

Tectonic Activities and Evolution of the Red River Delta (North Viet Nam) in the Holocene¹

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Abstract—The Red River delta with an area of about 12620 km² is one of the largest deltas of Viet Nam and it also is one of the remarkable deltas of Asia. The delta was formed during the Holocene, mainly from 9000 years ago to the present. The Red River delta belongs to the NW tip of the large tertiary basin that is the Red River basin (Song Hong basin). The NW tip of the Red River basin presents as Ha Noi graben, which is controlled by the Chay River fault in the SW and the Lo River fault in the NW. Both faults are belonging to the regional Red River fault zone that is a boundary between the South China block and the Indochina blocks. The Red River delta was formed on the top of tectonic active area. Due to tectonic activity the Red River bed is differentiated and revealed as in-uniform distribution of the Quaternary sediments. Evolution of the Red River delta has been closely connected with the Pliocene–Quaternary tectonics, specifically during transgression period after the last glacial maximum. The submarine area advanced along the NE and SW subsidence zones of the Red River delta area and created two remarkable lagoons, meanwhile the central part it had resisted transgression process and created a protrusive zone. Our study recognized that there were at least two tectonic movements occurred in the region since the Late Miocene, after a cessation of left-lateral strike slip of the Red River fault zone: those are NE–SW compression and then NE–SW extension under the general right-lateral strike slip of the Red River Fault Zone.

Keywords: tectonic evolution, North Viet Nam, Red River delta, Red River Basin, Red River Fault zone, Ha Noi Graben

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INTRODUCTION

The Red River delta (RRD) is located on the west coast of the Tonkin Gulf (Gulf of Bac Bo) and was formed as a result of the Red River sediment discharge into the its estuary. Morphologically the RRD has an isosceles triangle shape, with an apex at Viet Tri City (location: $X = 105^{\circ}24'36''$ and $Y = 21^{\circ}18'36''$). A base of the triangle spreads along shoreline from the Quang Yen town to the Day river mouth, with distance of about 146 km. The north side of the triangle is oriented west–east, while the west side is oriented almost north to south. The both sides have the same length of about 165 km. The height of the triangle is about 152 km, from Viet Tri City to the coastline. In general the RRD was formed at a specific place (Fig. 1).

The Red River Delta was formed in the NW end of the Tonkin gulf and at a mountainous valley of North Viet Nam. This situation stimulates rapid progradat-

tion of the delta towards the sea. As a result the RRD composes of three main sectors:

(1) The upstream fluvial-dominated sector locates at the upper NW part of the RRD and occupied an area along the main channel of the Red River, coming down to the area near the river mouth. It consists of meandering rivers, meander belts, floodplain, and fluvial terraces;

(2) The NE tide-dominated sector comprises tidal flats, marshes, and tidal creeks and channels. The tidal flat occurred at the elevation of about 3–5 m above the present sea level;

(3) The SW wave-dominated sector is characterized by sandy spits and alternating beach ridges and back marshes or swamps [6] (Fig. 2).

The relief of the RRD is quite wavy and comprises of three units:

(1) The upper-delta domains, relatively high and slightly eroded paleo-terraces at the north side with elevation of about 10–15 m above sea level (asl);

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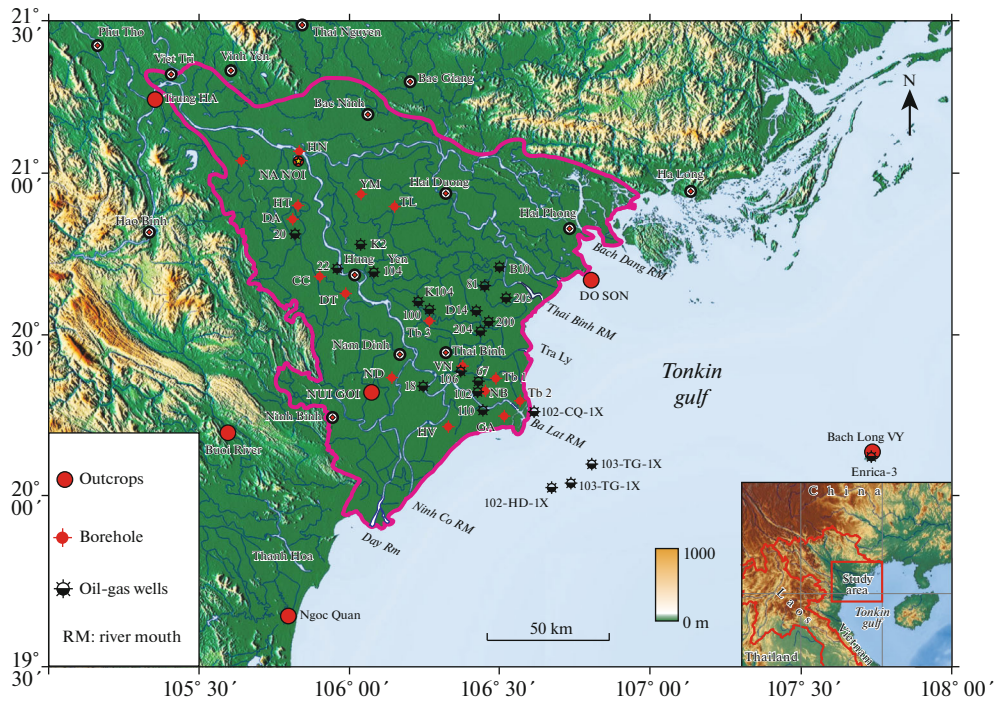


Fig. 1. The Red River Delta in the North Viet Nam and locations of the study outcrops.

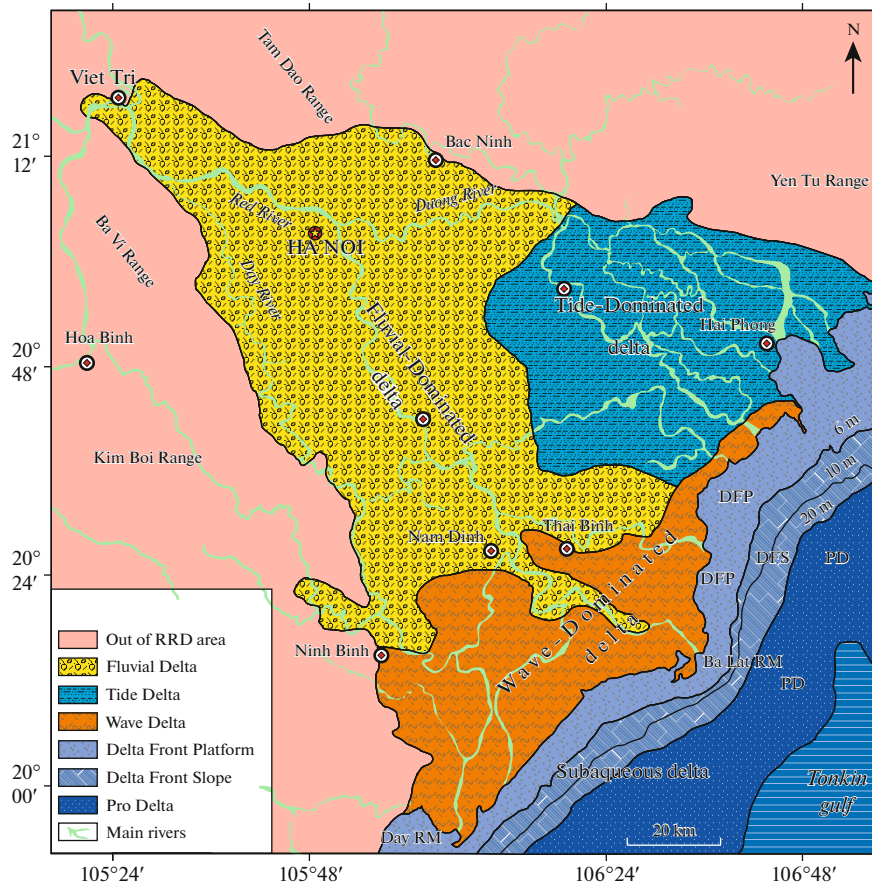


Fig. 2. The RRD zoning according to the origins of its formation (after [6, 15, 16], modified). DFP means Delta Front Platform; DFS, Delta Front Slope; PD, Pro-Delta (progradational delta).

