

# STRATIGRAPHIC CORE WELLS ENRECA-1, -2 AND -3: RESULTS OF THE SONG BA RIFT, PHU QUOC ISLAND AND BACH LONG VI ISLAND DRILLING CAMPAIGNS

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## Summary

*The long-term research co-operation between Vietnam and Denmark within basin analyses has generated many significant results. These have been used intensively in many ways including assessments of the hydrocarbon potential of the offshore basins, as input for license rounds, for promotion campaigns to attract industrial interest and for the publication of numerous scientific papers and presentations, which have contributed to the international appreciation of the fascinating geology of Vietnam.*

*Beside an extensive capacity building programme, one of the main activities of the ENRECA-programme has been the drilling of three stratigraphic core wells that have provided the research team with continuous cores of excellent quality, which have been analysed for sedimentary facies, source rock potential, age, petrography and reservoir properties.*

*The ENRECA-1 core-well was placed in the continental Song Ba rift in central Vietnam and cored 478m of the Oligocene (?) - Miocene fill of the rift. The cores document the variable depositional environments of the rift-fill. The most significant finding is the presence of two excellent lacustrine source rock successions, which have bearings on the occurrence of potential source rocks in the offshore Phu Khanh basin and thus the hydrocarbon potential of the basin.*

*The ENRECA-2 well was placed on the Phu Quoc island, where it cored 500m of Lower Cretaceous strata. The cores demonstrate the dominance of fluvial sandstones which in places show fair reservoir properties. Interbedded variegated mudstones were mainly formed in oxygenated lakes and flood plains and contain mostly inert organic matter.*

*The drilling of the ENRECA-3 well fulfilled an early proposal of coring the promising source rock bearing succession exposed in the Neogene inversion structure that forms the Bach Long Vi island. The cores document the presence of a minimum of 233m of excellent, world class oil-prone Palaeogene lacustrine source rocks. The source rocks are interbedded with various density current flow deposits including turbidites, hybridites and debrites, which together with sandstone dykes form an effective drainage system for hydrocarbons that may be generated where this prolific succession is deeper buried and matured.*

*The three strategically placed ENRECA core wells thus provided significant new insight that is discussed below.*

*The signing of a new Memorandum of Understanding (MOU) between VPI and GEUS will give the opportunity to their joint ENRECA research team to continue providing reliable and "demand-driven" research services to the public and industry in the years to come.*

**Key words:** ENRECA-1 well, ENRECA-2 well, ENRECA-3 well, Song Ba rift, Phu Quoc island, Bach Long Vi island.

## 1. History of research co-operation

The Vietnam Petroleum Institute (VPI) and the Geological Survey of Denmark and Greenland (GEUS) have been the core institutes in a long-term research programme between Vietnam and Denmark within basin analysis. Furthermore, the Hanoi University of Science (HUS), the Hanoi University of Mining and Geology (HUMG) and the Department of Geosciences & Natural Resource Management, University of Copenhagen (ING), have also been participating in this co-operation.

The programme was initiated by a visit to GEUS in

1993 by CCOP-representatives (Co-ordinating Committee for Geoscience Programmes in East and Southeast Asia) who investigated the possibility of co-operation within research capacity development in the CCOP-countries [20]. Funding was obtained from the Danish Energy Authority (DEA) and the first joint project between VPI and GEUS began in 1995. A need for interpretation tools at VPI was identified, and modern facilities were installed in 1996 with support from the Danish International Development Assistance (Danida). Following the successful completion of the project, DEA approved funding for a second project. The projects were accompanied by CCOP workshops held

at VPI, and "On-the-Job-Training" (OJT) programmes at GEUS for VPI geo-scientists. The implementation of these initial projects revealed the need for enhancement of the research skills of VPI geo-scientists, and support for long-term institutional development was obtained from ENRECA-programme at Danida in 2000.

The successful co-operation since 1995 has focussed on research and institutional capacity building and has included geo-scientific projects focussed toward assessment of the hydrocarbon potential of selected sedimentary basins in Vietnam. The aim has been strengthening of research capacity in Vietnam within the fields of basin analysis and modelling by offering "on-the-job-training" at GEUS in Copenhagen, technology transfer, in-house training at VPI, courses taught at the three universities, supervision of MSc. and PhD. students, preparation of technical reports and recommendations, and dissemination of research results at scientific conferences and in a large number of international publications.

