ADVANCED ANALYSIS OF BASINS ALONG THE VIETNAMESE MARGIN AND THE GREATER REGION: CENTRAL VIETNAM'S NEOGENE CARBONATE PLATFORM DEVELOPMENT

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Summary

For close to 20 years, Vietnamese geology and hydrocarbon prospectivity have been studied by the ENRECA research team (VPI/Petrovietnam & GEUS). During the course of this study, on- and offshore basins from the Hanoi Trough in the north to the Malay-Tho Chu basin in the south have been analysed. The research carried out includes amongst others tectonic, depositional, petrographic, geochemical, provenance and uplift analysis. In this paper, the ENRECA-work is exemplified by a study of Neogene carbonate growth along the central Vietnamese margin.

Miocene carbonate platforms cover a large part of the Central Vietnam's East Vietnam Sea margin. Early carbonate deposition took place on two regional platforms separated by a narrow depression developed along the trace of the East Vietnam Boundary Fault Zone. West of the East Vietnam Boundary Fault Zone, the Tuy Hoa Carbonate Platform fringes the continental margin between Da Nang and Nha Trang. Here, platform growth initiated during the Early Miocene and continued until Middle Miocene time when regional uplift led to subaerial exposure, termination of platform growth and karstification. East of the fault zone, the Tri Ton Carbonate Platform was also initiated during the Early Miocene. Carbonate growth thrived during Early and part of Middle Miocene time and a thick, clean Lower and Middle Miocene carbonate succession covers the Tri Ton Horst and the Quy Nhon ridge. During the Middle Miocene, partial drowning resulted in the split-up of the Tri Ton Carbonate Platform. Repeated partial drowning events throughout the Middle and Late Miocene resulted in westwards retreat of platform growth and eventual platform drowning and termination of carbonate deposition. Modern carbonate growth continues on isolated platforms hosting the Paracel Islands farther seawards. The onset of widespread carbonate deposition largely reflects the Early Miocene transgression of the area linked with early post-rift subsidence and the opening of the East Vietnam Sea. The mid-Neogene shift in carbonate deposition is interpreted as a consequence of regional uplift and denudation of central and south Indochina starting during Middle Miocene time when the Tuy Hoa Carbonate Platform became subaerially exposed. Stressed carbonate growth conditions on the Tri Ton Carbonate Platform probably resulted from increased inorganic nutrient input derived from the uplifted mainland, possibly enhanced by deteriorated climatic conditions and rapid sea-level fluctuations promoting platform drowning.

Key words: *Basin analysis, Neogene, carbonates, ENRECA project.*

1. Introduction

The Vietnamese shores outline the western margin of the East Vietnam Sea that opened by oceanic spreading during Oligocene and Miocene time [2, 3, 8]. The Vietnamese margin is now largely passive, underlain by a major Cenozoic rift system. The rift basins fringe the margin for approximately 2,000km, but none the less, share a comparable evolution history. From North to South rifting commenced sometimes during the Eocene or earliest Oligocene and lasted till near the end of Oligocene time. The subsequent history is signified by thermal contraction with rifting and inversion taking place in some basins throughout the Miocene. Neogene deposition is characterised by the vast amounts of siliciclastic sediments deposited mainly in deltaic to deep-marine settings along the margin of the East Vietnam Sea. In addition, carbonate platforms developed throughout the period and serve as excellent records of the geological development of the margin, its upland and the prevailing oceanographic conditions through time.

The Danish-Vietnamese collaboration research project, the ENRECA project (Enhancement of Research Capacities in developing countries) and its predecessor, has worked to improve the understanding of the Vietnamese geology and petroleum potential for almost 20 years. The ENRECA project initiated in 2001 with the aim of training Vietnamese geoscientists and conducting

demand-driven geological and exploration research. However, the Danish-Vietnamese geoscientific research collaboration dates back to 1995 when the Geological Survey of Denmark and Greenland (GEUS) and the Vietnam Petroleum Institute (VPI) started working together on assessing the petroleum potential of the Song Hong basin [1, 49, 51, 53, 55]. Since 2001, the ENRECA group has evaluated the geology and petroleum potential of the Phu Khanh [5, 21, 22, 23] Kua Luc [50], Nam Con Son [6, 21], Cuu Long [6, 21], Malay - Tho Chu [24, 52, 54] and the Phu Quoc [25] basins and in its latest phase is revisiting the Song Hong basin [26, 27, 56].

The ENRECA group has expanded during the years and apart from GEUS (Geological Survey of Denmark and Greenland) and VPI (Vietnam Petroleum Institute) presently encompasses the Institute of Geography and Geology from the University of Copenhagen, Petrovietnam, the Institute of Marine Geology and Geophysics, the Hanoi University of Mining and Geology, and the Hanoi University of Science. The ENRECA group further collaborates with international oil companies and a number of institutions in Vietnam and its neighbouring countries.

The research has been conducted by integrating information from seismic analysis with stratigraphic core well drilling, exploration well data, outcrop analogues, source rock and oil geochemical analysis, maturity modelling as well as petrographic, biostratigraphic, uplift and provenance studies [21, 24, 49, 50, 52, 54, 56].

Carbonate deposition and platform development from along the Song Hong, the Phu Khanh and the Nam Con Son basins have been studied during the course of the ENRECA Project [21, 22, 23, 26]. Cenozoic carbonates constitute one of the primary targets for petroleum exploration within the East Vietnam Sea region [13, 20, 35, 73, 76] (Fig.1). This is also true for the Vietnamese margin where considerable petroleum reserves are found and produced from Miocene carbonates in the Nam Con Son basin [43]. Miocene carbonates have been documented north of the Nam Con Son basin along the Vietnamese margin [21, 22, 23, 26, 34, 39, 59]. Although little explored, drilling on the Central Vietnamese margin, so far, has targeted mainly Miocene carbonates with a number of resulting oil and gas discoveries made.

This paper reports a combined study of the system of Neogene carbonate platforms flanking the basins offshore Central Vietnam analysed and presented by Fyhn et al. [26]. The study is based on approximately 13,000km 2-D seismic data tied to exploration wells (Fig.2). Seismic data range from vintage data acquired as early as 1974 to data acquired in 2003 constituting an open seismic grid with average line spacing ranging in between 3 - 40km. The seismic data quality varies. However, data generally has adequate resolution within the targeted Neogene carbonate successions with frequencies ranging from 20 - 50Hz corresponding to acoustic wavelengths in between *c*. 30 and 100m and a seismic resolution at best in between *c*. 7 and 25m.

The data document a very dynamic growth history of the carbonate system in the region. Factors such as regional Early Miocene transgression of structural highs along the Central Vietnamese margin combined with a warm climate probably catalysed massive carbonate platform growth. Onshore uplift and erosion linked with volcanism and associated inorganic nutrient pollution in the platform areas is interpreted as the primary mechanism governing the subsequent platform demise and drowning. The Cenozoic evolution of basins and highs together with Neogene volcanism and onshore uplift are therefore described initially before treating the Neogene carbonate growth.

2. Setting and structural framework

Cenozoic carbonates are widespread around the East Vietnam Sea, present from the Chinese margin in the north to offshore Borneo in the south [15, 17, 20]. In the south, platform growth began during Late Eocene and Oligocene time and locally continues to the present [4, 16, 18, 47, 74, 78]. Farther north along the Vietnamese and Chinese margins, widespread carbonate deposition initiated during the Early Miocene probably due to the absence of fully-marine conditions until the final stage of the East Vietnam Sea opening [21, 22, 26, 43, 44, 82, 83]. Oceanographic and climatic changes, terrigenous sediment supply, inorganic nutrient levels, volcanism, uplift and relative sea level fluctuations are factors interpreted to have had a significant influence on local and regional Neogene platform growth and demise in SouthEast Asia [19, 22, 26, 64, 80]. Carbonate platforms may therefore record information fundamental to unravelling the tectonic development of various regions and are useful indicators for local and global climatic and oceanographic changes.

2.1 Cenozoic basin development

Cenozoic basin development along the Central Vietnamese margin initiated through Paleogene rifting

[11, 21, 23, 39, 42, 59, 60, 87]. The exact timing of rift initiation is poorly constrained due to: 1) the scarcity of deep wells penetrating the oldest syn-rift succession and 2) the low biostratigraphic resolution of most of these non-marine rift systems. The significant crustal extension along the margin has been viewed in context with either the extension leading to the opening of the East Vietnam Sea and/or lateral movements along the Vietnamese margin linked with the India-Eurasia collision [21, 59, 70, 71] (Fig.1). The East Vietnam Boundary Fault Zone can be mapped seismically along the margin. In the study area it delineates the Quang Ngai graben - an elongated rift forming the southernmost extension of the Song Hong basin filled by Paleogene syn-rift deposits. The fault zone also delineates a coast-parallel Neogene depocentre and seems to have been a controlling lineament for the depositional system along this part of the margin (Fig.2).

