Vietnam Journal of Marine Science and Technology 2023, 23(4) 345–359

Vietnam Academy of Science and Technology

Vietnam Journal of Marine Science and Technology

journal homepage: vjs.ac.vn/index.php/jmst

Tectonic evolution of the Red River basin and adjacent area (Vietnam) in Cenozoic era

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Received: 17 July 2023; Accepted: 23 September 2023

ABSTRACT

Based on the structural and tectonophysic analysis of data collected from outcrops around Tonkin Gulf and the results of analysis of seismic sections of the Red River basin, the four main successive tectonic phases with specific paleostress fields since the beginning of the Cenozoic era have been established. The first, middle Eocene-early Miocene (45–15.97 My) tectonic phase, with sub-latitudinal compression and sub-longitudinal extension, was accompanied by large-scale sinistral displacement of the Red River fault, the extension centers of the Red River basin and seafloor spreading of East Vietnam Sea. The second, middle-late of middle Miocene (13.82–7.25 My) tectonic phase, with sub-longitudinal compression and sub-latitudinal extension, has created a local depocenter N-S orientation; right-lateral strike-slip of the Red River fault and first inversion of the basin. The third late Miocene (~7.25-5.33 My BP) tectonic phase, with NE-SW compression, has caused a strong inversion in the Red River basin with strong uplift of some blocks and significant shrinkage of the RRB up to 15–20%. The fourth Quaternary-to-Recent tectonic phase, with NW-SE compression and NE-SW extension, appears in an appearance of the hydraulic system offset, the recent grabens of NW-SE direction, the earthquakes, and GPS data. Formation and development of the Red River basin were controlled by tectonic activities and closely connected to NW-SE trending fault systems of regional scale such as the Red River fault, Chay River fault, Lo River faults, as well the local faults such as the Ca River fault, Rao Nay River fault, Tha Khet - Da Nang fault. Some spectacular examples of tectonic activity can be seen in the geographic features of Vietnam, Laos, and Thailand, particularly the mountain ranges, such as the Truong Son (or Viet-Lao) belt. When it comes to the sea, the Red River fault becomes less active, while the other faults of the RRFS, like the Chay River and Lo River, play the leading role in the developing the Red River basin.

Keywords: Red River basin, Red River fault system, Vietnam, Tonkin Gulf.

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https://doi.org/10.15625/1859-3097/18583
ISSN 1859-3097; e-ISSN 2815-5904/

INTRODUCTION

The Red River Fault (RRF) is an ancient tectonic fault that has been reactivated since 45 Ma BP due to the collision of the Indian and Asian continents. This New tectonics (or Extrusion tectonics) has created geomorphological features throughout China, Vietnam, and adjacent areas, as well as many geological structures, particularly the tertiary Red River basin (RRB).

The recent development of the oil-gas industry in Vietnam has stimulated the study of the Red River basin in terms of stratigraphy, tectonic structure, and oil and gas potential. The study was mainly concentrated in the Red River basin, and the inland part was less studied, particularly the SW flank of the basin. Some academic questions need to be resolved, such as the characteristics of the tectonic activities that affected the development of the RRB. In this paper, we will clarify this problem by analyzing tectonic events observed in seismic sections of the RRB and structural-tectonic data collected from numerous field trips and outcrops surrounding Tonkin Gulf and some islands.

GEOTECTONIC SETTING

Overview of the regional tectonic

The Red River fault system (RRFS) is composed of the Red River (RRF), Chay River (CRF), and Lo River faults (LRF) in North Vietnam. These faults are essential strike-slip faults in East Asia and play a significant role in the region's tectonic evolution, including the formation of the large Red River basin (RRB) as well as seafloor spreading of the East Vietnam Sea (EVS) (Figure 1).

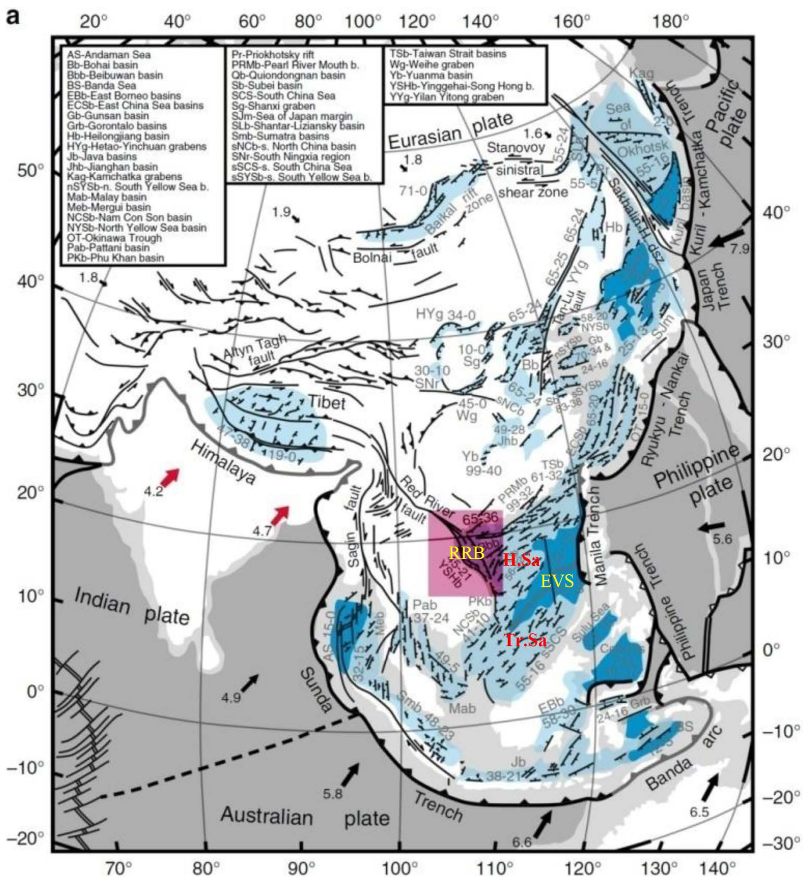

Figure 1. Study area in Structural - Tectonic map of East Asian Continent [1]

However, how the RRFS impacted the formation of the RRB is still debatable.

Firstly, the RRF's configuration shows that it turned to the south when approaching Tonkin Gulf. According to sinistral movement, that should be a compressional environment, not an extensional one (Fig. 2).