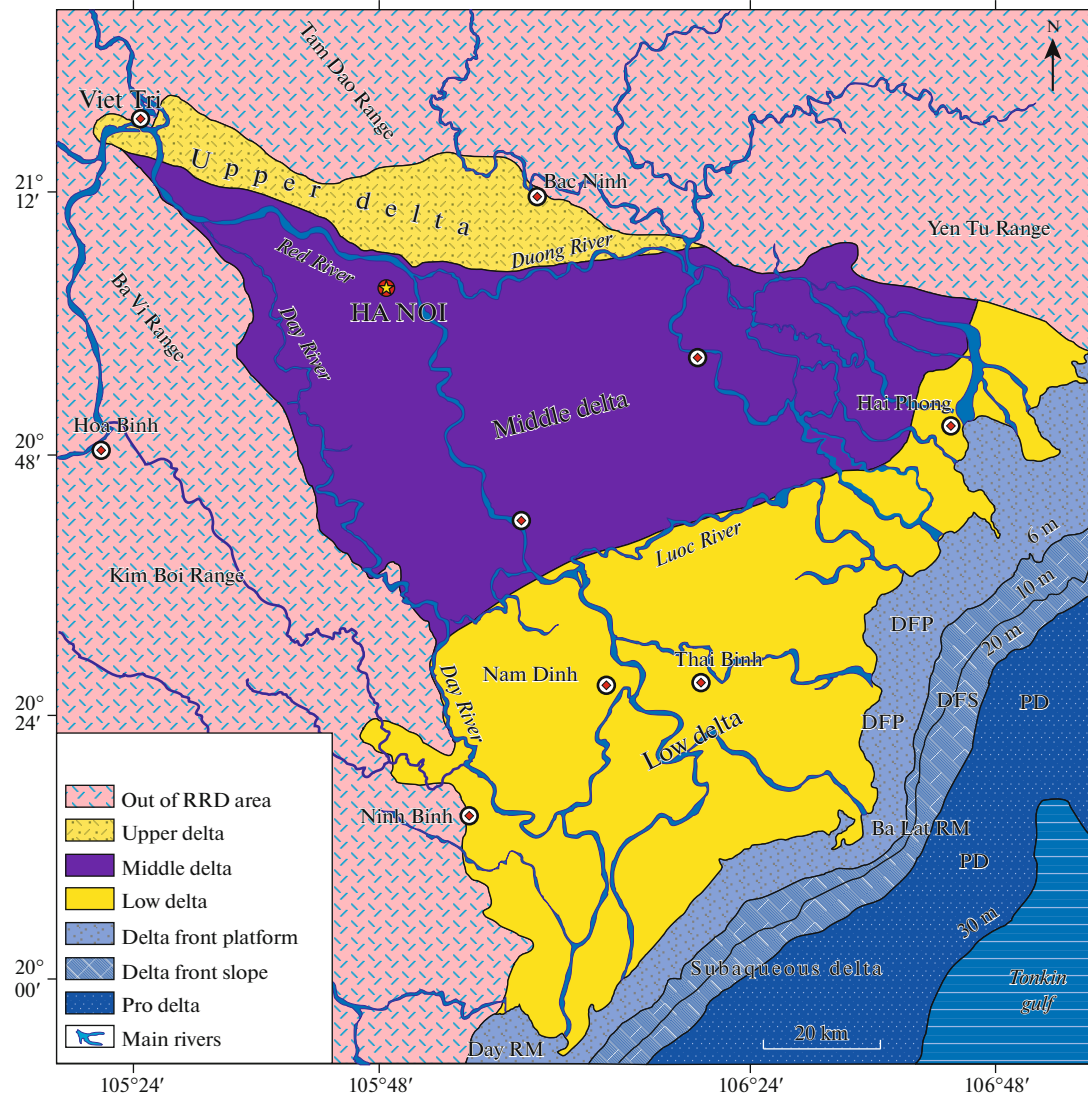


Fig. 3. Topological zoning of the Red River Delta (after [9], modified).

(2) The middle-delta composes of modern river-flood plains composed of the sediment of the late Holocene deposits of the Thai Binh formation (mQ12 IVtb), which contain grayish brown clayey silt and small portion of fine to coarse sand and overlain on LGM surface of Vinh Phuc formation (mQIIIvp). The Middle-delta plain is gentle wave-shaped surface and lies about 5–6 m asl with good drainage condition.

(3) The low-delta surface spreads near-shore area of the RRD and comprises mainly of coastal flood plain or strand plain, saltwater marshes, sand bars. Elevation of the surface is about 1–2 m (Fig. 3). The sedimentation in the RRD during the Quaternary and especially after the Last Maximum Glacial (LMG) showed high differentiation from NW to SE [15, 16]. The map of Quaternary basement (Fig. 4) exposed two sediment depocenters of NW–SE direction with izoline 120 m, that suggest two main river-channels in the Qua-

ternary period in the RRD. A Similar picture appears in the map of the LMG deposition of the RRD (Fig. 5). On this map a remarkable uplift can be seen in the center of the RRD, which separates the RRD into NW and SW parts, with izoline –20 and –25 m.

Up to now the tectonic activity of the North Viet Nam since the RRFZ changed its movement sense from left-lateral into right-lateral is still debatable (since Middle-Late Miocene) [12, 13, 20]. Most of scientists believe that the right-lateral movement should control the tectonic characteristics of the whole North Viet Nam region. However, our study of the region shows more complicated geodynamics with resulting in forming specific geo-structures, heterogeneous tectonic structure, topography and seismotectonics [19]. The Ha Noi graben, which affects very much development of the Red River Delta, is one of these structures. The graben was affected by NE–SW

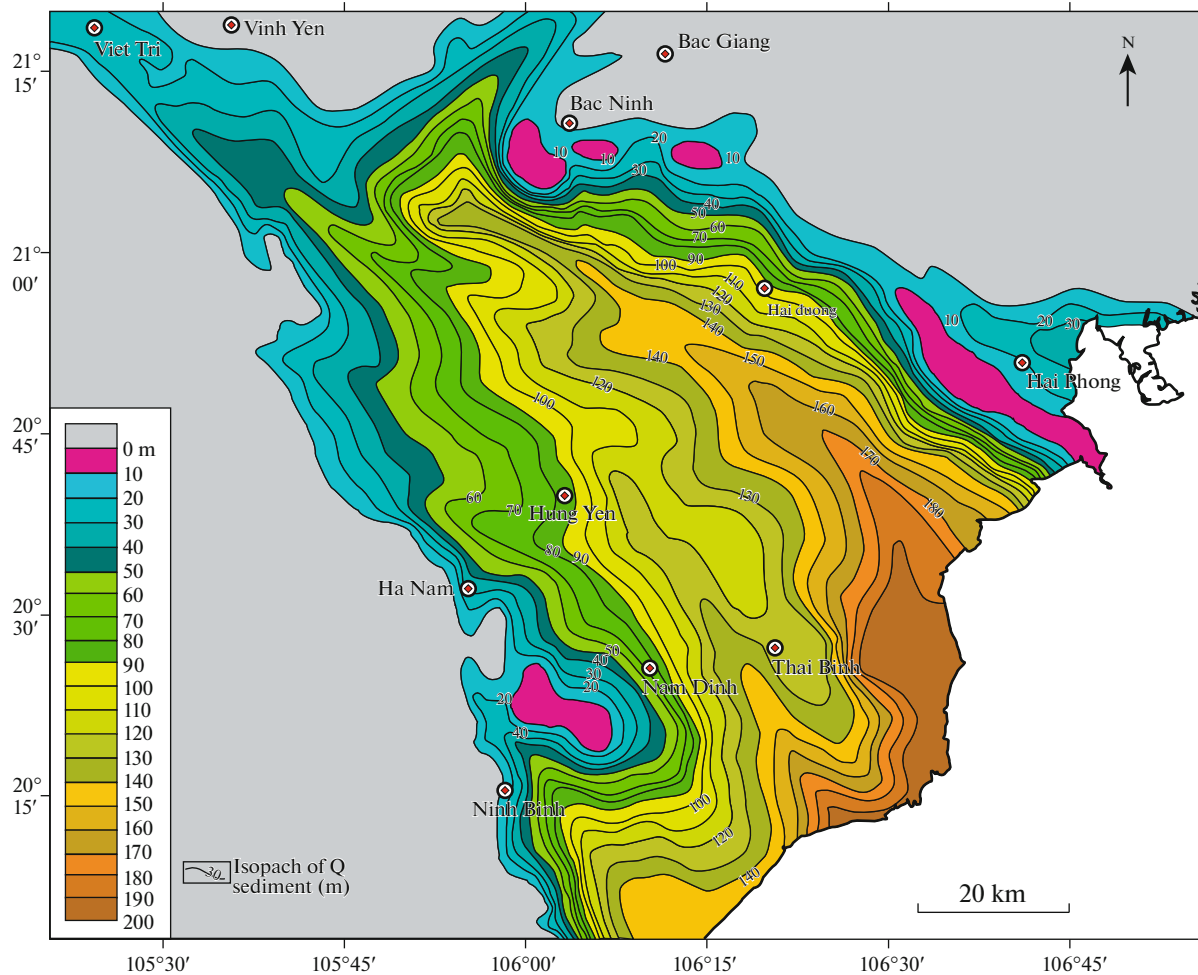


Fig. 4. Basement of the Quaternary sediments in the Red River Delta (after [9], modified).

compression and also NE–SW extension during Pliocene–Quaternary period. In this paper, we would like to make an attempt to clarify Pliocene–Quaternary tectonics and its role in development of the Red River delta.

GEOLOGICAL SETTING

The Red River delta was formed at the NW tip of Red River basin (RRB), which is bounded by the regional NW–SE striking tectonic faults, which consist of Red River fault (RRF), Chay River fault (CRF) and Lo River fault (LRF). Usually they are called as the Red River Fault Zone (RRFZ).

The RRTKB is one of the largest Cenozoic marginal basins in the South East Asia (~550 km long and ~150 km wide; total area ~150000 km²), composed of sediments from Eocene to Quaternary. According to the 3D image one can roughly count a volume of the Cenozoic body of the basin that must be about 420000–500000 km³. This huge quantity of sediments could take place thanks to much larger water catchment of the Red River in the past than it is today. The rate of

sedimentation of the RRB was very high compared with that of the Cenozoic basins offshore Yangtze River and Yellow River [2]. The rate of subsidence of the RRB has reached maximum value in Pliocene–Quaternary period. Among the total 14–15 km thickness of Cenozoic sediments (that has accumulated since Eocene or ~37 My BP) more than 4000 m represents a Pliocene–Quaternary. It means that the rate of the Pliocene–Quaternary accumulation is 2 times higher than average accumulation rate in the whole Cenozoic period. The Ha Noi graben, which is controlled by Lo River fault in the NE and Chay River fault in the SW is much smaller than the RRB with amount of the Cenozoic sediments is about 10000 km³ (Fig. 6).