Underlying the Tri Ton Horst to the Paracel islands (Figs.2 and 3) and adjacent basins are a number of grabens and half-grabens filled by tentatively dated Paleogene syn-rift deposits initially noted by Roques et al. [59] and Dang and Sladen [12]. Seismic resolution of the syn-rift succession on the uplifts is often only moderate, partly due to damping of the acoustic energy by the thick overlying carbonate succession. The Paleogene rift-system becomes more pronounced towards the Qiongdongnan and the Phu Khanh basins to the north and south filled by an up to several kilometres thick syn-rift succession confined to major grabens and half-grabens often measuring several tens of kilometres across (Fig.4).

The syn- and post-rift successions on and along the Tri Ton Horst are separated by an unconformity in places marked by distinct reflector truncations. The entire syn-rift succession tends to be strongly deformed and compressional deformation is tentatively interpreted in places affecting the top of the syn-rift succession (Fig.4). This may record a compressional pulse towards the end of the Paleogene possibly comparable to similar events in the Cuu Long and the northern Song Hong basins to the south and north, respectively [21, 58].

Kilometre-thick Neogene deposits deeply bury the syn-rift succession in large parts of the area. Farthest to the east, the thickness of the Neogene generally decreases due to the distal setting leaving Paleogene rift sediments and basement more shallowly buried. The kilometre-thick Neogene succession and the overall

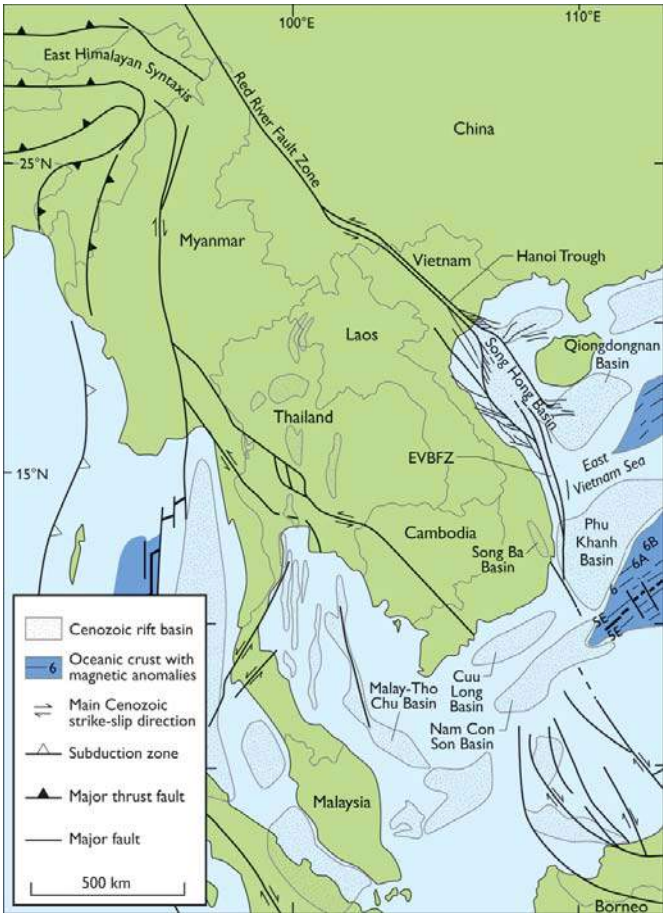

Fig.1. *Map of Indochina and the western part of the East Vietnam Sea showing the outline of main basins and Cenozoic structures. EVBFZ: East Vietnam Boundary Fault Zone. Modified after Fyhn et al. [26]*

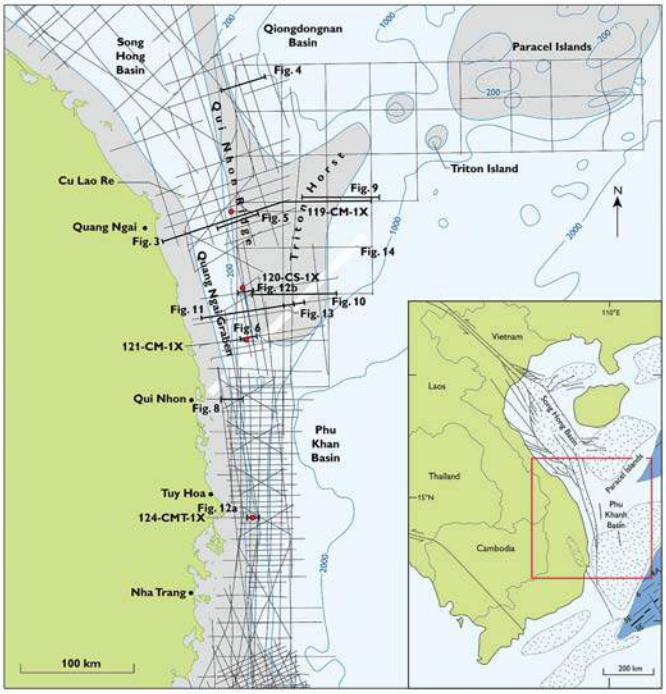

Fig.2. *Map outlining the distribution of seismic and well data included in the study. Bold lines mark the position of illustrated sections. Bathymetry in metres. Modified after Fyhn et al. [26]*

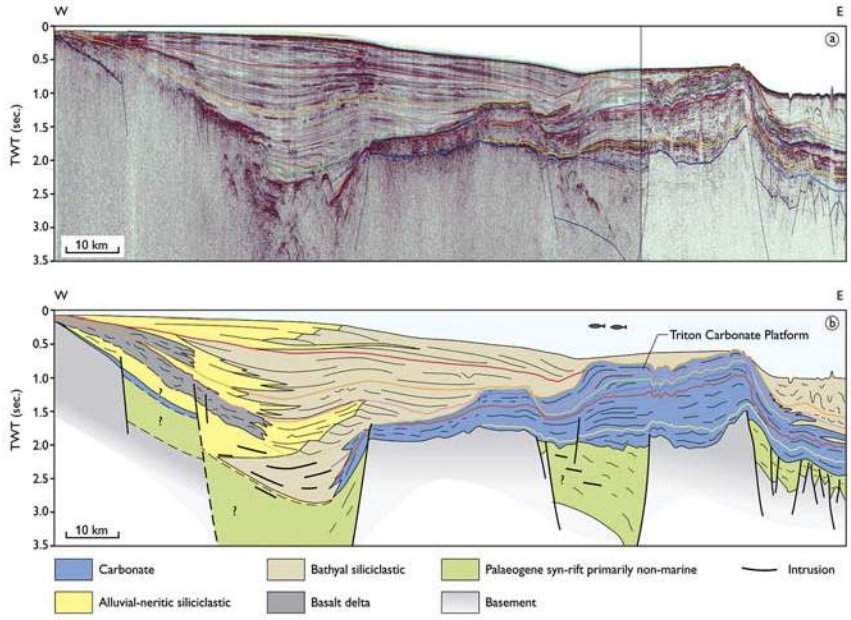

Fig.3. *Regional seismic transect (a) across the Quang Ngai graben and the Quy Nhon ridge and Tri Ton Horst and corresponding stratigraphic interpretation (b). The transect illustrates the interplay between the growth and drowning of the Tri Ton Carbonate Platform and Neoegene siliciclastic deposition and magmatism in the area. Carbonate growth peaked during the Early Neogene when terrigenous input was low. During the latter Neogene, carbonate growth retreated and eventually terminated concurrently with increasing siliciclastic input from the west, most likely associated with onshore uplift and magmatism. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

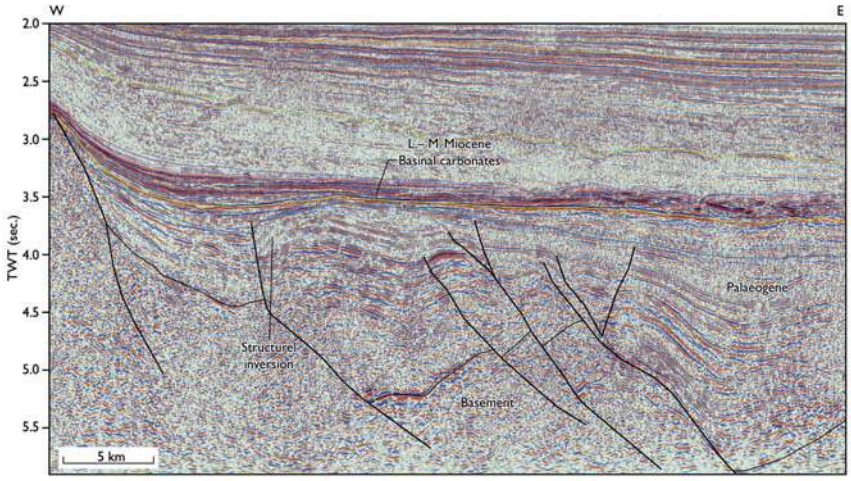

Fig.4. *Seismic transect illustrating the Paleogene rift style in the area. Indications of late syn-rift to early post-rift compression are tentatively interpreted from the structural inversion observed on this transect. The inversion preceded Neogene carbonate growth and seems to have been accompanied by a period of moderate uplift and erosion judging by the unconformity capping the inversion structure. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

Neogene transgressive trend leading to the modern bathymetric outline of the area indicate the Neogene as a period of generally rapid subsidence.