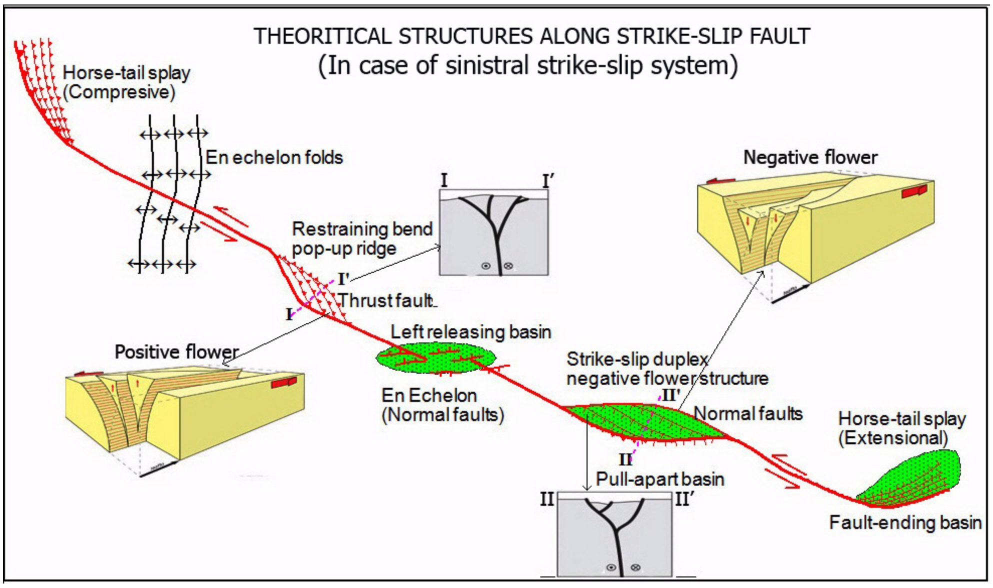

Figure 2. Theoretical tectonic structures along a strike-slip fault: Along the strike-slip systems, depending on changes of direction of the fault segments (where the orientation of the main fault is deflected), there can be local restraining bend (pop-up or push-up) or releasing bend (pull-apart), while at the ends of the strike-slip faults there can be some horsetail style (extensional or compressional) structures, in which can be formed strike-slip duplex (negative flower) or pop-up ridges (positive flower), just like thrust or normal-fault duplexes, but tilted to the vertical

Secondly, coming to the Tonkin Gulf, the RRF became less active and was blocked by a series of local faults of NW-SE or WNW-ESE directions, such as the Ca River fault, Rao Nay River fault, and Tha Khet - Da Nang fault. Instead of this, the Chay River and Lo River faults striking in the same direction as the RRF but shifting eastward had played a major role. It somehow acted as an extensional horsetail of the whole RRFS, according to the sinistral movement of the RRF. On the other hand, there could be some clockwise rotation of the Indochina terrain as rollback action while India has indented into Asia. This rotation could be reached 15^{o} [2–6]. This rotation must contribute significantly to the intensive extension and subsidence of the RRB. Schellartet et al. (2019) have done a practical model for the India-Asia collision and have concluded that indentation and rollback produce ~260–360 km of eastward extrusion and large-scale clockwise upper mantle circulation from Tibet towards East Asia and back to India. The optimal components of the experimental model that could produce the back-arc basins in the eastern Asian periphery require 1,740 ± 300 km of Indian indentation [1].

Nowadays, the opening of numerous marginal basins of the East Asian shelf is interpreted as a broad impact of mantle flow that came from the India-Asia collision and reached the eastern margin of Asia [1], overriding the westward flow of the Pacific mantle. Thanks to the movements underneath asthenosphere flows, component tectonic blocks have been moving in 30 million square kilometers of East Asia. We can judge how the asthenosphere flows by interpreting the upper tectonospheric blocks.

The mantle flows have a significant role in forming the marginal basins. Some basins like EVS were opened in a direction that does not match the Western Pacific subduction. So, they are not pure back-arc basins. The EVS basin was associated with large-scale strike-slip faults left-lateral RRFS radiating from the collision zone [7]. The role of mantle flow was mentioned before in [8]. When the India-Asia collision started, the eastern part of Asia was supported by a thin and warm lithosphere, and thinning continued until the Middle Miocene at least [9].

The EVS was opened under the influence of two mantle flows: a toroidal flow due to the lateral transition from continental collision in the Himalayas and oceanic subduction in the Sunda Trench induces a southward flow associated with retreat of Sunda Trench (or rollback movement). This opening was controlled by the sinistral large shear zone of the RRFS and by the dextral movement of the East Vietnam fault scarp [9].

Timing for the spreading of the EVS has been interpreted to have occurred during 32–15.5 Ma, based on magnetic anomalies [10]. Barckhausen and Roeser (2004) [11] interpreted that seafloor spreading of 5.6 cm/year at a total rate began at ~31 Ma in the central part of the East Vietnam Sea. At 25 Ma, spreading accelerated to 7.3 cm/year, contemporaneously activating a second spreading center in the West.

The RRB is the thickest sedimentary basin in SE Asia. Large sediment thicknesses both in the rift and post-rift stages have been observed. New geophysical data shows that the deepest part of the basement of Cenozoic sediment can reach 20 km [12]. The underneath crust has suffered from a necking process and may be thinner than 5 km. Besides tectonic movement, there is a specific role of the gravitational effect of quick sediment loading. The process of subsidence of the RRB was following thermal subsidence until 5 Ma. During the Pliocene and Quaternary, the dextral strike-slip movement of the basin marginal fault (Lo River fault) resulted in the formation of enormous sediment sequences in the middle and southeastern parts of the basin.

In addition, the RRB consists of some depocenters and some workers believe their positions may change from time to time, migrating to SE [14] (Figure 3).

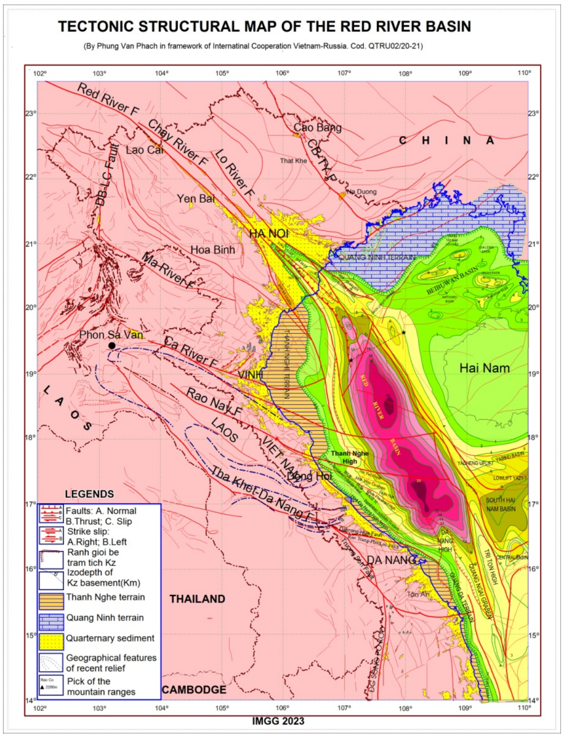

Figure 3. Tectonic-structural map of the Red River basin and adjacent area [*Photo by* PV Phach (2022)]

Data and methods of study

To solve the problem of this paper, we use both inland and offshore data. The inland data consists of many field trip observations and measurements we collected during several scientific projects on the Tonkin Gulf and surrounding areas over the last decades, and the data we recently collected when we carried out the joint Vietnam-Russian project.