The basement of the RRB is heterogenic (Fig. 7) [18]. In the center of the RRB, the main components are expected:

- (I.2) high metamorphic belt Day nui Con Voi;
- (1.1) Early Pz intraplate orogeny West Viet Bac;
- (1.2) Early Pz intraplate orogeny East Bac Bo. At the well number 104 (Phu Cu, Hung Yen) the base-

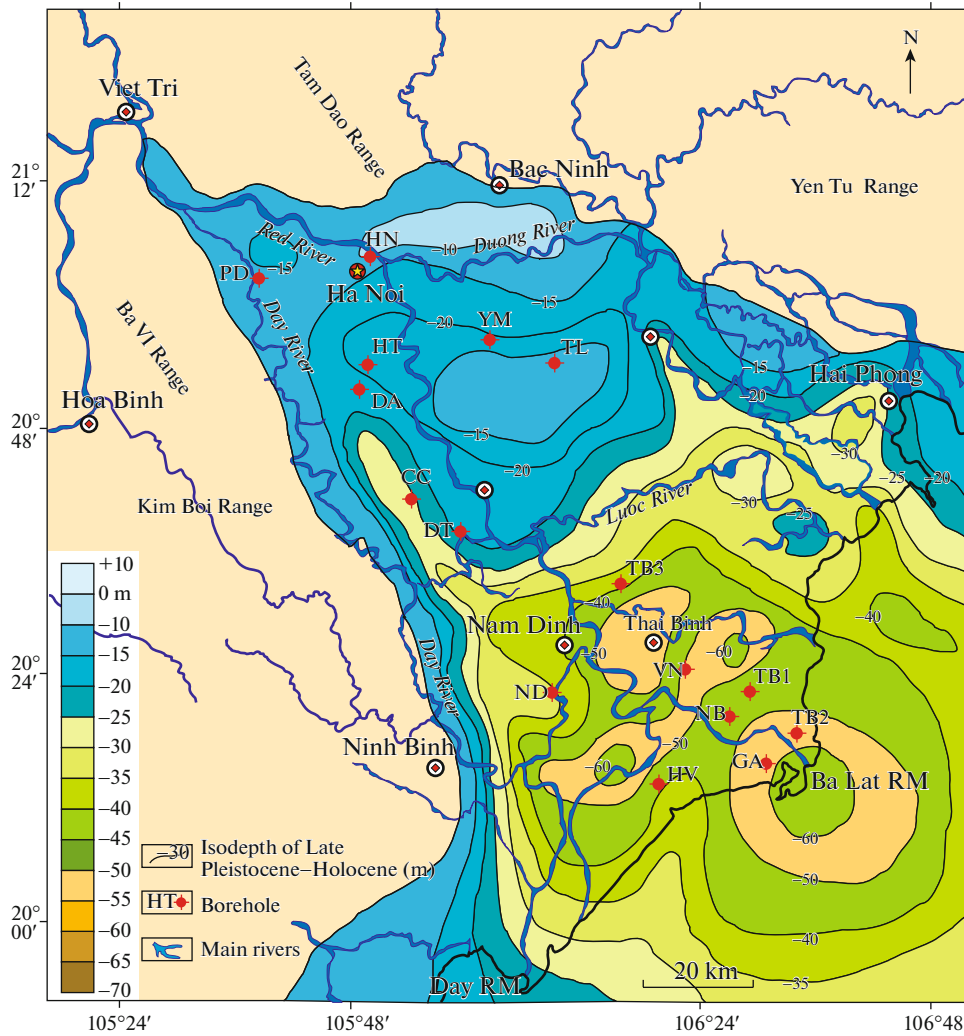


Fig. 5. Basement relief of the last maximum glacial sediment in the Red River Delta (after [9], modified).

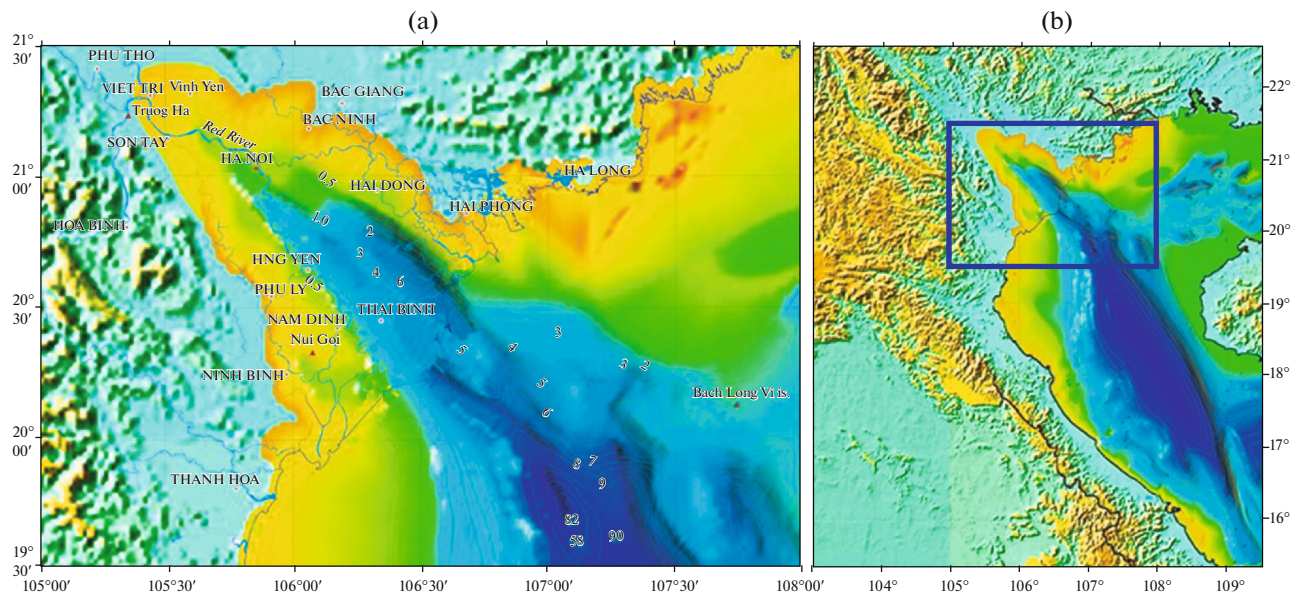


Fig. 6. The Ha Noi graben (a) in the relationship with the RRB (b). 3D image of the RRTKB according to Kz-isopachs (after [9], modified).

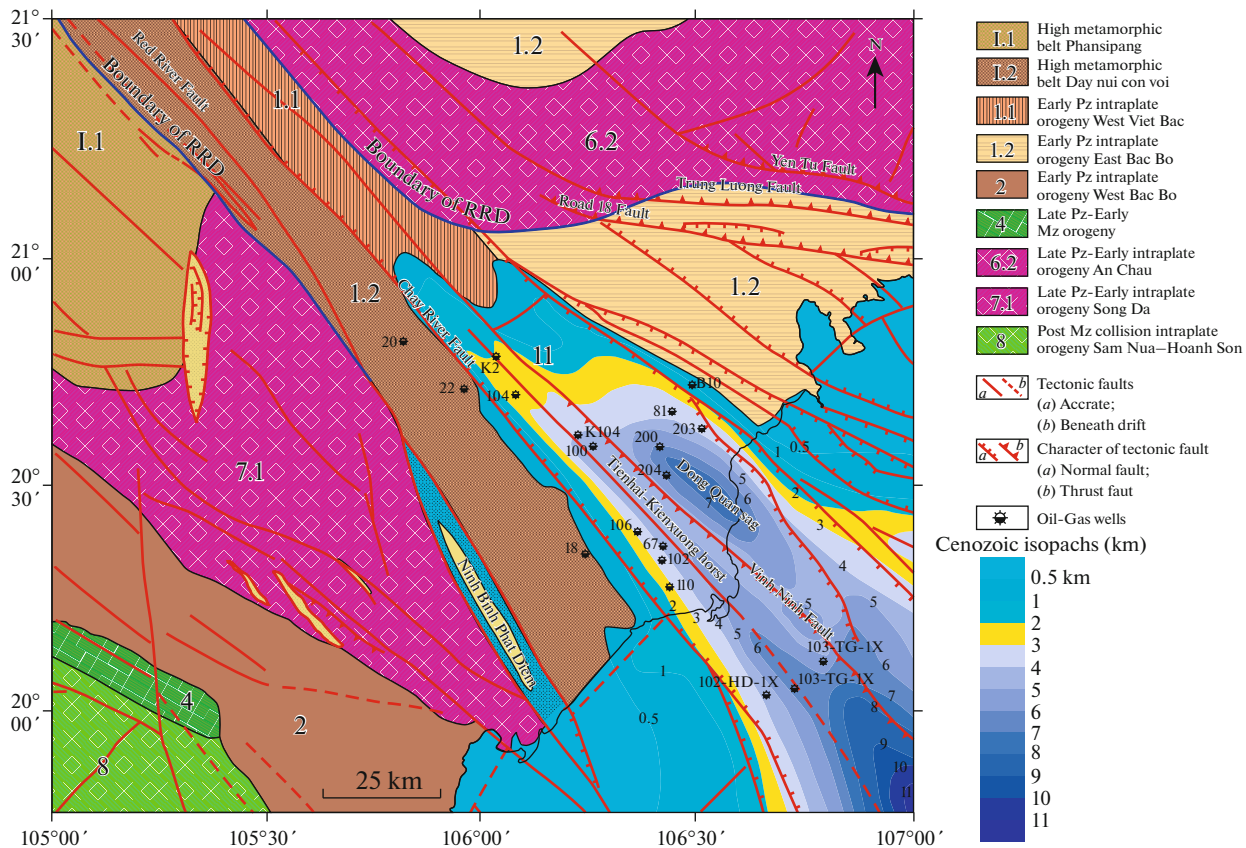


Fig. 7. Tectonic structural map of Red River Delta and adjacent area (after [9], modified). In the SW flank of the basin: (I.1) High metamorphic belt Phansipang and (I.2) high metamorphic belt Day nui Con Voi; (7.1) Late Pz-Early T intraplate orogeny Song Da; (2) Early Pz intraplate orogeny West Bac Bo; (4) Late Pz-Early Mz orogeny; (8) Post Mz collision intraplate orogeny Sam Nua-Hoanh Son. While in the NE flank the there are some terrains of South China block, such as (1.1) Early Pz intraplate orogeny West Viet Bac; (1.2) Early Pz intraplate orogeny East Bac Bo and (6.2) Late Paleozoi-Early Triassic intraplate orogeny An Chau.

ment depth reaches to 3941m, that composes of rhyolite (T_2).

