligocene magmatism and left-lateral transtensional shearing. Comparable Oligocene alkaline intrusions in the Bu Khang Dome probably formed in response to extension and exhumation of the metamorphic core complex (Jolivet et al. 1999; Nagy et al., 2000). A similar mechanism could be speculated for the formation of Eocene–Early Oligocene alkaline magmas within and along the ASRRSZ. The metamorphic fabric of the core complexes of the ASRRSZ suggests pervasive Late Eocene–Oligocene transtension (Jolivet et al., 2001; Leloup et al., 2001a). Massive transtension is similarly indicated by the narrow rift basins along the ASRRSZ that are likely to have formed contemporary with the alkaline magmatism and the Song Hong Basin. This is supported by Late Eocene intrusions in Eocene–Oligocene rift basins along the northern reaches of the ASRRSZ (Schärer et al., 1994). Late Eocene–Early Oligocene metamorphism within the ASRRSZ was suggested to be linked with compression and crustal thickening (Searle et al., 2010; Palin et al., 2013). Extensional basin development both along the core complexes and more regionally seems incompatible with this. This would suggest either that the oldest metamorphic ages record left-lateral shearing comparable to the slightly younger metamorphic ages, or that the rift-basins formed entirely after the Early Oligocene. The latter is contradicted by biostratigraphic evidence and Late Eocene magmatic intrusion of the basin fill.

This raises a number of questions as to the original nature and formation of the metamorphic core complexes. The fact that the Song Chay and the Vinh Ninh faults confine both the Song Hong Basin depocenter and the Dai Nui Con Voi metamorphic core complex points to a direct link between the metamorphic core complexes and basin formation. The metamorphic core complexes along the ASRRSZ are often considered to have formed and exhumed throughout a continuous extrusion-related process (Anczkiewicz et al., 2007; Burchfeld et al., 2008; Yeh et al., 2008; Searle et al., 2010; Zhang et al., 2014). The basin analysis presented here of the greater Song Hong Basin points towards that Indochinese extrusion took place through tectonically distinct steps initiating with massive later Eocene through Oligocene transtension. Transtension was superseded by transpression and uplift during latest Oligocene to earliest Miocene time, which in turn was followed by early Neogene moderate transtension and Late Neogene transpression (Fyhn and Phach, 2015). The formation and exhumation of the metamorphic core complexes along the ASRRSZ most likely also reflect a stepwise evolution compatible to that of the Song Hong Basin.

The Dai Nui Con Voi metamorphic core complex delineates the landward continuation of the central northern Song Hong Basin. In contrast to the central northern Song Hong Basin, Paleogene deposits are absent above the core complex and the complex represents a deeper crustal level compared to the basin fill. On the other hand, the Dai Nui Con Voi metamorphic core complex has a pervasive transtensive fabric and is flanked by Paleogene rift basins comparable to the Song Hong Basin.

This could reflect that the metamorphic core complex constitutes the crustal root of erosionally removed Paleogene basin either delineating the northwestern continuation of the Song Hong Basin or a separate basin comparable to the Song Hong Basin (Fig. 17). Subsequently, most Paleogene strata and upper crustal rocks have been stripped off during uplift, eventually exhuming the Dai Nui Con Voi metamorphic core complex from deeper levels (Fig. 17b). ASRRSZ metamorphic core complexes farther northwest show a compatible relation to other flanking Paleogene basins, and may similarly reflect the roots of former pull-apart basins now removed through uplift and erosion.

