DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/7

Structural geology of the Nam Du island and neighbouring areas in the Phu Quoc Basin, SW Vietnam

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Structural field investigations of the Nam Du archipelago and adjacant coastal areas at the eastern margin of the Phu Quoc Basin, south-western Vietnam

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Danmarks og Grønlands Geologiske Undersøgelse

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Introduction

During the last two years geological investigations of the Phu Quoc Basin have been carried out in co-operation with Vietnam Petroleum Institute and Geological Survey of Denmark & Greenland. The preliminary interpretations of the studies carried out until the end of 2007 indicate that the Phu Quoc Basin is a retro-arc foreland basin with deposits from the Triassic to early Cretaceous time. The basin increases in thickness towards the east, where it is border by a marked N–S trending deformation belt subjected to tectonic inversion. This belt extends more than 500 km along its N–S trend, and the top of the deformation structures crops out to form the archipelago centred around the island Nam Du.

For the support of the geological modelling of the Phu Quoc Basin and adjacent areas to the east it was decided to make a field investigation trip to the Nam Du area as part of the ENRECA program. The aim of the field trip was primarily to investigate the structural geology of the outcropping formations, secondly to collect samples from the various formations for dating the uplift in the Nam Du deformational belt, and thirdly to search for pre-Jurassic source rocks.

Field trip logistics

The field trip started from Rach Gia 21st of January 2008 from where the ferry brought the participants to Nam Du. In the middle of the afternoon the main town at Nam Du was entered, and a reconnaissance motor-bike trip was organised for evaluating the accessible outcrops.

The 22nd January the field party separated into two teams, one carrying out detailed measurements of three localities in the central part of Nam Du island, and the other organising a fishing boat for recognisance on the south coast of Nam Du and the nearest islands.

The 23rd January one team made detailed investigations on the island of Hòn Mâú in the morning, which was decided due to the direction of wind and waves, and in the afternoon the south coast of Nam Du was investigated. The other team investigated the east coast of Nam Du, where Upper Cretaceous rocks are indicated on the geological map.

The 24th January the field party left Nam Du in the morning for sailing to Hòn Nghe and further on to the mainland at Hòn Chóng for accommodation. Due to harsh weather the visit at Hòn Nghe became very brief and the arrival at the mainland rather late.

The 25th January Hòn Nghe was revisited, and the field party started out from the Permian carbonate rock housing the Buddha Pagoda. From here the two field teams separated, one investigating the eastern coast of the island, and the other investigating the outcrops on the northwest coast. In the afternoon both teams met at the latter outcrop for carrying out detailed structural investigations. Back at the mainland the accommodation was repeated at Hòn Trem Resort.

The 26th January the field team investigated the outcrops near Duong Hóa, where Permian carbonates are exploited for cement production and stone quarries in which Upper Paelozoic kataclastic meta-sediments including Carboniferous graphite schist are excavated. The Peninsula south of Duong Hóa was also investigated, where a thick succession of arkosic gravel stones were recognised. Late in the afternoon the granitic plugs at Hòn Dát was visited before the end of the day's trip at evening time.

The 27th January the field party concluded the trip at Ho Chi Minh, from where the Vietnamese team returned to Hanoi and the Danish team returned to Copenhagen via Bangkok.

Field participants

The field party consisted of five members from GEUS/KU (Denmark) and six members from VPI, HUMG, HUS (Vietnam):

Denmark: Ioannis Abatzis, Lars Henrik Nielsen, Lars Ole Boldreel, Stig A. Schack Pedersen, Michael Fyhn,

Vietnam: Pham Huy Long, Mai Thanh Tan, Phan Trung Dien, Le Chi Mai, Luong Thanh Huyen and Tran Thanh Nhan.

The aim of this report

This report gives the preliminary geological record of the observations made during the field trip to the Nam Du archipelago in January 2008. Furthermore the frame for understanding the geology is provided in the chapters under the heading Geological Setting and Stratigraphy of the Phu Quoc Basin. The field report should be regarded as the summery of data from the visited outcrops supplemented by overview from existing maps supported with new satellite images and relevant seismic sections form the off shore area in the vicinity of Nam Du.

Fig. 1. *Field work on Nam Du at locality 3a. Note the steeply bedded rhyolites and the high degree of local interest in the geological investigations.*

Geological Setting

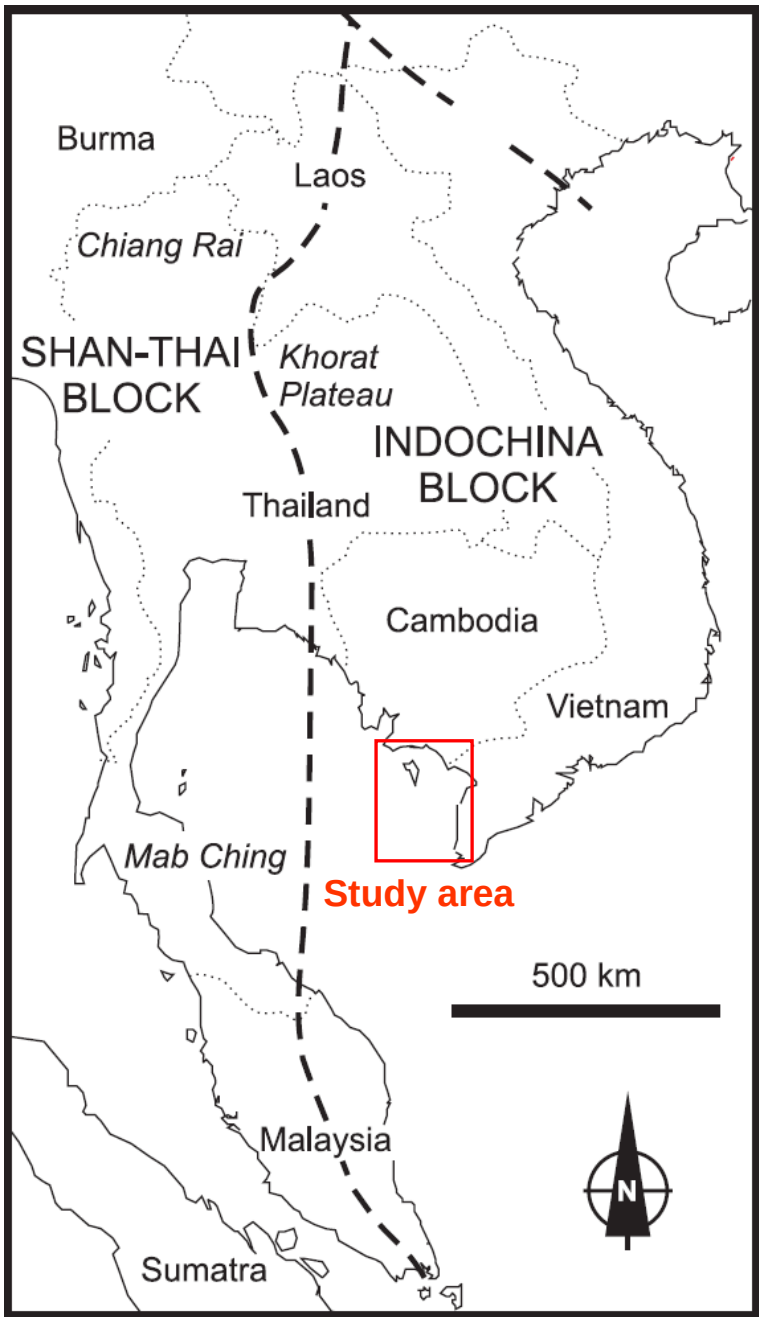


Fig. 2. *Location of the study area in the south-western part of Vietnam. The modern boundary of the western termination of the Indochina Block is indicated by the dashed line on the map.*

South Vietnam forms part of the Indochina Block (Fig. 2). Only limited knowledge exists on the pre-Tertiary tectonic evolution of the block. The block is believed to have formed part of Gondwana super-continent during the early part of the Paleozoic (Metcalfe, 1998). By later Devonian times, the block rifted from Gondwana and was drifting northward through the Paleo Tethys. It seems conceivable that the Devonian clastic sediments in southern Vietnam form part of the basin fill in rift basins that probably developed in response to the splitting of the Indochina block from Gondwana.

Thick Latest Devonian – Late Permian carbonate and chert accumulations were deposited during Indochina's northward drift and now crops out as spectacular karst formations in Vietnam. Similar carbonate formations exist on the South China Block and on the Sibumasu Block. These blocks, like Indochina, separated from Gondwana during the Late Paleozoic and drifted northward (Fig. 3).

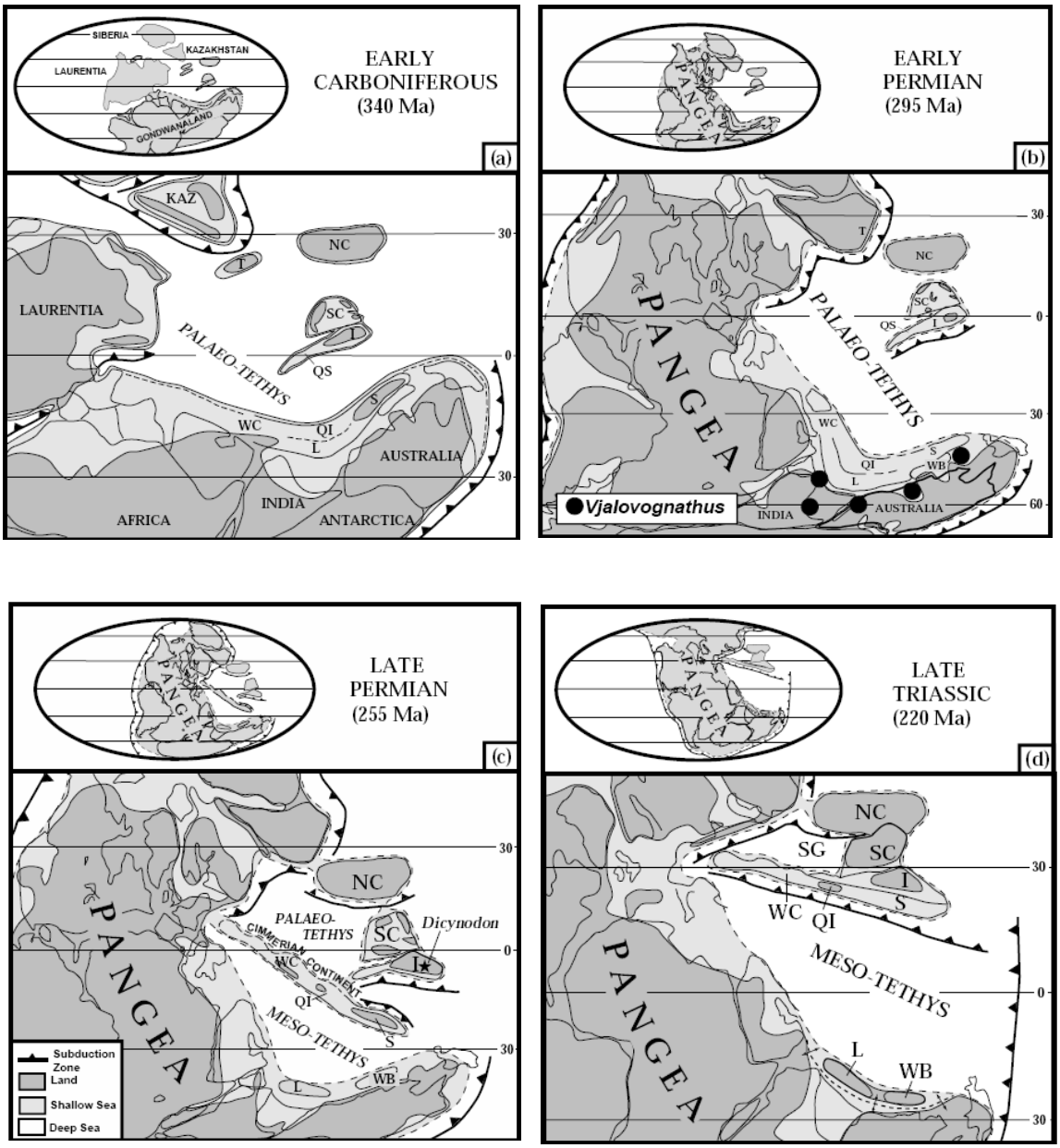


Fig. 3. *The late Palaeozoic to early Mesozoic tectonic development of the Palaeo-Tethys and Meso-Tethys geological setting. The break-up of Gondwana resulted in a number of smaller continental fragments including Indochina, South China and the Shan Tai Blocks, which during the Late Permian to Early Triassic amalgamated due to the destructive reduction of the Palaeo-Tethys ocean basin and the constructive development of the Meso-Tethys ocean basin.*

The collision of these three continental blocks, termed the Indocinian Orogeny, started during the latest Permian and lasted through greater parts of the Triassic period (Metcalfe, 1998). In response to the Indosinian Orogeny, carbonate platform built-up ceased and Triassic foreland basins formed dominated by silisiclastic deposition. The main collision zone stretches from northern Vietnam through Laos and southward towards the gulf of Thailand (Fig.2). Farther south the trace of the collision zone is interpreted to continue underneath the gulf of Thailand and crops out on the Malaysian Peninsula (Fig 2). The zone runs c. 300 km west of southwestern Vietnam and shares the distinct north-southerly verging structural grain observed in southwestern Vietnam.

