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Tectonophysics

TECTONIC EVOLUTION OF THE SOUTHERN PART OF CENTRAL VIET NAM AND THE ADJACENT AREA

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Abstract: Interpretations of seismic, gravity and magnetic anomalies and structural data on the coastal zone of southern part of Central Viet Nam (SCVN) and the adjacent Tertiary basins suggest several phases in the tectonic evolution of the study region since the Late Cretaceous to Quaternary. In this paper, we try to clarify the tectonic evolution of SCVN and the adjacent continental margin. The Cretaceous – Paleocene tectonic phase commenced after cessation of the West Pacific plutonic magmatic activity that produced numerous diabases and aplite dykes of mainly submeridian orientation. It was characterized by N–S compression and E–W extension. The geomorphology and geology of SE Asia were considerably changed during the Neotectonic phases caused by collision between the Indian plate and the Eurasian continent. Two tectonic phases – Early and Late Neotectonic – are separated by a regional unconformity represented by a boundary surface between below strongly deformed strata (synrift) and above less deformed formations (post-rift). The Early Neotectonic phase was related to the left-lateral movement of the Red River Fault Zone (RRFZ) and includes two tectonic sub-phases: Eocene – Oligocene (NW–SE compression), and Oligocene – Miocene (E–W compression). Activity in the Oligocene-Miocene sub-phase gave birth to rift basins in the continental margin of the SCVN. The Late Neotectonic phase began since the RRFZ stopped left-lateral movement and the East Viet Nam (or South China) Sea stopped spreading. The Late Neotectonic phase is also divided into two tectonic sub-phases: Late Early Miocene (sub-meridian compression), and Late Miocene – Pliocene (NE–SW compression). The Late Miocene – Pliocene sub-phase is characterized by vertical movements that caused episodic uplifting of the onland terrains, and subsidence of the offshore Phu Khanh basin. Besides, Miocene – Pliocene-Quarternary basaltic eruptions were widespread all over the southern Indosinian terrain and the continental margin.

Key words: Southern part of Central Viet Nam (SCVN); Red River fault zone (RRFZ); East Viet Nam fault scarp (EVFS); East Vietnam Sea (EVS); Phu Khanh basin; East Asian global strike-slip zone (EAGSZ); tectonophysics

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Тектоническая эволюция южной части Центрального Вьетнама и прилегающей территории

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Аннотация: Путем интерпретации данных о сейсмических, гравитационных и магнитных аномалиях, а также данных о структуре прибрежной зоны южной части Центрального Вьетнама и прилегающих к нему третичных впадин можно выделить несколько этапов тектонической эволюции изучаемого региона, с позднего мелового до четвертичного периода. Цель статьи – получить более точную картину тектонической эволюции южной части Центрального Вьетнама и прилегающей территории. Тектоническая фаза, датируемая как мел – палеоцен, началась после прекращения глубинного магматизма в западной части Тихого океана, приведшего к образованию многочисленных диабазов и аплитовых даек, ориентированных в основном субмеридионально. В течение этой фазы происходило меридиональное сжатие (С-Ю) и расширение в широтном направлении (З-В). В геоморфологическом и геологическом отношении ЮЗ Азия значительно изменилась в течение неотектонических фаз вследствие столкновения между Индийской плитой и Евразийским континентом. Ранняя и поздняя неотектонические фазы разделены региональным несогласием, которое установлено как поверхность, разграничивающая сильнодеформированные толщи (синрифтовые) и перекрывающие, менее деформированные формации (пострифтовые). Ранняя неотектоническая фаза, связанная с левосторонним смещением в зоне разлома Ред-Ривер, может быть разделена на две тектонические подфазы: эоцен – олигоцен (сжатие в СЗ-ЮВ направлении) и олигоцен – миоцен (широтное сжатие, В-З). В течение подфазы, датируемой как олигоцен – миоцен, возникли рифтовые впадины на континентальной окраине южной части Центрального Вьетнама. Поздняя неотектоническая фаза началась после прекращения сдвигового смещения в зоне разлома Ред-Ривер и прекращения расширения Восточного (Южно-Китайского) моря. Поздняя неотектоническая фаза также может быть разделена на две тектонические подфазы: поздний ранний миоцен (субмеридиональное сжатие) и поздний миоцен – плиоцен (сжатие в СВ-ЮЗ направлении). В течение подфазы, датируемой как поздний миоцен – плиоцен, происходили вертикальные движения, приведшие к формированию ряда поднятий на суше, а также опускания в районе морской впадины Фухань. При этом по всей южной части Индокитая и на континентальной окраине широко распространены миоцен-плиоцен-четвертичные базальтовые извержения.

Ключевые слова: южная часть Центрального Вьетнама (SCVN); зона разломов Ред-Ривер (RRFZ); Восточный Вьетнамский разлом (EVFS); Восточное море (EVS); впадина Фухань; Восточноазиатская глобальная сдвиговая зона (EAGSZ); тектонофизика

1. Introduction

The geological history of South East Asia landmass is closely related to ocean spreading and transformation of the geoblocks that belonged to Gondwana. At the beginning of Paleozoic, this region was a part of the Gondwana supercontinent. The separation and breakage of the Gondwana continental margin started in Cambrian-Ordovician. Continental fragments detached from Gondwana moved northward to connect to the Eurasian continent in the Phanerozoic. Opening of oceans took place in Asia: Paleo-Tethys opened in Devonian, Mezo-Tethys in Permian, and Neo-Tethys in Triassic-Jurassic [*Metcalfe, 1997, 1999, 2011*]. The continental fragments joined together through collision zones (ophiolite belts) and/or strike-slip zones.

In the Mesozoic, orogenic collision (Norian-Jurassic – Late Cretaceous, 200–100 Ma BP) took place in SE Asia due to the Indosinian tectonic activity. It was terminated by the Yen Son orogenic folding caused by collision between the Myanmar and Lhasa micro-plates and the Eurasian continent. At the same time, an alkaline volcano-plutonic island-arc belt, known as the Zhejiang – Da Lat belt, was formed along the coastal area of Vietnam and China. It resulted from subduction of the Pacific plate under the Eurasian continent. In the Jurassic–Cretaceous period, the relief of the SE China and SE Vietnam region was similar to the present Andes Mountain range of America [*Honza, Fujioka, 2004; Hutchison, 2007; Tran Van Tri, Vu Khuc, 2010; Yan et al., 2014; Kasatkin et al., 2017*]. The Zhejiang – Da Lat volcano-plutonic belt stopped its activity at the end of Cretaceous. By that time, the Viet Nam-China, Indosinia, Sinoburmalaya, Sumatra, and Borneo continental fragments joined together and connected with the Eurasian continent, resulting in its considerable accretion to the SE.

Later on, the Early Cenozoic tectonic quiescence in the region stimulated formation of planation surface in the region, and the Anamnese cordillera was changed into a more or less flat plain. The evidence of such plain can be found today in southern part of Central Viet Nam (SCVN) and the Central Highland of Tay Nguyen, known as the Paleogene Pediment of Indosinia (at ~2000–3000 m high). The largest remnant of that surface (~50 km^2) can be found in the Kon Ka Kinh area. The first sediment layer at the bottom of the synrift strucrures (grabens, haft-grabens) offshore of SCVN suggests a low-energy origin, which confirmed that the sediment came from a gentle relief [*An, Khanh, 2012*].