The small Paleogene sedimentary troughs flanking the Dai Nui Con Voi metamorphic core complex could be preserved remnants of such larger basin. The absence of reworked clasts derived from the Dai Nui Con Voi metamorphic complex within these sedimentary troughs was interpreted to suggest that the core complex was unexposed during deposition (Wysocka and Swierczewska,

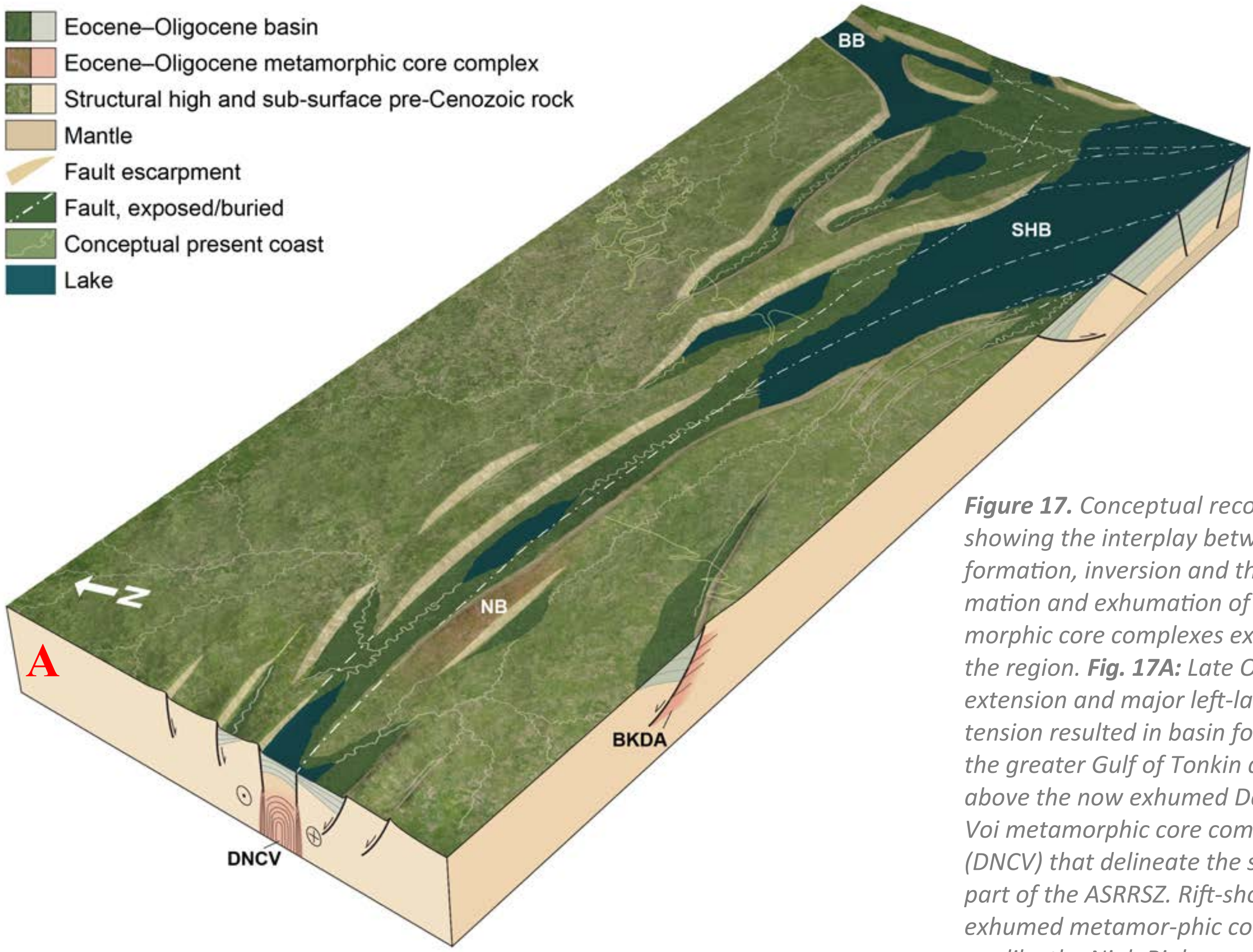


__Figure 17.__ Conceptual reconstruction showing the interplay between basin formation, inversion and the formation and exhumation of the metamorphic core complexes exposed in the region. __Fig. 17A:__ Late Oligocene extension and major left-lateral transtension resulted in basin for-mation in the greater Gulf of Tonkin area and above the now exhumed Dai Nui Con Voi metamorphic core complex (DNCV) that delineate the southern part of the ASRRSZ. Rift-shoulder uplift exhumed metamor-phic core complexes like the Ninh Binh complex (NB) along the flank of Chay Fault and the Bu Khang Dome. BKDA=Bu Khan Dome Analogue