The Neogene succession is dominated by siliciclastic deposits in the basin centres and to the west along the Vietnamese margin (Fig.3). The clastic sediments tend to thin seaward on the Tri Ton Horst and in the Phu Khanh basin reflecting the increasing distance to the source areas.

2.2. Neogene volcanism and onshore uplift

The Upper Miocene through Pleistocene makes up the overwhelming majority of the siliciclastic strata in the region indicating an increase in siliciclastic deposition during the later part of the Neogene. This increase has previously been interpreted to reflect the coeval uplift and denudation of Central Vietnam and adjoining areas [9, 21, 22]. Although knowledge of the Neogene uplift of Central Vietnam remains fragmentary, denudation rates seem to have peaked during the Late Neogene similar to the offshore siliciclastic depositional rates [9].

The increased Late Neogene clastic input may in addition be linked with the climatic development during the period and to a lesser degree to erosion from uplifted areas farther away [11]. The northernmost part of the study area experienced latest Neogene southeastwards siliciclastic progradation induced by sediments spilling from the central Song Hong basin. Much of these sediments may be derived from regions farther away such as supplied by the paleo-Red River.

Basaltic volcanism took place in Central and South Vietnam from the Early - Middle Miocene onwards. The contemporaneous Late Neogene uplift has been attributed to igneous processes taking place in the region [9, 33]. Comparable Neogene magmatism was documented offshore in the southern part of the study area [21]. Seismic and well data combined with the outcropping geology onshore and on small islands suggest the presence of Miocene to sub-recent extrusives along the Vietnamese margin in the northern part of the study area as well (Fig.3). Extrusives and intrusions in the area have been interpreted previously

and show close resemblances to similar magmatic successions imaged seismically e.g. along the North Atlantic margin [7, 21, 57] and are generally characterised by their strong upward confining reflections, beneath which the seismic signal strongly deteriorates.

Volcanoes appear as kilometre-wide knoll-features between a few tens to hundreds of milliseconds (TWT) high (Fig.6). Some volcanic edifices have well-defined concentric internal reflectivity whereas others display a more chaotic internal reflection pattern. Some volcanic edifices on seismic data resemble carbonate pinnacles. In the 121-CM-1X well a mounded feature was confused with a carbonate pinnacle prior to drilling, but drilling revealed a basaltic volcano probably of Middle Miocene age tentatively dated by apatite fission track analysis. The drilled volcano is interpreted as being mainly of submarine origin due to the presence of quench textures in the basalts and due to intercalation with marine sediments. Often, volcanic edifices distinguish from the local carbonate buildups and platforms either by their gravimetric/magnetic response or by the often very chaotic internal and external appearance in contrast with the more organised architecture of the carbonate platforms along the margin. In contrast to carbonate platforms occupying structural highs, volcanic mounds mostly occur in basinal settings and were extruded down to several hundred metres below paleo-sea level as indicated by their relative position to coeval shelf breaks and carbonate platform margins.

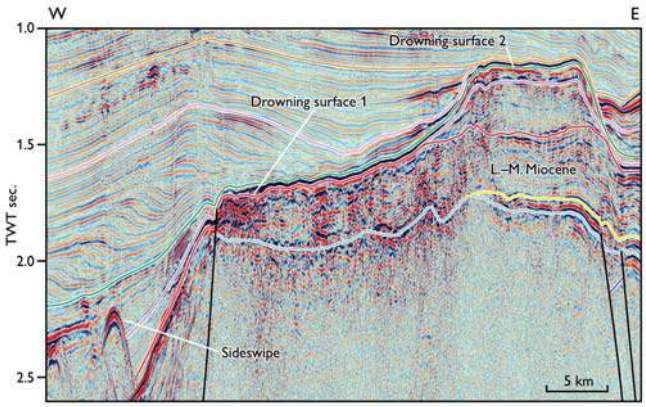

Fig.5. *Blow-up of Fig.3 illustrating two platform drowning surfaces. Drowning surface 1 is base-lapped by a series of toesets. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

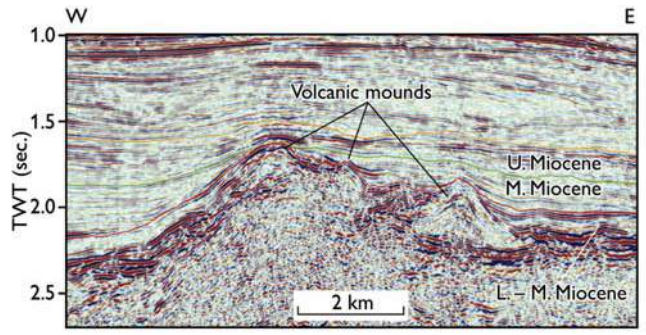

Fig.6. *Miocene volcanic structures characterised by their mounded appearances. A comparable volcanic mound belonging to the same cluster of volcanoes was drilled in the 121-CM-1X well. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

Surrounding the Cu Lao Re island hosting an active volcano (Fig.2), numerous strongly reflected mounds immediately underlie the seafloor and thus suggest a similar volcanic origin.

Lava deltas are interpreted to fringe part of the margin. These often occur in areas where Upper Neogene basalts crop out along or near the present shore. The lava deltas are characterised by strongly reflected wavy or sub-parallel reflectors with upper surfaces conformable with overlying strata (Fig.3). Characteristically, the units show abrupt lateral terminations and seaward interfingering with moderate to well-reflective topset facies representing siliciclastic shelf deposits. The actual lateral terminations are characterised by subtle seaward inclined foresets interpreted as lava delta-fronts (Fig.3).

Strongly reflective sills were emplaced at various stratigraphic levels and occur concentrated in specific areas often associated with above-lying extrusives. The sills mostly parallel the adjacent strata but in places show sharp discordant cross-cutting relationships. Slight doming of the strata occurs above some sills and chimney-like features may exist above sills that tend to head into more shallow amplitude anomalies.

In one volcanic area to the north, stratigraphic reflectors are transected by numerous strong convex parabola-shaped reflections between 3 and 8km wide (Figs.3, 5). The reflections have similar phase on each limb of the parabola and cannot be explained as diffraction but are interpreted as sideswipes from steep-sided intrusions and/or volcanic mounds located next to the trail of the seismic transect.

3. Neogene carbonate growth

3.1. Early and Middle Miocene initial growth

Early Miocene carbonates form the oldest robustly dated drilled carbonates offshore Central Vietnam. The deepest drilled carbonate sections are likely of Burdigalian age although a slightly older Aquitanian age cannot be

ruled out due to insufficient biostratigraphic control. The deepest parts of the platforms tend to be made up by dolomites in contrast to the limestone-dominated upper part of the platforms.

Platform growth initiated on two major platforms; a platform fringing the Vietnamese coast referred to as the Tuy Hoa Carbonate Platform and a platform situated east of the Quang Ngai graben referred to as the Tri Ton Carbonate Platform (Fig.7a). The carbonates form the oldest Neogene deposits in the area and directly overlie the Mesozoic granitic basement, pre-Paleogene sediments and tentatively dated Paleogene non-marine deposits.

The oldest platform deposits signify a distinct Early Miocene regional transgression of the area. On the Tri Ton Horst, a thin undrilled deep succession onlaps the top of the syn-rift sequence. This may represent the initial inundation sequence recording the flooding of the ridge, which may have taken place during the Early Burdigalian and/or (?) Aquitanian time.

On the Tri Ton Carbonate Platform, the succession is fault confined along the Quy Nhon ridge and faults in places offset the deepest carbonates and influence the thickness of the platform deposits suggesting a slight continuation of faulting following the Paleogene in the area.