The Early Cenozoic equilibrium in SE Asia was disturbed by commencement of the Neotectonic phases. This was evidenced by the following: (i) strike-slip tectonics was widely observed in Viet Nam and the adjacent area; there were hundreds kilometers of horizontal displacement along the NW-SE fault system; and the Indosinian landmass moved considerably to the SE; (ii) formation of numerous extended centers in the peripheral margin caused opening of the East Viet Nam Sea (South China Sea) (EVS). Due to the SE movement of the Indosinian landmass, SCVN became a frontal tectonic zone where the Indosinian geoblock contacted the EVS terrain via the N-S-trending East Viet Nam fault scarp (EVFS). Therefore, studies of SCVN and the adjacent area can clarify the tectonic evolution of the region, considering in particular the processes of formation and development of EVS.

2. Database and methods of study

2.1. Database

In this study, we use structural measurements of about 100 outcrops in SCVN in the area from Quang Nam to Ninh Thuan provinces, including the islands (from 16°N to 11°N). The measurements were taken from 6552 fractures and 169 fault planes with slickensides. The outcrops are mostly composed of intrusive rocks dated Late Jurasic (J_3) to Cretaceous (K_1-K_2) (Dinh Quan and Deoca formations), extrusive rocks of Nha Trang (K_{nt}), Don Duong (K_{2dd}) formations, Neogene-Quaternary basaltic rocks, and sedimentary rocks from Middle Triasic (Mang Giang,T_2 mg), Mid-Late Jurasic (La Nga, J_{2ln}; Bao Loc,J_{3dbl}) to Neogene (Nsb) formations. Geophysical survey of the continental margin is also an important source of data.

2.2. Methods of study

Structural tectonophysical analysis was used to identify and study tectonic phases and their characteristics from reconstructed paleostress fields (σ_1, σ_2, σ_3). The tectonic phases were then classified by the order of their ocurrence, and older/younger phases were established. The tectonic phases were constructed in the regional scale, and their relationship with the regional evolution was considered. However, this kind of analysis failed to provide clear timing of the tectonic phases.

Interpretation of the seismic sections of the Tertiary basins gave us a good overview on timing of the main tectonic events that took place in each Tertiary basin. Based on these data, we determined the ages of each tectonic event from the tectonic unconformities.

Combining the data from the two sources (the onland outcrops, and the Tertiary basins) and other regional data, we consolidated the database for clarifying the tectonic evolution of the study area by analyzing the tectonic phases on the basis of the reconstructed paleostress fields.

The structural tectonophysical analysis was conducted using Open Stereo [*Grohmann, Campanha, 2010*] and FaultKin v7.5 software packages [*Marrett, Allmendinger, 1990; Allmendinger et al., 2012*]. The tectonophysical analysis method described in [*Sherman, Dneprovsky, 1989; Sherman et al., 1991*] was also in use.

3. Geological setting

In the Cenozoic, the India-Asia collision considerably changed the tectonic structure and geodynamic regime in the East and SE Asia. According to paleomagnetic data, the Indian continent and the Asian landmass experienced 'soft collision' ~58 Ma BP, which was followed by 'hard collision' that started at ~44 Ma BP [*Tapponnier et al., 1982, 1986; Lee, Lawver, 1994*]. These processes caused thickening of the crust and created the Tibet high mountain region. In the experimental model of Tapponnier, collision between the two plates occurred not only as accordion-like transverse compression, but was also accompanied by strike-slip displacements along the faults in the vulnerable zones of the crust. It was calculated from the model that from the beginning of collision to the present days, the Indian continent has moved northwards for over 2000 km. The energy of its movement has been partially released by strike-slip faulting. The role of the major strike-slip zones, in particular, the Ailao Shan-Red River fault zone, is very high, according to [*Tapponnier et al., 1982, 1986*]. In Oligocene and the beginning of Miocene, strong left-lateral strike-slip with horizontal displacement of about 700 km occurred along the Red River fault (RRFZ) and made the Indosinian geoblock move southeastward (Fig. 1). Some scientists suggested that along with the SE movement, the Indosinian geoblock underwent some significant clockwise rotation with an angle of about 15° [*Richter, Fuller, 1996; Hall, 2002*].

At the end of Cenozoic, the RRFZ experienced reversal of slip sense from left- to right-lateral, as a consequence of cessation of the southeastward movement of

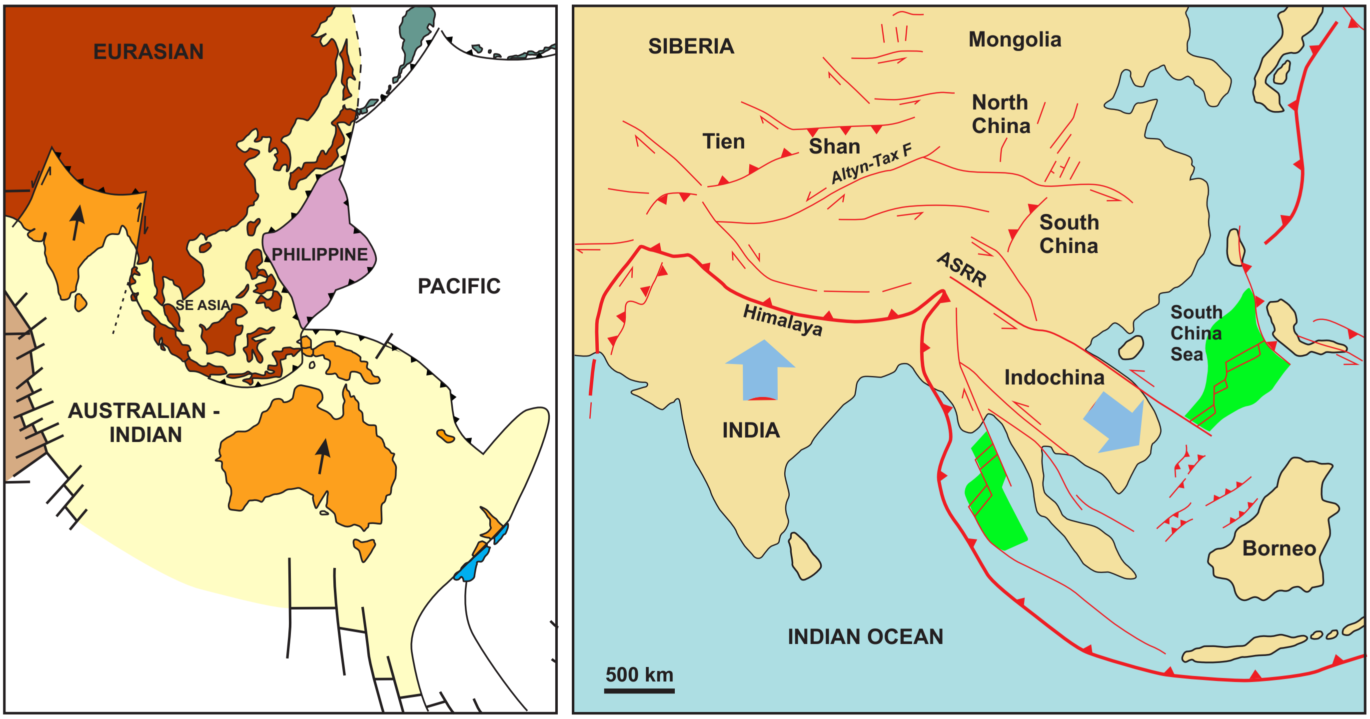


Fig. 1. Extrusion tectonics and formation of the East Viet Nam Sea (or South China Sea) after [*Tapponnier et al., 1982, 1986*].