Over the years, VPI, GEUS and Petrovietnam have provided considerable in-kind contributions and additional funding to further support the implementation of this comprehensive list of activities.

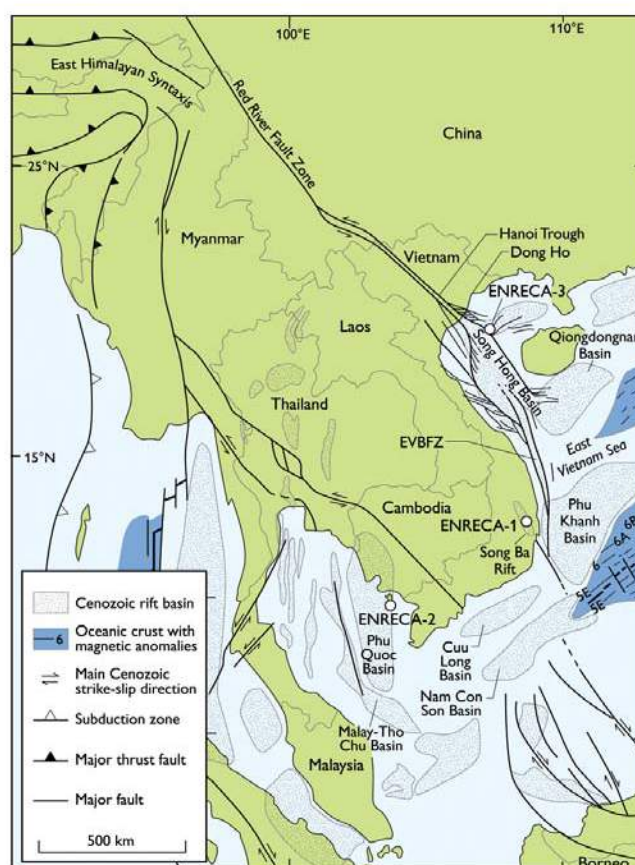
VPI and GEUS, considering the future challenges in E&P of oil and gas in Vietnam and taking advantage of the vast knowledge and experiences accumulated within the joint ENRECA Research Team, will soon sign an MOU (November 2014), that will establish the framework for continuing their research co-operation in the years to come. Thus, VPI and GEUS will be able to provide jointly reliable and "demand-driven" research of high standards to both the public authorities and the industry in Vietnam and abroad.

**2. Scientific results**

The two first geo-scientific projects were aimed at analysis of the hydrocarbon potential of the Song Hong basin (Fig.1). Seismic interpretation, field work and evaluation of results from the few exploration wells drilled in the basin were carried out [1, 2, 6, 7, 8, 19]. Seismic facies analyses, biomarker analyses of oil samples and investigations of thermally immature potential source rocks from onshore localities, including the Dong Ho and other outcrops, where oil-prone Oligocene lacustrine mudstones and thin coals are exposed, led to the identification of areas for future exploration in the Song Hong basin [3, 22, 25, 28].

The following project was focussed toward assessment of the hydrocarbon potential of the Phu Khanh basin, which at that time was almost un-explored [18]. The available seismic data was carefully interpreted and tied to well-sections north and south of the basin. The development of the basin was analysed and a number of possible play types were identified [11, 12, 15]. Oil seeps occurring at the basin margin have been reported from the Thi Nai lagoon area, but their nature remained controversial [31]. The area was thus visited and a number of oil samples were collected and analysed. The results show the presence of biodegraded petroleum, with biological markers pointing to a marly source rock with some terrestrial input and Cenozoic lacustrine oil similar to those from the Song Hong basin [4]. Available oil samples from neighbouring basins were also analysed for comparison and discussion on the character of the source rocks [5, 26].

The next period was focussed toward the Malay and Phu Quoc basins. Significant results regarding



**Fig.1.** Tectonic framework of Southeast Asia. Notice the Vietnamese offshore basins, the Song Hong, Phu Khanh, Cuu Long, Nam Con Son and Phu Quoc basins. The position of the three stratigraphic core wells ENRECA-1, -2 and -3 are indicated in the Song Ba rift and on the islands of Phu Quoc and Bach Long Vi. The Dong Ho locality in North Vietnam is marked

the understanding of the potential of the Vietnamese part of the Malay basin were obtained by applying seismic mapping, basin modelling and the utilisation of knowledge on the Cenozoic source rock obtained from the previous studies [13, 27]. Further, the structural development of the Phu Quoc basin was analysed [10, 14].