In the area of Nam Dinh there is a hill Nui Goi (>300 m high) that composes of metamorphic rock of Day nui Con Voi belt. Some wells such as well 15 (Nam Dinh) and well 57 (Hai Hau) also reached the basement of metamorphic rock. The other wells at the NE flank of the RRB reached the basement of carbonate of Devonian or Carbon-Permian in age [5].

The RRFZ had experienced trans-extension and trans-compression during the Cenozoic Era (Fig. 8), which is confirmed also by [20]. These activities had influenced on the fault system in the Red River delta area: while remained as strike-slip the faults of the RRFZ were sometimes extensive, other times compressive. In the rifting stage the Chay River fault and the Lo River fault acted as principal bordering faults of the Hanoi graben and for whole the RRB, while in the compressive stage the normal faults inverted to thrust faults and a new thrust fault had appeared in the middle of the Hanoi graben (The Vinh Ninh Fault).

RESULTS AND DISCUSSION

Cenozoic Activities of the RRD and Adjacent Area

Tectonically the RRB was formed at the regional tectonic RRFZ, which represents a strike slip boundary between South China block in the NE and Indochina block in the SW since Triassic period [18]. The formation of the RRB was stimulated by a strong left-lateral strike slip of RRFZ resulted from the collision of Indian to Eurasian plates and, partly, by a 15° clockwise rotation of Indochina block since Eocene period. Due to India-Eurasia collision since Eocene the RRFZ became very active, with two distinct tectonic phases: the early left-lateral strike slip and the late right-lateral strike slip [17]. The RRFZ had shown trans-pressive and trans-extensional senses occasionally, or in the one end it showed trans-pressive while in the other end it showed trans-extensional at the same time (Fig. 9).

Timing of change from the first to the second phases is still debated. The onset of right-lateral motion along the RRFZ is poorly constrained. Some scientific workers believed that between the two phases

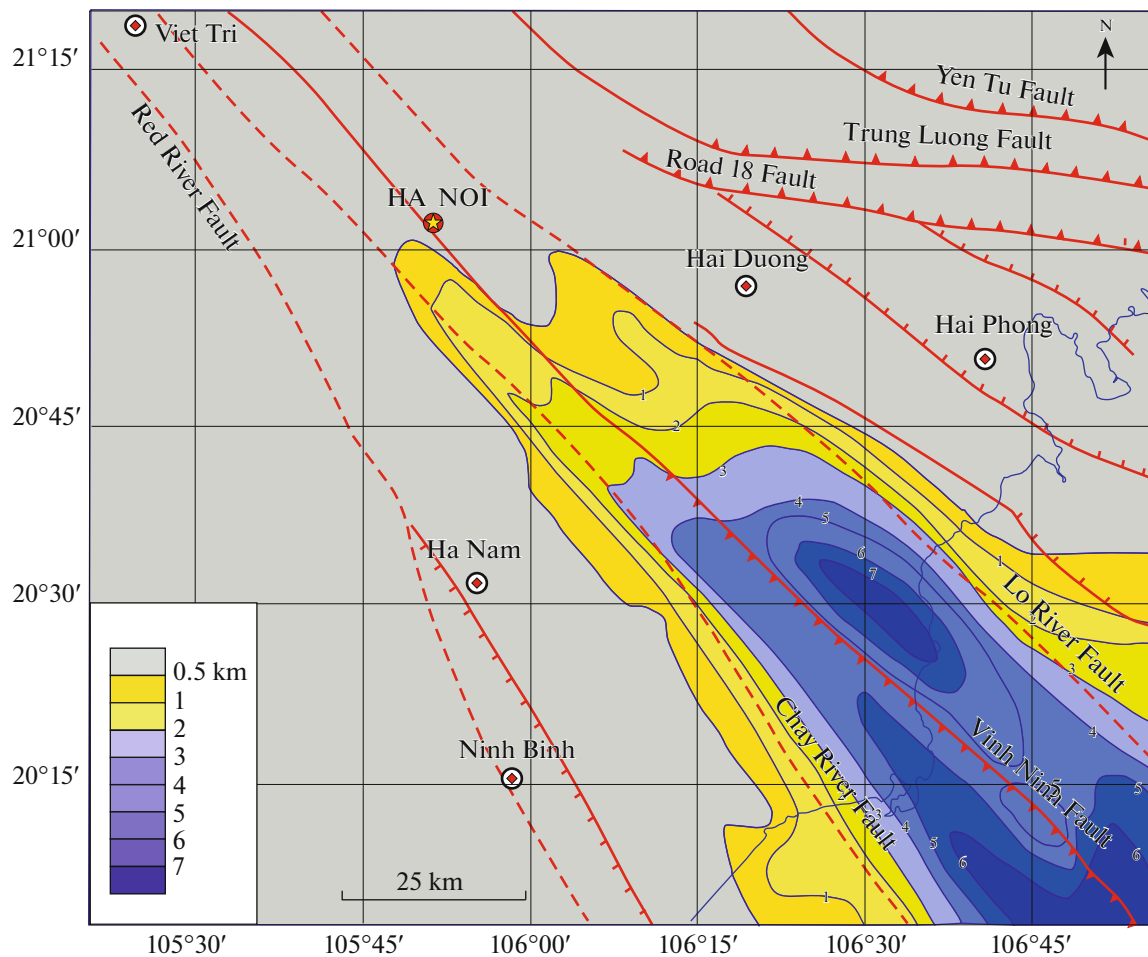


Fig. 8. The tectonic fault system of the Red River Delta and surrounding area (after [9, 10], modified).

must be a significant silent period. Based on the extrusion tectonic models, Tapponnier et al. [17] predicted a Neogene slip reversal across the fault zone due to the northward progression of the Indian indenter into Eurasia. The expected reversal has subsequently been verified by right-lateral offsets of the hydraulic system observed across the fault zone taken to imply Pliocene–sub-Recent right-lateral motion across the fault zone [1, 4, 13, 20]. Total left-lateral strike slip could reach 500–700 km [17], while the total right-lateral offset was estimated in range from approximately 5 km to more than 50 km and more recently the estimation is about 40 km [13, 14].

NE–SW Compression

The NE–SW compressional activities could take place since Middle Miocene that can be seen in the seismic profiles of the RRB (Fig. 10). The development of the RRD has been strictly controlled by the Chay River fault and Lo River fault, which created the Hanoi graben with Vinh Ninh fault in the center. The Vinh Ninh fault divided the Hanoi graben into two