Рис. 1. Экструзивная тектоника и формирование Восточного (Южно-Китайского) моря [*Tapponnier et al.*, *1982, 1986*].

the Indosinian landmass and further eastward movement of the China block. Placing precise constraints on the timing of the slip reversal remains controversial. According to the model of *Tapponnier et al.* [*1982*], the first phase terminated about 16–15 Ma BP, and then the the RRFZ slip changed from left- to right-lateral. The slip reversal caused reverse tectonic phase in the NW part of the Red River-Tonkin Gulf basin. As a result, major folds and uplifts were formed, which were truncated by subsequent erosion, forming clear regional unconformity surfaces [*Rangin et al., 1990, 1995; Bui Cong Que, Phung Van Phach, 2001; Morley, 2002*].

The NW-SE-trending regional faults, such as Ailao Shan-Red River, Song Hau-Maeping, and Three Pagodas, play a very important role in the movement of the Indosinian geoblock towards the SE, while the RRFZ plays an important role in releasing the energy brought about by the India-Asia collision by strike-slip movements along this fault.

Meanwhile, the collisional tectonics data shows that the formation and development of the EVS oceanic crust in the Cenozoic was closely related to the RRFZ strike-slip. In the model described in [*Tapponnier et al., 1986*], the left-lateral strike-slip of RRFZ caused the formation of the EVS basin.

According to the models in [*Tapponnier et al., 1986; Hall, 1996, 2002; Leloup et al., 1995a, 1995b, 2001*], during the first phase of the Neotectonic period (starting from Eocene), the Indosinian geoblock moved southeastward and thus caused an intensive left-lateral strike-slip movement of the RRFZ. In the models, the East Viet Nam Fault Scarp (EVFS) was considered as the eastern boundary of the Indosinian geoblock and was similar to the left-lateral strike-slip Red River fault. Tapponnier et al. considered EVFS as the main dynamic force forming the EVS oceanic crust (32–15.5 Ma BP).

The collision-extrusion tectonic model shows that the Tertiary basins, such as the Cuu Long and Noth Bac Bo, were formed at the end of the extentional horsetail-style NW-SE-trending fault system in the Eocene-Miocene epoch. At that phase, the W-E compression took place, as evidenced by the strong left-lateral strike-slip of the NW-SE-trending fault system (Cao Bang-Tien Yen, Chay River, Red River, Ba River, Rao Nay River, and Iasir-Song Ba faults), and the right-lateral strike-slip of the NE-SW-trending fault system (Tuy Hoa-Cu Chi, and Nha Trang-Tanh Linh faults).

Taylor and *Hayes* [*1983*] proposed that opening of the Cenozoic EVS was closely related to the EVFS right-lateral slip in conditions of the triple junction in the vicinity of the Southern Hainan Island. According to them, rifting and subsidence started in Eocene, and numerous rift structures occurred in South East Asia. Due to crustal stretching, normal listric faults, grabens and half-graben were formed. Most of the rifts extended prominently in the NE-SW and sub-latitudinal directions. The primary rift structures were filled with continental and lacustrine sediments. The main rifting

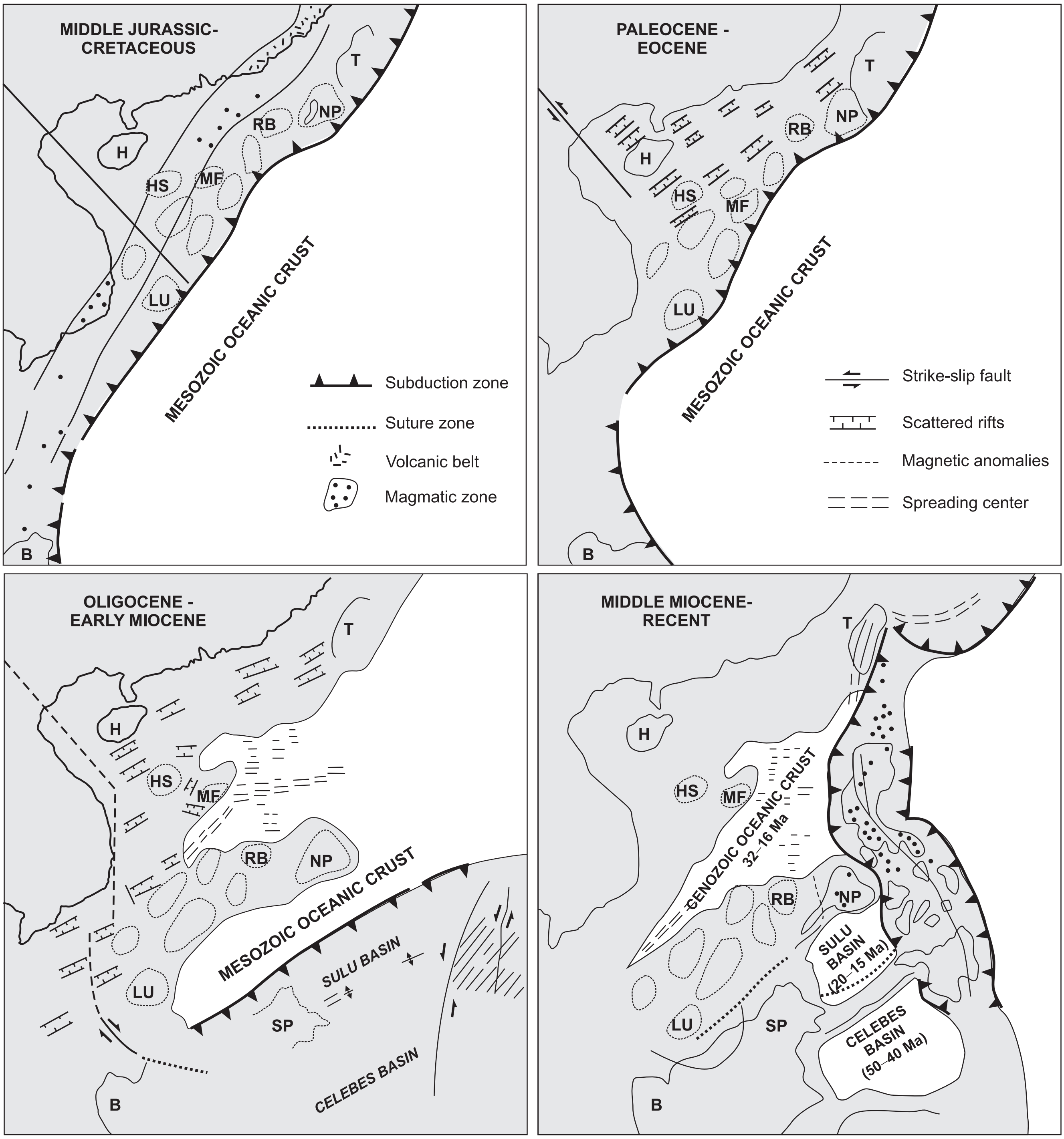


Fig. 2. Models of regional tectonics and formation of the East Viet Nam Sea (or South China Sea). After *Taylor* and *Hayes* [*1983*] and *Hall* [*1996*].