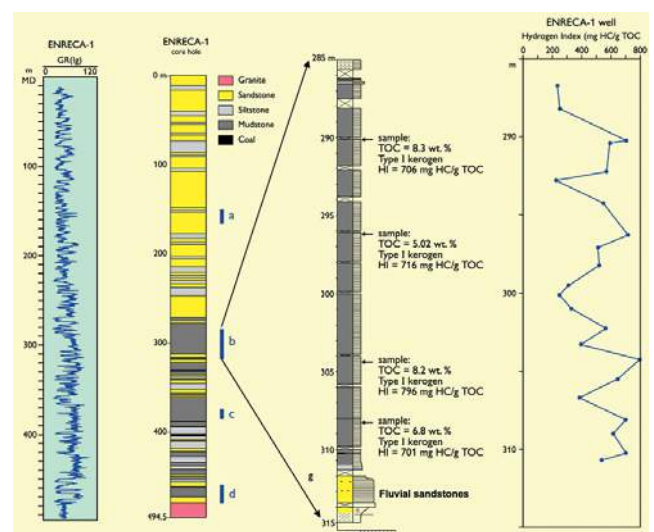
The most recent research studies have been focussed toward a revisit to the Song Hong basin with a focus toward the north-eastern parts. The previous findings of the ENRECA research team and a number of new encouraging well results with significant oil shows have generated renewed interest in the Song Hong basin, and it was obvious that existing exploration models could be strengthened by better data on the distribution and generation potential of the source rocks. It was thus decided to carry out a comprehensive seismic mapping campaign and to drill the Bach Long Vi island. The results were presented at VPI's 35 year's anniversary and are now prepared for publication [16, 23].

**2.1. ENRECA-1**

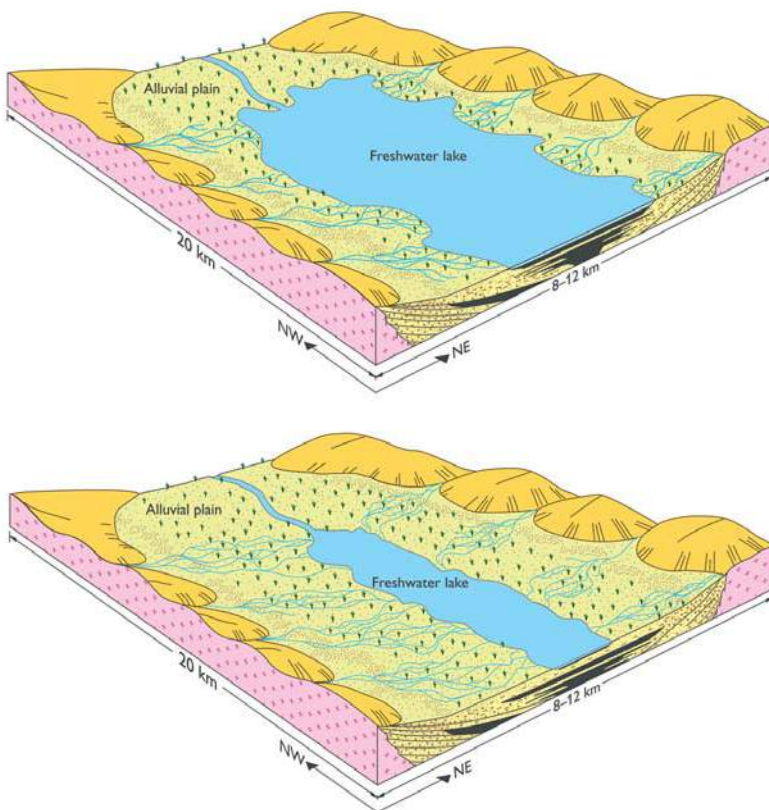
The presence of lacustrine source rocks in small grabens in the offshore basins as indicated by seismic data and biomarker analyses of oil shows and seeps [3, 4, 22, 25, 28] fostered the idea of investigating the fill of the Song Ba rift in central Vietnam. The rift seems to constitute the onshore continuation of the complex Tuy Hoa fault-zone marking the southern boundary of the Phu Khanh basin (Fig.1). The scientific approach was an attempt to develop a model of small, narrow continental rifts as a supplement to the well-established models for large rift-lake systems of Sladen (1995) and Lambiasi (1990). Thus, after a reconnaissance fieldtrip followed by dedicated field work on outcrops exposing coarse-grained sandstones and conglomerates interbedded with lacustrine mudstones and scattered coal beds, it was decided to drill a core well to investigate the deeper part of the graben fill. The ENRECA-1 core well was placed in the Krong Pa graben, one of several depressions within the Song Ba rift, and the 494.5m deep well was TD-ed in granite and provided excellent cores. The core well encountered 478m of sediments beginning with thin fluvial sandstones overlying the granite. The sandstones are overlain by lacustrine mudstones interbedded with thin sandstones, whereas fluvial sandstones dominate the upper part of the core. The lacustrine mudstones contain organic matter, commonly exceeding 5wt.% and occasionally reaching up to 8.3wt.%, and many samples have a hydrogen index (HI)