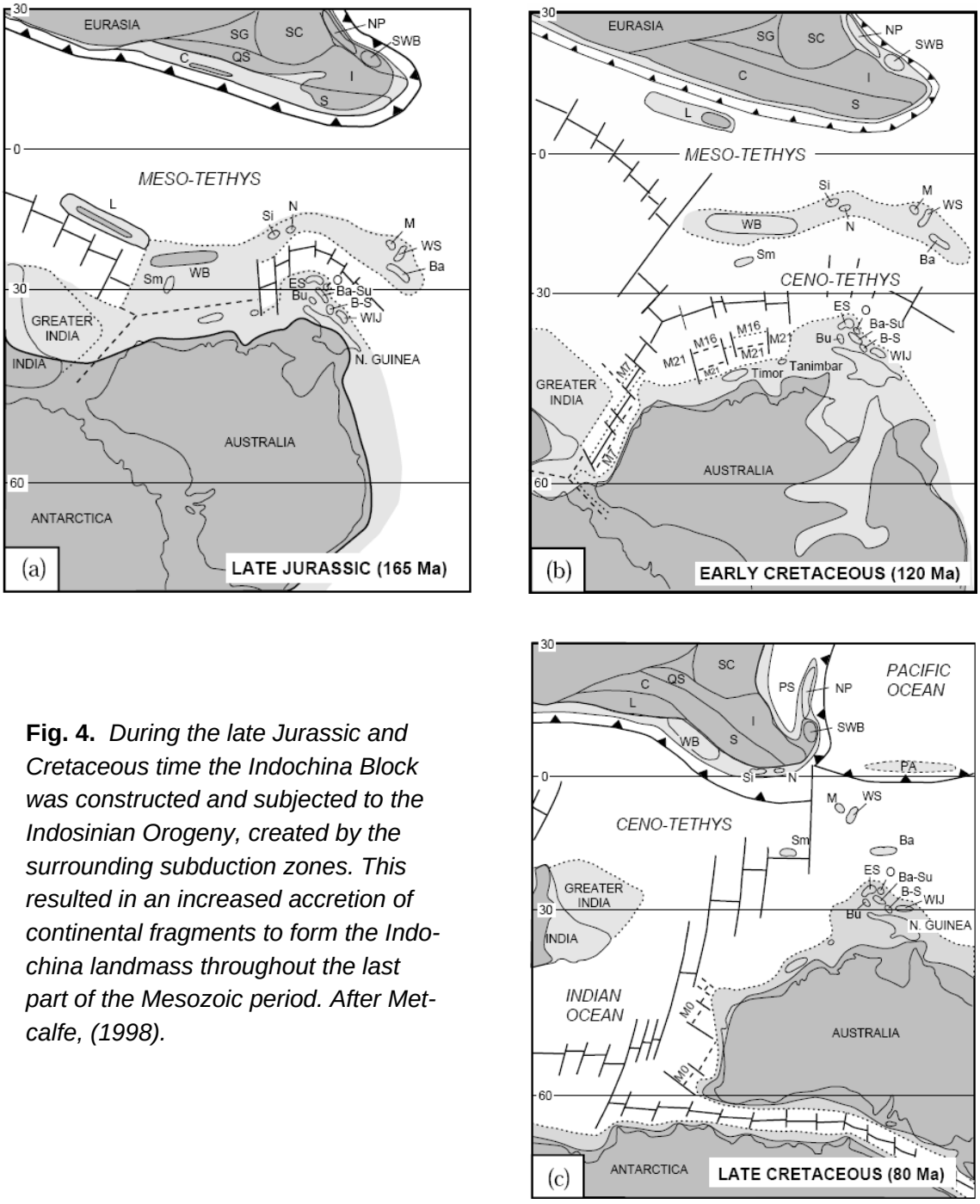


Fig. 4. *During the late Jurassic and Cretaceous time the Indochina Block was constructed and subjected to the Indosinian Orogeny, created by the surrounding subduction zones. This resulted in an increased accretion of continental fragments to form the Indochina landmass throughout the last part of the Mesozoic period. After Metcalfe, (1998).*

Triassic rift basins recognized in Thailand formed after the Indochinian Orogeny (Smith *et al*., 1996). Similar basins may also exist in southwest Vietnam. In Vietnam these rift basins were filled by continental and shallow marine deposits. Seismic transects across part of the northern Laos indicate that the Triassic rift basins suffered uplift and erosions sometime during the latest Triassic or the Early Jurassic (Smith, 1996).

The amalgamated Indochina and Sibumasu blocks were surrounded by a subduction zone during the Late Jurassic and the Cretaceous (Metcalfe, 1998). Smaller continental fragments accreted to the region as the result of the long-lasting subduction that took place during the Jurassic and the Cretaceous (Fig. 4). A magmatic arc formed in response to the subduction along the coast of southeastern Vietnam. The Phu Quoc Basin developed during this period as a retro arc foreland basin west of the arc (Fig. 5). The basin is filled by the Phu Quoc Formation and can be traced c. 500 km from southern Cambodia far into the gulf of Thailand (Fig. 6). Seismic transects of the Phu Quoc Basin indicate an eastward depositional thickening toward the arc. Outcrop and well data suggest that the basin was dominated by alluvial deposition with some shallow marine incursions.

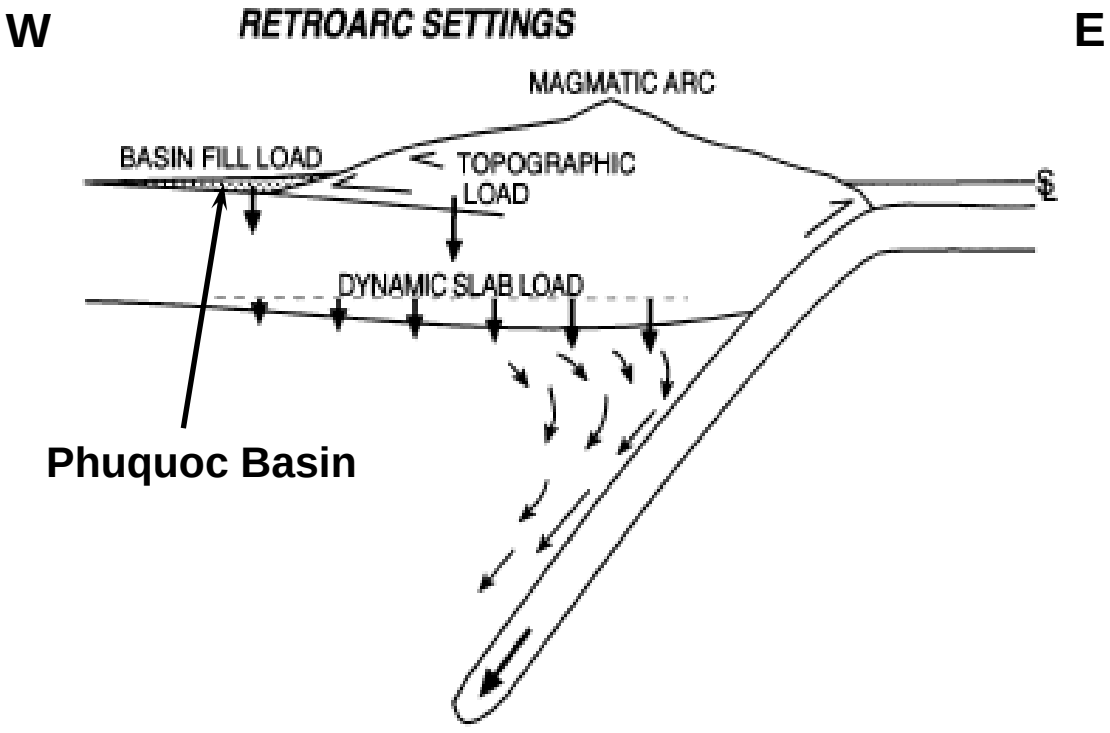


Fig. 5. *Model of the late Jurassic and early Cretaceous formation of the Phu Quoc Basin. Modified after DeCelles and Giles (1996).*

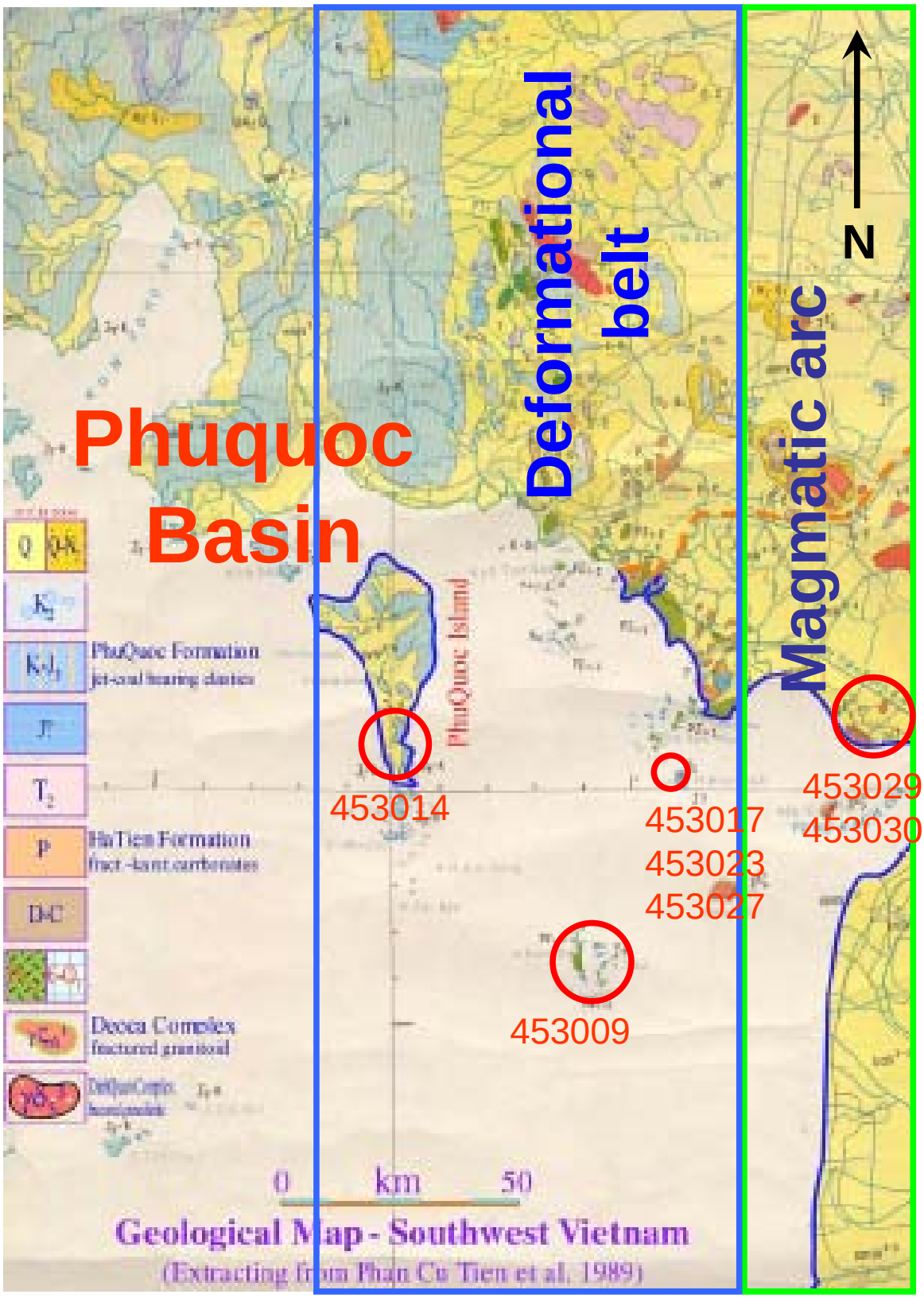


Fig. 6. *Geological map of the study area. Circles represent sites for AFTA and radiometric dating. Modified after Dien (2007).*