Inland data, including geomorphological data, seismic data, GPS data, and, in particular, structural-tectonic measurements, may be used for structural analysis, including tectonophysic methods to help establish paleostress field of specific tectonic activity using fault planes with slip surfaces and slickensides on them. The results of these data can help us to recover characteristics of each tectonic phase in the past, even their successive (or their sequences), but it is impossible to fix the time when it happened.

Offshore data comprise seismic sections, borehole data, and geophysics field maps from Vietnam Petroleum offices. These data are good enough for structural analysis and to recognize tectonic events via unconformities in the seismic sections. In this case, we can establish the ages of each event via analysis of samples from boreholes at the unconformities surfaces. However, we cannot fix their dynamic characters.

So, by combining inland and offshore data, we can recover a history of the study area's tectonic evolution.

We also use a vast source of published documents in the study area.

TECTONIC ACTIVITY OF THE RED RIVER BASIN AND NORTHERN CENTRAL VIETNAM

Based on the structural and tectonophysic analysis of data collected at outcrops of Northern Central Vietnam (from Thanh Hoa to Binh Dinh provinces) from the last decade, as well as the results of geologic-geophysical analysis of seismic sections of the tertiary basins, we tried to fix the main tectonic phases with specific paleostress fields.

The principal tectonic phases and their order were established using structural analysis and tectonophysic calculation of stress fields based on the fault planes, their relationship, slickensides, and sense of their movements. The tectonic phases are then compared with events in the offshore seismic sections. As a result, the succesions of the tectonic activities of the region and their characteristics, including timing, stress fields, and consequences, were calculated.

Tectonic activity in the RRB is well shown in the typical seismic sections across the basin. The RRB generally has a typical pattern of unconformities and mega-sequences. Each mega-sequence corresponds to a distinctive environment. According to some workers, stratigraphic sections of the RRB could be divided into 5 [13], 7 [14], or 9 sequences [15]. Among the unconformities, the following ones are typical: 32 Ma, 15.5 Ma, 10.5 Ma, and 5.5 Ma, according to break-up unconformity; cessation of seafloor spreading; a change of slip direction of the RRFS from left-lateral transtentional to right-lateral transpressional and regional inversion.

Tectonic phase 1 (45-15.97 Ma)

Tectonic sub-phase 1A (45-23.03 Ma)

The left-lateral transtension along the RRF has caused rapid subsidence of the RRB. The sediments are composed mainly of alluvial, deltaic, estuarine, and offshore marine environments, with the deposition of sandstones and mudstones.

To analyze the depocenters of sediment for different times, based on Hoang Huu Hiep et al.'s data, we can make clear that the depocenters directly reflect the characteristic of each tectonic phase that it depends on, that is, the shape of the depocenter usually is elongated along compressional stress σ_1. This geodynamic status can serve as direct evidence of the sinistral movement of the RRFS. So, in the first stage, there were numerous scattering extensional centers in the form of local grabens or half-grabens, controlled by tectonic faults (usually strict ones). The axis of those extensional structures mainly is sub-latitudinal (Fig. 4).

The most prominent example of E-W compression, N-S extension, and the extensional horse-style ends of the local faults (Ca River, Rao Nay River, and Tha Khet - Da Nang fault) is the existence of several depocenters (or sub-basins), such as North, Central and South sub-basins. The thickness of sediments demonstrated active subsidence during this period. Most of them were oriented east-west, showing N-S extension. From NW to SE, the depocenters showed a decreasing tendency for sub-phase 1a: 10 - 8 - 7 km thick; for sub-phase 1b: 6 - 5 - 4 km thick for the whole period of rifting and sea-floor spreading (from 45 to 15.97 Ma). These depocenters (or North-Central-South sub-basins) had 16 - 13 - 11 km thick strata. We can see that the North Sub-basin was under impaction due to both Ca River and Red Rivers faults, so this consonance should strongly stimulate extension-subsidence of the North Sub-basin (Figs. 5, 6). At the same time, the Hue sub-basin appeared to be differentiated.

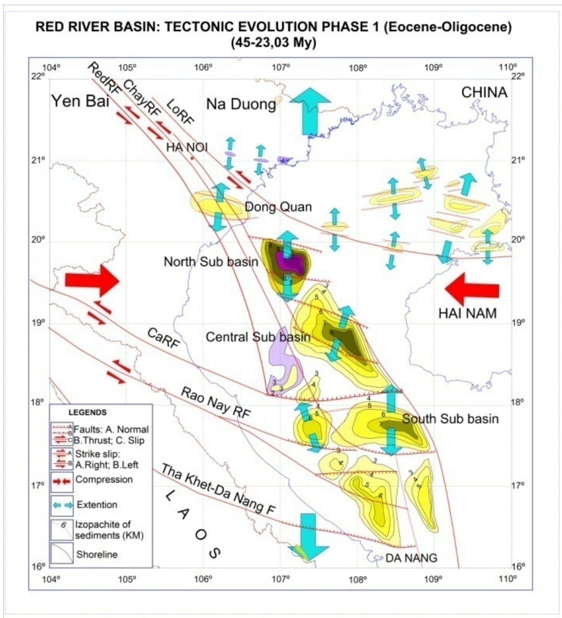

Figure 4. Tectonic status of the Red River basin and adjacent area in the middle Eocene-Oligocene (45-23.03 Ma) - Sub-Phase 1A (A), with East-West compression, causing left-lateral strike slip along NW-SE faults and sea-floor spreading of EVS (32-15.97 Ma) (PV Phach (2022))

This extensional environment matched a widespread regional stress field in East Asian continent (an area of over 30 million km^2). Because it occurred even a bit earlier in a collision between the India block and the Asian plate, many workers believed that the source of tectonic force should come from the westward movement of the Pacific mega-plate [1]. This action can explain why some well-known grabens of Eocene sediments exist in the North of Tibet.