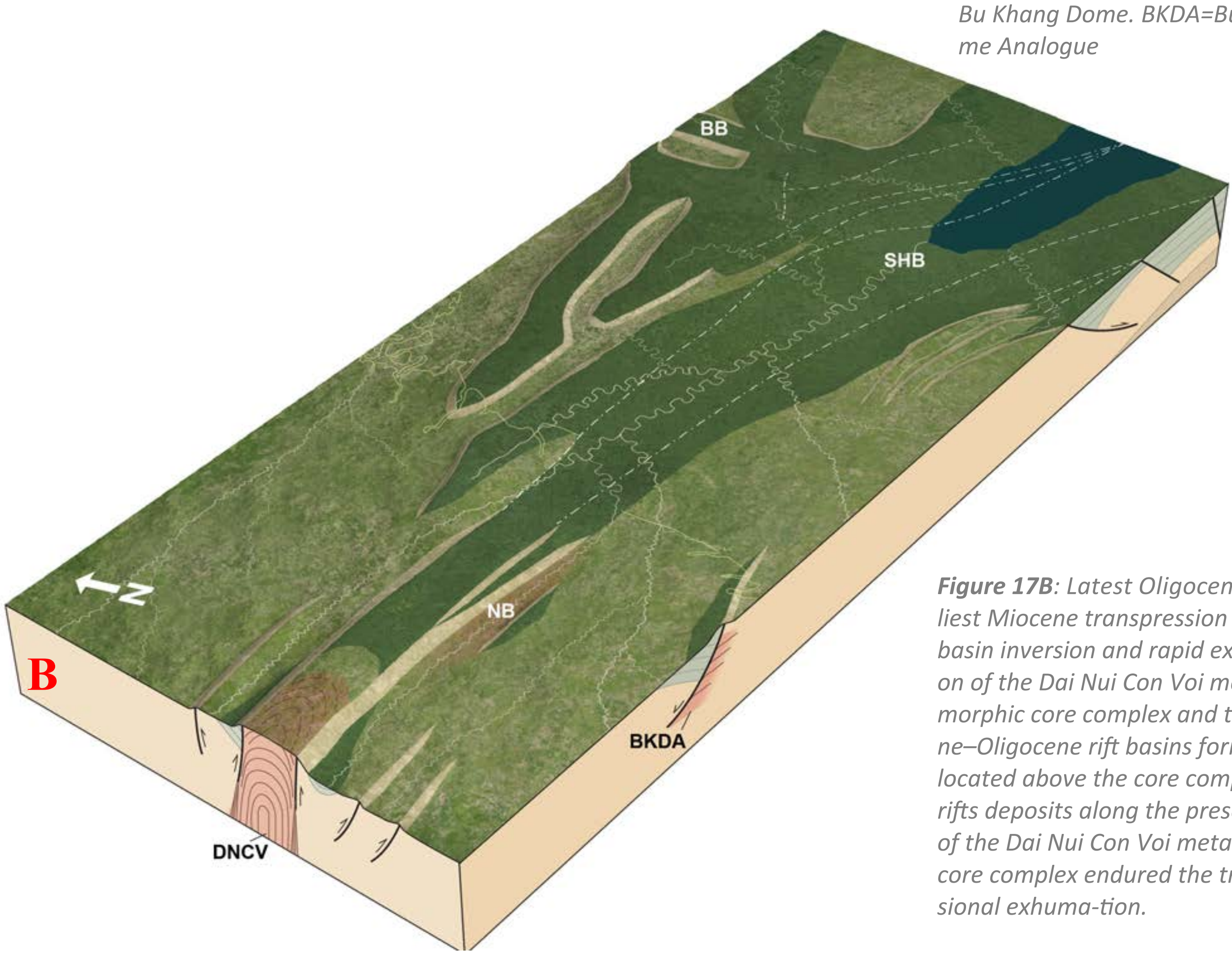


__Figure 17B__: Latest Oligocene to earliest Miocene transpression caused basin inversion and rapid exhumation of the Dai Nui Con Voi metamorphic core complex and the Eocene–Oligocene rift basins formerly located above the core complex. Only rifts deposits along the present flank of the Dai Nui Con Voi metamorphic core complex endured the transpressional exhuma-tion.