The Phu Quoc Basin was inverted sometime during the period between the Albian and the Eocene, which resulted in regional uplift and erosion. The basin inversion seems related to a combination of compressional thin-skinned thrusting and transpressional wrench tectonics, which is intensified toward a more than 500 km long N–S trending belt to the east. The belt is c. 100 km wide and has a western flank composed of the intensely deformed eastern margin of the Phu Quoc Basin. The Phu Quoc Island forms the northward continuation of the deformed basin margin. Farther north, in Cambodia the intensely deformed part of the Phu Quoc Formation forms a N–S trending mountain range (Elephant Mountain). In the eastern flank of the deformational belt, the Phu Quoc Formation was nearly completely removed by erosion caused by the inversion uplift. Alternatively the Phu Quoc Basin never extended as far east as across the eastern flank of the deformational belt. In case of the later model, scattered Jurassic?/Cretaceous sediments (The Nha Trang Formation) exposed on the Hon Nghe Island and on the mainland may be parts of local piggy-back basins related to the magmatic arc/foreland basin setting. In the absence of the Phu Quoc Formation in the eastern part of the deformational belt, Paleozoic and Triassic deposits crop out along with Mesozoic intrusive and volcanic rocks.

The two basins, the Khorat Basin in Thailand and Laos and the Gagau/Tembeling Basins offshore and in the Malaysian Peninsula, are very similar to the Phu Quoc Basin in Vietnam and Cambodia. These basins formed contemporary (Late Jurassic – Early Cretaceous) and were all dominated by continental to shallow marine deposition. All basins were subsequently deformed prior to the Eocene. The Khorat Basin fill in by the Khorat Group is a foreland basin that was inverted during the Late Cretaceous (Ngah, 2000). The Gagau Group is found below the southwestern part of the Malay Basin on Malaysian territory. Like the Phu Quoc Formation, the Gagau/Tembeling Group floors the Malay Basin and forms a distinct angular unconformity in the southwestern part of the basin.

The inversion unconformity forms the base of the post-Eocene Malay and Khmer basins situated in the Gulf of Thailand. The Malay and the Khmer basins are Tertiary rift basins that most likely formed in response to transtension linked to the collision of India and Eurasia (Tapponnier et al., 1982) (Fig. 7). Rifting of these basins took place in the central part of the Gulf of Thailand and was probably initiated during the Late Eocene. However, dating of the oldest basin fill remains uncertain. At the end of the Oligocene rifting seized and thermal sacking came to dominate. This has since resulted in widening of the basins that now stretches from the southwestern shore of Indochina to the shores of the Malaysian Peninsula. During the Early and Late Miocene, structural inversion took place in the central part of the Malay Basin. However, no signs of inversion are traceable in the Vietnamese part of the Malay and the Khmer basins. Meanwhile, modest extension reactivated the area during the Middle and Late Miocene.

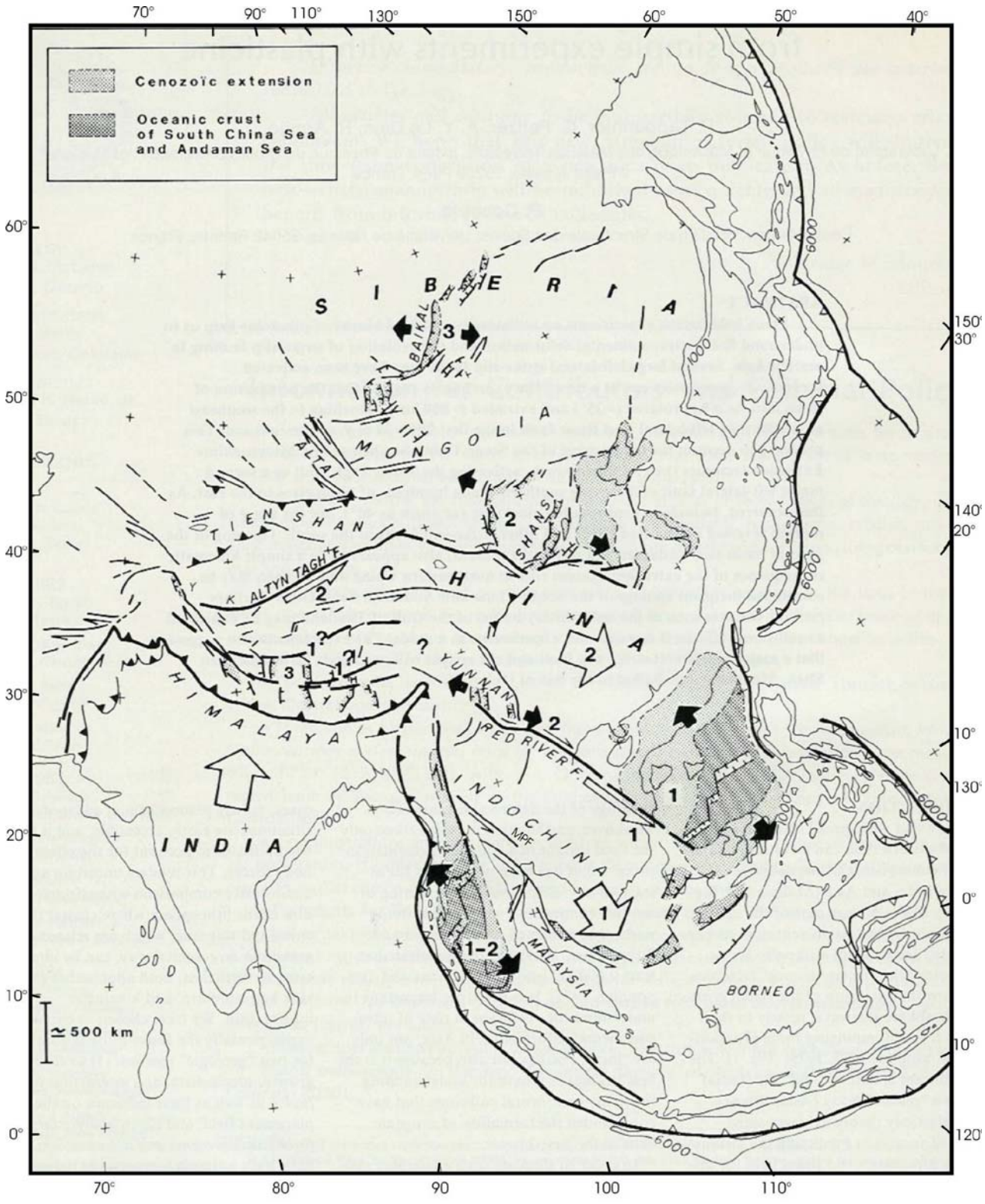


Fig. 7. *Modern geological outline of the Southeast Asia. The map illustrates the extrusion hypothesis where South China, Indochina and Malaysia were forced towards the southeast in response to the collision of India and Eurasia. During this event several rift basins formed including the Malay and the Khmer Basins (at arrow annotated no. 1).*

Physiographic setting

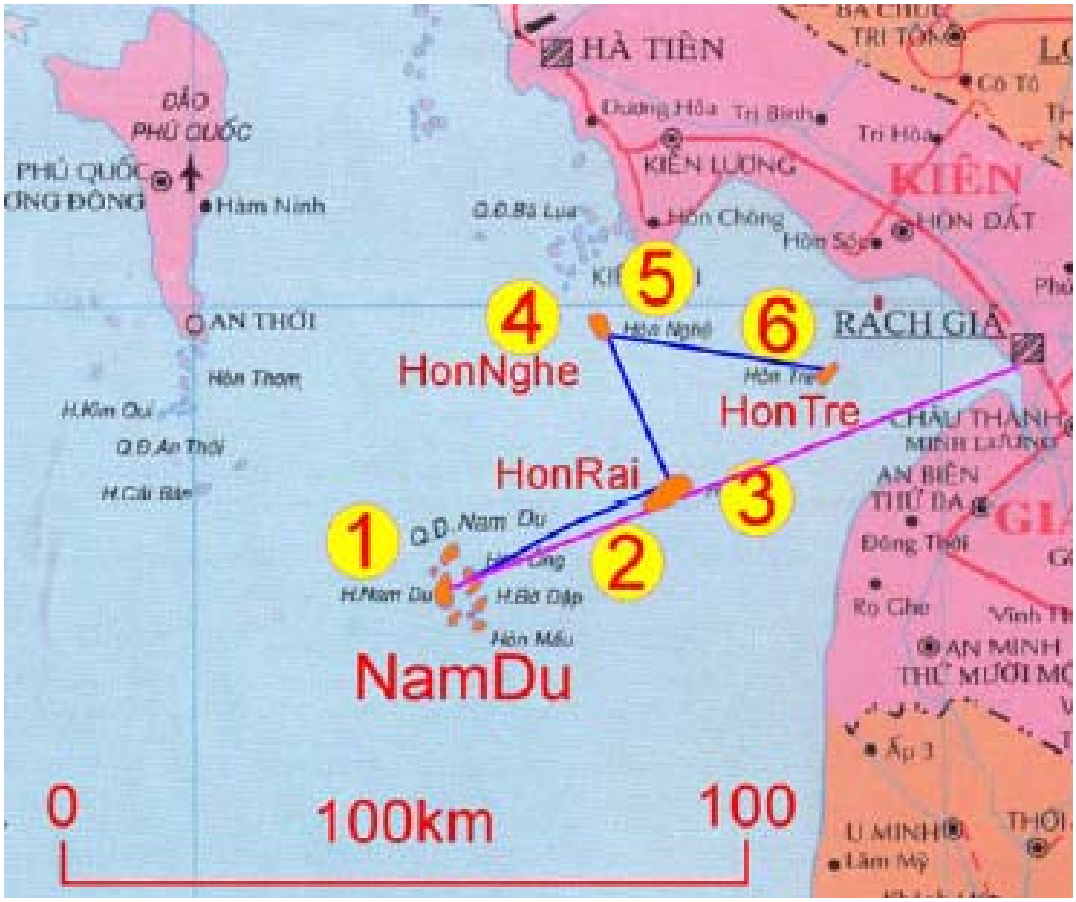
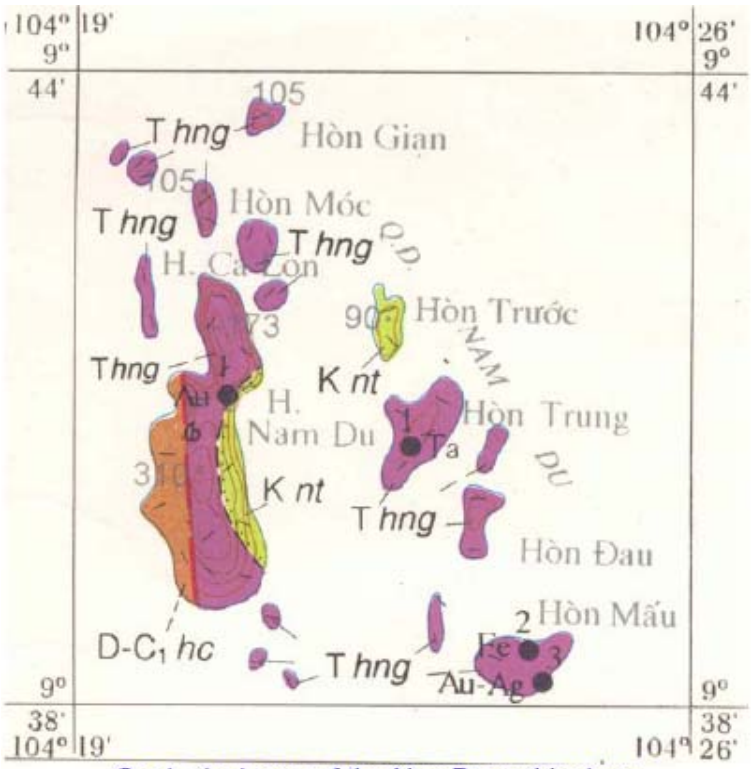