Tectonic sub-phase 1B (23.03-15.97 Ma)

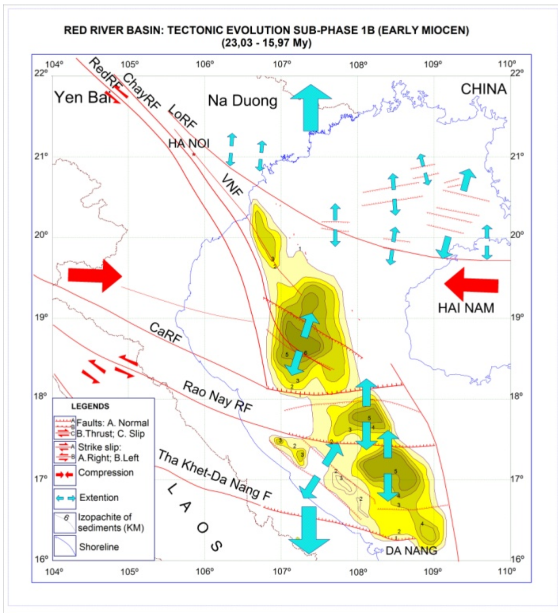

Figure 5. Tectonic status in the early Miocene (23.03-15.97 Ma)-sub-phase 1B (B), with East-West compression, causing left-lateral strike slip along NW-SE faults and multi-center of sea-floor spreading of EVS (PV Phach (2022))

There was an abrupt change in the seafloor spreading of EVS since the early Miocene (23.03 Ma), when a new spreading center was set up and developed in the west, at the Vietnam shelf zone, while the eastern earlier developed sea-floor spreading center continued to grow. The spreading rate could be the same for the two centers, but the spreading direction differed [10]. As the East Center continued spreading in the N-S direction, the new center of spreading had an NW-SE extension, creating a sharp wedge, coming close to the Vietnam shelf zone. The East Vietnam fault scarp, striking N-S, began to move in the right-lateral strike-slip sense [10, 16, 17]. This movement of EVNFS can be explained as a "rollback" of the east region in the process of India's indentation to Asia. Depending on the time, this rollback could be very active quickly and become weak. Some calculations supposed that the amount of horizontal displacement of EVNFS could reach as much as 500 km [4, 18–20]. We questioned how the roll-back affected Red River basin development. Our sketch map for the period of early Miocene (23.03-15.97 Ma) based on the thickness of sediment shows that the tectonic activity of this period was almost the same, with strong affection of left-lateral displacement of local faults (Ca River fault, Rao Nay River fault, Tha Khet - Da Nang fault) (Fig. 5).

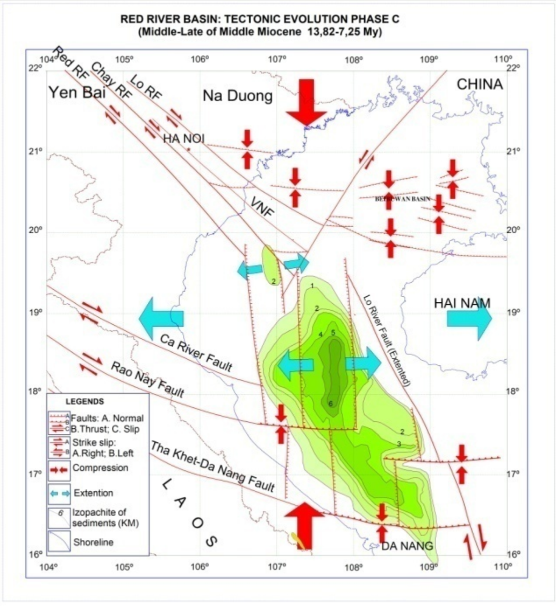

Figure 6. Tectonic status of the Red River basin and adjacent area in the middle-late of middle Miocene (13.82-7.25 Ma)- Phase 2 (C), with North-South compression, causing right-lateral strike slip along NW-SE faults and formation of a large N-S graben with 170 × 70 km in size, with over 6000 m of sediments of middle-late of middle Miocene. This situation shows east-west extension and North-South compression (PV Phach (2022))

Tectonic phase 2 (early Miocene: 13.82-7.25 Ma)

At the end of the early Miocene, along with the cessation of seafloor spreading of EVS (15.97 Ma), they believed that the RRF had changed its sense of displacement from left-lateral transtensional to right-lateral transpressional. However, before that, some quiet period should have occurred in this time, and some minor inversion had happened there, which is quite clearly shown in the seismic sections of the basin. A compression was north-south, and the extension was East-West. This status of stress field should have lasted more than 6 million years. Our paleo-tectonic map for period of middle-late middle Miocene (13.82-7.25 Ma) shows excellent change in depocenter configuration. A large depocenter with North-South orientation of 160 × 60 km in size was recognized in the center of the RRB, with 7000 m sediment thick of middle-late of middle Miocene sedimentation (13.82-7.25 Ma) (Fig. 6, Phase 2C),... This sub-basin configuration matched the tectonic stress well (i.e., N-S compression and E-W extension). Besides, this activity also caused some inversion inside the Red River basin.

Tectonic phase 3 (7.25-5.33 Ma)

North-South compression could last about 6 million years or more within the middle and late middle Miocene and should end at the end of the Middle Miocene or slightly later. Some workers show 10.5 Ma reflector as unconformity of this event [13, 14, 23]. This reflector did not show very clear angular unconformity, and we can see continuous sedimentation of thick deltaic units of sandstones, siltstones, mudstones, and brown coals deposited in middle-late Miocene times in the northern RRB. These deposits are grouped into the Phu Cu and Tien Hung formations. Our detailed analysis of this sedimentation shows some syn-sedimentation deformation of these units. The similar deposits in the southern part of the basin are dominated by shallow marine clastics, grouped into the Song Huong and Quang Ngai formations, or the Bac Bo Group, which partly alternated with various carbonates, including platform carbonates, barrier and pinnacle reefs of the Middle Miocene Tri Ton Group [24, 25].

However, when it came to the Late Miocene epoch (7.25-5.33 Ma), the geodynamic situation has changed abruptly; some strong NE-SW compression had appeared to act in large areas of North Vietnam and RRB. This tectonics activity can be seen everywhere around Tonkin Gulf. According to the RRB seismic sections, this epoch's tectonic activity has caused the most prominent inversion and shrank the RRB to approximately 15–20%. It has also strongly uplifted whole stratigraphic section of the RRB. In the seismic sections, a widespread angular unconformity deeply truncates the inversion structures (Figure 7).