2010). This is in line with the metamorphic core complex forming coevally with the flanking basins comprising the root of a once larger basin. However, post-depositional lateral juxtaposition of the core complex and flanking basins could also explain these observations and further analyses are warranted.

Southeast of the Dai Nui Con Voi metamorphic core complex, Oligocene $^{40}Ar/^{39}Ar$-ages are recorded from the isolated metamorphic complex cropping out east of Ninh Binh at the flank of the Song Hong Basin (Fig. 4). The complex was originally interpreted as the southeastward extension of the Dai Nui Con Voi metamorphic core complex (Leloup et al., 2001), but the location along the shoulder of the Song Hong Basin show that the core complex is not situated centrally within the ASRRSZ. This could indicate that exhumation occurred in response to transtension associated with basin formation somewhat comparable to the extensional detachment exhuming the Bu Khang Dome (Fig. 17).

Similar metamorphic core complexes could exist beneath the Neogene cover farther seaward along part of the Song Chay Fault at the western flank of the Song Hong Basin in some of the areas characterized by a seismically transparent or chaotic facies typical for crystalline basement rocks. In contrast, on the eastern Song Hong Basin flank, metamorphic core complexes flooring the base of the Cenozoic are not supported by the seismically imaged, regionally distributed pre-Cenozoic sedimentary succession (Fig. 7). This could be a result of the structural difference between the western and eastern basin flank also reflected in the well-developed Paleogene rift system on the eastern basin flank. Alternatively, the sub-Cenozoic difference could owe to a substantial left-lateral offset juxtaposing different pre-Cenozoic terrains across the basin.

Rangin et al (1995) suggested that left-lateral motion was transferred from the Song Hong Basin and into the Beibuwan Basin through fault splays through the Tra Co Graben (Fig. 4). The Beibuwan Basin mainly connects to faults along the Song Hong Basin flank and could only have taken up lateral movements along the Song Hong Basin flank, such as from the Kien An and the Tien Lang faults (Fig. 4). Hence, most left-lateral shearing taking place across the central part of the Song Hong Basin must have been transferred farther south.

The NE–SW-striking fault trend of the Beibuwan Basin recurs in northern Vietnam and was similarly suggested to have taken up part of the ASRRSZ left-lateral motion by Pubellier et al. (2003) (Fig. 4). These onshore NE–SW faults delimits Upper Triassic grabens and half-grabens and must have originated before the Cenozoic. The fault trend thus characterize zones of pre-Cenozoic crustal weaknesses. The fault trend may even have an earlier history as Zhang and Cai (2009) and Cai and Zhang (2009) projected the major Permo-Triassic Hepu-Hetai Fault Zone from onshore South China into the Gulf of Tonkin along the trend of the Beibuwan Basin (Fig. 1). Reactivation of this crustal lineament may have governed the geometry and position of the Cenozoic NE-ward fault splays from the northern Song Hong Basin and the ASRRSZ, and thus have determined the overall location and structural trend of part of the Beibuwan Basin.

End-Oligocene Inversion and Initial Exhumation of Metamorphic Core Complexes.