On the Tuy Hoa Carbonate Platform, increased platform thicknesses on hanging-wall blocks towards confining faults indicate rotational fault-block movement throughout the growth period. Extensional faults outline large parts of the platform margins and in places form the landward boundary of the Tuy Hoa Carbonate Platform suggesting that moderate faulting probably controlled the overall outline of part of the platform (Fig.8).

However, seismic resolution does not resolve the platform facies adequately and pinpointing the position of the platform margin is not possible everywhere. A detailed analysis of the internal platform facies of this interval is thus not possible based on the available data, and a clear distinction between platform and basinal carbonate facies was not accomplished in part of the study area. A very strong and generally continuous reflectivity typical for carbonates characterises the interval and is compatible with the reflection pattern of the overlying succession. In the Tri Ton area, the succession covers more than 40,000km^2 and is up to a few hundred metres thick in places.

In the southern part of the area, a distinct succession characterised by strong to very strong reflections makes up the off-platform deposits. These are interpreted to be composed of carbonate detritus shed from the platforms and basinal marls. Fyhn et al. [23] suggested these marls to contain organic rich intervals sourcing the Thi Nai lagoon seep oils occurring along the present coast near Quy Nhon. Biomarker analyses indicate marly source rocks for these oils [6, 72], and modelling suggests that the burial depth of the off-platform deposits and stratal dip of the overburden rocks are compatible with adequate maturation of the interval and shoreward migration of potentially generated oil [23].

The Quy Nhon ridge gradually became inundated and was buried by carbonates during Burdigalian time judging by the seismic pattern and the age of the oldest carbonates capping the ridge (Figs.3, 7a, b). In the following period carbonate growth concentrated on the Quy Nhon ridge and the Tri Ton Horst and a prominent platform margin was established outlining the margin of the structural highs towards the Quang Ngai graben and the Qiongdongnan and Phu Khanh basins (Fig.7b).

The platform interval corresponding to this period in places measures more than 600ms (TWT). This corresponds to more than 1km of Lower to Middle Miocene carbonates given an average acoustic velocity between *c*. 3.5 and 4.5km/sec comparable to that measured in available wells penetrating the Miocene carbonates in the area.

A well-developed carbonate apron flanks especially the eastern, southern and northern part of the Tri Ton Platform and grades basinward into an up to *c*. 500msec (TWT) thick interval characterised by high-amplitude, low-frequency, continuous reflections interpreted as deep-marine basin floor carbonates derived by gravity flows from the platform (Fig.9). Away from the platform, the basinal carbonates thin and intercalate with intervals distinguished by a more transparent seismic facies typical for deep-marine siliceous sediments [62] (Fig.9).

To the west in between the Tri Ton - and the Tuy Hoa Carbonate Platforms, a succession characterised by relatively high-amplitude, continuous reflections fills the lower post-rift part of the Quang Ngai graben. Drilling of the succession indicate a composition dominated by siliciclastic gravity flow sand- and siltstones [12].

On the Tri Ton Platform, a wavy and discontinuous reflection pattern characterises much of the Lower to

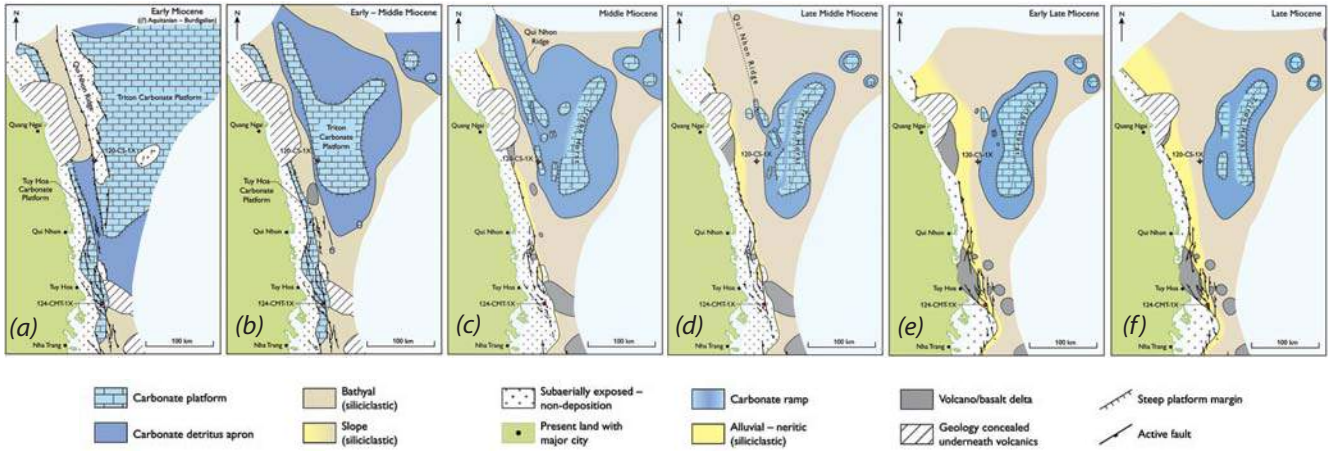

Fig.7. *Paleogeographic maps based on seismic and well data. The maps represent the Early to Late Miocene development offshore Central Vietnam and reflect the interplay between carbonate platform growth, siliciclastic deposition and volcanism.*
a) Early Miocene: Burdigalian carbonates constitute the oldest carbonates drilled offshore Central Vietnam and overly basement and the Paleogene syn-rift. Slightly older, undrilled carbonates may exist in areas away from the most elevated part of structural highs. Deposition during the period reflects the initial transgression following Paleogene rifting when existing topography gradually became flooded
b) Early - Middle Miocene: During Early to Middle Miocene time, all structural highs were inundated and carbonate growth focused on these elevated features. Carbonate detritus was shed far from the platform areas as carbonate production significantly exceeded the general creation of accommodation space on the platforms. Volcanism initiated during this period
c) Middle Miocene: Partial platform drowning led to the break-up of the Tri Ton Carbonate Platform during the Middle Miocene. Farther landward, uplift resulted in subaerial exposure and termination of carbonate growth on the Tuy Hoa Carbonate Platform. Carbonate growth was replaced by fan-deltas along the paleo-Vietnamese margin sourced by the erosional products from the uplift. Volcanism increased significantly during the period
d) Late Middle Miocene: Partial platform drowning continued on the Tri Ton Carbonate Platform during the late Middle Miocene restricting platform growth to the central part of the Tri Ton Horst and to a few satellite platforms persisting on the most elevated highs. Carbonate production was barely able to keep up with relative sea-level rise which resulted in drowning of the shoreward platforms and limited off-platform export of carbonate detritus
e) Early Late Miocene: A number of satellite platforms drowned during the former period leaving only the central part of the Tri Ton Carbonate Platform and a handful of smaller isolated buildups to persist. The central part of the Tri Ton Carbonate Platform recovered after partially drowning during the former period, while the western satellite platforms drowned during the period
f) Late Miocene: The remaining part of the Tri Ton Carbonate Platform struggled to keep up with relative sea-level rise but ultimately drowned during the Late Miocene. The area offshore Central Vietnam is presently dominated by siliciclastic deposition. Only sporadic carbonate growth takes place on restricted highs farthest to the east in the area. Modified after Fyhn et al. [26]

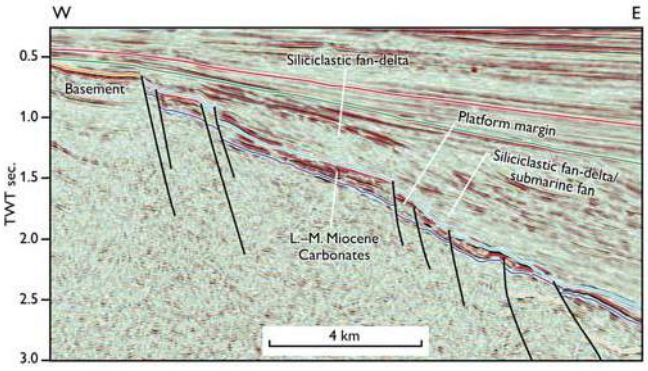

Fig.8. *Transect across the Tuy Hoa Carbonate Platform. Normal faults outline the landward boundary of the carbonates and subtle faulting may also have confined the platform margin. Middle to Upper Miocene fan-deltas/submarine fans onlap the platform margin and buries the platform. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