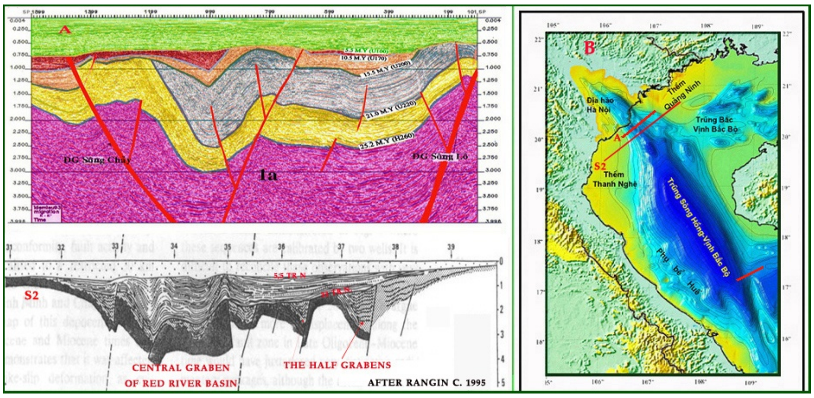

Figure 7. The NE-SW compression has caused strong inversion in the RRB, in particular at the NW part. The two typical sections near shoreline show some 15–20% shortening in NE-SW direction [13]

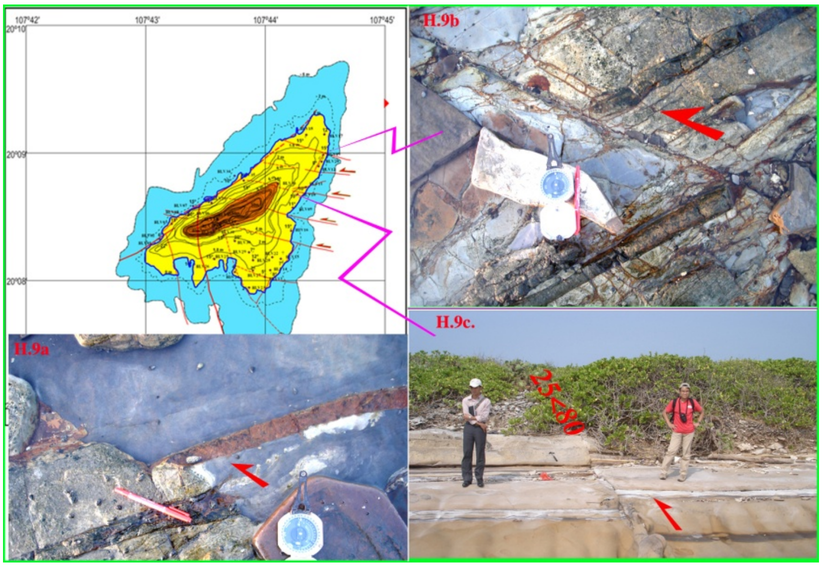

Figure 8. In Bach Long Vi island there are numerous sediment dykes in Oligocene strata were cut and displaced sinistrally: H.9a (BLV11) shows sinistral slip of WNW-ESE fault with horizontal amplitude of 25cm; H9.b (BLV12) shows sinistral slip of WNW-ESE fault with horizontal amplitude of 50cm; H.9c (BLV10) shows sinistral slip with thrusting component (S115E, dipping 80^o) [*Photo by* PV Phach (2007)]

The upper thick sediments of renewed increased subsidence of the RRB are draping and virtually undisturbed. Those are Pliocene-Quaternary strata lying on top of stratigraphic sections almost horizontally.

Many sections showed uplift up to hundreds or thousands of meters. The following erosion has truncated uplifted strata as deeply as the early Miocene. The inversion could be seen in the undersea seismic sections and at many outcrops along the Red River faults, Chay River Fault, Lo River fault, and around the Red River delta. At the Yen Bai basin, some sections with inverse activity displayed in the form of overturning of former normal faults into thrust faults or a lot of mini folded structures with NW-SE axis in Neogene strata [21]. While in Bach Long Vi island (at Tonkin Gulf), many local faults struck WNW-ESE that cut through Oligocene strata and displayed it left-laterally with compression component (Figure 8). The stress field of this activity can be calculated from fault planes and other remnants of displacements on them: σ_1: 24∠29, σ_2: 135∠34, and σ_3: 263∠43 (this is a strike-slip with a significant compressional component).

This inversion is also recognized at the Pearl River Mouth basins [5, 6, 22].

The thrust faults can be found in many places along west coast of Tonkin Gulf. For example, at Da Nhay outcrop (Quang Binh province) numerous faults and folds show strong NE-SW compression (Figs. 9, 10).

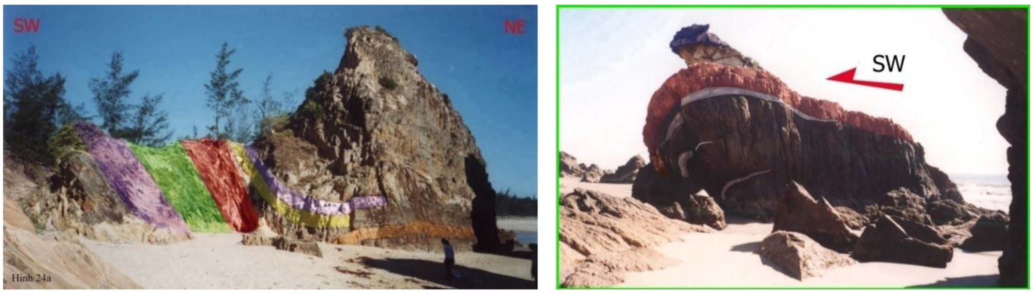

Figure 9. Thrusted faults are widely spread in Da Nhay beach, Quang Binh provcince (Location: 106, 51,453°E-17,66068° N) [*Photo by* PV Phach (2003)]

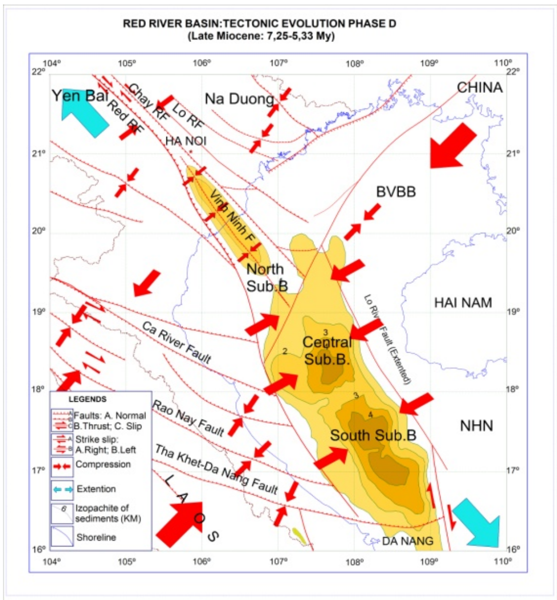

*Figure 10.*Tectonic status of the RRB and adjacent area in the Late Miocene (7-25-5.33 Ma) - Phase 3(D), with NE-SW compression and NW-SE extension, causing strong inversion and shortening of the RRB (PV Phach (2022))

Tectonic phase 4 (Quaternary - now: 1.81-0 My)

The NE-SW compressional phase ended at the end of the Miocene and has created a regional angular unconformity. Upper this unconformity, Pliocene-Quaternary sediments lay almost horizontally, showing a tectonically weak period.