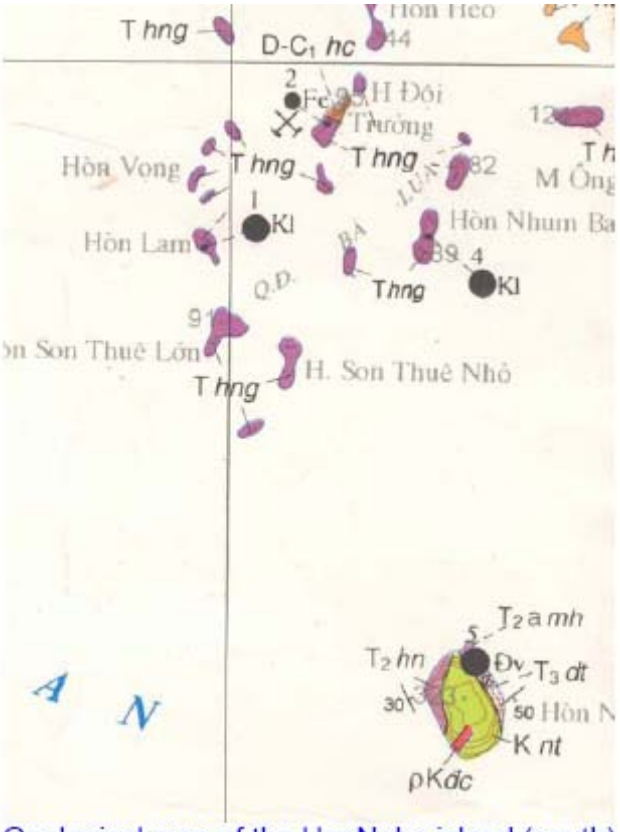
Fig. 8. *Map of the Hon Nghe island and the Nam Du archipelago.*

The Nam Du archipelago is situated in the offshore Phu Quoc basin about 100 km west of Rach Gia. The archipelago consists of 20 islands with a height from less than100 to a somewhat higher than 300 m. Many of the islands have an elongated shape trending N–S mirroring the main structural trend of the thrust-fault belt recognised offshore.



Geological map of the NamDu archipelago

Fig. 9. *The Nam Du archipelago. According to the geological map the islands consists mainly of Triassic formations with a fault boundary to the Upper Palaeozoic formations and a depositional contact to the superposed Cretaceous formations.*



Geological map of the HonNghe island (south)

Fig. 10. The geological map of the Hon Nghe island and the smaller island north of Hon Nghe. From the map it is indicated that the islands are dominated by Triassic rocks, and that Hon Nghe is occupied by a core of Cretaceous rocks intruded by a granitic pegmatite.

Structural geology

Meso-scale structures on outcrops visited during the field trip

The localities investigated during the Nam Du field trip comprise three sites on Nam Du, namely Site 1 (Loc. 1) on the mountain ridges crest central in the island, Site 2 (Loc. 2) the western fishing village, Site 3 (Loc. 6-9) on the south coast of Nam Du. The last site on Nam Du was Site 4 (loc. 6-9) on the south coast of the island. South east of Nam Du the smaller island Hòn Mâú was visited, where the Site 5 (Loc. 4) and Site 6 (Loc. 5) were investigated on the north-western corner of the island.

The following group of sites visited was situated on the island of Hon Nghe. Site 7 (Loc. 10 & 11) was located near the landing entrance to the island at the central part of the west coast. Site 8 (Loc. 12) was the chalk cliff under the Buddha pagoda on the northern tip of the island. Site 9 (Loc. 13) was situated on the NE-corner of the island, and Site 10 (Loc. 14-17) comprises all outcrops investigated along the east coast south of the Buddha pagoda location. The last site on Hon Nghe was Site 11 (Loc. 18) which comprises the bedrock exposed at the shore along the NW-coast.

The last group of sites was concentrated on the mainland near the peninsula of Hon Chong. Here Sites 12 (Loc. 19) was the stone quarry with mylonitic Upper Palaeozoic metasediments. On the north site of the peninsula the coastal exposures were investigated referred to as Site 13 (Loc. 20 & 21). And finally Sites 14 and 15 comprise the investigations of the granite plugs popping up in the north-western fringe of the Mekong Delta (Loc. 22 & 23).

The Loc.-references in brackets indicates the GIS positioned points from where the UTM coordinates have been registered.

Fig. 11. Investigations of rocks at Nam Du had really the local people's attention.

Nam Du Site 1 (loc.1), the central hill on the island.

This locality is an exposure along the road from the main N-S trending road down to the fishing settlements on the west coast. A cross-section c. 50 m long trending E–W has been measured up.

The rocks constitute highly kataclastic felsites and kaolinised breccias. In the centre of the investigated cross-section normal extensional faults with listric geometry affected Cretaceous (?) sandstones (Fig. 12). These features are interpreted as gravity gliding structures or even slump-slides developed on the foreland-dipping steeply inclined limb of a hanging-wall anticline in the proximal part of a piggy-back basin. The main trend of the bedding, the breccia and fault surfaces is N–S (Fig. 13). However, roll-over anticline structures with irregular strike-and-dip orientation were also recognised (Fig. 14), supporting the gravity gliding interpretation of the extensional fault structures.

Fig. 12. Extensional normal faults with listric shaped fault surfaces occurring in the central part of the cross section at Site 1 on Nam Du. The sedimentary rocks consist of fine-grained sandstones probably of Cretaceous age. The structures trend N-S (Fig. 13) with a displacement directed towards the west. They are interpreted as gravity gliding structures developed in the proximal of a piggy-back basin formed on the foreland-dipping steeply inclined limb of a hanging-wall anticline or antiformal stack.

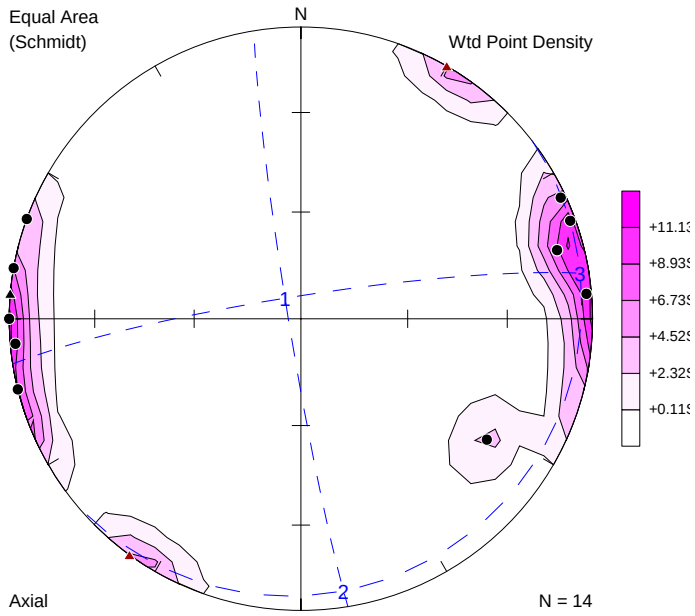


Fig. 13. Main structural trends at the Nam Du Site 1 locality. The points represent normal to bedding and planar fractures in the breccia zones in the stereographic projecting plane of lower hemisphere (Wulff net). The following stereograms have a similar set up.

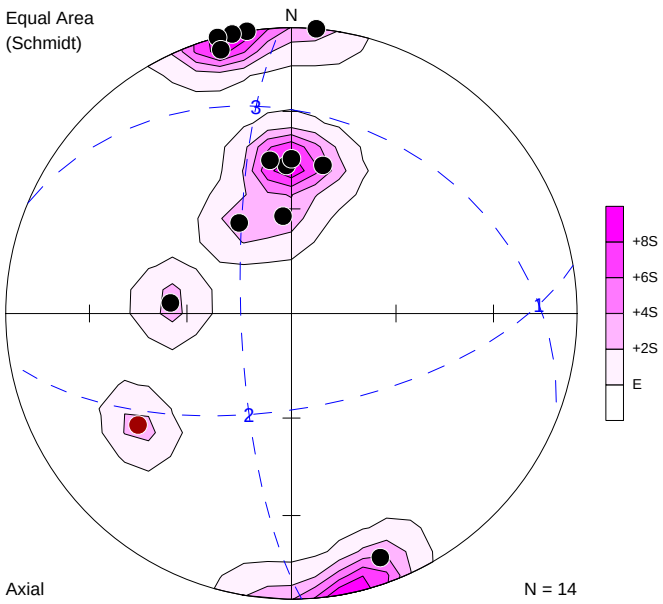


Fig. 14. Strike and dip orientations of beddings folded in a roll-over anticline. The interpreted fold axis has a direction towards SE with a plunge of about 30°.

Nam Du Site 2 (Loc. 2), the western fishing-village

Fig. 15. View towards the north side of the fishing village on the west coast of Nam Du. The mountain slope behind the village consists of white rhyolitic breccias with a strong facture pattern striking to the NE (see Fig. 16). The bedrock in the foreground consists of felsic tuffites also striking towards the NE.

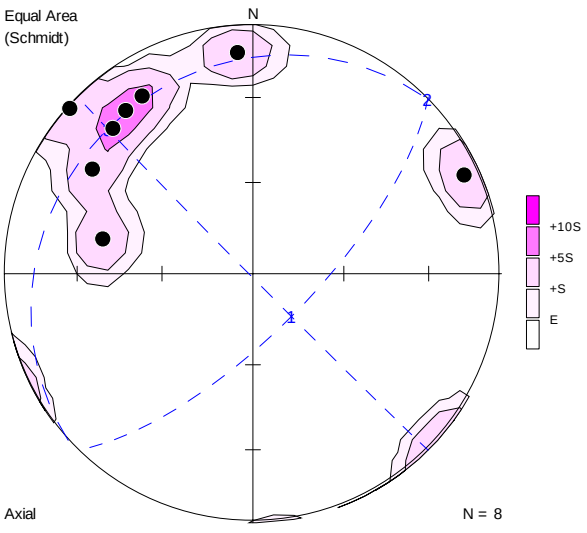


Fig. 16. Stereogram showing the planar direction of joints and fractures north of the fishing village. The main trend of the planar features is towards the NE.

The rocks in the mountain slope north of the fishing village (Fig. 15) comprise white rhyolites strongly crossed by kataclastic brecciation. The bedding as well as the main direction of shear fractures are steeply dipping and striking towards the northeast (Fig. 16).

Nam Du Site 3 (loc.3), coast exposure south of fishing village

Well exposed outcrops of layered rhyolitic rocks occur along the coast south of the fishing villages on the west side of Nam Du. The white, felsic rocks contain quartz, sanidine feldspar and scattered grains of hornblende. The layering of the rocks display graded bedding and agglomeratic sedimentation. The bedding is strongly folded into overturned and recumbent isoclinal folds with irregular orientation of fold axes (Fig. 17). The rock units are interpreted to represent slump folded ignimbrite clouds deposited and deformed during the volcanic eruption events.

Fig. 17. Slump folded ignimbrite beds exposed along the coast south of the fishing village.

Nam Du Site 4 (loc. 6–9), south coast of Nam Du

On the south coast of Nam Du exposed cliff sections occur up to 40 m high. The strike of bedding and major fractures is N–S and the general dip of the bedding is about 30° to the east. The rocks comprises andesitic and rhyolitic pyroclastic and hyaloclastic lavas and breccias. Some of the volcanogene deposits are strongly altered by iron oxidations resulting in bright yellow, orange and red colours (Fig. 18). The paragenesis of the rocks might suggest them to be related to gold, silver and other rare metallic elements.