of more than 300mg HC/g TOC, occasionally up to 800mg HC/g TOC (Fig.2). The organic matter is mainly composed of fluorescing amorphous organic matter, alginite, and liptodetrinite, corresponding to type I kerogen and is an excellent source for oil. The cores thus show oil-prone source rocks of good to excellent quality attaining a cumulative thickness of approx. 50m. The results suggest formation of oil-prone mudstones primarily during rift climax when sedimentation rate was outpaced by formation of new accommodation space.

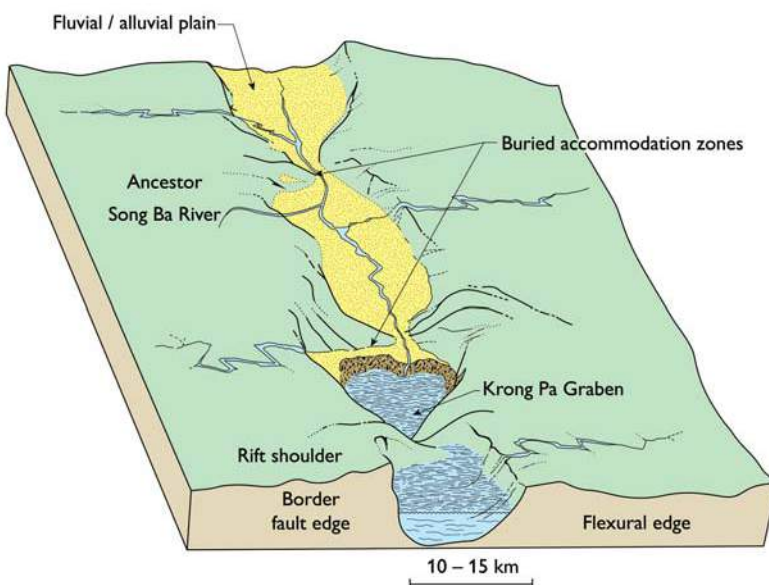
The cores in combination with information from other core wells in the area and the investigated outcrops led to the establishment of a local model describing the development of the graben fill (Fig.3 [21]). This local Krong Pa model has been combined with the general model of Lambiasi (1990), a conceptual model with large impact on exploration strategy has been proposed (Fig.4). The conceptual model proposed that if small grabens located on a string within a faulted zone is connected by a major trunk river system as the Song Ba ancestor river, the upstream grabens may function as sediment sinks that catch the coarse clastic river bed loads, whereas the lower downstream grabens may function as the locus for establishment of lakes in which prolific algae production may lead to the formation of lacustrine oil-prone source rocks. This clearly shows that even small and narrow (downstream) grabens may have a hydrocarbon potential, and this exploration model may be used in the offshore basin, where careful analyses of seismic facies may pinpoint the location of sweet spots.



**Fig.2.** The ENRECA-1 core well showing a gamma-ray (left), general lithology, a selected detailed log of the upper lacustrine mudstones sequence with specific samples marked, and measured HI values shown (right). Refer to Fig.1 for location



**Fig.3.** A schematic model showing high lake level in a small graben during rift climax when formation of new accommodation space exceeds deposition (left). The graben is dominated by fluvial deposition during the waning phase of subsidence (right)



**Fig.4.** Block diagram showing a series of grabens located within a fault zone. The proximal upstream grabens are filled with fluvial sand and function as sediment sinks, whereas the downstream distal grabens are more prone to accumulate lacustrine mudstones, in particular during periods of rapid subsidence and formation of accommodation. Applied to the Song Ba rift system, the Krong Pa graben (and the grabens further downstream in the offshore Tuy Hoa shear zone) corresponds to the distal grabens shown occupied by prolific freshwater lakes with deposition of organic-rich mudstones. Modified from Lambiase (1990)