However, some Pliocene-Quaternary activity can be seen in morphological deformations, like the offset of hydraulic systems, the existence of the Quaternary-Recent extensional valleys, earthquakes, and GPS data. So, along the Ca River valley there is some good systematical offset of the streams from 1,000 m to 5,000 m showing right-lateral strike-slip with NW-SE compression (Fig. 11).

NE-SW extension can be seen as valleys filled with Quaternary-Recent sediments. These valleys usually orient along some tectonic faults of NW-SE direction, as a rule, such as along the Red River, Chay River, Lo River, Ca River, Rao Nay River, and Tha Khet - Da Nang River faults.

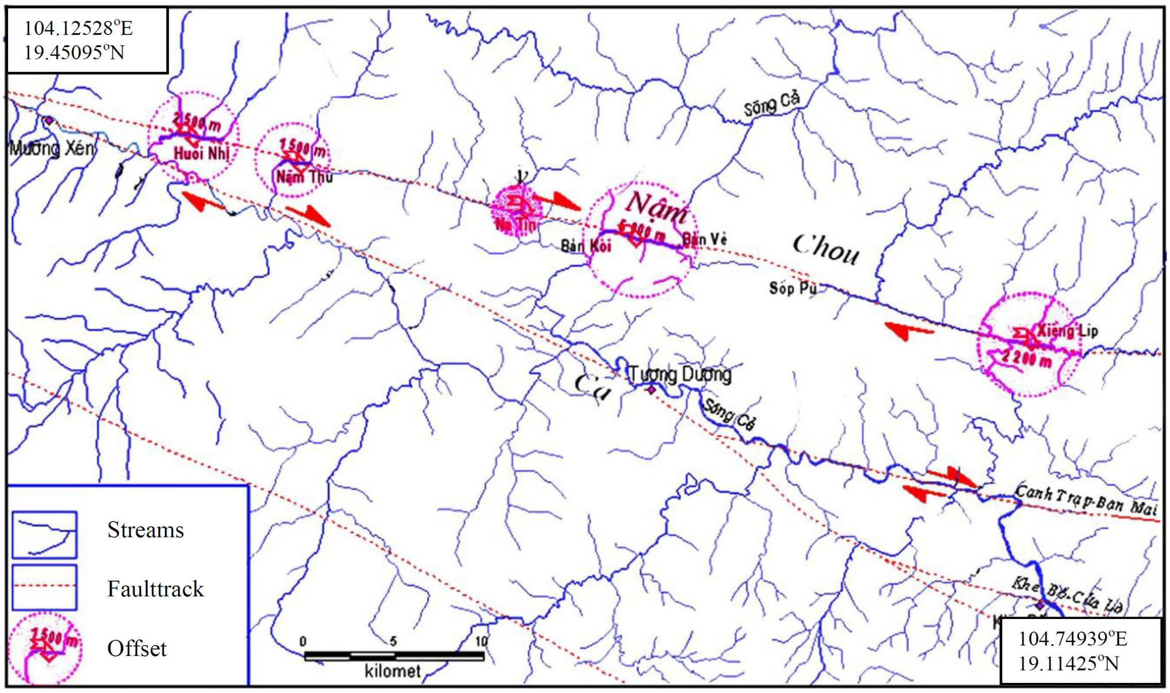

Figure 11. Systematical offset of the streams alongthe Ca River valley, Nghe An province

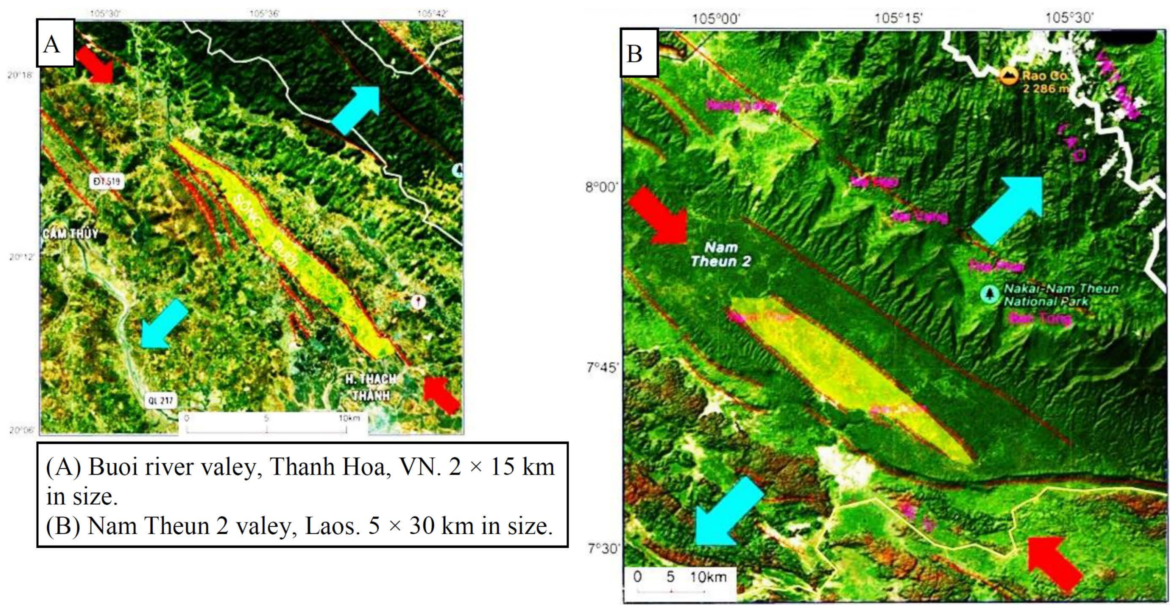

Figure 12. The Quaternary-Recent tectonic valleys: (A). Song Buoi River and (B). Nam Theun valleys (PV Phach (2022))

A good example can serve the Buoi River valley (Thanh Hoa province) with a meandering River inside showing a clear NE-SW extension. The same valley can be seen in Nam Theun 2 valley in Laos, where we can see step subsidence of the western flank of Truong

Son uplift massive, with some hanging valleys and sharp triangle facets showing strong NE-SW extension (Figure 12). Similar valleys can also be recorded at Mon Son, Anh Son along the Ca River, and A Sau - A Luoi valley along the Tha Khet - Da Nang fault.