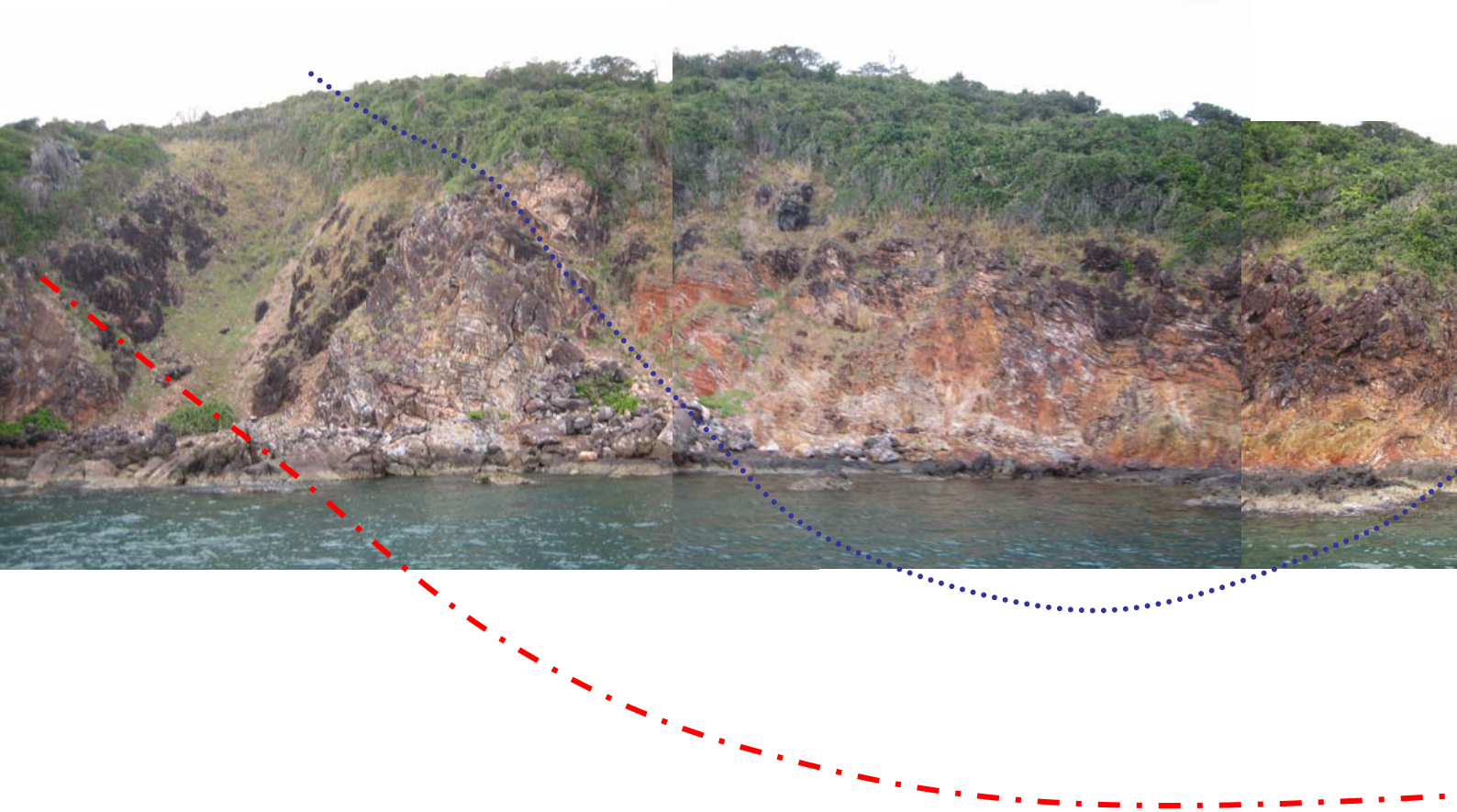


Fig. 18. Easterly dipping andesitic and rhyolitic volcanogene deposits on the south coast of Nam Du. The red stippled line is an interpreted thrust fault. The blue dotted line is an interpreted unconformity at the base of a piggy-back basin.

Hòn Mâú Site 5 (loc. 4) volcanic centre on the SW coast

The SW-corner of the Hòn Mâú island attracted the attention due to the high variation in inclination of the bedding and well exposed meso-scale structures. A sedimentological log was measured up through the main part of the exposed coastal cliff, which documents the main stratigraphy within a volcanic cone deposition (Fig. 19 & 20).

Fig. 19. Outcrop in the volcanic succession at the SW coast of Hòn Mâú. The persons are standing on a light coloured acid tuffites, in which pyroclastic breccias occur randomly.

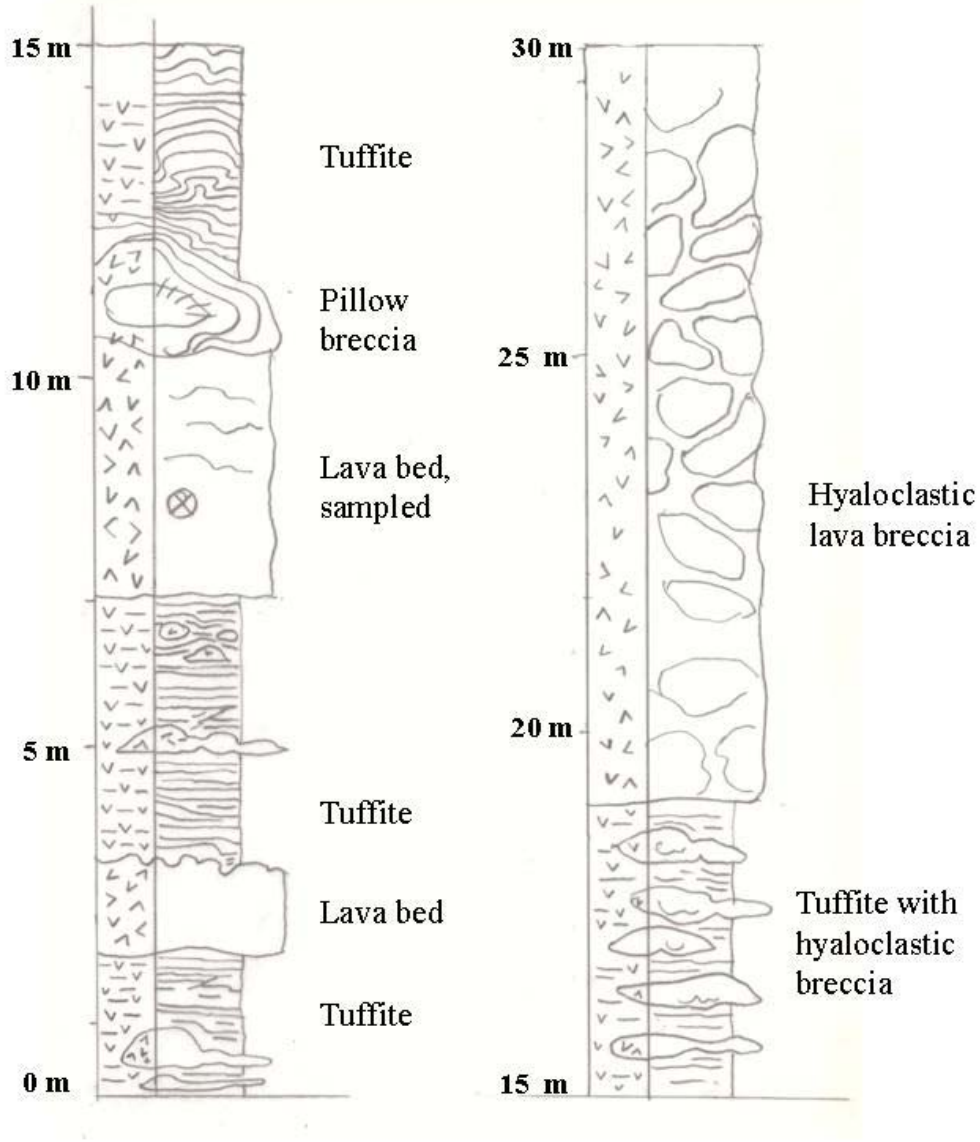


Fig. 20. Geological log of the tuffites and hyaloclastic/pyroclastic acid volcanic succession at the SW coast of Hòn Mâú. A sample for radiometric dating was collected in the lava at 8 m in the log (sample no. GEUS 453016). At the top of the succession an other 25 m thick pile of medium bedded lavas were deposited in a lava stream succession discordantly overlain the measured section (see Fig. 21).

Fig. 21. Steeply dipping lava beds in the volcanic succession at the SW coast of Hòn Mâú. These beds overly discordantly the volcanic succession below, indicating lava flows in various direction away from the volcanic cone in the centre of the volcano to the left (compare with Fig. 24).

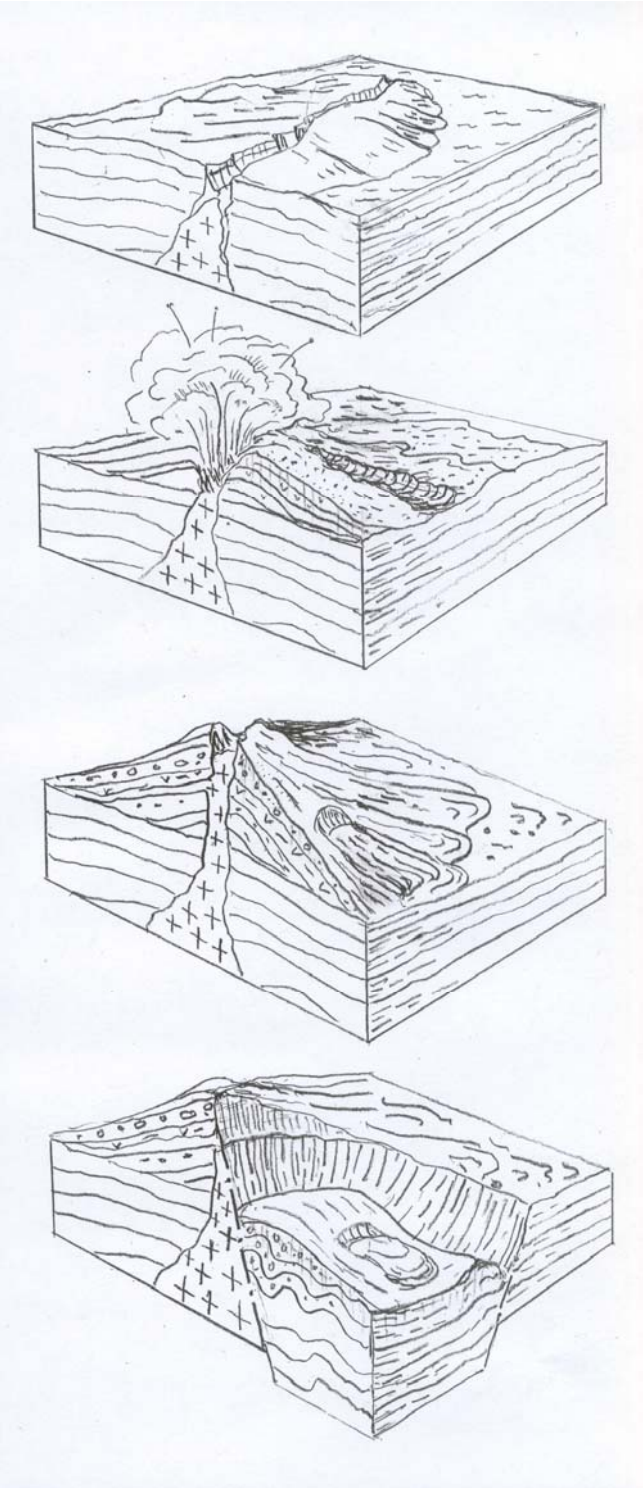
In the cliff section on the SW-point of Hòn Mâú a cross-section through the centre of the volcanic cone is exposed (Fig. 22, 23 & 24). The volcanic beds consist of tuffs and lava flows with a tendency of grading up into lava flows and hyaloclastic breccias (compare with the log Fig. 20). The volcanic succession was deposited in a shallow marine to coastal environment with pillow lavas developed locally. This may imply a volcanic arc setting for the volcanic succession.