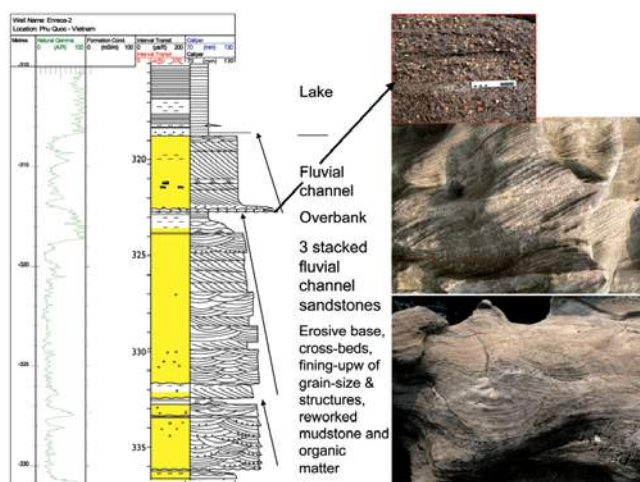
**2.2. ENRECA-2**

The Phu Quoc basin is located in the Gulf of Thailand offshore Southwest Vietnam and continues onshore Southern Cambodia (Fig.1). The available offshore seismic data shows a complicated structural development, and the basin is poorly explored and its hydrocarbon potential is difficult to assess. The Phu Quoc Island forms part of the north-south trending deformation belt that continues onshore Cambodia in the Elephant mountain belt and exposes parts of the Upper Mesozoic basin fill [14]. As an attempt to contribute to better constrained assessment of the basins hydrocarbon potential, field work was carried out on the Phu Quoc island and in Cambodia. The island mainly exposes Lower Cretaceous fluvial sandstones and conglomerates. Furthermore, seismic analyses, evaluation of well-sections and analyses and modelling of source rock maturation led to identification of possible source rock kitchens and contributed to the existing exploration models of the Vietnamese part of the Malay basin [13, 14, 24].

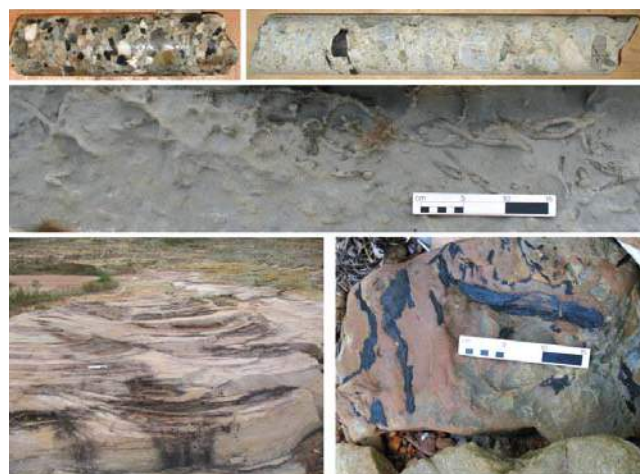
The ENRECA-2 core-well was placed on the south-western tip of the island and it provided 504 high quality cores interbedded with variegated mudstones and siltstones. The sandstones show weakly upward-fining channel successions with sharp erosive bases marked by pebbles of variable lithology overlain by thick cross-bedded, coarse- to medium-grained sandstones, which show an upward decreasing bed thickness (Figs.5 & 6). The sandstones contain scattered coalified wood fragments. The interbedded greenish, reddish and brownish mudstones and siltstones typically form few metres thick successions showing parallel lamination and small ripples. Rootlets are common and fragments of leaves and wood occur in places, but coal beds have not been observed. Large tree trunks, forming the so-called jet coal are reported to be abundant at a few stratigraphic levels on the island probably recording humid periods with a high groundwater table. Marine shoreface sandstones with abundant trace fossils occur at few stratigraphic levels in the cores and in

outcrops (Fig.6); the shoreface sandstones are associated with lagoonal mudstones and siltstones containing few marine dinoflagellates in the well [29].