The tectonic activity of the Quaternary-Recent period can also be recognized in the appearance of some minor earthquakes surrounding the area of Tonkin Gulf and GPS data showing NW-SE compression.

Paleo-tectonic basing on izopachit map of Quaternary-Recent (1,81-0 Ma) sediments also shows good NE-SW extension in the RRB, with NW-SE elongated depocenters (Fig. 13).

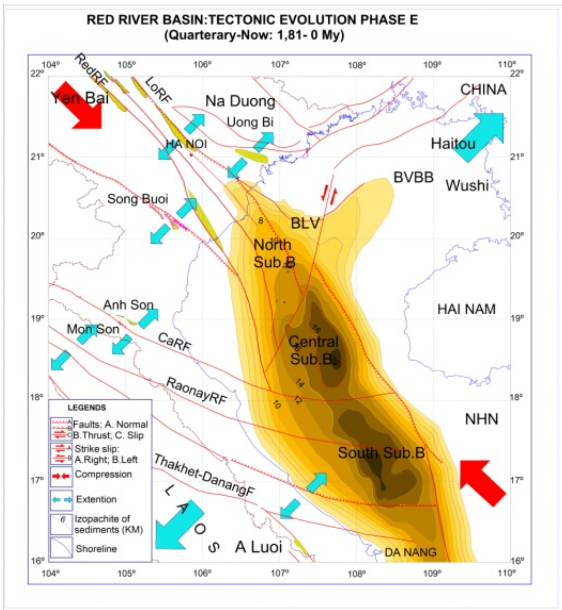

Figure 13. Tectonic status of the RRB and adjacent area in Quaternary-Recent (1.81-0 Ma)- Phase 4(E), with NE-SW extension and NW-SE compression, causing some extensional valleys and normal faults of NW-SE direction (PV Phach (2022))

TECTONIC MODEL

Tectonic evolution of the RRB and adjacent area can be resumed in 4 important tectonic activities, which affected the study region. The fault system of NW-SE has played important role as a boundary between two major domains of the region: South China-North Vietnam and Indochina. In the first stage, the RRFS had acted left-lateral trans-extensionally and moved the Indochina block SE-ward rotating clockwise (to approximately 15°). In contrast, the NE block of the South China-North Vietnam domain is considered stable during the Cenozoic Era (or Neotectonic period).

We supposed that the Indochina domain moved southeastward at a distance of 500 km and rotated clockwise 15°. The amounts of displacement and rotation had ended at the end of early Miocene 15.97 Ma (Fig. 14. Phase 1 and Sub-Phase 1B). The RRFS acted "grouply" via the activity of the Chay River and Lo River faults. At the same time, the RRF, when approaching sea, became weak and was blocked by a local fault system of Ca River, Rao Nay River, and Tha Khet - Da Nang River faults that also struck in the NW-SE direction. These local faults played an essential role in forming the RRB when they acted left-laterally. This movement caused the formation of some sub-basins (depocenters) inside the RRB (Fig. 14. Phase sub-1a, 1b).

Some compression effects can be seen in Sam Nua province (Laos) in the form of relief deformation, where mountain chains meet and collide, creating a spectacular bend of relief at 103.17°E (Phase 1 and 1B) (Fig. 15A).

After cessation of the left-lateral strike-slip of RRFS and cessation of seafloor spreading of EVS, there should be some quiet period before it transferred into the right-lateral strike-slip of the RRFS. It caused the first inversion in the RRB.

Regarding the Middle of the Middle Miocene, the RRF moved dextrally, under some N-S compression and E-W extension. At the same time, the E-W grabens (or half grabens) of the rifting and spreading period had shrunk with numerous thrust faults of sub-latitudinal direction. Some mountain ranges could be formed during this period, such as Dong Trieu - Yen Tu in the Ha Long area and Dangrek along the North border of Cambodia with Thailand. In the Dangrek mountain range, there are widespread thrust faults and over-thrusting structures in terrigenous sediments (sandstone, slate, and silt) (Fig. 15B).

According to our data and interpretation of the paleo-tectonic mentioned above (isopach) maps, there is no clear tendency of the location change of the depocenters of the RRB.