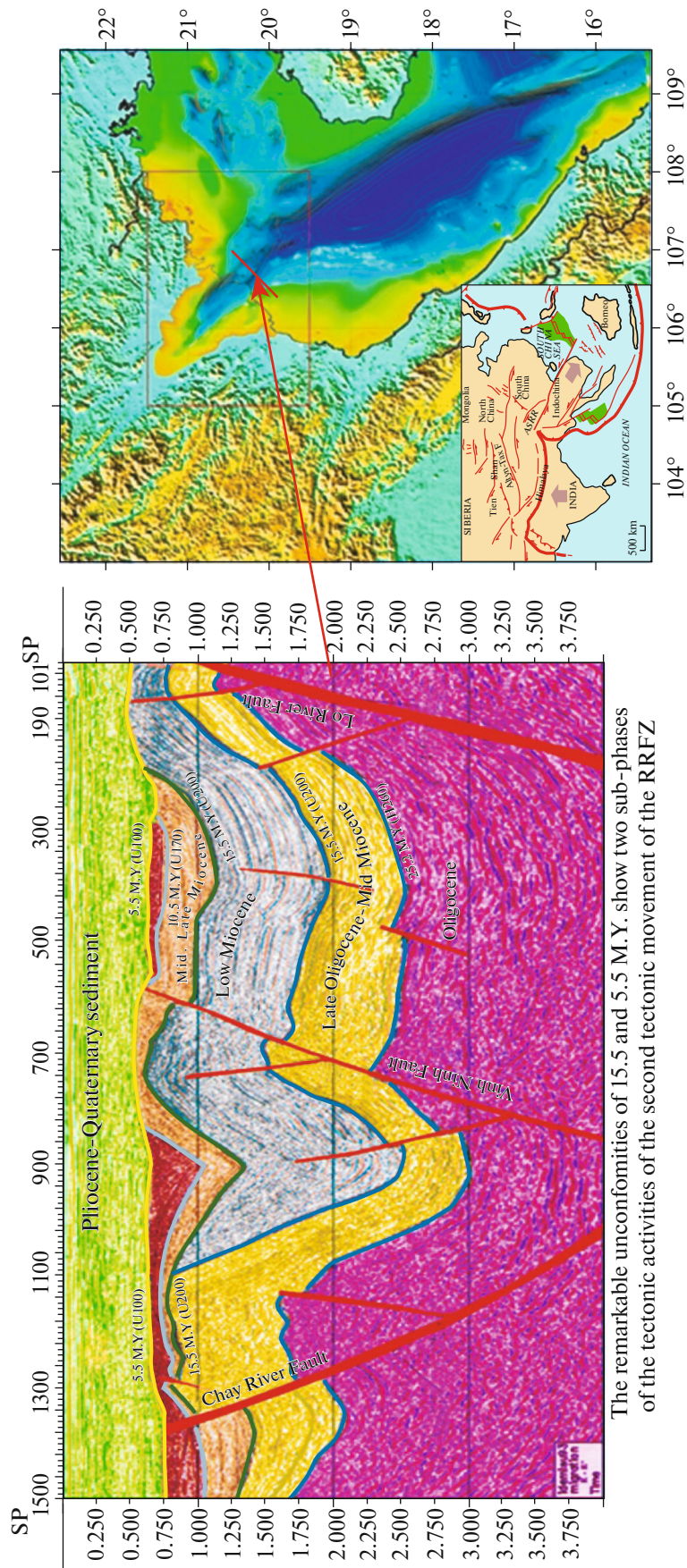
parts: the NE Dong Quan sag and the SW Tien Hai-Kien Xuong horst (Fig. 7). At first, the Vinh Ninh fault was normal and then turned into thrust fault since the late Miocene inversion. Due to strong NE–SW compression, the Vinh Ninh Fault might change its dip direction from NE to SW.

Our study [3, 4, 8, 10] revealed a strong NE–SW compression in the late Miocene, that caused left-lateral with thrusting component along W–E fault system and right-lateral strike slip along the N–S fault system in the west coastal zone of Tonkin Gulf and the Bach Long Vy Island.

The Late Miocene reversed movement in the central section of the RRB had created an uplift zone in the center of the RRD. This tendency could continue from the Late Neogene up to now. It is clearly shown in the maps of Kz-, Q-, and Holocene isopachs (Figs. 4–6). Based on the data of the oil-gas wells and seismic sections we could propose a situation of hydraulic system of the RRD area in the Late Miocene. After the strong Late Miocene inversion the central Kien Xuong-Tien Hai uplift zone had raised up to hundreds of meters and divided the RRD into two low parts at the NE and SW



Fig. 9. Model of tectonic evolution of Viet Nam and the adjacent area during the Cenozoic Era (after [9], modified).



The remarkable unconformities of 15.5 and 5.5 M. Y. show two sub-phases of the tectonic activities of the second tectonic movement of the RRFZ

Fig. 10. Seismic section across the Ha Noi graben shows remarkable tectonic inversions in the RRTKB: 15.5 M. Y. and 5.5 M. Y. BP (after [12], modified). Arrow indicates location of the seismic section.

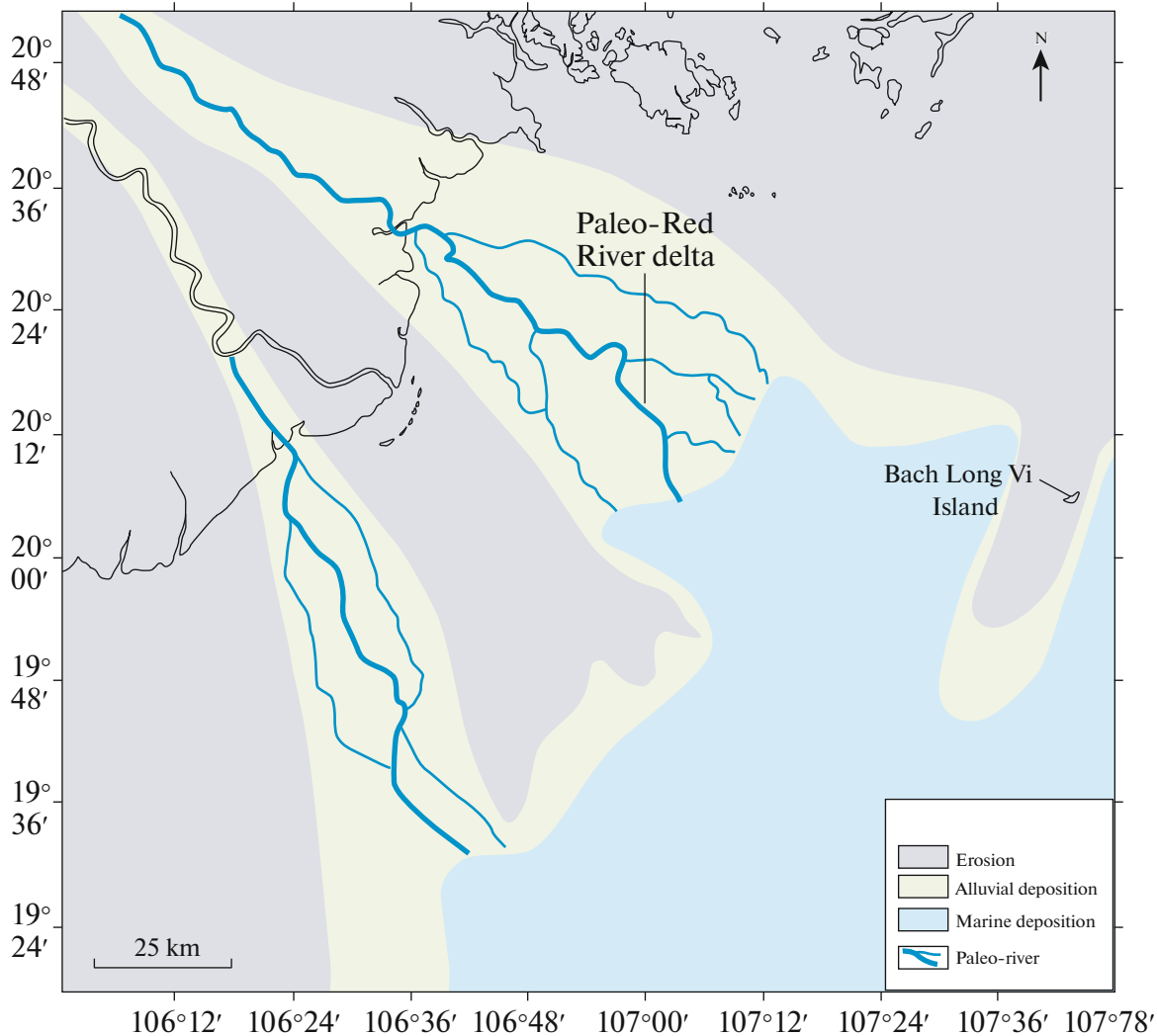


Fig. 11. Conceptual latest Miocene gross-depositional reconstruction of the northern Gulf of Tonkin. The approximate position of the paleo-Red River delta located east of the modern Red River delta due to inversion of the central northern Song Hong basin is indicated (after [3], modified).

flanks of the RRD. This certainly had affected the hydraulic system of the area and the river system could divide into two main branches: one in the NE and one in the SW peripheral area of the RRD (Fig. 11).

The NE–SW compression had strong remark on the fault plain displacements that can be seen not only along the RRFZ but also in the area around the RRD. Our investigation at different part of the RRD area, shows clear evidences for this, for example, in Trung Ha bridge (in the NW), Ngoc Quan (in the SW), Nui Goi (in the center) and Bach Long Vy Island (in Tonkin gulf).

In the NW, near the Trung Ha Bridge, the Oligocene–Neogene conglomerate at the Da River bank was strongly deformed by NE–SW compression activity. The pebbles in side conglomerate were cut and deformed in the manner that show systematically compression of NE–SW direction: that is the N–S

cracks displaced the pebbles dextrally, while the cracks of NE–SW direction displaced the pebbles as normal faults and the cracks of NW–SE directions showed as thrusts (Fig. 12, Table 1).

The similar deformation of the NE–SW compression activities also widely shown in the west and SW area of the RRD, where the red Cretaceous sandstone also were cut and displaced dextrally by the N–S vertical fault system, that showed strong NE–SW compression. One of the typical such fault plane is shown in the Ngoc Quan village, near the Song Ly bridge (National road number 01), Thanh Hoa province (Fig. 13). This compression can be found in vast area of west Tonkin coastal zone.