The sandstones are mainly coarse- and medium-grained, in places fine-grained, and are mostly well cemented mainly with poor visible porosity. Petrographic analyses show they may be classified as sublitharenite, litharenite and feldspathic litharenite containing mainly quartz, minor feldspar, mica and common rock fragments, in particular of volcanic and metamorphic origin. Well log evaluation and macro- and microscopic evidence indicate intervals with 10 - 15% porosity, and up to 20% in a few places. Screening



**Fig.5.** Selected part of the ENRECA-2 core well showing well logs and sedimentological core log with interpretations. The cored succession consists of fluvial cross-bedded, coarse-grained, sandstones and lacustrine mudstones. Outcrop examples of fluvial cross-beds and parallel-stratified pebbly sandstones are shown (right)



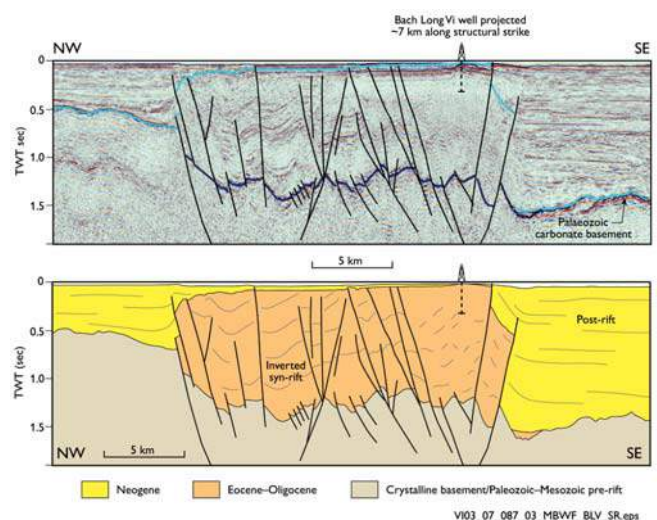
**Fig.6.** Selected photos of cores and outcrops. The two core pieces show polymict conglomerates indicating a complex source area (upper). An example of bioturbated, shallow marine sandstone exposed on the southeast coast (middle). Trough cross-bedded medium-grained sandstones and coalified wood fragments in fluvial sandstones (lower)

analyses of core and outcrop mudstones samples indicate a very low hydrocarbon generation potential.

### 2.3. ENRECA-3

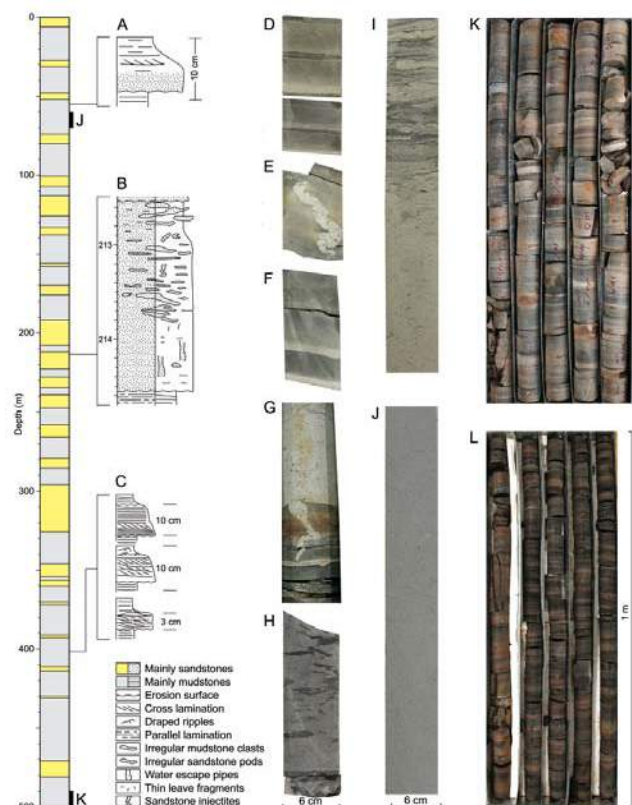
The Bach Long Vi island constituting the uppermost part of a Neogene inversion structure situated at the intersection of the Song Hong and Bei Bu Wan basins provides a unique geological window into the Paleogene syn-rift fill of the basins (Fig.7). Oil-prone lacustrine source rocks have been documented from the island and the sea bottom around it [25], but exploration wells located nearby such as the 107Pa-1x that drilled a thick syn-rift succession did not encounter hydrocarbon shows nor source rocks [3]. This disappointing result halted exploration in the area for some time, and the need for investigating this enigma increased. The ENRECA team thus suggested Petrovietnam to drill a fully cored well on the island to investigate the inverted syn-rift succession and the thickness and composition of the potential source rocks. It was decided to place the well in the southeastern corner of the island to supplement the exposed stratigraphy. The well was drilled in spring 2012 and has provided excellent cores with a very high recovery (Fig.8).