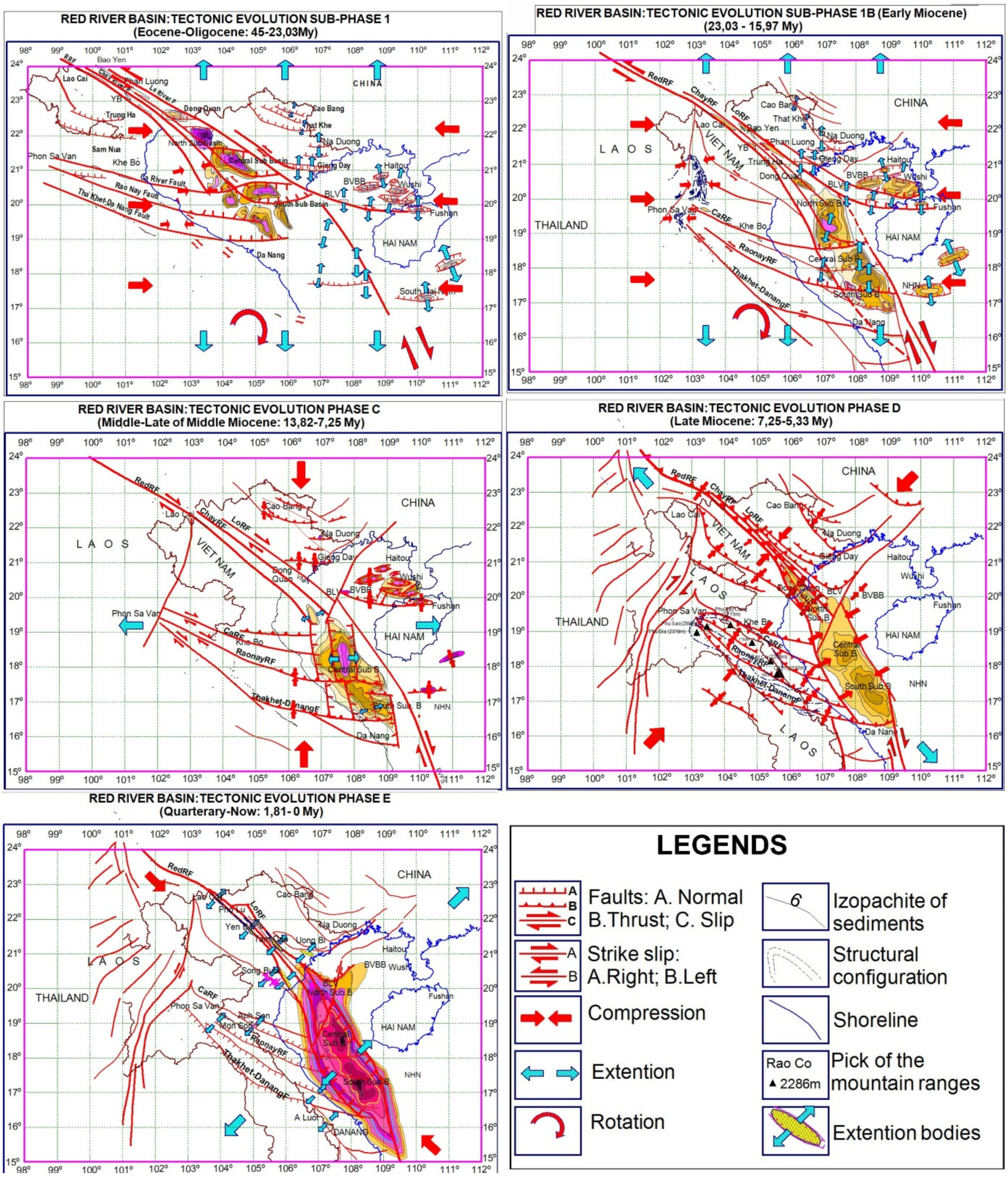

Figure 14. Tectonic evolution model of the RRB and adjacent area from Eocene to now (45-0 My BP) (PV Phach (2022))

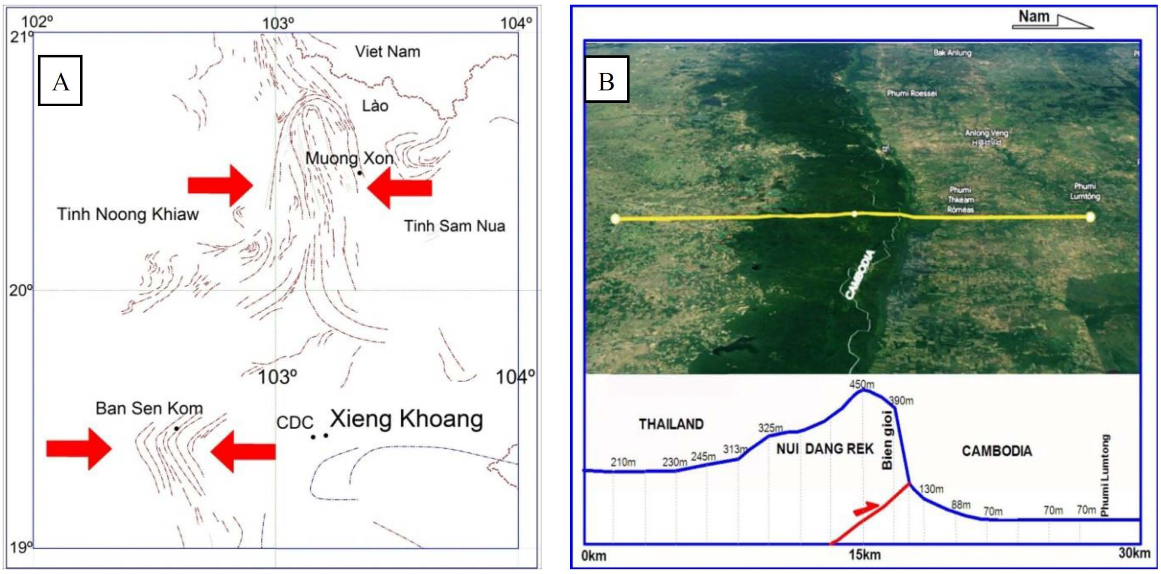

Figure 15. Some morphological evidence for (A) - East-West compression at the mountainous area between Noong Khiaw and Sam Nua provinces (in Laos) and (B) - North-South compressions along Dangrek mountain range in Thailand-Cambodia border (CDC = Canh Dong Chum)

CONCLUSION

1. Cince the beginning of the Cenozoic era Four main successive tectonic phases have affected the region of the Red River basin and adjacent area.

The first tectonic phase had sub-latitudinal compression and sub-longitudinal extension. It took place as early as Middle Eocene (45 Ma) and was accompanied by large scale sinistral displacement of the RRFS. This phase created numerous scattering extension structures, including North, Central, and South depocenters of the RRB and the spreading of EVS (32-15.97 Ma).

The second tectonic phase has marked a radical change in the tectonic status of the RRB and adjacent area. It occurred in the middle-late of the Middle Miocene (13.82-7.25 Ma). It created a local depocenter in the RRB, with N-S orientation and some right lateral strike-slip of the RRF. This phase also created numerous thrust structures in the area, particularly at RRB, causing the first inversion.

The third tectonic phase occurred in the Late Miocene (~7.25-5.33 Ma) with NE-SW strong compression. It caused the second strongest inversion in the RRB and shrank the basin to 15–20%. Strongly uplifted strata were truncated deeply. This phase can be caused by far-field stress (from Sumatra seduction?).

The Fourth Quaternary-to-Recent tectonic phase, with NW-SE compression and NE-SW extension, can be shown via deformation of the hydraulic systems, recent grabens, earthquakes, and GPS data.

2. Formation and development of the RRB were controlled by closely connected regional RRFS and the local faults such as the Ca River fault, Rao Nay River fault, and Tha Khet - Da Nang faults directly connected with the local depocenters of the RRB.

3. The tectonic activity of the local faults had created a sub-basin Hue-Da Nang near the SW shore of Tonkin Gulf. This sub-basin has a complicated structure, with local grabens, horsts, and numerous tectonic fault systems.

4. Besides the existence of the RRB, tectonic activity of the region of Central Vietnam also contributed to the formation of geographic features of the land area of Vietnam, Laos, and Thailand, in particular the mountain ranges, such as Truong Son (or Viet-Lao) belt and specific mountain chains in west Laos and at the border between Thailand and Cambodia.

5. The RRF, when it comes to the sea, became less active, while the Chay River and Lo River played the leading role in the development of the RRB. The Lo River fault in the NE flank of the RRB is coming to connect with the East Vietnam Fault Scarp.

Acknowledgments: This paper is part of a joined Vietnam-Russian Project between the Far East Geological Institute (FEGI) and the Institute of Marine Geology and Geophysics (IMGG), VAST, between 2020 and 2021 with the code of the project is QTRU02.03/20–21 and a VAST's Project with code of ĐLTE00.09/22–23. We thank IMGG and VAST for their support.

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