The end-Oligocene inversion along the northern Song Hong Basin signifies a regional tectonic shift. The inversion unconformity denotes a change from major left-lateral transtensional rifting to left-lateral transpression and decelerated lateral faulting (Fig. 16). The shift to transpression recorded in the basin coincide with rapid uplift and exhumation of the metamorphic core complexes along the ASRRSZ and decreasing left-lateral shearing (Table 1) (Leloup et al. 2001; Viola and Anczkiewicz, 2008; Searle et al., 2010; Cao et al., 2011a; Liu et al., 2012; Palin et al., 2013; Tang et al., 2013). A common mechanism is speculated to have caused both basin inversion and metamorphic core complex exhumation (Fig. 17). This is in accordance with severe folding and thrusting of both Paleogene syn-rift strata and older rocks along the ASRRSZ following Eocene–Oligocene transtension, the latter evidenced by ductile deformation of the metamorphic core complex and rifting.

In the offshore Song Hong Basin, the strongest inversion is centered along the basin flanks with inversional erosion fading towards the basin center. In the distal central part of the Song Hong Basin, end-Oligocene uplift was probably counterbalanced by sediment compactional subsidence and pre-existing accommodation space in the basin center. The thick, coal-bearing Neogene overburden and Miocene deformation hampers assessment of the end-Oligocene inversion across the narrow onshore central part of the basin. More intense inversion of this part of the basin is expected if exhumation of the metamorphic core complexes and basin inversion in the Song Hong Basin are linked (Fig. 17). The observed decrease in left-lateral shearing towards the end of the Oligocene along the ASRRSZ fits well with the inversion in the northern Song Hong Basin and the subsequent decrease in tectonic activity within the basin. After the end-Oligocene inversion, tectonism decreased substantially in the Early Miocene. This is compatible with the distinct decrease in left-lateral shearing towards the earliest Miocene within the onshore ASRRSZ.

Regional Geological Implications

Rifting in the Song Hong Basin took place in response to left-lateral movement along the ASRRSZ. The age of rifting suggests that major left-lateral movement initiated during latest Middle Eocene or Late Eocene time and continued to near the end of the Oligocene.

Only a fraction of the left-lateral motion was accommodated within the Beibuwan Basin. Instead most motion was transferred farther south across the central Song Hong Basin fault system and strongly influenced basin development along the central Vietnamese margin (Roques et al., 1997; Fyhn et al., 2009a; 2009b; Savva et al., 2013).

Rifting along the western South China Sea margin including the Gulf of Thailand are interpreted to be in places governed by escape tectonics and elsewhere to have been influenced by it (Matthews et al., 1997; Lee and Watkins, 1998; Fyhn et al., 2009a; b; 2010). This is supported by the age of rifting occurring coeval with that in the northern Song Hong Basin and lasting throughout the Oligocene (Matthews et al., 1997; Bat et al., 2009; Fyhn et al., 2009a; 2010; Morley and Racey, 2011; Morley, 2014; Pubellier and Morley, 2014). Our findings in the northern Song Hong Basin support such a close link between basin formation and the extrusion of Indochina resulting from the India-Eurasia collision. The more or less simultaneous onset of rifting suggests that extrusion tectonism in the Indochina realm roughly coincided, which in some aspects contrasts with previous notions of a time-transgressive northward progression of extrusion tectonics (e.g. Huchon et al., 1994).

Rangin et al. (1995) interpreted the end-Oligocene inversion unconformity as a mid-Oligocene break-up unconformity associated with the initial continental break-up in the South China Sea. The revised younger age of the unconformity based on new well biostratigraphy hampers a connection to the initial Early–mid-Oligocene break-up of the South China Sea (Briais et al., 1993; Barchausen et al., 2014; Li et al., 2014b). As documented in this study, the unconformity formed in response to massive compressional basin inversion which is difficult to reconcile with a classic break-up unconformity (Franke, 2013; Franke et al., 2014).

Compared with the Vietnamese part of the Beibuwan Basin, the Chinese part of the basin was less affected by the inversion judging from published basinal transects (Huang et al., 2013; Liu et al., 2014), although rifting similarly was brought to a halt and end-Oligocene uplift and erosion took place (Huang et al., 2017). Similarly, the initial rift period terminated near the end of the Oligocene along much of the western South China Sea margin farther south, and end-

Oligocene inversion affected some of the marginal basins (Matthews et al., 1997; Lee et al., 2001; Xie et al., 2006; Fyhn et al., 2009a; b; 2013; Sun et al., 2010).