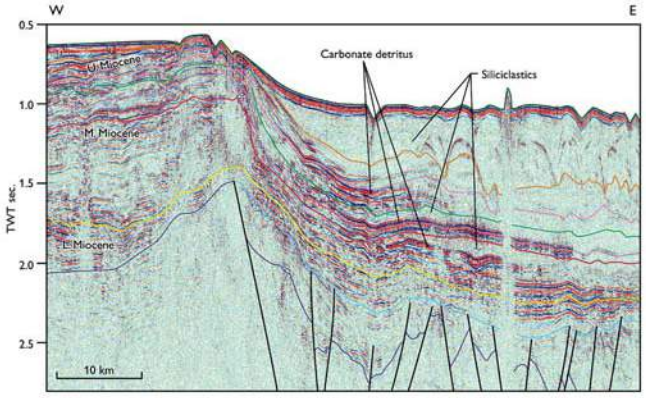

Fig.9. *Carbonate detritus shed from the platform distinguishes from deep-marine siliciclastics by its strong reflectivity and intercalate with less reflective deep-marine siliciclastic sediments. Large amounts of Lower to Middle Miocene carbonate detritus formed compared to the subsequent period. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

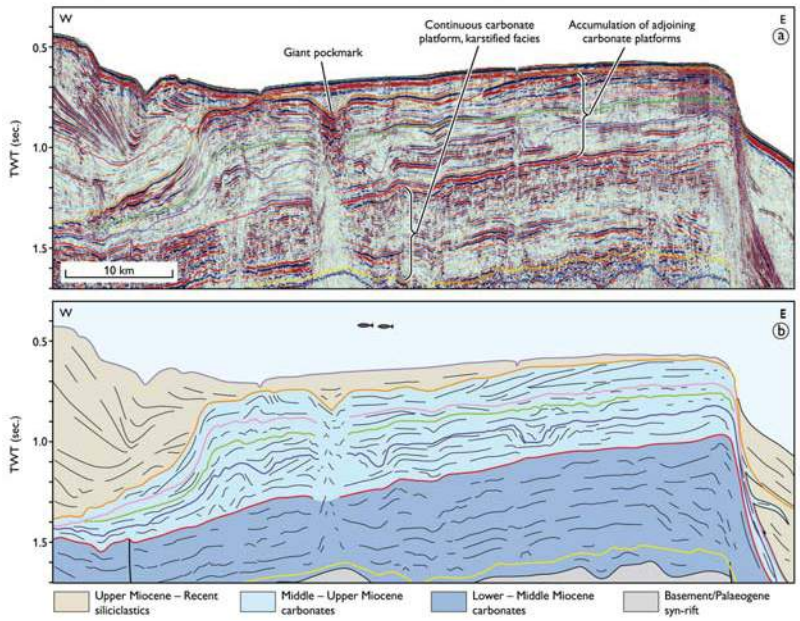

Fig.10. *Seismic transect (a) across part of the Tri Ton Carbonate Platform and corresponding stratigraphic interpretation (b). Neogene platform growth offshore Central Vietnam took place in two consecutive phases. During the Early to Middle Miocene (corresponding carbonates marked in dark blue on Fig.10b), a discontinuous, strongly reflected seismic facies interpreted as karstified platform carbonates is common. During the subsequent Middle to Late Miocene period (corresponding carbonates marked in light blue on Fig.10b), the platform split up into discrete buildups with an internal reflection architecture suggesting very dynamic platform growth. The generally more continuous reflectivity suggests only modest karstification of most of the upper Middle to Upper Miocene carbonates compared to the former period. A prominent depression in the top-platform surface marks a giant collapse structure in the underlying carbonate succession. The collapse depression caps a chaotically reflected column in the underlying platform carbonates that in turn overlies a Paleogene fault zone. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

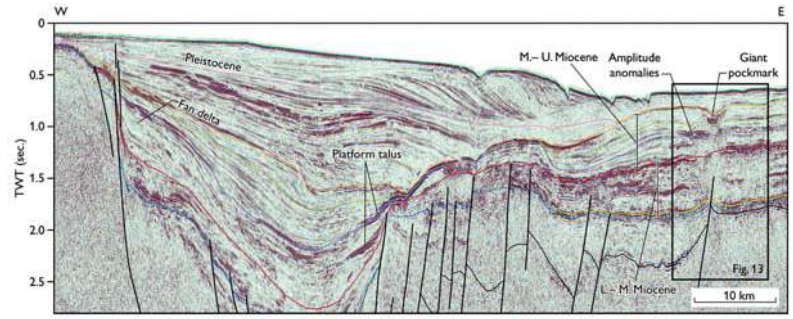

Fig.11. *Seismic transect across the Quang Ngai graben and part of the Quy Nhon ridge. Platform carbonates dominate the Neogene succession in the east whereas terrigenous deposits prevail farther landward. Consequently, metres thick drowning sequences above Miocene Carbonate platforms grade into hundreds of metres thick siliciclastic successions to the west. Upper Middle Miocene to Quaternary siliciclastics in the west dominates volumetrically above Lower to lower Middle Miocene siliciclastic sediments and document a vast Late Neogene increase in terrigenous sedimentation. A Middle to lower Upper Miocene fan-delta fringe faults along the Quang Ngai graben in the west. Coeval basinal deposits farther east intercalates with platform talus towards the Tri Ton Carbonate Platform. The younger part of the Tri Ton Platform baselaps the older drowned part of the platform and is in turn gradually buried by prograding Upper Neogene siliciclastic deposits. A giant collapse scar marks the youngest drowning surface of the Tri Ton Platform to the east. A blow-up of the collapse scar is presented in Fig.13. Location indicated on Fig.2. Modified after Fyhn et al. [26]*

Lower Middle Miocene succession (Fig.10). Together with the often relatively high reflection amplitudes this distinguishes the lower half of the Tri Ton Platform from the younger part (Figs.10, 11). The overall internal outline of the lower half of the Tri Ton Platform is characterised by parallel to sub-parallel strata apart from along the platform margin. Along the platform margin, aggradation and very limited progradation characterise the reflection pattern (Fig.10).

The wavy and discontinuous reflection pattern together with the often relatively high reflection amplitudes characterising much of the lower Tri Ton Platform resembles karstified parts of other Miocene carbonate platforms in the East Vietnam Sea [4, 22, 31, 46, 74]. The lower part of the Tri Ton Carbonate Platform is therefore interpreted to have been affected by repeated periods of subaerial exposure and moderate leaching, which is in accordance with karst induced caverns and enhanced porosity interpreted in wells that resulted in instantaneous drilling mud-losses associated with intervals of enlarged drill hole calibres. In addition, the presence of small patch reefs may contribute to the wavy and discontinuous reflection pattern of this part of the platform and other diagenetic effects may have contributed to part of the reflector brightening.

To the west, the Lower to lower Middle Miocene Tuy Hoa Carbonate Platform constitutes an up to many hundreds of metres thick, clean carbonate succession that is generally characterised by very strong, low-frequency internal reflectors (Figs.8, 12a). The top of the carbonates is emphasised by a very strong "hard-kick" reflection that erosionally truncates the underlying carbonates and marks a pronounced downwards acoustic impedance increase (Fig.12a). Only in the northern part of the Phu Khanh basin is a steep platform margin recognisable. Farther south, more extensive erosion