Рис. 2. Модели региональной тектоники и формирования Восточного (Южно-Китайского) моря [*Taylor, Hayes, 1983*; *Hall, 1996*].

period terminated by the begining of sea-floor spreading, forming the EVS oceanic crust (33–32 Ma BP). The forces responsible for rifting and opening of the EVS basin were the trench-pull forces along the Palawan trench (Fig. 2).

According to *Rangin et al.* [*1995*], *Roques* [*1996*], *Roques et al.* [*1997*], *Huchon et al.* [*1994, 1998*], and *Savva et al.* [*2013, 2014*], there is strong evidence of the global left-lateral strike-slip of the NW-SE fault system and its triggering role in opening of the EVS. However,

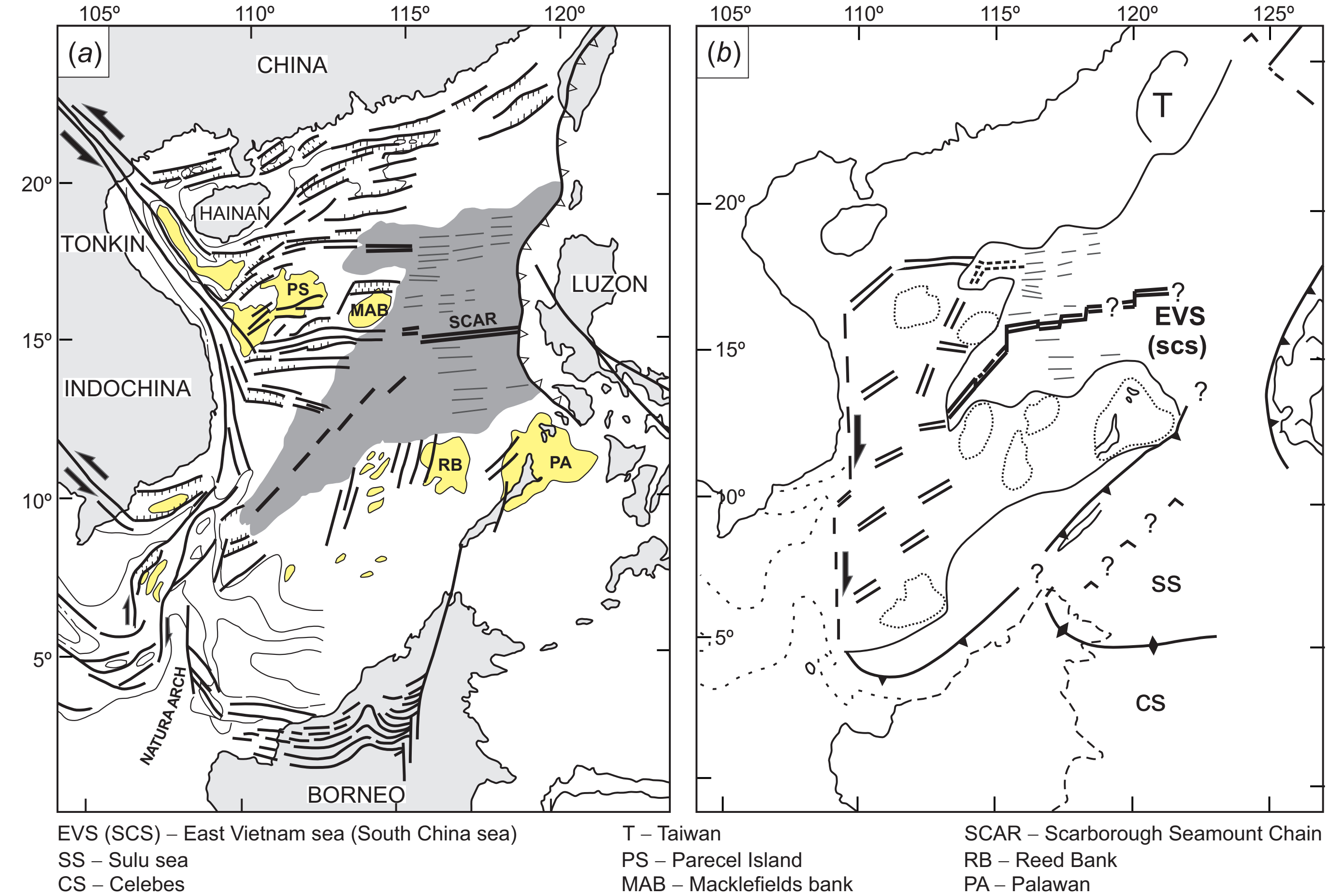


Fig. 3. Regional tectonics and formation of the East Viet Nam Sea (South China Sea): (*a*) – after *Rangin et al.* [*1995*]; (*b*) – after *Taylor* and *Hayes* [*1983*].

Рис. 3. Региональная тектоника и формирование Восточного (Южно-Китайского) моря: (*a*) – по [*Rangin et al., 1995*]; (*b*) по [*Taylor, Hayes, 1983*].

the above-mentioned papers say nothing about the left-lateral strike-slip of the EVFS. On the contrary, the right-lateral displacement of EVFS during the second phase is mentioned (Fig. 3).

Roques [*1996*] pointed out very strong stretching of the crust offshore of the Central Viet Nam region, especially in the Phu Khanh basin. In the central part of the basin, the Moho surface is raised up to the depth of 18 km. Respectively, if the sediment thickness is subtracted, the crustal thickness was only 8–10 km. Based on the seismic data interpretation, it is concluded in [*Savva et al., 2013, 2014*] that the sediment strata in the center of the Phu Khanh basin sits right on the uplifted Moho surface. *Vu et al.* [*2017*] suggested that left-lateral transtension of RRFZ and the EVFS took place mostly during Eocene-Oligocene and ceased during the Early Miocene. However, the NE-striking listric extensional faults in the Hoang Sa grabens and the outer Phu Khanh basin suggest the right-lateral transtension within EVFS. In view of the above-mentioned contradicting opinions and uncertainties, it is important to clarify the tectonic evolution of SCVN in order to obtain a more clear understanding of the tectonic evolution of the whole region.

Our study shows that the Tertiary basins in the study area typically have two synrift generations separated by distinct unconformities. The first synrift represents the Early Neotectonic phase. In seismic sections, it occupies the interval from Eocene to Early Oligocene. The unconformity on top of the first synrift is dated 32 Ma BP, i.e. the begining of the EVS opening. The second synrift developed in Oligocene–Early Miocene mainly at the western continental margin of EVS [*Franke, 2013; Franke et al., 2014*]. It is generally stated that the second rifting ceased in the Middle Miocene, and the unconformity is thus named Middle Miocene Unconformity (MMU).