The southern part of the Hòn Mâú island evidently constituted a volcanic cone. The structure of the cone with the intrusive magmatic rock in the centre is documented in Fig. 22 and 23, and the setting is illustrated in the uppermost diagrams in Fig. 24. When the volcanic cone had developed, the cone was displaced by normal faulting. The measurements on the fault faces indicates a conic shape of the downthrown deposited, which are most likely interpreted as a cauldron subsidence of the volcanic cone due to a catastrophic extrusive event (compare with lowermost diagrams in Fig. 24).

The uppermost volcanic succession was probably deposited after the cauldron subsidence (Fig. 24), wherefore the lava flows changed directions and are discordantly overlying the lower succession as it may be seen from Fig. 21. These deposits are over thrust by the western limb in the “flower structure” recognised east of the cone centre (Fig. 25).

Fig. 22. The centre of the volcanic cone at the SW coast of Hòn Mâú. The person for scale is standing in the fine grained intrusive igneous rock popping up into the bedde extrusive volcanic rocks above. The cone-shaped feature is evidently seen from the beddings dipping in opposite directions away from the intrusive centre.

Fig. 23. A normal fault displays the centre of the volcanic cone at the SW coast of Hòn Mâú. The person is standing in front of the fault plane pointing to the upper left. Below the person to the right a synclinal drag fold appears in the hanging-wall block.



Early intrusive doming and fracturing

Volcanic eruption and cone accumulation phase

Volcanic cone culmination phase

Cauldron subsidence, caldera phase,

Fig. 24. Four stages of the volcanic development of the cone at the SW coast of Hòn Mâú. The first stage constituted the initial development of doming and intrusive fracturing of the feeder dyke submitting the pyroclastic material. The second stage was the building up of the volcanic cone including accumulation of thick piles of tuffs (Fig. 19) represented by the lower part of the log in fig. 20. In the third stage the lava flows dominated the deposition on the sides of the volcanic cone (compare with Fig. 20 and 21). And finally the cauldron subsidence stage is represented by the normal fault seen in Fig. 22 and 23.

Hòn Mâú Site 6 (loc. 5), positive flower structure on S coast

Fig. 25. The “flower structure” exposed along the coastal cliff on the south side of Hòn Mâú. The cliff section is about 100 m long and the consists of white, brownish weathering tuffites and redeposited acid volcanic ash layers. The measured section is shown in Fig. 26.

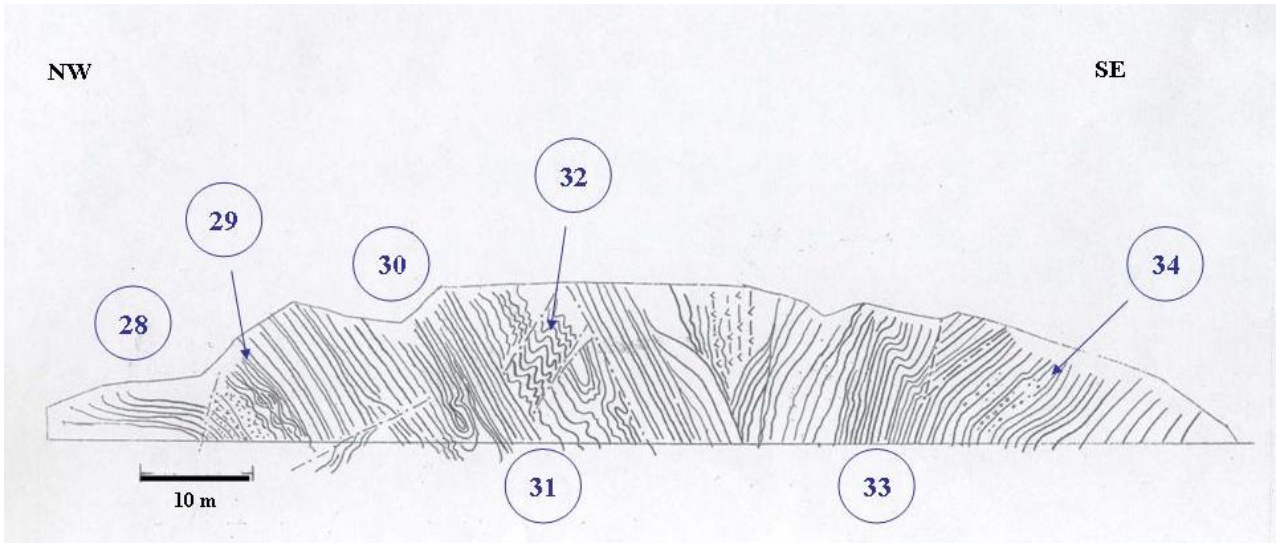


Fig. 26. The measured section of the “flower structure” on Hòn Mâú. The blue numbers in circles refer to the number of figure, in which photos illustrates the detailed observations in the cliff section.

The second locality investigated on Hòn Mâú, was the steeply bedded tuffites exposed in the cliff section on the south side of the island. Due to its geometry and a preliminary suggestion of its structural nature it was called the “flower structure” of Hòn Mâú. The cliff section is about 100 m long and consists of white, brownish weathering tuffites and redeposited acid volcanic ash layers. The measured section is shown in Fig. 25 and 26. In Fig. 26 all the location of detailed observations has been indicated with figure numbers. The main orientation of the beddings is shown in Fig. 27, where the constructed fold axis of the structure gives a plunge of 15° to the SW (224°).

Towards the west the bedding of the western part of the structure is bended over to be very gently dipping to the east (Fig. 28). East of these flat-lying structures the bedding raises into 50° SE dipping structures. The sedimentary rocks in this part of the section comprise redeposited hyaloclastic sandstones and volcanic ash, which due to the hummocky cros-stratification of the beds (Fig. 29) are interpreted as deposited in a shallow marine environment, where they have been affected by redeposition during storm events.

Above the hummocky stratified beds thin-bedded tuffites occur, which are irregularly folded into recumbent, isoclinal folds (Fig. 30). The fold axis is horizontal with a direction towards 30°. The axial plane of the recumbent fold has subsequent been reorientated into a 60° SE dipping position parallel to the orientation of the main bedding in this part of the section. The fold structure is interpreted as a foot-wall syncline, which has been dragged along the overlain thrust plane (Fig. 31).

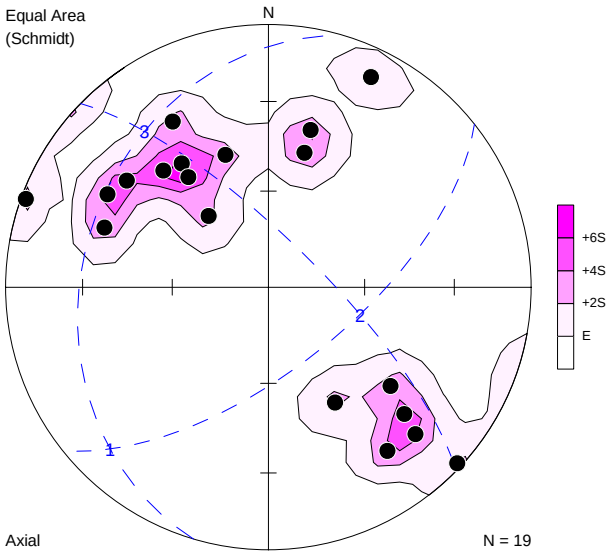


Fig. 27. Stereogram showing the bedding orientation in the “flower structure” on Hòn Mâú, main fold axis is orientated 224°/15°.

Fig. 28. In the northwest side of the “flower structure” on Hòn Mâú the bedding is bended over and dip gently to the east.

Fig. 29. Hummocky cross-stratification in the redeposited tuffite sediments in the “flower structure” on Hòn Mâú. The sedimentary structures indicate that the volcanic tuffs were deposited in a wave dominated shallow marine environment.

Fig. 30. Isoclinal fold developed below a thin thrust-fault plane in the thin bedded tuffites.

Fig. 31. Thrust-fault structure appearing in the north-western part of the “flower structure” on Hòn Mâú. Note the isoclinal fold in the foot-wall block just below the person with the white hat and the box folds, and the westerly turned anticlines in the hanging-wall block to the right (above the thrust fault).

Fig. 32. Upright westerly verging folds developed in thin bedded white tuffite, western part of the “flower structure” on Hòn Mâú. The fold structures are interpreted as parasitic folds on the western limb of a huge hanging-wall anticline.

Fig. 33. Thin to medium bedded white tuffites are steeply dipping to the northwest in the eastern part of the “flower structure” on Hòn Mâú. This structure is interpreted as the foreland-dipping limb of a huge hanging-wall anticline with its core located to the right.

Fig. 34. Zeolite granules deposited in the succession of tuffite in the eastern part of the “flower structure” on Hòn Mâú.

In the central part of the cliff section the bedding is very steep, up to 70°, and here a large number of parallel, upright folds appear with vertical axial planes and slightly overturned to the west (Fig. 32). Obviously the style of folding is controlled by the uniformly bedded tuffites, and dynamically the folding is related to the compression along the thrust fault. The displacement for the hanging-wall block is up to the left (sinistral).

Where the beds diverge in the central core of the “flower structure” layers of hyaloclastic breccias occur. These layers overlay a c. 25 m thick succession of greyish and brown weathering white tuffites (Fig. 33). In the lower part of this succession remarkable layers of zeolitic granules, 1 cm in size, occur (Fig. 34). The interpretation of these layers is that they represent redeposited hyaloclastic breccias, which probably primarily were deposited on land, where a tropical weathering altered the volcanic glass into zeolite.

Interpretation of the “flower structure” on Hòn Mâú

The final interpretation of the “flower structure” on Hòn Mâú is that the sedimentary rocks represent a volcanogenic deposition starting with an extensive ash eruption, probably during a main uplift of the area during which the deposition took place on land. During the volcanic development hyaloclastic breccias also reached the area, which finally subsided and was transgressed by the sea. The subsidence could easily be contemporaneous with the cauldron subsidence described previously. The timing of the volcanic event is around Early Cretaceous.

The “flower structure” is interpreted as a hanging-wall anticline thrust up over a foot-wall ramp onto the back of a foreland located thrust sheet. During thrusting the foot-wall syncline was drag-folded into a tight structure, and along the hanging-wall ramp parasitic folds were formed in the drag of the foreland-near limb. The stratigraphical succession in the hanging-wall anticline is regarded to represents the oldest deposition and the beds in the foot-wall block as the youngest deposits (Fig. 35).

The thrusting is regarded to be part of the general thrust fault tectonics in the Phu Quoc Basin. New age determinations on the exhumation in the basin indicate a Paleogene age (Palaeocene–Early Eocene, c. 62–52 Ma).