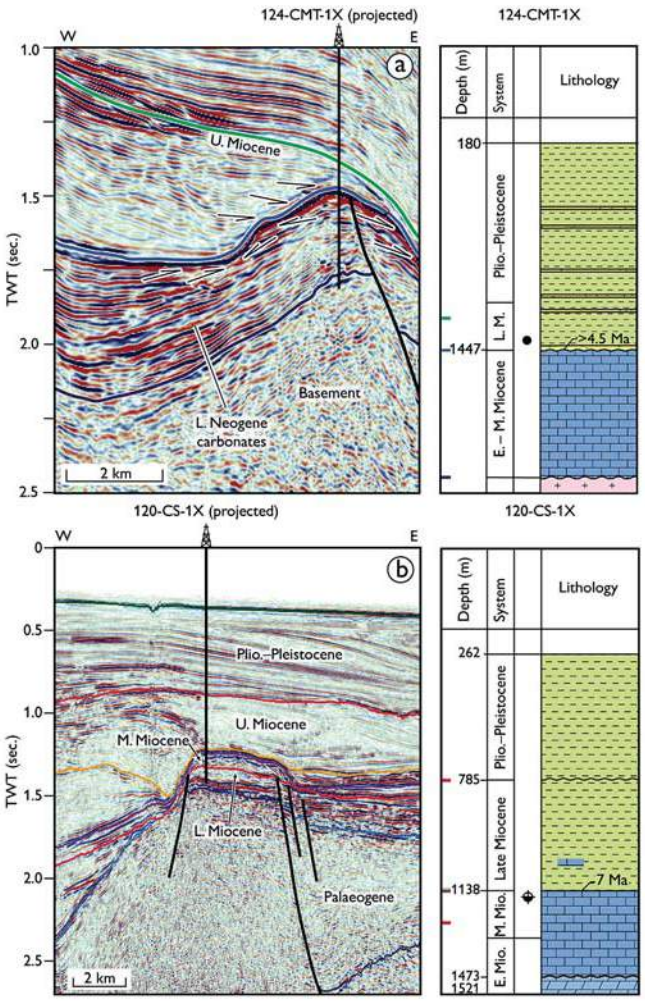

Fig.12. *Miocene carbonates have been the primary target for exploration drilling offshore Central Vietnam so far with a number of oil and gas discoveries made in Lower to Middle Miocene carbonates. a) 124-CMT-1x targeted Lower to Middle Miocene shallow water carbonates and is the first of only four wells drilled in the Phu Khanh basin (at the time of writing). The well transected an oil column with two net pay intervals totalling approximately 20 metres in thickness. The distinct top-carbonate unconformity formed in response to protracted subaerial uplift and represents a hiatus spanning at least 4.5Ma. 124-CMT-1x stratigraphy modified after Johansen (2011). b) The 120-CS-1x well tested intermediate to shallow water Lower to Middle Miocene platform carbonates. The buildup drowned during the Middle Miocene but was only buried ca. 7Ma latter by siliciclastic deposits. Intersecting depths to seismic horizons are indicated on the left side of the well logs. Location and well positions are projected on Figs.2 and 7. Modified after Fyhn et al. [26]*

envisaged by pronounced reflector truncation probably resulted in alteration or complete destruction of the original geomorphologic outline of the platform.

The erosional unconformity capping the Tuy Hoa Platform spans much of the Middle and Late Miocene, and reflector truncation suggests widespread erosional removal of as much as a few hundred metres of platform carbonates. Wedge-shaped sedimentary bodies interpreted as siliciclastic fan-deltas and submarine fans characterise the strata immediately post-dating the Tuy Hoa carbonates in places. The oldest of these wedges occurs seawards of the Tuy Hoa carbonate Platform and onlaps the lower part of the platform slope and thus together with the prominent erosional unconformity capping the platform suggests a significant fall in relative sea level (Fig.8). The hiatus therefore seems to have formed in response to subaerial uplift probably linked with faulting and lithospheric heating associated with magmatism since voluminous volcanics of that age occur widespreadly in the area (Figs.7b - e).

3.2. Middle and Late Miocene phased platform drowning

Most of the Tuy Hoa Carbonate Platform remained subaerially exposed for more than 4Ma during the rest of the Middle Miocene as suggested by the hiatus dated in wells and seismic stratigraphy (Fig.12a). The platform area was reflooded during the Late Miocene, but platform growth did not resume regionally in the area. Middle and Late Miocene carbonate deposition was thus restricted mainly to the Tri Ton Horst and the Quy Nhon ridge farther to the east (Figs.7c - f).

During the Middle Miocene, the Tri Ton Carbonate Platform stepped back and split up into a number of separate platforms as a result of partial drowning (Figs.5, 7c - f). Middle Miocene partial drowning especially affected the area in which the Tri Ton Horst and the Quy Nhon ridge merge. As a result, carbonate growth continued on two isolated platforms occupying the central parts of the Quy Nhon ridge and the Tri Ton Horst as well as on a number of smaller buildups in between the two larger platforms.

A few tens of metres thick condensed hemipelagic pyritic and slightly calcareous mudstone succession caps the drowned Lower to Middle Miocene Platform carbonates. Well data suggest that the succession was deposited throughout a more than 7Ma long Middle to Late Miocene period. In places the condensed sequence caps a very hard silicified platform crest drilled by exploration wells that probably formed in response to a protracted period of non-deposition. The succession is interpreted as a drowning sequence covering part of the Tri Ton Platform (Fig.5).

Off the platform in the Quang Ngai graben, the drowning sequence thickens and is represented by an eastwards prograding, siliciclastic mudstone-dominated succession several hundred metres to more than one kilometre thick (Fig.5).

In the north, the lower part of the Middle - Upper Miocene carbonates covering the Quy Nhon ridge as well as the smaller isolated platforms immediately to the south are characterised by a seismic facies made up by low-frequency, moderately continuous to discontinuous reflectors showing intermediate to very high reflection amplitudes (Fig.10a). An overall aggrading build-up pattern characterises these platforms (Fig.10b), although a few kilometres of progradation took place locally following early subtle platform back-steps.

Strongly reflected platform aprons radiate a few kilometres westwards from these platforms where they intercalate with basin floor siliciclastic deposits imaged by much weaker higher frequency reflectors (Fig.11). Towards the east, platform aprons merge with the much thicker and more extensive developed aprons radiating from the carbonate platform(s) occupying the Tri Ton Horst (Figs.7c - d, 11).

The siliciclastic sediments in the west intercalated with platform talus constitute the basinal part of an eastwards prograding siliciclastic succession. Well-developed clinoform topsets, foresets and toesets separate the siliciclastic sediments into shelf, shelf-slope and basinal deposits (Fig.11). The lower part of the succession is genetically linked with a coast-parallel fault system confining a well-developed fan delta system. Offshore Quang Ngai and farther south, the siliciclastic deltaic system intercalates with a volcanic delta (Fig.3).

During the later half of the Middle Miocene, the carbonate platforms occupying the Quy Nhon ridge and the area immediately to the south eventually drowned (Fig.7c - e). For a limited period of time, a couple of smaller buildups managed to keep pace with relative sea-level rise by backstepping and aggradation. However, these too eventually succumbed to drowning during the latest Middle to Early Miocene time.

Farther east, during the later half of the Middle Miocene and the Late Miocene, the platform(s) thriving on the Tri Ton Horst managed to keep up with relative sea-level rise. The reflection pattern on these eastern platforms are characterised by intermediate to strong reflections that in general are somewhat weaker than the underlying Lower to lower Middle Miocene succession (Figs.10, 11). Moreover, the reflections tend to be slightly more continuous than the older carbonates.

Compared with the initial Lower - Middle Miocene platform on the Tri Ton Horst, the subsequent Middle to Upper Miocene platform architecture was characterised by a substantial intra-platform relief signified by the presence of smaller buildups (a few kilometres in diameter and *c.* 100 - 200m high) separated by channels and intra-platform deeps that together make up the greater platform area of especially the eastern and largest part of the Tri Ton Platform area (Fig.10). However, the available open seismic grid does not adequately resolve the spatial and temporal outline of these sub-platforms, and more detailed mapping is required.

Characterising the four mapped later Middle to Late Miocene sub-stages, up to three considerable platforms, each covering in between 500km^2 to more than 2000km^2, were recognised on the Tri Ton Horst (Figs.7d - f). Externally, these platforms were confined most frequently by hundreds of metres high, steep margins that became higher and steeper through time. In contrast, ramp-like margins outline most of the internal margins facing neighbouring platforms on the Tri Ton Horst (Figs.7d, f). Fast and rapidly changing progradation and aggradation resulted in continually alternating platform outlines throughout the period.

The relative volume of the distinct high amplitude talus aprons fringing platforms towards the east substantially reduced during the Middle Miocene as compared with the previous period, and continued to decrease throughout Middle and Late Miocene time (Figs.3, 9). West of the Tri Ton Horst, substantial volumes of talus aprons fringe the carbonate platforms. The aprons radiate up to *c.* 20km from the platform margins and intercalate with the more modest talus aprons of the western platforms, and within the uppermost Middle to Upper Miocene baselap the flanks of drowned platforms in the west (Figs.3, 11). In contrast, the coeval talus aprons from the westernmost platforms only radiate less than 5km off the platform margins and rapidly thin to close to the brink of seismic resolution.

The youngest Upper Miocene part of the platform carbonates is buried underneath an up to a few hundred metres thick low-reflective to semi-transparent mainly Pleistocene succession interpreted as hemipelagic deep

marine deposits (Fig.10). Farther east, the platform margin in places subcrops the modern seafloor at 400 - 500m depth (Fig.3). This suggests final drowning of the Tri Ton platform carbonates sometime during the Late Miocene thus documenting eastwards younging platform drowning ages.

East of the Tri Ton Horst, isolated platforms capping structural highs survive to the present day. These platforms constitute prominent elevated features surrounded by several hundred metres deep water that form the basis of the Paracel Islands. However, seismic data suggest a number of guyots - flat-topped seamounts - interpreted as drowned carbonate platforms located in several hundred metres of water depth thus indicating that Late Neogene platform drowning affected this area as well.