In our study, we attempted to specify the tectonic structures and clarify the tectonic evolution of SCVN and the adjacent offshore area from the database including the data collected by us in the last decade, as well the data published in Vietnam and abroad. We also

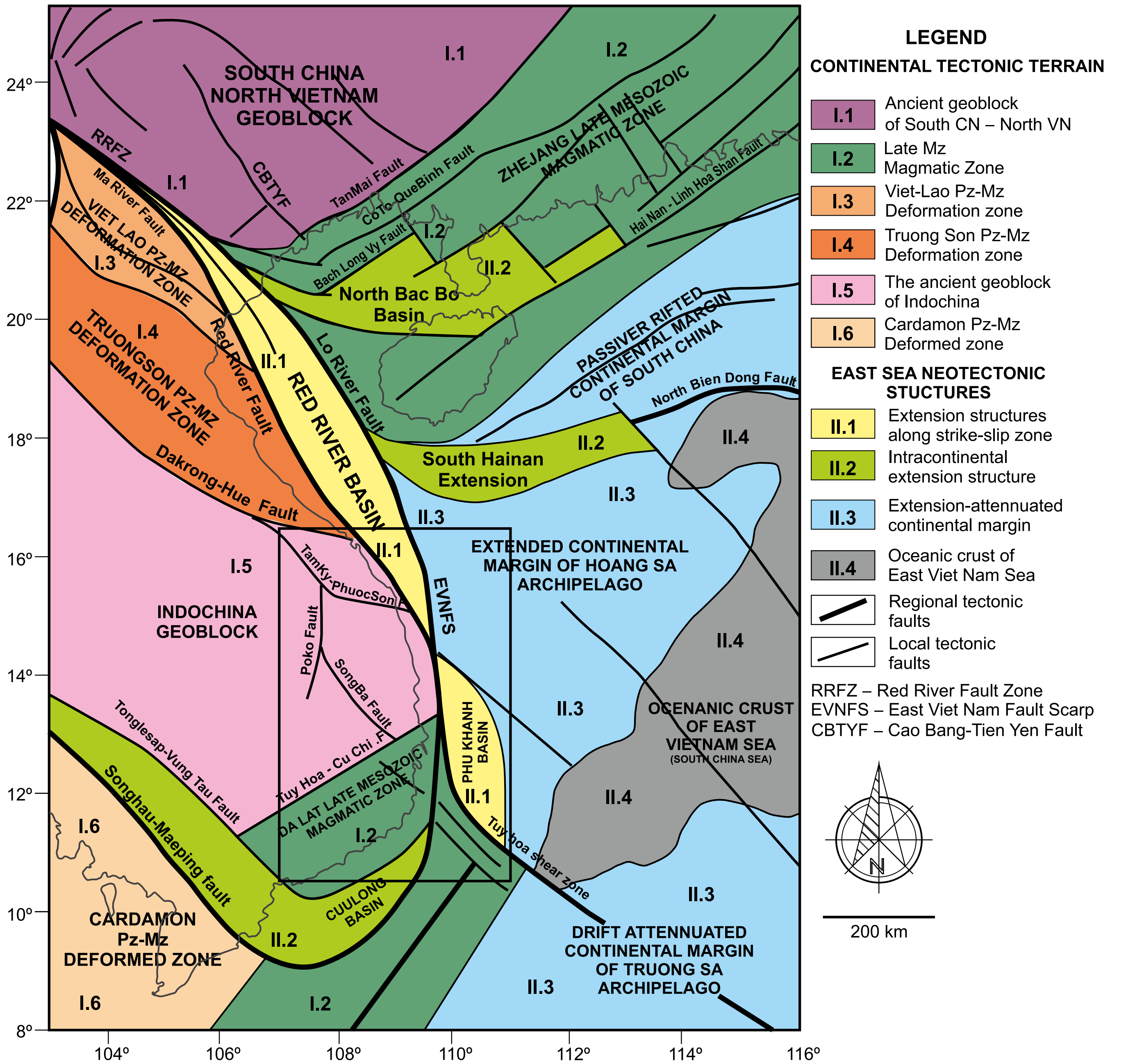


Fig. 4. Tectonic zonning of Viet Nam and the adjacent area [*Phung Van Phach, Le Duc Anh, 2018*].

Рис. 4. Тектоническое зонирование Вьетнама и прилегающей территории [*Phung Van Phach, Le Duc Anh, 2018*].

aimed to identify the characteristic features of tectonic phases and to reveal the order of their occurrence.

In the map (Fig. 4), the main tectonic units of the study area and the adjacent territories are shown. The geological units belong to two principal terrains: (1) the continental tectonic terrain, and (2) the EVS Neotectonic terrain. The terrains themselves and tectonic units inside the terrains are separated by tectonic faults that were activated during the evolution of the region and reflect the geodynamic regimes of tectonic phases.

The fracture patterns were reconstructed for the three main blocks of the study area, and it was revealed that the Kontum block is dominated by N-S fractures; the Da Lat block is dominated by NE-SW fractures; and the Quang Nam block shows a more complicated pattern of fractures with dominating NW-SE, W-E and NE-SW directions (Fig. 5).

In Binh Dinh and Phu Yen provinces (Kontum block), the stereographic diagram of fractures shows the domination of the sub-meridian direction.

In Khanh Hoa and Ninh Thuan provinces (Da Lat block), the stereographic diagram shows a variety of fault systems, among which the NE-SW faults and fractures are dominant.