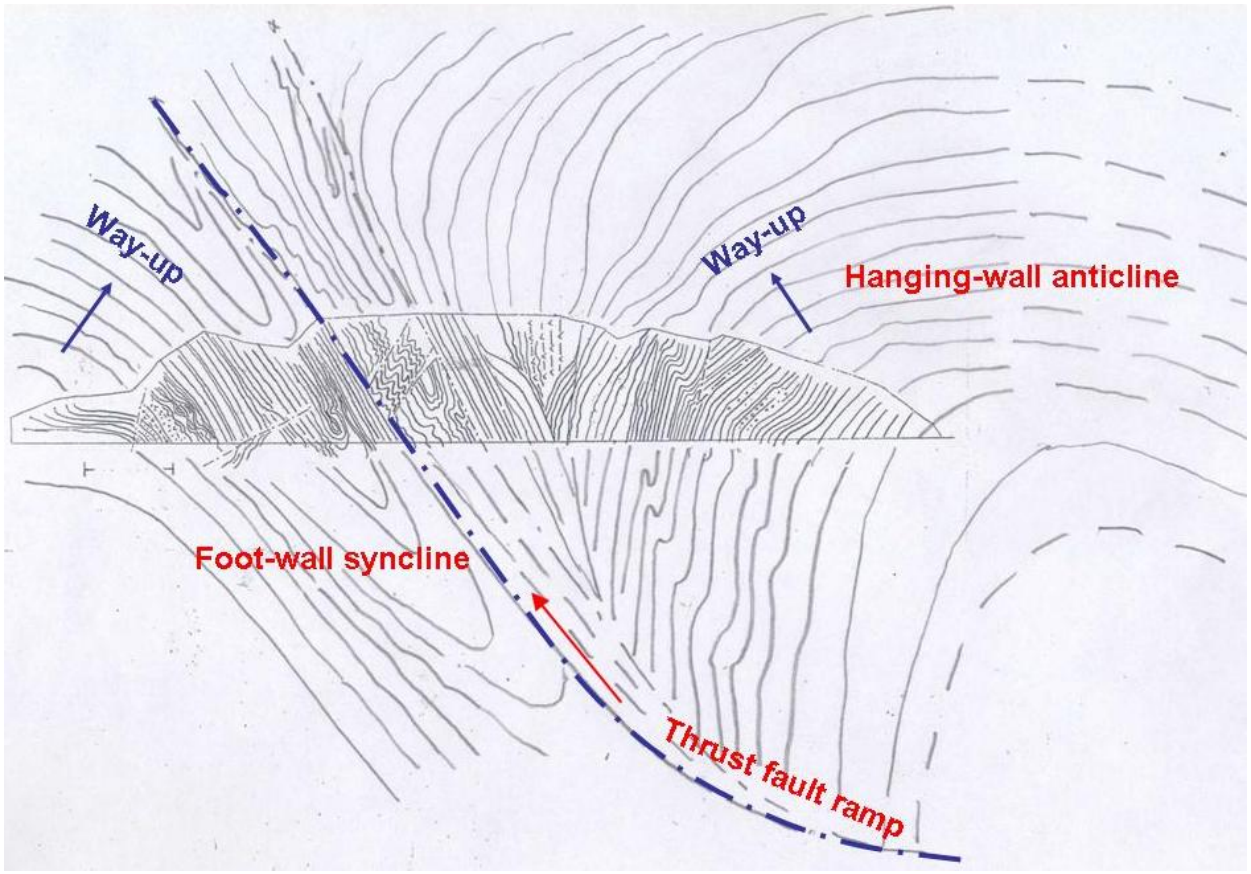


Fig. 35. The “flower structures” on Hòn Mâú is interpreted as a thrust-fault zone with a hanging-wall anticline situated above the thrust to the east and a foot-wall syncline isoclinally drag folded along the thrust in the western block. The hanging-wall anticline has a steep and overturned westerly limb, which was intensively folded during the displacement along the thrust-fault ramp.

Hòn Nghe Site 7 (loc.10–11), the Hòn Nghe granite and breccias

The trip from Nam Du to Hòn Nghe on the 25th of January 2008 was very exhausting and time consuming due to the harsh weather with a strong wind blowing against us from the NNW. Half of the expedition members got seasick, while others were hardened by the sun and salty swash of the sea waves. We managed to get on land on Hòn Nghe late in the afternoon and visit a few outcrops, including the Hòn Nghe granites, a grey coloured, medium grained, granodioritic granite, which form an important part of the southern part of the island. A number of granitic blocks derived from the mountain in the inner part of the island are randomly scattered along the coast (Fig. 36).

On the SW coast of the island an outcrop of conglomerates with angular clasts of gneisses in a sand grained matrix was observed. Dextral sense of displacement was observed on in a fault splay zone with a vertically orientation trending 66°.

Due to the late time of the day we didn't succeeded in getting more observations this day, but had to return the next day for visiting the remaining localities on the Hòn Nghe island.

Fig. 36. The lithology of the dominant granite occurring on Hòn Nghe.

Hòn Nghe Site 8 (loc.12), Permian carbonates at the Buddha Pagoda

The northern tip of the Hòn Nghe island constitutes an impressive white limestone of Permian age. The carbonate rock is strongly compacted and may be classified as a marble. The cliff is an obvious place for a focused attention, and naturally a Buddha Pagoda has been founded here (Fig. 37).

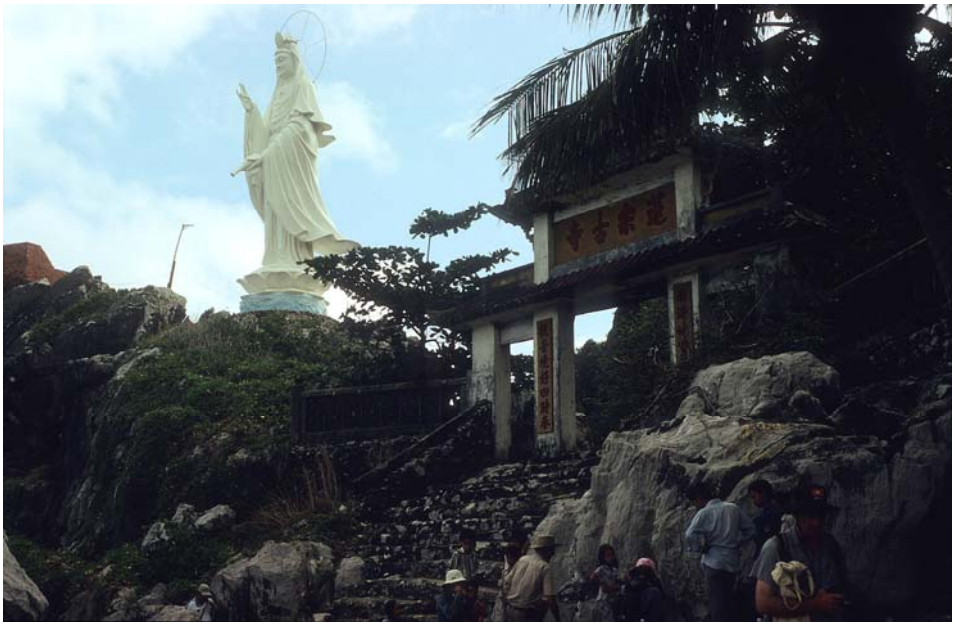


Fig. 37. The entrance to the Buddha Pagoda passes over the western slope of the Permian limestone cliff on the northern tip of Hòn Nghe.

Fig. 38. From the inner yard of the Buddha Pagoda there is an entrance to the temple hidden in the cavities of the Permian marble.

Hòn Nghe Site 9 (loc.13) NW trending fault south of Permian limestone

From the pagoda there are steps down to the coast on the east site of the island. Here the bedding was observed to be steeply dipping (60–70°) and the strike trending N–S (Fig. 39). The white grey, partly dolomitized Permian carbonate was observed to be intersected by a number of ankerite containing veins.

Fig. 39. Vertically bedded Permian limestone on the north-east coast of Hòn Nghe. The view is to the south from the pagoda.

Hòn Nghe Site 10 (loc.14–17) east coast of Hòn Nghe

The carbonate rock was further observed behind the huts at the foot of the cliff on the north-eastern part of the Hòn Nghe island. However, the exposures on this part of the island are sparse and only a few observations from exposures along the coasts beach zone added to our knowledge of the structures in the basin.

The rock types observed range from kaolinised agglomeratic breccias and rhyolitic hyaloclastics with 2 mm big phenocrysts of bipyrimidal quartz, to sequences of 25 m thick successions with fining up layers of conglomerates and sandstones interlayered by rhyoloitic sills one to a few meters in thickness.

Hòn Nghe Site 11 (loc.18) fold structures NW-coast of Hòn Nghe

On the NW coast on Hòn Nghe exceptional outcrops of Mesozoic dark coloured sandstones and mudstones occur in the gravely beach plane. A 300 m long section was here measured from the NE to the SW, which documented intensively folding and thrust faulting. Moreover the contact to apophyses from the granitic intrusion was recognised as well as the hornfels contact-metamorphic alteration at the boundary of the granite (Fig. 40).

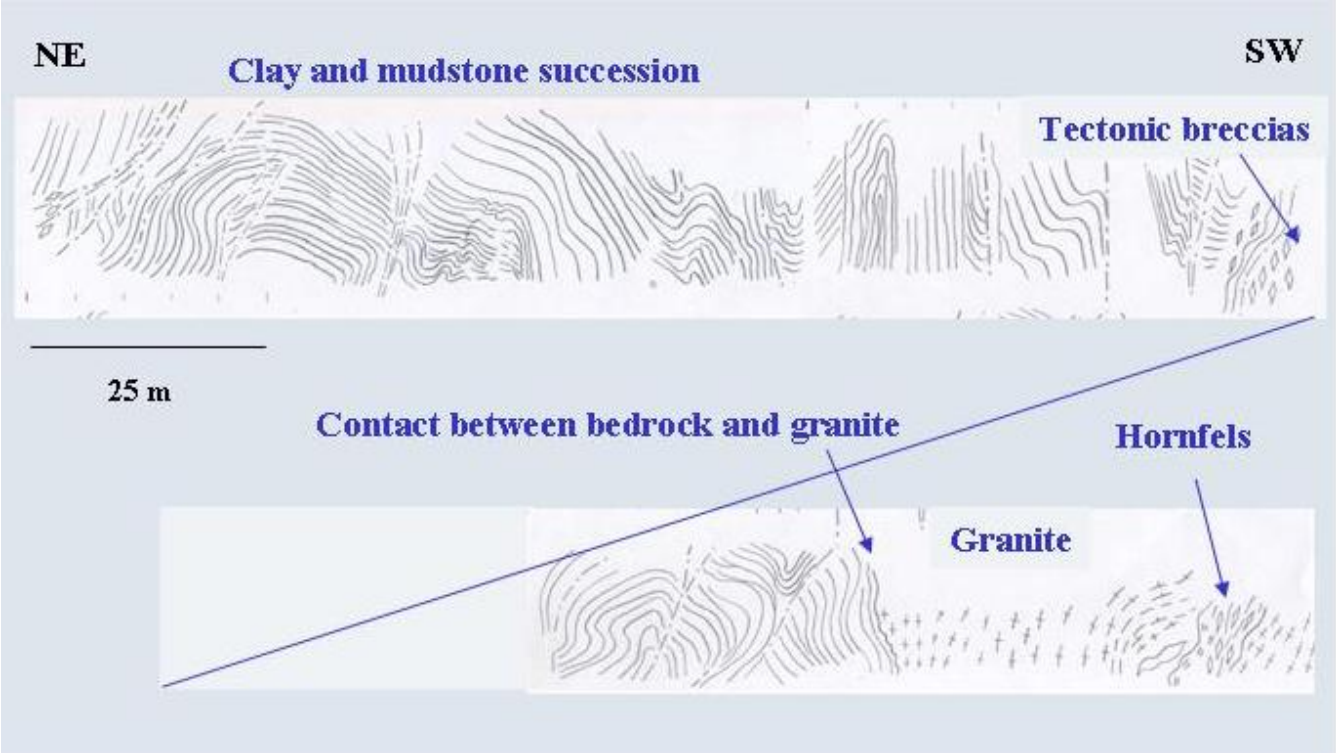


Fig. 40. Measured section of the outcrops along the gravelly beach plane on the NW coast on Hòn Nghe. The section demonstrates the intensive and irregular folding probably related to deformation related to the intrusion of the granite superimposed by the thrust fault orogenic deformation.

Fig. 41. The outcrop along the gravelly beach plane on the NW coast on Hòn Nghe Site 11.

Fig. 42. The dark brownish shale outcropping along the gravelly beach plane on the NW coast on Hòn Nghe Site 11 is a sedimentary rock characterised as a mudstone, which has been affected by weakly metamorphic alteration. Note the internal slip planes that formed during the tectonic deformation.

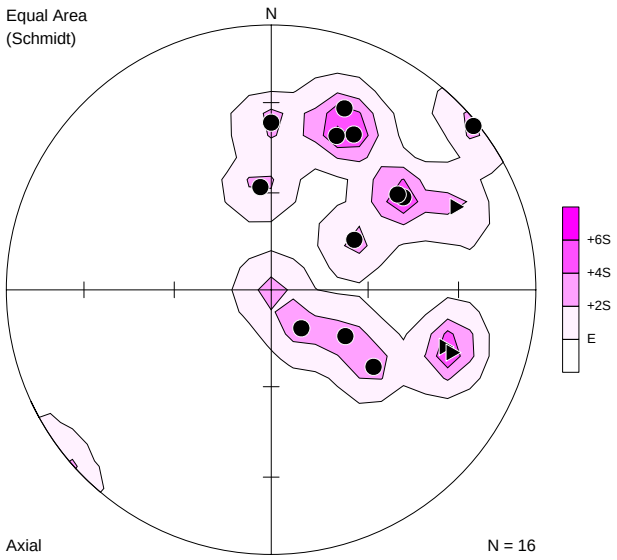


Fig. 43. Stereogram plot of the bedding orientation of the sedimentary rocks on the beach locality on the NW coast on Hòn Nghe. Dots represent normals to bedding and small triangles represent normals to thrust fault planes.