3.3. Giant buried craters

Peculiar depressions form up to a few hundred metres deep scars in the upper surface of the carbonate platform overlying the Tri Ton Horst (Figs.10, 11). The depressions are up to a few kilometres wide and often filled with Late Neogene siliciclastic sediments (Fig.13). The features overly poorly to chaotically reflected columns of platform carbonates. The upper part of these columns frequently contains very strong reflections whereas the underlying levels appear semi-transparent. Concave upwards reflectors frequently signify the upper part of these columns whereas up-warping of deeper platform reflectors occur along the flanks of the deeper parts of the columns.

The depressions are interpreted to represent giant pockmarks associated with Late Neogene arealy restricted "cave-in" of underlying carbonates. The concave upward pattern within the upper part of these features reflects the collapsed material itself often amplified by velocity pull-down associated with the siliciclastic deposits filling-in the collapse craters. The up-warpings of the reflectors along the deeper flanks of the columns are more enigmatic. They could reflect drag structures related with injection of fluids from below. However, it cannot be ruled out that the up-warpings represent strong velocity pull-ups beneath highly cemented parts of the carbonate platform that more than compensates for any velocity pull-down associated with the siliciclastic in-fill of the sink holes above.

Comparable giant pockmarks exist entirely within the carbonate platform overlying the Tri Ton Horst. In these cases the collapse-induced relief was mainly buried by Middle to Late Miocene platform carbonates testifying to slightly earlier collapse.

The observed depressions often overlie deeper seated basement cored faults possibly indicating a relationship to the structural setting. Furthermore, amplitude anomalies (mostly "soft kicks") regularly occur within the collapse zone or within the carbonates flanking the vertical collapse columns. This could reflect either anomalous fluid content within and next to the zones or diagenetic effects.

The above observations may indicate that the giant pockmarks formed in response to localised massive subsurface carbonate dissolution and fluid venting occurring mainly during the Late Neogene. Although

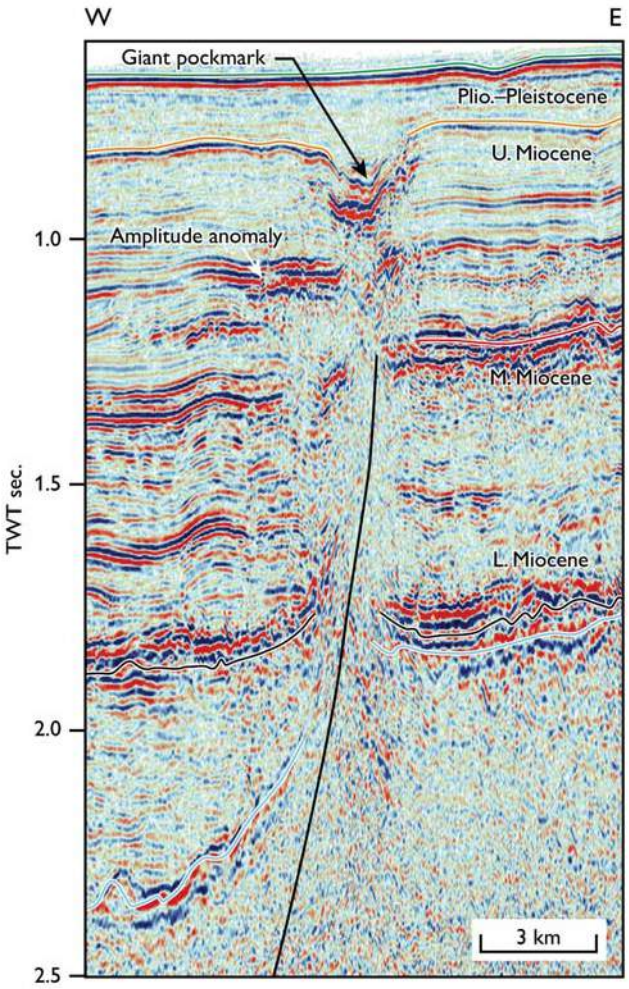

Fig.13. *A giant pockmark marks the top of the Tri Ton carbonate Platform and is filled by Plio-Pleistocene siliciclastic deposits. The giant pockmark caps a chaotically reflected column that overlies a Paleogene fault zone. Amplitude anomalies flank the collapse zone. Location indicated on Figs.2 and 11. Modified after Fyhn et al. [26]*

controversial, the mechanism responsible for dissolving such massive volumes of carbonates and creating these massive craters is speculated to be CO_2- and/or methane-enriched fluid venting compatible with the venting taking place within the central Song Hong basin immediately to the north.

The region is notorious for the occurrence and accumulations of CO_2 derived from either mantle or crustal sources or a combination of the two [36]. Together with the presence of soft-kicks along the collapse features that could reflect trapped CO_2 in the subsurface this supports the genesis of the giant pockmarks considered above. Moreover, densely spaced giant pockmarks in the area immediately to the east of the Tri Ton Horst records an active fluid circulation system which likely relates to either seepage of CO_2 or hydrocarbons [68].

However, hydrothermal circulation and venting guided by pre-existing faults associated with e.g. deeper seated intrusions cannot be ruled out as the cause for the giant pockmarks. Deep-burial carbonate dissolution has in some cases previously been attributed to hydrothermal circulation focused along faults [14, 32], Esteban & Taberner, 2003. Late Neogene magmatic activity is documented regionally by the presence of volcanic mounds, basalt deltas and intrusions.

The collapse features show some striking similarities with hydrothermal vent complexes along the British and Norwegian Atlantic margin [30, 37, 57]. Similar to the observed Vietnamese features, the North Atlantic vent complexes are characterised by distinct several tens to hundreds of metres deep craters between a few hundred metres and 11km in diameter underlain by chaotic reflected fluid conduits and diatremes. Both up-warping and down-warping of strata occur along the flanks of these North Atlantic hydrothermal conduits, and amplitude anomalies along their flanks are common [57] similar to what is observed on the Tri Ton Ridge.

In contrast to the Vietnamese features, most - but not all - hydrothermal vent craters reported are associated with sediment/volcaniclastic cones filling in the craters, extruded during the final stage of venting [30, 37, 57, 69]. However, these vent complexes formed in siliciclastic dominated basins speculated to be more prone to mechanical remobilisation of subsurface sediments. In contrast, dissolution and hydrothermal karstification could be more common in the Tri Ton Ridge area dominated by carbonates.

None the less, and in contrast to giant pockmarks induced by magmatic activity in other parts of the world, no magmatic intrusions have been demonstrated directly beneath the collapse features on the Tri Ton Ridge. Hence, CO_2 - and/or methane-enriched fluid venting not directly linked with magmatism are considered most plausible to explain the observed giant pockmarks.

4. Discussion and mechanisms governing platform growth and demise

The regional distribution of thick Lower and Middle Miocene carbonates testify to a depositional environment favourable for carbonate platform growth including a suitable and subsiding substrate promoting nucleation of carbonate growth, warm tropical climate, low terrigenous and nutrient input and optimal oceanographic conditions [26]. The clean Lower and Middle Miocene carbonates of the Tuy Hoa Carbonate Platform fringing Vietnam's paleo-shores and of the Tri Ton Carbonate Platform support low terrigenous input into the area, although the sand and silt dominated Lower Neogene succession within the Quang Ngai graben document coeval siliciclastic supplies to the area (Fig.14). It is noteworthy, however, that the Lower Neogene basinal siliciclastic sediments are distinctly coarser than the overlying Upper Neogene basinal deposits in the one well penetrating this succession [12]. These relatively coarse grained deposits may be more widely distributed judging by the distinct seismic reflection pattern of this interval. This may be an indication of a variation with time not only in terms of the supplied volume of terrigenous sediments but also in the nature of these. Furthermore, this could together with the very clean carbonates of the Tuy Hoa platfom along the margin indicate more restricted point sourced terrigenous supplies to the basinal areas during the Early Neogene in contrast to the Late Neogene.

Following the initial Early Miocene transgressional phase, carbonate growth stabilised on the most prominent structural highs (Figs.7b, 14). The outline of the Lower to lower Middle Miocene part of the Tri Ton Carbonate Platform indicates that carbonate deposition took place on a coherent large platform with only moderate internal relief. The aggradation and progradation along the platform margin suggest that Early to early Middle Miocene platform growth kept pace with the creation of accommodation space. The well-developed platform apron and the significant export of carbonate detritus to the basin areas indicate a substantial surplus of carbonate

production and a consequent keep-up style of deposition during the Early to early Middle Miocene on the Tri Ton Platform. This is in accordance with the signs of repeated periods of karstification, since even moderate relative sea-level fluctuations on such platform would have resulted in recurring subaerial exposure events.