In the center of the RRD there are some hills of more than 300 m high composing from high metamorphic rock of the Song Hong formation (PR_{1sh}) that continues from the Day Nui Con Voi metamor-

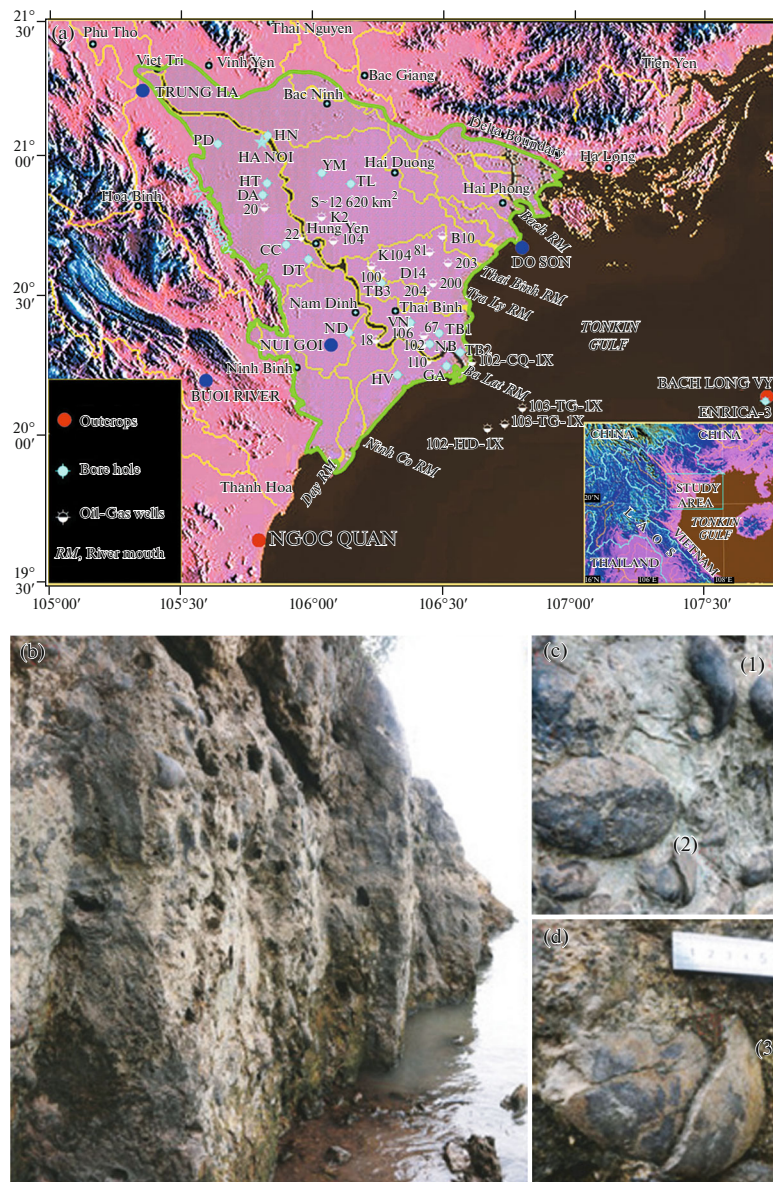


Fig. 12. Systematic offset of the Oligocene–Neogene conglomerate by right-lateral strike slip of N–S-directed fault system, showing NE–SW tectonic compression sub-phase (after [9], modified). Location: X. $105^{\circ}21' 18.9792''$; Y. $21^{\circ}13' 56.784''$, at Trung Ha, 50 km west of Ha Noi (after [9]), (see location in Fig. 1).

phic range along the Red River Fault Zone into the RRD. At the Nui Goi hill (near Nui Goi railway station), in front of a Pagoda there are exposed some conjugate fault system of the N–S and E–W directions. The N–S (submeridional) faults show right-lateral displacement, while the E–W faults show left-lateral displacement (Fig. 14).

The NE–SW compression widely found at the Bach Long Vy Island (in the middle of the Tonkin gulf). This compression should increase strongly the uplift of Bach Long Vy area. This phase made some area of the RRB raised up to hundreds of meters and subsequently those areas suffered from latter erosion. The inverse structures were truncated deeply and then

were buried by younger sediments (Pleistocene–Quaternary). The Bach Long Vy Island is the only place where the inverse masses exposed. The uplift of the Bach Long Vy area was even stronger than in other inverse places because the Island area is situated at the junction of two principal fault systems: NW–SE of RRFZ and the NE–SW from coastal of SW of China. They both were very active at the Middle and Late Miocene (Fig. 15).

SW–NE Extension

Our study indentify that the second tectonic activity had performed not only as right lateral strike-slip of the

Table 1. The Late Neogene stress fields of the tectonic activity with NE–SW compression at some outcrops around the Red River Delta

NN	Locations	Fault plains/Slikensides (P, North = Pitch and direction of inclination)	Calculation stereonet	Stress field		
				σ_1	σ_2	σ_3
1	Trung Ha X. 105.3531° E Y. 21.2286° N	$290^0 < 90^0$ P = 10 ⁰ , North, Dextral slip		245.4 ⁰ < 07.1 ⁰	020.0 ⁰ < 80.0 ⁰	154.6 ⁰ < 07.1 ⁰
2	Trung Ha X. 105.3531° E Y. 21.2286° N	$120^0 < 85^0$, P = 10 ⁰ , North, Dextral slip		255.8 ⁰ < 03.5 ⁰	003.7 ⁰ < 78.8 ⁰	165.1 ⁰ < 10.6 ⁰
3	Trung Ha X. 105.3531° E Y. 21.2286° N	$110^0 < 65^0$, P = 5 ⁰ , North, Dextral slip		063.4 ⁰ < 14.1 ⁰	301.7 ⁰ < 64.5 ⁰	158.9 ⁰ < 20.8 ⁰
4	Nui Goi X. 106.0756° E Y. 20.3306° E	$110^0 < 80^0$, P = 10 ⁰ , South, Dextral slip		245.9 ⁰ < 00.1 ⁰	155.4 ⁰ < 75.9 ⁰	335.9 ⁰ < 14.1 ⁰
5	Nui Goi X. 106.0756° E Y. 20.3306° E	$20^0 < 70^0$, P = 0 ⁰ , Sinistral slip		246.8 ⁰ < 4.0 ⁰	020.0 ⁰ < 70.0 ⁰	153.2 ⁰ < 14.0 ⁰
6	Ngoc Quan X. 105.8020° E Y. 19.63260° N	$90^0 < 88^0$, P = 10 ⁰ , South Dextral slip		045.6 ⁰ < 05.6 ⁰	168.8 ⁰ < 79.8 ⁰	314.8 ⁰ < 08.5 ⁰

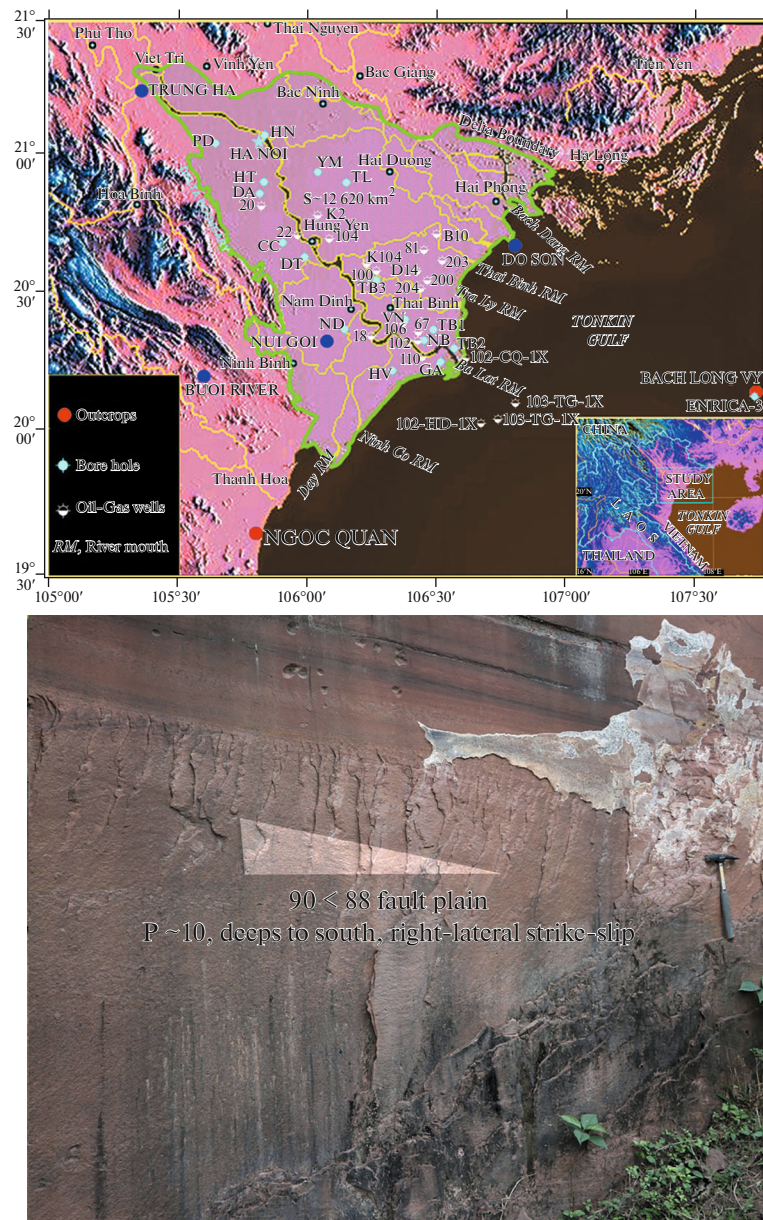


Fig. 13. Systematic offset of the Cretaceous red sandstone at the west coastal zone of the Tonkin gulf by N–S-directed fault system, showing NE–SW tectonic compression sub-phase (after [9], modified). Location: X . 105.8020° E, Y . 19.63260° N, at Ngoc Quan village, Thanh Hoaprovince (after [9]), (see location in Fig. 1).