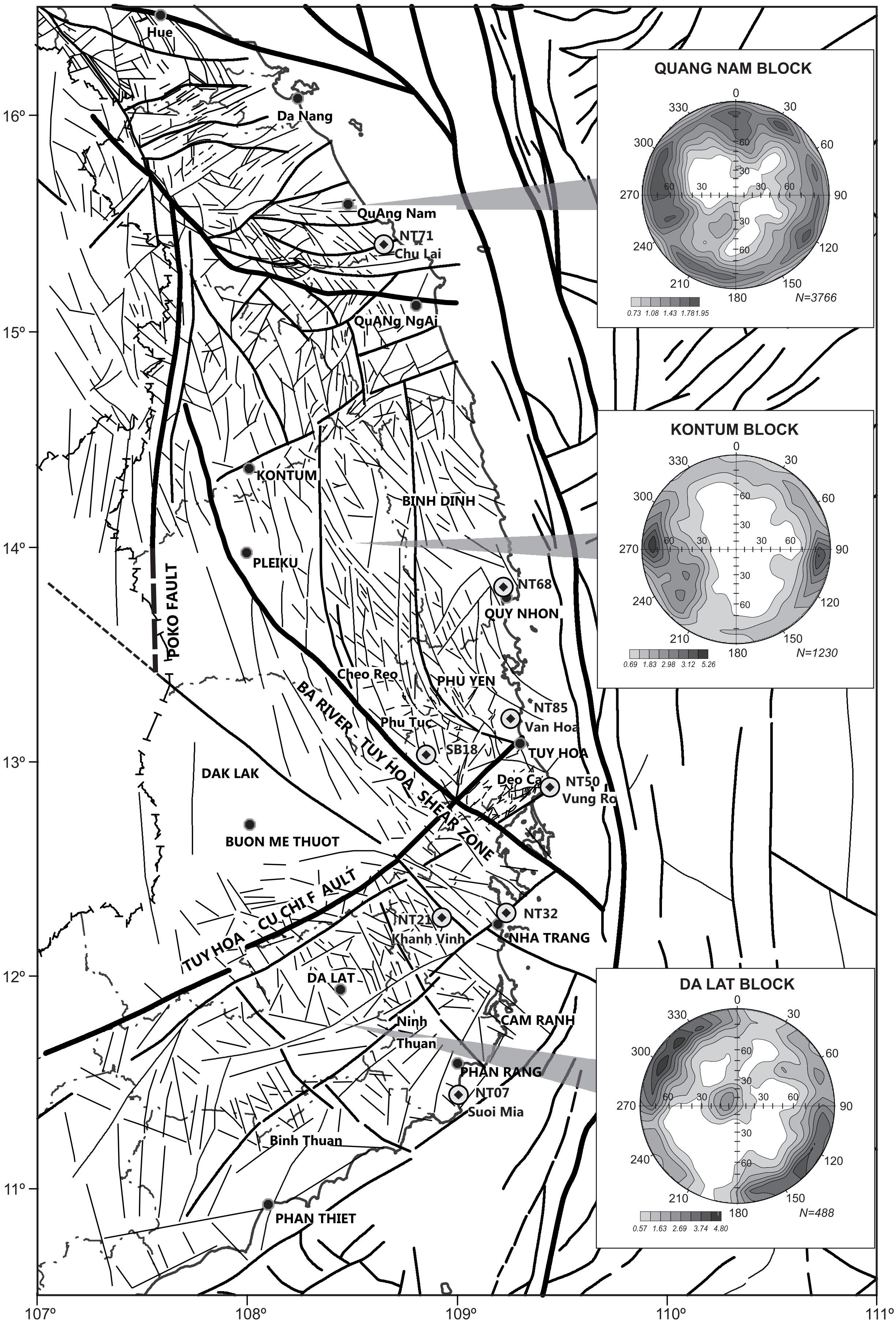


Fig. 5. Tectonic faulting in SCVN.

Рис. 5. Формирование тектонических разломов южной части Центрального Вьетнама.

4. Tectonic evolution of the Southern Central Viet Nam region

Based on the structural tectonophysical analysis of the data collected at the outcrops in the SCVN region from Quang Nam to Binh Thuan provinces during the last decade, as well the results of the geological and geophysical analysis of the seismic sections of the Tertiary basins, we attempted to specify the main tectonic phases in relation to the reconstructed paleostress fields.

In order to reveal the tectonic phases, we used structural analysis and tectonophysical calculations to reconstruct the stress fields from the data on fault planes, their relationships, slickensides, and sense of their movements. The tectonic phases were established from the onland data and then correlated with the events detected from the seismic sections of the continental margin. As a result, we have determined the succesion of tectonic phases in the region and established the characteristics of the tectonic phases, including their stress fields and time of occurrence.

4.1. Tectonic events in the Tertiary Phu Khanh basin

The tectonic events in the Tertiary basins of the Viet Nam continental margin are well recorded in seismic sections that are widely available for this region. Those events reflect the onset of rifting, break-up and other later tectonic events. In EVS, the break-up took place 32 Ma BP [*Briais et al.*, *1993*]; after that seafloor spreading commenced. The first oceanic crust appeared in the southern part of the China margin, then in the eastern part of EVS. The SW sub-basin of EVS began to spread only after magnetic anomaly 7 (~25.8 Ma BP). *Hayes* and *Nissen* [*2005*] suggested that rifting in the western margin of EVS continued up to 24–22 Ma BP. He concluded that extension of the Viet Nam continental margin ceased at the end of Oligocene.

Rifting and uplifting processes dominated during Oligocene and the Early Miocene. Later on, the basins were subject to continuos subsidence. The analysis of the multichannel seismic survey data shows that the Phu Khanh basin developed as a typical rift margin as follows: first, faulting started from the basement, and then it was followed by synrift sedimentation, formation of the break-up unconformity, and subsequent postrift sedimentation (Fig. 6, Table 1).

In general, the Tertiary basins of the Central Viet Nam continental margin have similar patterns of unconformities and seismic sequences. At least 5–6 regional unconformities are recognizable in Phu Khanh basin. The major seismic sequences (4 to 7 or may be more) are confined by the regional unconformities.

Many researches have been conducted to investigate and interprete the structure of the Phu Khanh basin. *Lee* and *Watkins* [*1998*] established six unconformities (SB1 to SB6) and six seismic sequences in the basin. *Fyhn et al*. [*2009*] identified four major unconformities (MB1, MB2, MB3, and MB4) and four megasequences (MS1, MS2, MS3, and MS4). *Nguyen Thu Huyen et al.* [*2014*] established and interpreted five unconformities (SH1 to SH5).

4.2. Tectonic phases of the SCVN region

Based on the structural tectonophysical analysis, we identified the major tectonic phases during the evolution of the SCVN region and determined the major tectonic phases. Results of the tectonophysical interpretation and structural analysis were used to specify the time constraints and to establish what event was older and what event was younger. The tectonic phases are correlated with the tectonic events in the Phu Khanh basin, as described below.

Cretaceous–Paleocene phase (~70–65 Ma BP). The Cretaceous–Paleocene phase is well established on the basis of abundant evidence discovered along the coastal zone of SCVN. It is evidenced by numerous mafic and felsic dykes that formed very soon after the Cretaceous granite intrusion, at the end of Cretaceous. Typical dykes located north of Nha Trang City vary in thickness from several centimeters to few meters (Fig. 7).

The widespread dykes in SCVN belonged to the Late Mesozoic volcanic-plutonic belt of Da Lat. The dykes had been also controled by the movement of the East Asian Global Strike-Slip Zone (EAGSZ), in particular the left-lateral strike-slip under N–S compression (Fig. 8) [*Kasatkin et al.*, *2017*].

Early Neotectonic Phase (~45–17 Ma BP). The Early Neotectonic phase is related to the left-lateral movement of the Red River Fault Zone and can be divided into two tectonic sub-phases: Eocen–Oligocene (NW–SE compression), and Oligocene–Miocene (E–W compression).

Eocene–Oligocene tectonic sub-phase (~45–32 Ma BP). Abundant evidence of the Eocene–Oligocene tectonic sub-phase was discovered in SCVN. This subphase included the NW-SE compression and the right-lateral strike-slip along the sub-laditudinal faults that displaced the previously formed dykes.

In the Khanh Vinh district (west of Nha Trang City, outcrop NT21, see in Fig. 5), a series of sub-laditudinal thrusts or over-thrust faults with right-lateral components displaced the Jurassic schist sandstone and mudstone strata (Fig. 9). Other outcrops showing strong evidence of the NW-SE compression were observed in the Deo Ca mountain pass (Vung Ro) where numerous sub-latitudinal fault planes cut through the granite rock of the Deo Ca formation with mafic dykes and displaced the dykes in the manner similar to displacements in outcrop NT50 (Fig. 10).