Fig. 44. The folded shaley mudstone outcropping along the gravelly beach plane on the NW coast on Hòn Nghe Site 11. The white arrow points in the direction of the fold axis plunging moderately to the SE (compare with Fig. 45).

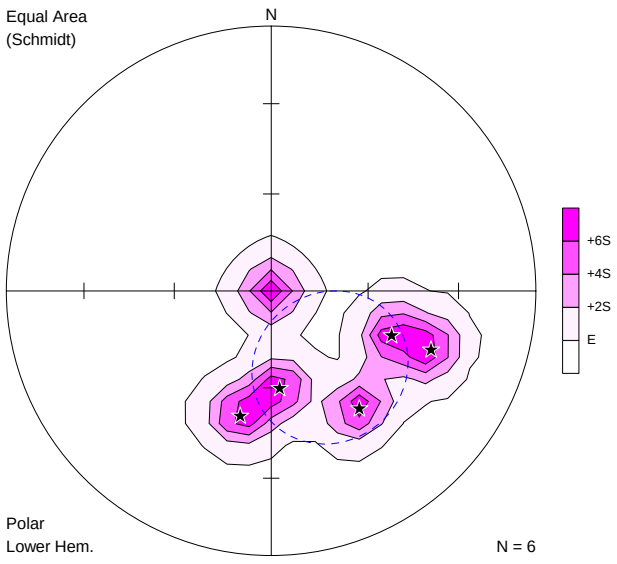


Fig. 45. Stereogram plot of the fold axes orientations show that the folds are steeply to moderately plunging towards the S and SE on the beach locality on the NW coast on Hòn Nghe. The spreading in fold axes orientations indicate an early deformation directed from the NE superimposed by an orogenic deformation from the SE.

On the outcrop of Site 11, NW coast on Hòn Nghe (Fig. 41), the folded beddings of dark coloured sandstones and mudstones can easily be traced and the sedimentary structures can be studied (Fig. 42). Due to the steeply dipping orientation of the bedding (see Fig. 43) the measured section along the beach plane may be regarded as a cross-section (Fig. 40). The fold style is very complicated and the plunge of the fold axes (Fig. 44 and 45) clearly indicates that the structure represent a superimposed deformation.

In the south-westerly end of the cross-section (Fig. 40) the mudstone succession has been intruded by a granite body. The granite intrusion is probably an irregular sill extending out from the central granite batholite on the island, which has given a U/Pb-dating of 95 Ma. Along the contact of the granite the sediments are altered into a hornfels in a zone extending about one to a few meters away from the contact (Fig. 46). During this magmatic event the sediments overlying the intrusion became folded and displaced by faulting. This event probably occurred in the late Cretaceous.

Preceding the magmatic event the orogenic event deformed the rocks on Hòn Nghe. On the west coast of the island the deformation during the magmatic event is interpreted to be a compression from the east. Thus the fold axes original had a southerly orientation (Fig. 45). During the orogenic event in the Eocene time sedimentary rocks were refolded from a south-easterly direction, which resulted in the steep plunges of the fold axes.

Fig. 46. The contact between the granite and the sedimentary rock at the locality on the NW coast on Hòn Nghe Site 11. The child is sitting on the granite to the left of the contact, whereas the light coloured rock to the right is the contact-metamorphic hornfels.

Stone pit N of Hòn Chong Site 12 (loc.19), mylonitic meta-sediments

The last part of the expedition focused on localities on the Hòn Chõng peninsula. The first locality in this area was the stone pit in the northern part of Hòn Chõng, where Upper Palaeozoic metasediments and melanges of granites are exposed (Fig. 47). The sedimentary rocks includes sandstones, chlorite slates with sulphides and graphitic slates.

The rock units are intensively deformed by folding and thrusting. The direction of the mainly horizontal fold axis is 140°, and the orientation of thrust planes is 150°/35° NE indicating a thrust direction from the ENE. In the thrust zones the rocks were altered into mylonitic kataclastites (Fig. 48) with a green schist metamorphic grade, which may imply that the rocks were displaced from a depth of about 10 km below present surface.

Fig. 47. The stone pit Site 12 in the northern part of Hòn Chõng. The thrust fault deformation was directed from the northeast towards the southwest. The sandstones are probably of Devonian age, whereas the graphite containing chlorite schist is Carboniferous.

Fig. 48. The green-schist facies mylonitic chlorite schist occurring in the stone pit Site 12 in the northern part of Hòn Chõng. The highly shear deformed chlorite schist is probably a meta-sedimentary rock of Carboniferous age, which was thrust-fault deformed during the orogenic event in the Eocene.

Nui Cop Formation and Hòn Heo point Site 13 (loc. 20 and 21)

In the Hòn Chõng area two more localities were investigated. The first of these was the Nui Crop Formation, the “tiger sandstone”, which is a yellowish coloured medium bedded quartcitic meta-sandstone of Late Palaeozoic age. The formation is steeply dipping at the outcrop along the main road due to the general orogenic deformation. Moreover extensionnal faults were observed which indicated extensional movements during the basin formationn in the Mesozoic.

The other locality was the north coast of the point Hòn Heo, where upper Palaeozoic (or Mesozoic) conglomerates, sandstones and especially arkoses are outcropping. The large amount of arkoses may be paid some attention. These sedimentary rocks indicate a short transport way and a granitic source. They might therefore be related to an early granitic magmatic event affecting the Phu Quoc Basin. The sedimentary rocks are regarded to be of Upper Palaeozoic age, wherefore the magmatic source rocks must be of Devonian age or even older.

Hòn Sóc and Hòn Dat Site 14 (loc.22 and 23), U.Cretaceous granite

The last two localities visited during the expedition were the granitic plutonic plugs popping up over the delta plane in the north-westernmost part of the Mekong Delta (Fig. 49). The first of these was the Hòn Sóc granite in which active quarrying is taking place (Fig. 50).

The Hòn Sóc granite is medium grained, light grey coloured with a few dark coloured aplites scatterly distributed in the granite (Fig. 50). In the Hòn Sóc quarry an easterly dipping thrust fault displaces the granite. The thrust plane has a strike of 150° and it dips 50° NE. This thrust is probably contemporaneous with the Eocene exhumation of the granite, whereas the granite itself was intruded in the Cretaceous.

The last visit was dedicated the mounting of the Hòn Dat granite plug a few kilometres away from the Hòn Sóc quarry. This granite is a little more dark grey coloured with a composition in the field of granodiorite. The dark colour is mainly caused by the high content of hornblende, which here an there forms medium grained radial aggregates. The granite is dated to be about 154 Ma.

Fig. 49. The Hòn Sóc granite plug pops up over the flat delta plain in the western fringe of the Mekong Delta. The view is seen from the neighbouring plutonic plug Hòn Dat.

Fig. 50. The Hòn Sóc granite quarry. In the photo above, the thrust displacing the granite has the strike 150° and it dips 50° NE. This thrust is probably contemporaneous with the Eocene exhumation of the granite, whereas the granite it self was intruded in the Cretaceous.

The photo to the left illustrates the main medium grained texture of the light grey coloured granite. A few dark coloured aplites are scattered distributed in the granite like the one in the left side of the picture.

Summary and conclusion

For the support of the earlier investigations in the Phu Qouc Basin carried out in the ENRECA project structural and sedimentological field investigations were carried out in three areas of the basin: 1) The archipelago at Nam Du, 2) The Hòn Nghe island and 3) The Hòn Chõng–Hòn Dát area. The three areas represent three different tectonic positions within the Phu Quoc Basin, namely the central part of the thrust-Fault deformational belt, the transition from magmatic belt into magmatic belt, and finally the magmatic belt including up thrust units of metamorphic meta-sedimentary successions.

In the central deformation belt extrusive volcanic rocks dominates the stratigraphy. This is documented with rhyolites and andesitic successions at Nam Du, where the central part of the island constitutes brecciated volcanic and clastic sediments. Furthermore andesitic and rhyolitic volcanics are exposed at the south coast of the island, and on the Hòn Mâú island and acid volcanic extrusion centre was recognised, which yielded evidences of cauldron subsidence.

The transitional belt is represented by the outcrops on Hòn Nghe, where marine sediments of Triassic–Jurassic age are intruded by granitic sills spreading out from the granitic plug in the central part of the island. Older parts of the basin are also represented by the Permian carbonates outcropping at the Buddha Pagoda on the northern tip of the island.

The magmatic belt is represented by the granitic plugs Hòn Sóc and Hòn Dat. In addition the islands of Hòn Rai and Hòn Tre are regarded also to represent plugs in this belt. However, time limits did not provide possibilities of making research on these islands.

The field investigations are followed up by laboratory analyses, which in combination with interpretation of the seismic cross-sections of the basin, have provided clues to the understanding of the geological setting of the Phu Quoc Basin.

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Appendix 1: List of specimens

Table 1

Sample	Lat. (N)	Long. (E)	Rock type	U/Pb age (Ma)	AFT age (Ma)	Strat. age	Comments
453001			Sandstone		51.3 +/-3.6	Aptian	Well-core sample (496.46-496.73 m)
453009	09°40'33	104°23'58	Meta-sandstone		62.7 +/-5.9	Palaeozoic	
453011	09°40'28	104°21'37	Tufite				
453014	09°41'15	104°20'59	Tufite				
453015	09°38'12	104°23'38	Rhyolite				
453017	10°01'20	104°32'50	Granosyenite	94.9 +/-0.5	58.8 +/-3.8		Few inherited Triassic zircons
453023	10°02'09	104°32'53	Sandstone		89.6 +/-12.6	Triassic	Recording adjacent plutonism
453027	10°02'04	104°32'49	Granosyenite	95.4 +/-0.6	59.1 +/-7.9		Few inherited Paleozoic and Proterozoic zircons
453028	10°09'05	104°54'12	Granosyenite		52.8 +/-3.3		
453030	10°06'16	104°53'50	Granodiorite	154	53.4 +/-2.7		Vietnamese single grain K/Ar age*

Table 1. List of specimens collected for radiometric dating (U/Pb age) and fission track analysis (AFT).

Appendix 2: List of location coordinates

Table of coordinates for localities, UTM zone 48 P

Locality	X-coordinate	Y-coordinate	Elevation m a.s.l.	Comments
Central part of Nam Du				
1	04 29 359	107 12 09	64	Cross-section
2	04 28 750	107 13 40	10	Outcrop NW village
3a	04 28 545	107 08 46	4	Cliff SW village
3b	04 28 336	107 07 45	2	Coastal cliff
6	04 28 755	106 82 60	1-25	Coastal cliff SSW
7–8	04 28 890	106 82 99	1–10	Coastal cliff SSW
9	04 29 861	106 78 24	1–5	Coastal cliff SSW
Coastal cliff sections Hon Mau				
4a	04 33 524	106 52 46	1–5	Coastal cliff S
4b	04 33 523	106 53 07	1–5	Coastal cliff S
5	04 33 688	106 50 39	1–5	Coastal cliff SW
Localities on Hon Nghe				
10	04 50 395	110 79 01	6	Granite boulder
11	04 50724	110 72 39	3	Coastal outcrop
12	04 51 080	110 95 82	5–10	Entrance Pagoda
13	04 51 153	110 94 04	16	Perm. carb. breccia
14	04 51 404	110 91 55	25	Shear zone
15	04 51573	110 90 42	2	Coastal outcrop
16	04 51 910	110 83 30	1	Coastal outcrop
17	04 51 946	110 80 49	2	Coastal outcrop
18	04 50 800	110 80 00	2	Beach cross-section
Localities on Hon Chong and Hon Dat				
19	04 49 376	113 88 55	24	Stone quarry
20	04 48 360	114 07 52	17	Road outcrop
21	04 48 631	113 61 77	2	Hon Heo point
22	04 89 440	112 21 65	25	Hon Soc granite quarry
23	04 88 756	111 69 87	24	Hon Dat granite

Table 2. Number of localities investigated during the structural field trip January 2008 with their UTM coordinates, all in reference frame zone 48 P.