The cores have been logged sedimentologically and on the basis of the detailed core log a large number of samples for source rock screening, sandstone petrography, clay mineralogy, por-perm measurements and biostratigraphy were sampled. Although a detailed and integrated interpretation of the many results remained to be concluded by the ENRECA research team, several



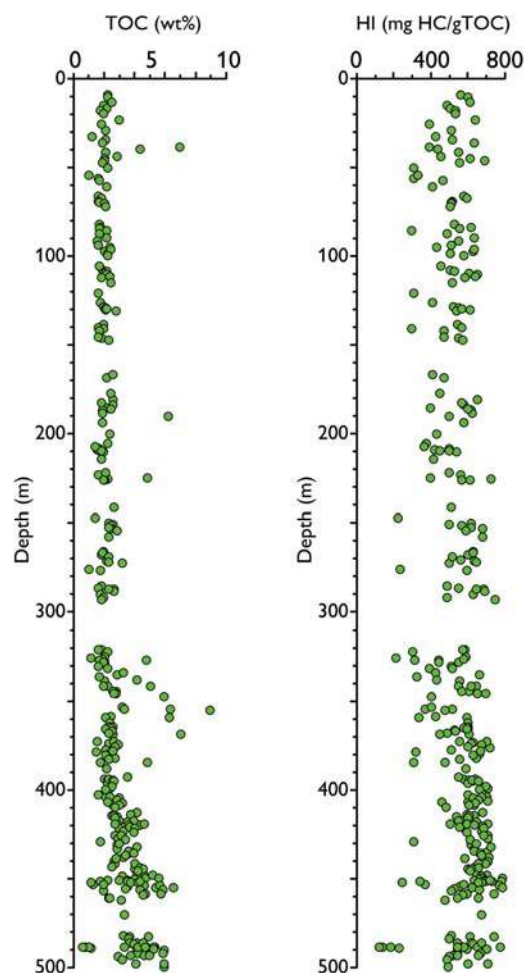
**Fig.7.** Interpreted seismic section and geo-section from the Bach Long Vi graben illustrating the inverted Paleogene syn-rift section. The Bach Long Vi island constitutes the top part of the inversion structure and offers a geological window into the syn-rift section

important conclusions can be drawn. The cored section constitutes a continuous succession without indications of significant unconformities or stratigraphic breaks. No significant faults are cutting the core succession. The absence of marine macro- and micro fossils, the abundance of freshwater algae, spores and pollen, the absence of fluvial and shallow water deposits and the presence of laminated mudstones with interbedded



**Fig.8.** Simplified lithological log of the 500m deep ENRECA-3 well (left) showing ca. 163m of sandstone-dominated intervals (yellow) interbedded with intervals dominated by mudstones (grey). Detailed logs of thin-bedded turbidites Bouma  $T_{abcde}$  (A) and  $T_{cde}$  (C) occurring interbedded with the mudstone source rocks are shown to illustrate the complicated nature of the succession. (B) Sedimentological log of thick density-current deposits (hybrid bed) with water-escape structures, floating intraformational rip-up clasts of mudstones and pods of sandstones. (D) and (F) show core pieces of thin-bedded fine-grained turbidites; (E) Sandstone injected into soft mud and later compacted. (G) Grey mudstones with thin sandstone layers and brownish concretion and injected sand at the base of an overlying density-current sandstone. (H) Muddy sandstone debris with poor por-perm; (I) Sandstone dominated hybrid bed with land-derived organic debris; (J) Thick sandstone turbidite with delicate leaf fragments and fair por-perm. (K) Light grey mudstones alternating with thin fine-grained sandstones and brownish cemented layers and concretions. The mudstones are highly oil-prone. (L) Dark grey to black, highly oil-prone mudstones alternating with light grey to greyish/brownish mudstones with a lower and varying generation potential. Modified from Petersen et al. 2014

sandstones indicate that the depositional environment was deep lacustrine. The age has been determined to Late Oligocene on the basis of poor biostratigraphic evidence as age-diagnostic fossils are poor [9]. Deposition of organic-rich pelagic and hemi-pelagic mud on a dysoxic lake bottom dominated. Occasionally, due to collapse of the more shallow parts of the lake and lacustrine deltas coarser-grained sediment was brought by turbidity currents and other sediment gravity flows to the deep part of the lake, where sand, silt and mud was deposited on the soft lake bottom often causing spectacular soft sediment deformation structures (Fig.8). The thicker turbidite beds are mostly medium-grained, fairly clean sandstones with fair porosities, whereas the muddy debris beds have poor reservoir properties. Based on the source rock screening data in combination with the sedimentological corelog, the cumulative thickness of the excellent oil-prone source