RRFZ, but also at least two sub-phases that can be recognized with NE–SW compression and NE–SW extension activities that can be seen in the fractures of the Neogene strata of the narrow grabens or half-grabens along the RRFZ. The normal NW–SE faults offset the conglomerate layers inside the Neogene sandstone to form typical horst and graben structures showing NE–SW extension, while the NE–SW compression turned the strata from horizontal position to very steep position (Fig. 16).

The recent tectonic activity has been causing NE–SW extension again and there are numerous of

recent normal fault systems or young grabens in the RRD and peripheral zone can be seen, such as Ninh Binh graben, Buoï River graben. The grabens are stretching NW–SE or NNW–SSE. The Buoï River graben is one of the most typical graben, with size of 2×25 km. It is shown very well in the relief and space image ETM. This graben is revealed clearly, controlled by two tectonic faults. The Buoï River is meandering within the graben. A relief of the graben surface is quite unstable. The similar scene can be seen in the north flank of RRD, in Quaternary period we can recognize a very manifested trough along river Da Bac-

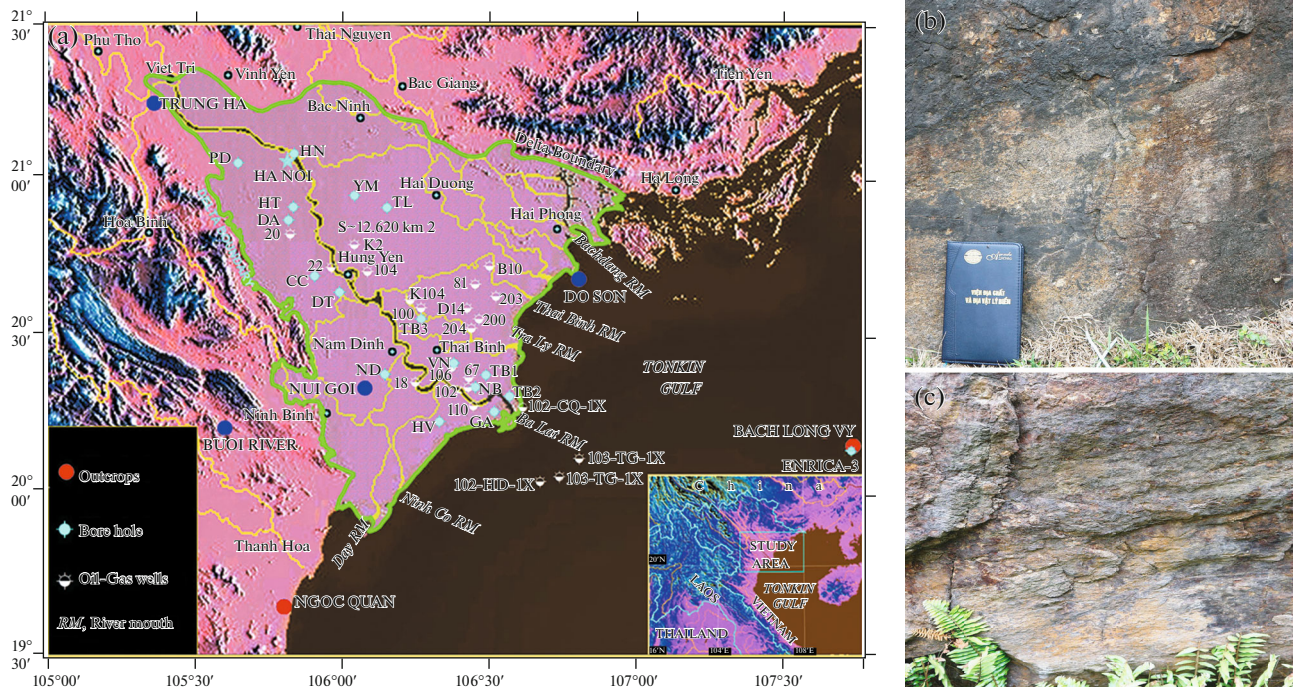


Fig. 14. (a) Location of the Nui Goi Hill Outcrop near Nam Dinh town(see location in Fig. 1). (b) Conjugate fractures of submeridional, and (c) sublatitudinal directions showing NE–SW compression (after [9], modified). The submeridional fractures show right-lateral displacement while the sublatitudinal fractures show left-lateral displacement (after [9]).

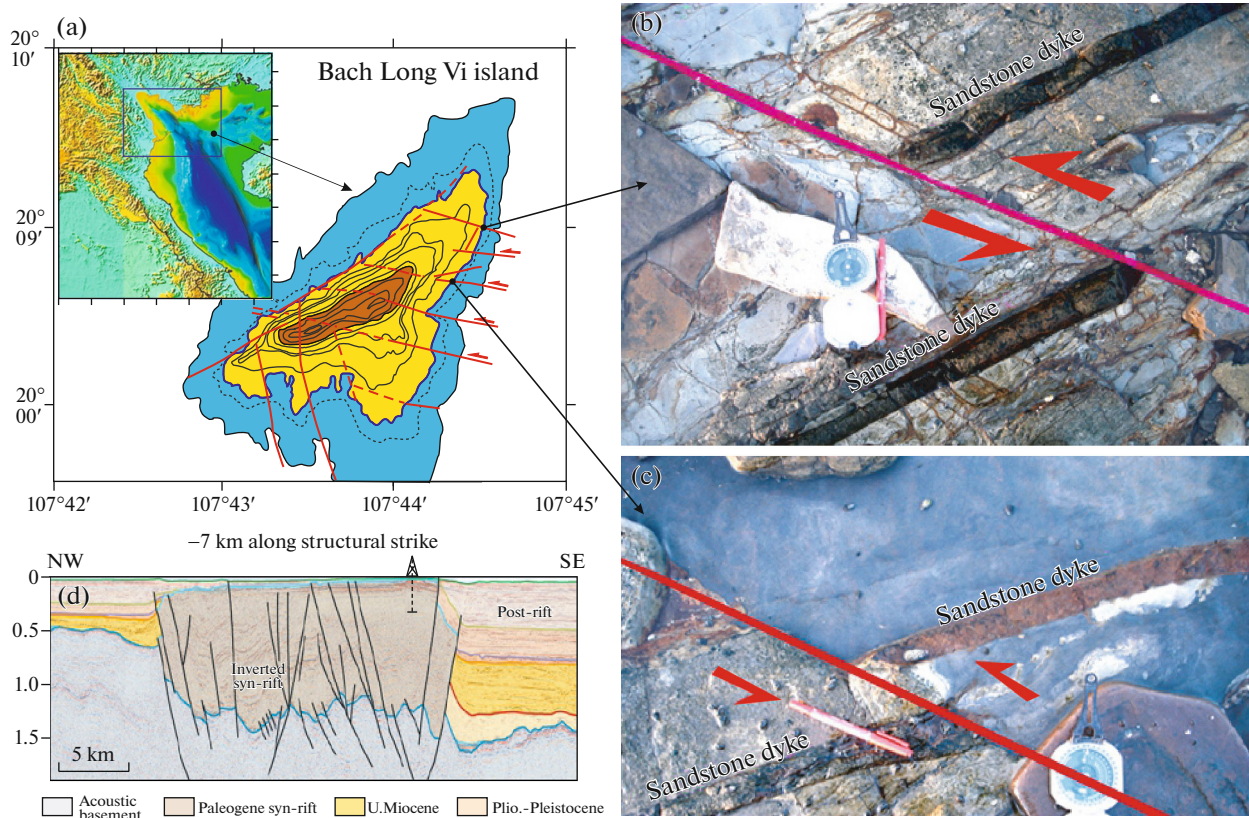


Fig. 15. (a) Location of the Bach Long Vi Island in the Tonkin gulf; (b) and (c) The sandstone dykes in the Late Oligocene–Early Miocene strata at the Bach Long Vi Island (Tonkin Gulf) were displaced left-laterally by the faults of WNW–ESE direction, showing strong NE–SW compression; (d) A seismic section across the Bach Long Vi island from SW to SE (after [4]).

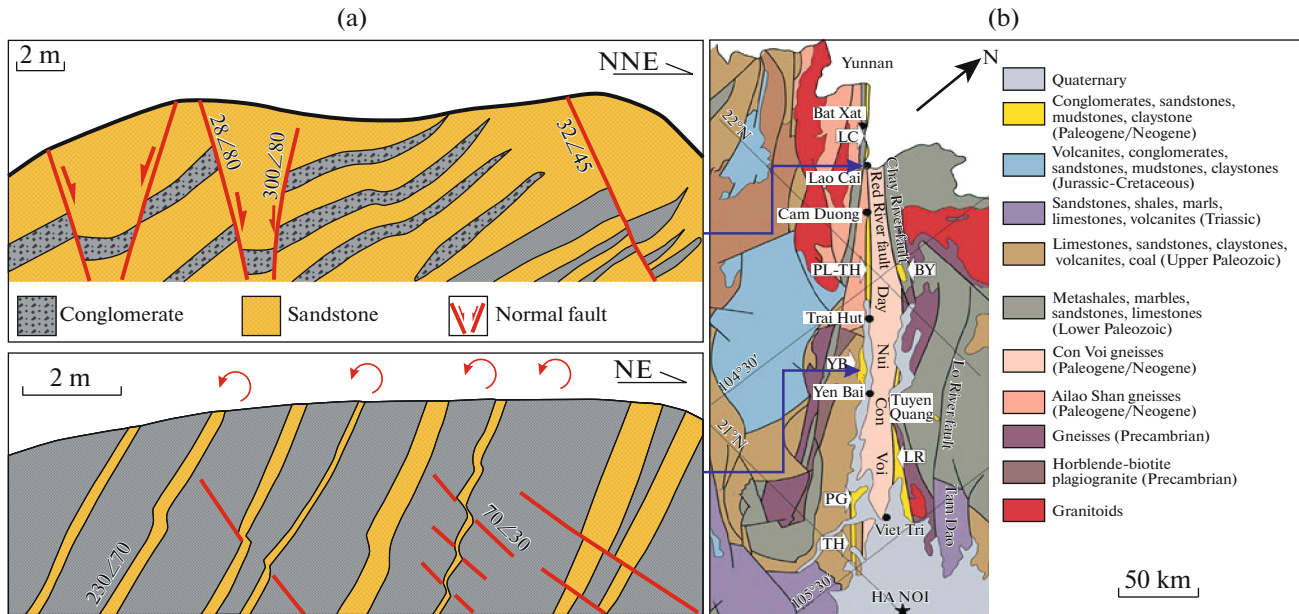


Fig. 16. Alternative NE–SW extension and compression along the RRFZ: (a) Extensional structures at the Lao Cai Town due to NE–SW extension; (b) The normal faults turned into thrust faults at the Yen Bai Town due to NE–SW compression (after [13], modified).