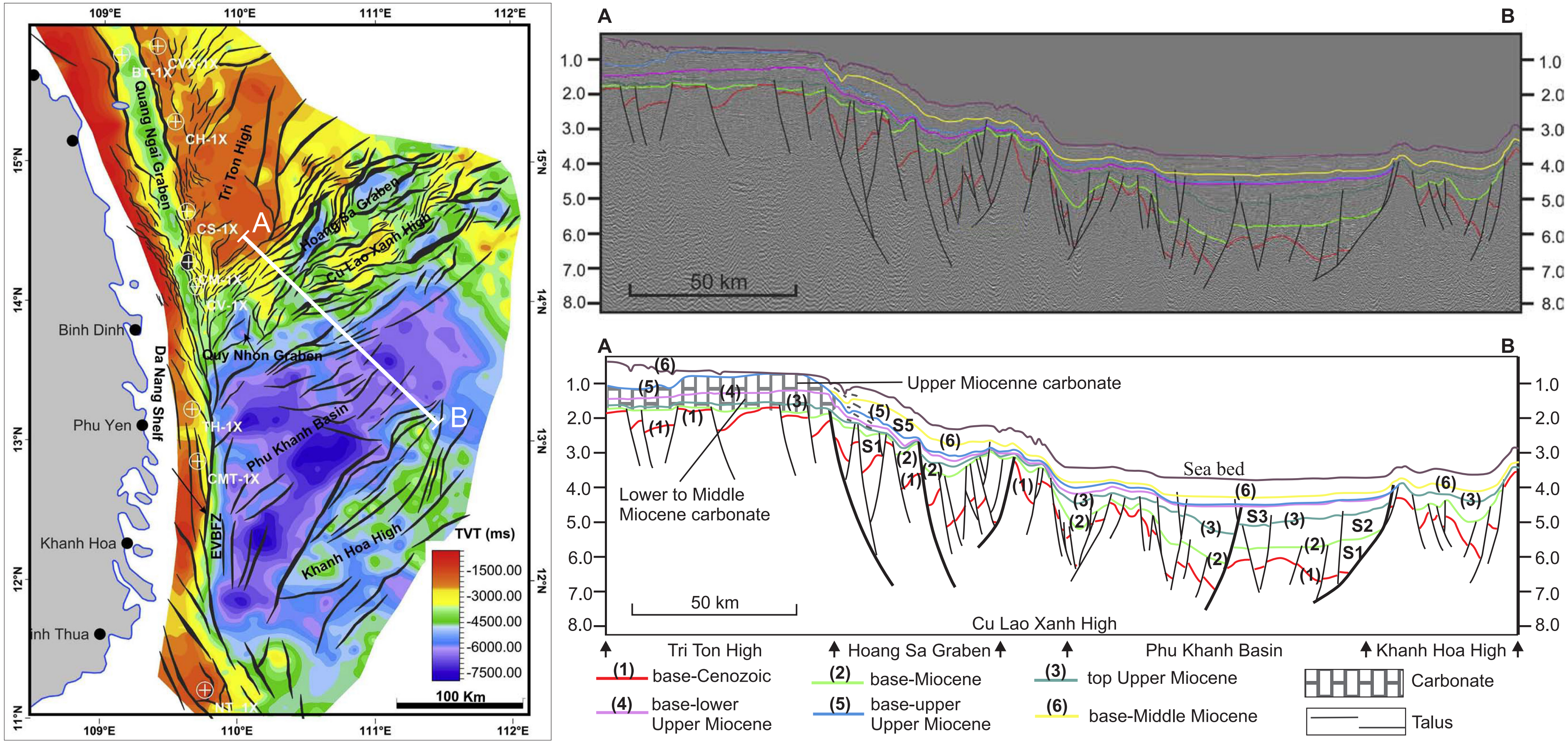


Fig. 6. Structural map of the Phu Khanh basin, seimic section showing the main unconformities [*Anh et al., 2017*] and schematic section.

Рис. 6. Карта структуры впадины Фухань, сейсмический разрез основных несогласий [*Anh et al., 2017*] и схематический разрез.

T a b l e 1. **The principal sequence boundaries (unconformities) in the Phu Khanh basin, according to different authors**

Т а б л и ц а 1. **Основные границы (несогласия) во впадине Фухань по данным, опубликованным разными авторами**

No.	[*Lee, Watkins, 1998*]	[*Fyhn et al., 2009*]	[*Nguyen Thu Huyen et al., 2014*]	Tectonic phases (our study)
1	SB1 >65 Ma	MB1 >65 Ma	SH1 >65 Ma	Cretaceous–Paleocene tectonic phase. Rifting in the continental margin
2	SB2 30 Ma	MB2 30 Ma	–	Eocene-Oligocene tectonic phase. Uplifting, break-up unconformity, and cessation of rifting in the continental margin (~32 Ma BP). Onset of spreading
3	SB3 25 Ma	MB3 24 Ma	SH2 23.3 Ma (top of Oligocene)	Oligocene-Miocene tectonic phase. Uplifting, erosion, and cessation of rifting in the SCVN continental margin (25–23 Ma BP)
4	SB4 16 Ma	–	SH3 16.3 Ma (top of Early Miocene)	Late Early Miocene tectonic phase. Cessation of sea-floor spreading in the entire EVS, and cessation of the left- lateral strike-slip along RRFZ (17±1 Ma BP)
5	SB5 10 Ma	MB4 10 Ma	SH4 10.4 Ma (top of Middle Miocene)	–
6	SB6 5.5 Ma	–	SH5 5.2 Ma (top of Upper Miocene)	Late Miocene–Pliocene tectonic phase (6–5.2 Ma BP). Commencement of the right-lateral strike-slip along RRFZ. Uplifting of the SCVN landmass, and subsidence of EVS. Onset of basalt eruption

N o t e. SCVN – Southern part of Central Viet Nam; EVS – East Viet Nam Sea (South China Sea); RRFZ – Red River Fault Zone; MB, SB, and SH – unconformities.

П р и м е ч а н и е. SCVN – южная часть Центрального Вьетнама; EVS – Восточное Вьетнамское море (Южно-Китайское море); RRFZ – зона разломов Ред-Ривер; MB, SB и SH – несогласия.

Fig. 7. Sub-meridian mafic and ultramafic dykes located north of Nha Trang city. Outcrop NT32 (location: 109°13’58’’E, 12°17’43’’N, see in Fig.5).

Рис. 7. Субмеридиональные дайки основного и ультраосновного состава, расположенные к северу от г. Нячанг. Обнажение NT32 (координаты: 109°13’58’’В и 12°17’43’’С, см. рис. 5).