**Fig.9.** Source rock screening data showing the high TOC and HI values throughout the cored section. Note that the high values most likely continue below the cored section; in addition high values are found in the outcrops on the island that represents a higher stratigraphic level above the top of the cored section. Modified from Petersen et al. 2014

rocks is estimated to approx. 233m (Fig.9). The cumulative thickness of beds without an oil-generating potential or a poor potential, i.e. the thicker sandstones, the numerous thin sandy and silty turbidites and the many concretionary beds amounts to approx. 163m. The cumulative thickness of fine- to medium-grained sandstones thicker than 0.2m have a cumulative thickness of approx. 55m and these may serve as conduits or reservoirs for generated hydrocarbons. In addition to the "thick-bedded" sandstones, the numerous thin-bedded (cm-scale) very fine- to fine-grained turbidite sandstones, which are intimately interbedded with the source rock mudstones, may together with the sandstone injectites such as vertical dykes form a very effective drainage system for generated hydrocarbons.

The core well was therefore a great success demonstrating the presence of thick world-class source rocks interbedded with carrier beds. Furthermore, the cored succession shows no indications of a declining source rock quality towards the base of the cores succession and we also know from the outcrops that several tens of metres of source bearing strata occur above the core section (Fig.9). Thus the above mentioned cumulative thicknesses of the source rocks are minimum figures.

### 3. Future challenges

The conditions for the continued research co-operation between GEUS and VPI are changed now that the financial support from ENRECA/Danida is coming to a definitive end. This long-term co-operation has been very successful and has overcome a number of challenges and obstacles. The scientific success is confirmed by the great number of co-authored international papers in peer reviewed journals and the many oral and poster presentations at conferences that have received overwhelming recognition and acknowledgement by the international research community and the industry. With the upcoming research co-operation agreement (MOU) between VPI and GEUS, the organisational framework for new initiatives and projects will be defined. The ENRECA research team has through the years identified a number of tasks and projects, the implementation of which would strongly strengthen the existing understanding of the geological development of the Vietnamese basins and their hydrocarbon potential.

One of the most obvious initiatives to be taken is a thorough study of the implications of the very positive ENRECA-3 findings. This well has provided invaluable

new geoscientific information for the study area, but it has also raised a number of significant research questions of mandatory importance for understanding the oil potential of the North-eastern Song Hong basin: which geological factors - such as structural development, climatic conditions, drainage patterns, bed rock geology etc. - governed the formation and distribution of the syn-rift lacustrine source rocks? If the determining influence of these factors can be fully understood, the present day occurrence of mature source rock pods (i.e. hydrocarbon kitchens) can be mapped out, and an effective exploration strategy for the area can be lined out. Thus, as a result of these considerations, the ENRECA research team has proposed the initiation of a multi-disciplinary and integrated study that, among others, must include tectonic restoration, sequence stratigraphic analyses, detailed sedimentological investigations of the mudstones, studies of the activation energies of the organic components in the source rocks. The integration of the findings of these studies will contribute greatly to the establishment of a new reliable predictive exploration model for the selected study area.

Another obvious research task is to reduce the exploration risk by focussing toward predictions of reservoir quality. Different rock types exposed to weathering processes provide great variability in the resulting sediments depending on factors such as climate, transportation and depositional environment. Thus source to sink studies could be significant contributions to exploration strategies if the studies are focussed toward the prediction of reservoir composition and quality in the offshore basins by investigating the timing and amount of uplift of the Vietnamese mainland, the timing of exposure to weathering of the various bed rock units, and mapping of paleo-drainage patterns, sediment transportation routes and the significant sediment entry points to the basins.

In addition to these research themes a number of focussed studies need to be carried out to reduce exploration risks and expenditures, and the ENRECA research team is prepared for these research challenges.

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