The above observations and the up to more than one kilometre thickness of the Lower to lower Middle Miocene carbonate successions encountered on the Tuy Hoa and Tri Ton Carbonate Platforms suggest substantial regional carbonate production and a rapid platform accumulation generally in the order of 100 - 200m/My throughout the period in areas with the highest rates. This seems to support the notion of favourable growth conditions during the Early Neogene.

The deterioration of the carbonate system in the study area seems to have initiated during the later half of the Middle Miocene (Fig.14). Platform termination on the Tuy Hoa Carbonate Platform was coeval and linked with the protracted Middle to Late Miocene subaerial uplift affecting a large fraction of the Vietnamese margin.

In contrast, the Tri Ton Carbonate Platform succumbed to drowning following a protracted period of Middle and Late Miocene partial drowning and recovery events. However, the fundamental cause of this gradual platform demise remains cryptic.

Carbonate platforms drown when relative sea-level rise exceeds the rate of carbonate accumulation bringing platforms beneath the euphotic zone of rapid carbonate production [65]. Factors considered to promote platform drowning include: 1) rapid pulses of relative sea-level rise, 2) slowed platform growth induced by deterioration of the carbonate production and accumulation potential and 3) over-steepening and self-erosion of platform margins [65, 66, 81].

A number of factors strongly impact carbonate production and accumulation rates. These include variation of sea-surface temperatures, inorganic nutrient levels and terrigenous/volcaniclastic input as well as variation of other factors such as ocean chemistry including surface water pH and salinity [67]. Increased terrigenous/volcaniclastic input and decreasing sea-surface temperatures (within the most common temperature range) tend to reduce carbonate production [61, 67, 77, 79]. Increased sea-surface inorganic nutrient levels similarly tend to decrease the overall rate of carbonate production and further may act to decrease the carbonate accumulation potential due to enhanced bioerosion [28, 29, 48].

The initiation of partial drowning in the Middle Miocene on the Tri Ton Carbonate Platform occurred at the same time as regional magmatism intensified and terrigenous supplies to the basins substantially increased (Fig.14). Even so, clean carbonates make up virtually the entire platform succession including the youngest part. This does not support increased siliciclastic supplies or volcanic input to the platform area during the later growth stages. Moreover, biostratigraphic evidence from the thin hemipelagic siliceous succession capping the platform document condensed deposition during a more than *c*. 7Ma long period (Fig.8b). This precludes increased siliciclastic sedimentation across the Tri Ton Platform during the period and thus rules out increased siliciclastic supplies to the platform area or volcanism as direct stressing factor leading to platform drowning.

The Miocene was a period of rapid climatic changes; and global temperatures started dropping during the Middle Miocene [41, 84]. At the same time, glaciations and deglaciations in higher latitudes resulted in significant sea-level fluctuations [45]. Moreover, Miocene monsoon intensification affected the SouthEast Asian climate and probably influenced oceanographic conditions [10, 22, 75,

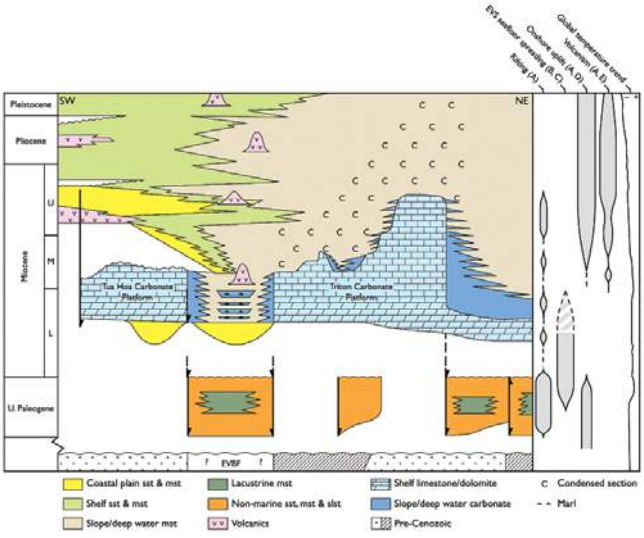

Fig.14. *Stratigraphic chart illustrating the overall depositional development together with the timing of the main regional geologic events and the smoothed relative global temperature trend after Zarchos et al. [84] based on the δO^{18}-ratio of deep-marine benthic foraminiferous. A: Fyhn et al. [21]; B: Briais et al. [8]; C: Barckhausen and Roeser, [2]; D: Carter et al. [9]; E: Lee et al. [39]. EVS = East Vietnam Sea; EVBF = East Vietnam Boundary Fault; mst = mudstone; slst = siltstone; sst = sandstone. Approximate transect location indicated on Fig. 2. Modified after Fyhn et al., [26]*

86]. These global and super-regional climate changes may have acted to stress carbonate production on the Tri Ton Carbonate Platform during Middle and Late Miocene time.

However, partial platform drowning seems to have initiated in the west and progressed eastwards (seawards) throughout the Late Neogene, and modern carbonate growth continues farther east around the Paracel Islands. This pattern does not support climatic deterioration as the primary cause for platform drowning. Instead, the seawards migrating drowning trend could indicate a deterioration of the growth environment linked with factors rooted in the onshore coeval evolution.

Comparable regional platform drowning events elsewhere in the East Vietnam Sea has been attributed to increased inorganic nutrient supplies to platform areas associated with coastal run-off and increased terrigenous input to the basinal areas [19, 22, 37, 63].

This study documents a similar substantial increase in terrigenous supplies to the area immediately landwards from the Tri Ton Carbonate Platform occurring simultaneous to the onset of platform drowning offshore Central Vietnam (Fig.14). There seems to be a good correlation with this seawards migrating trend of platform drowning and the coeval progradation of the shelf and by inference increasing input of inorganic nutrients.

Combined with climatic deterioration and fluctuating sea level, offshore increased inorganic nutrient input derived mainly from Central Vietnamese uplift and denudation is thus interpreted as the most plausible cause for Neogene carbonate platform drowning. Future high-resolution geochemical studies and microfacies analysis of the late-stage growth intervals and overlying drowning sequences of the Tri Ton Platform may help test this hypothesis of nutrient pollution as carbonate growth-inhibitor offshore Central Vietnam.

6. Conclusions

A Danish-Vietnamese earth scientific research initiative, the ENRECA project, has been ongoing for almost 20 years. During the course of the project, the Vietnamese geology and petroleum potential has been investigated. A highly diversified basin-analytical programme has been carried out and is exemplified in this paper by the investigation of Miocene carbonate growth and demise along the Central Vietnamese margin.

Miocene carbonate deposition was widespread on structural highs offshore Central Vietnam. Platform carbonates cover several tens of thousands of square kilometres and constitute an important exploration target in the area with hydrocarbons sourced mainly from Paleogene lacustrine syn-rift shales and humic coals, although a Miocene marine marl source rock may also contribute to the petroleum systems of the area.

Platform growth initiated probably in the Burdigalian during the transgression associated with the final opening of the southwestern part of the East Vietnam Sea and promoted by the transgressed relief left behind after Paleogene rifting.

Between Early and Middle Miocene time, platform growth thrived regionally with high carbonate production rates presumably encouraged by favourable climatic and oceanographic conditions and low terrigenous and nutrient input to the platform areas.

From Middle to Late Miocene time, carbonate growth retreated seawards and repeated periods of partial drowning and platform breakup took place.

Contemporary with platform retreat and breakup, the Vietnamese mainland was uplifted triggering rapid denudation. This resulted in a pronounced increase in terrigenous detritus being shed into the offshore basins, and caused subaerial exposure and termination of the Tuy Hoa Carbonate Platform fringing the Central Vietnamese margin. The regional uplift could be linked with the coeval magmatism and was likely associated with distinctly increased inorganic nutrient supplies to the platform areas farther offshore sourced from the mainland. The elevated nutrient input polluted the platform areas and possibly combined with climatic deterioration stressed carbonate production resulting in platform split-up and partial drowning.

Stressed carbonate growth conditions led to drowning of the remaining part of the Tri Ton Carbonate Platform during the Late Miocene. However, small-scale platform growth continues to the present farther offshore around the Paracel Islands isolated from terrigenous nutrient pollution.

A number of giant pockmarks characterise the final drowning surface of the Tri Ton Carbonate Platform and the youngest carbonates below. The giant collapses could be interpreted as the effects of subsurface carbonate dissolution and mobilisation associated with hydrothermal circulation and venting. Alternatively, carbonate dissolution could have been induced by either CO_2 - enriched fluids or acidification caused by biodegradation of hydrocarbons.

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