More regionally, rifting also terminated near the Oligocene–Miocene transition farther south in the eastern Gulf of Thailand and to the north in China (Fyhn et al., 2010; Qi and Yang, 2010; Morley and Racey, 2011; Pubellier and Morley, 2014). This indicates a super-regional tectonic change towards the end of the Oligocene. In the northern Song Hong Basin, the end-Oligocene tectonic shift seems linked with the rapid denudation of the metamorphic core complexes along the ASRRSZ and the slow-down of left-lateral transtension. A comparable link between the end-Oligocene rift termination and reduced escape tectonism may exist more regionally. Along part of the southwest Vietnamese margin, the end of Paleogene rifting is considered to be related with the latest Oligocene southward jump of the South China Sea spreading ridge, however (Lee et al., 2001; Li et al., 2014b). Better age constraints of the end of Paleogene rifting along the Indochinese margin and of the ridge jump are required to investigate if the spreading ridge jump is linked with the regional termination of rifting, widespread basin inversions and rapid exhumation of the ASRRSZ metamorphic core complexes. If such a link exists, termination of rifting and the initiation of transpression could have been caused by the isolation of the northwestern South China Sea from the slab-pull forces exerted by a subducting proto-South China Sea farther south after the ridge jump (Hall, 2002). Alternatively, both ridge jump, rift-cessation, transpression and basin inversions are rooted in a regional escape tectonic reconfiguration linked with the northward progression of the Indian continental indentation or in another more poorly constrained super-regional latest Oligocene geodynamic reconfiguration. The considerable end-Oligocene tectonic change observed in large parts of East and Southeast Asia is poorly understood and thus calls for further investigation. The Song Hong Basin with its central position linking the ASRRSZ with the South China Sea basins is ideally situated for addressing this issue in future studies.

CONCLUSION

The rift basins underneath the Gulf of Tonkin, Vietnam, constitute an example of how extrusion tectonics drives continental rifting and transtensional basin development. Rifting in the Song Hong and the Beibuwan basins was forced by left-lateral shearing transferred from the ASRRSZ running from eastern Tibet to the Gulf of Tonkin. Biostratigraphic evidence suggests a later Eocene to Late Oligocene age for the transtensional rifting and thus for left-lateral shearing. Rifting was terminated by major latest Oligocene to earliest Miocene inversion reflecting a change to left-lateral transpression. In comparison to the early phases of shearing, the Neogene was affected only by moderate amounts of lateral displacement. This points towards left-lateral shearing and extrusion tectonics initiating sometime during the later Eocene and further corroborates a latest Oligocene or earliest Miocene slow-down of left-lateral shearing and termination of ductile deformation observed along the ASRRSZ onshore.

The Song Hong Basin most likely originally extended father to the northwest along the present-day trail of the ASRRSZ, but especially latest Oligocene–earliest Miocene basin inversion caused uplift and removal of most of this part of the basin apart from isolated pods of syn-rift deposits preserved along the flank of e.g. the Dai Nui Con Voi metamorphic core complex. The exposed metamorphic rocks is suggested to be the now exhumed lower to mid-crustal root of former transtensional pull-apart basins comparable to the Song Hong Basin. Like the Song Hong Basin, these basins were inverted and exhumed during the end of the Paleogene. This model suggests a stepwise development of the metamorphic core complexes comparable to the basin evolution in contrasts to other recent models.

The end-Oligocene termination of rifting in the Gulf of Tonkin and the associated rapid exhumation of the ASRRSZ metamorphic core complexes occurred simultaneous with termination of Paleogene rifting along most of the western South China Sea and the eastern Gulf of Tonkin and a common causal mechanism seems likely. Whether this mechanism is rooted in escape tectonic changes forced for instance by the northward progression of the Indian indentation into Eurasia, the ocean break-up of the southwestern South China Sea or another plate tectonic reconfiguration near the Oligocene–Miocene transition awaits future investigation.

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