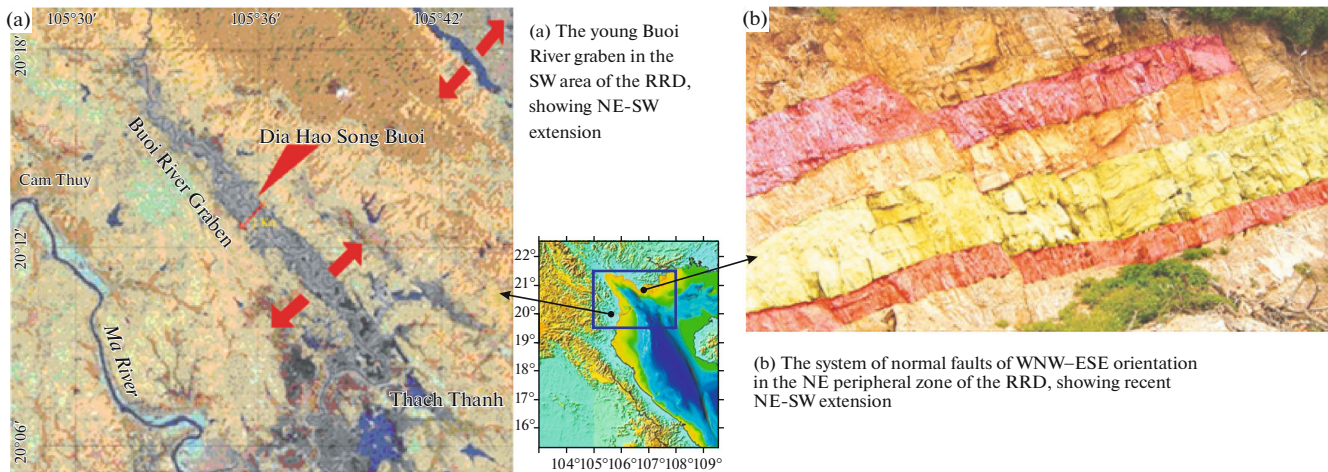


Fig. 17. The recent NE–SW extension in the Red River Delta and adjacent area.

Bach Dang belt, with estuary river mouth and numerous young normal faults can be observed at the Do Son peninsula, Kien An hills (Fig. 17).

The map of Quaternary sediments of the RRD indicates high differentiation, which reflecting the activity of tectonic faults: the Lo River Fault (LRF) reveals a NE depression of the Thai Binh river system, while the Chay River Fault (CRF) depicts a SW depression of the Day River system (Fig. 18). The similar scene can be seen in the map of Holocene sediments of the RRD (Fig. 5).

Our study shows that the Pliocene–Quaternary tectonics of the Red River delta and adjacent area was

active and divided into two main sub-phases of NE–SW compression and NE–SW extension. They both controlled development of the Ha Noi graben and the Red River delta. As a result, the Red River Delta has been developing in the extension environment with existence of the subsiding troughs in the peripheries and uplift zone in the center. This tendency perhaps has happened many times in the Pliocene–Quaternary periods. This characteristic of geodynamic regime of the region resulted from more complicated tectonics of the region. Besides right-lateral strike-slip of the RRFZ the geoblocks of the region have been rotating or move away. M. Pubellier et al. [11] proposed Cogwheel-style model, which

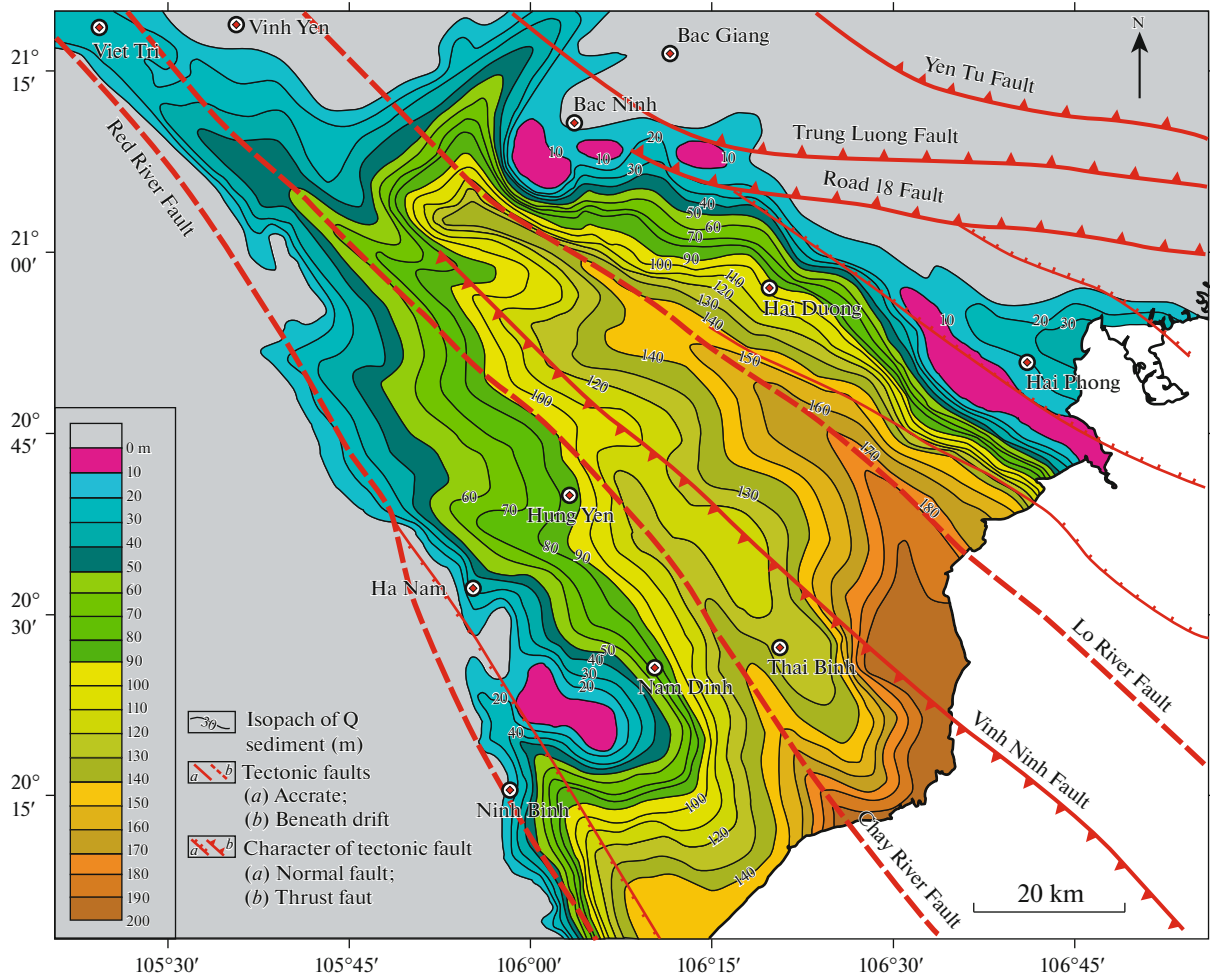


Fig. 18. The Red River Delta in the relationship with the tectonic fault system.

explain some right-lateral movement of the Cao Bang-Tien Yen fault in the NE Viet Nam border (parallel to the RRFZ) and anti-clockwise of the geoblocks in the NE Viet Nam–SE China region.

CONCLUSIONS

(1) The RRD is one of the largest deltas of Asia with an area of about 12620 km² was formed during Holocene period and strongly influenced by tectonic activity. It is divided into several blocks by the NW–SE striking tectonic faults. The central part of the delta laid over the Ha Noi graben, which is controlled by Lo River fault in the NE and Chay River fault in the SW. Due to tectonic activity the RRD basement is differentiated and revealed as in-uniform distribution of Quaternary sediments.

(2) Two tectonic sub-phases occurred in the region since the Late Miocene, after a cessation of left-lateral strike slip of the Red River fault zone: those are NE–SW compression and then NE–SW extension.

(3) The Late Miocene–Quaternary tectonic activity had created a reversed Tien Hai-Kien Xuong central block and young extension structures, such as the Ninh Binh graben along Red River fault and Dong Quan sag along Lo River fault. This characteristic of the tectonic activity of the RRD region and adjacent area had created typical hydraulic system with two distinctive river systems in the NE and SW or the area.

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