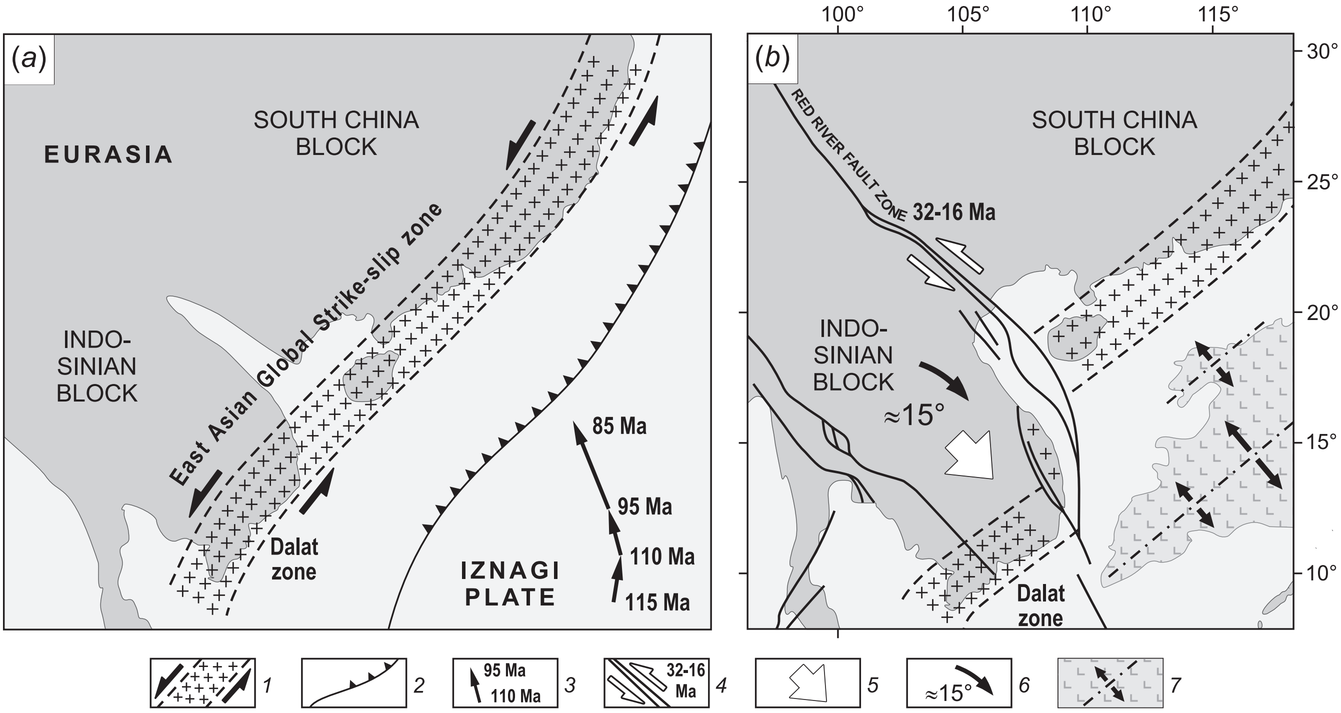


Fig. 8. Geodynamic reconstruction of the SE margin of Asia for Cretaceous (*a*) and Cenozoic (32–16 Ma BP) (*b*) [*Kasatkin et al., 2017*].

Рис. 8. Реконструкция геодинамики окраины СВ Азии: (*a*) – меловой период, (*b*) – кайнозой (32–16 млн лет) [*Kasatkin et al., 2017*].

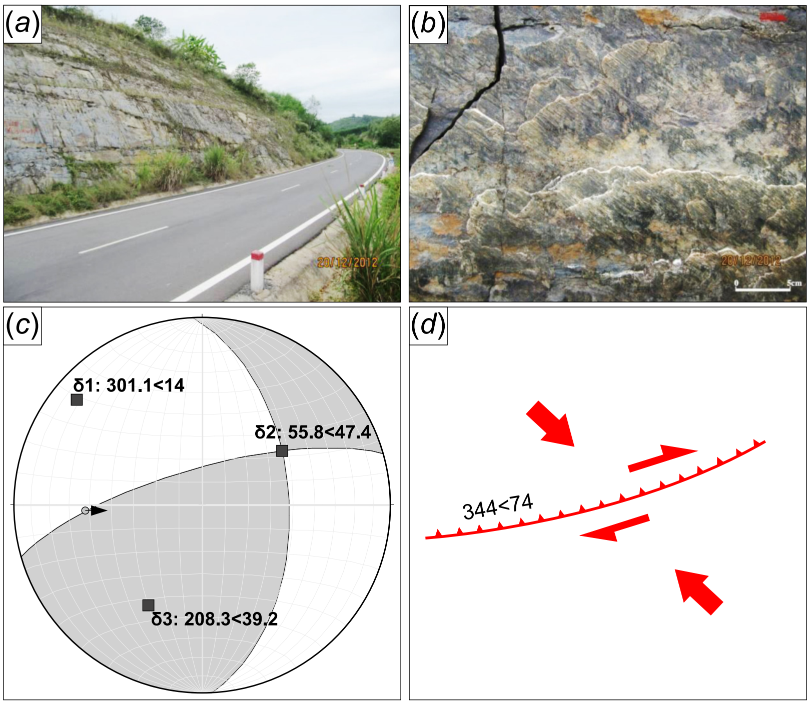


Fig. 9. Strong NW-SE compression resulted in the thrust righ-lateral slip of the sub-latitudinal fault in the Jurassic rock (outcrop NT21 located west of Nha Trang city: 108°55’35’’E, 12°16’21’’N, see in Fig. 5). (*a*) – outcrop along the road from Nha Trang to Da Lat. Sandstone and siltstone dip to the south (α=40–45°). (*b*) – clear right-lateral strike-slip: fault plane 344<74°, slickensides P=40°, dip to SW. (*c*) – stereographic diagram of the fracture data and the principal paleo-stress field: σ_1: 310<14°; σ_2: 56<47°; σ_3: 208<39°. It shows the thrust-strike-slip stress field (NW-SE compression). (*d*) – W-E-trending fault system. Large red arrows show compression.

Рис. 9. Сильное сжатие в СЗ-ЮВ направлении привело к образованию правостороннего надвиго-сдвига на субширотном разломе в породах юрского периода (обнажение NT21 к западу от г. Нячанг, координаты 108°55’35’’В и 12°16’21’’С, см. рис. 5). (*a*) – обнажение у дороги Нячанг-Долат. Породы: песчаник, алевролит; падение на юг (α=40–45°). (*b*) – явный правосторонний сдвиг: сместитель 344<74°, зеркало скольжения P=40°, падение на ЮЗ. (*c*) – стереодиаграмма трещиноватости и поле основных палеонапряжений: σ_1: 310<14°; σ_2: 56<47°; σ_3: 208<39°. Показано поле напряжений надвиго-сдвига (сжатие в СЗ-ЮВ направлении). (*d*) – система разломов широтного простирания. Крупные красные стрелки показывают направление сжатия.

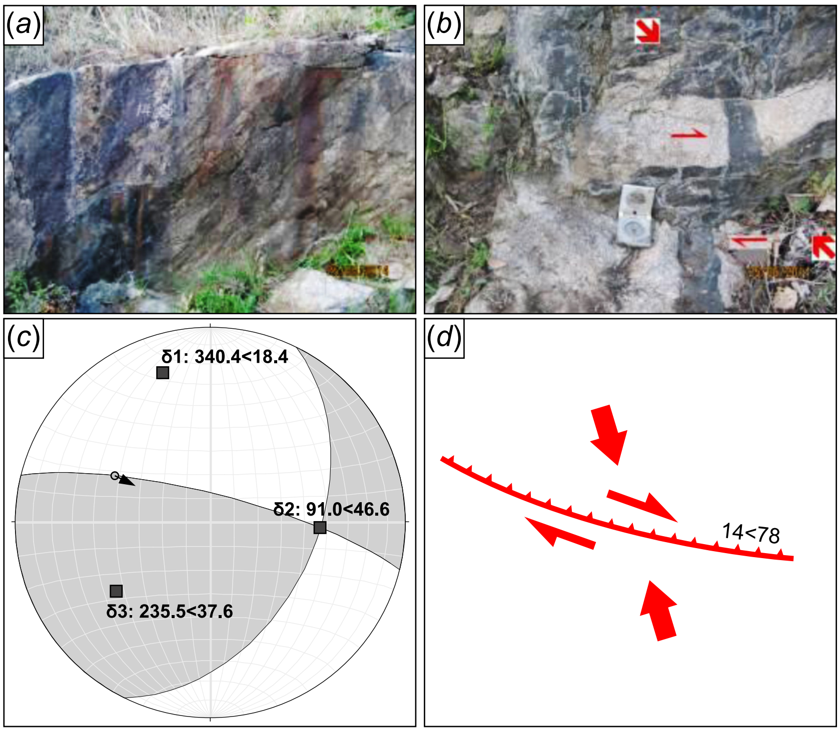


Fig. 10. Due to the NW-SE compression, the W-E-trending faults cut and displaced the mafic dyke in the granite rock of the Deo Ca formation as a thrust righ-lateral slip (outcrop NT50 located east of the Deo Ca mountain pass, location: 109°26’29”E, 12°52’58”N, see in Fig. 5). (*a*) – the W-E-trending fault cut and displaced the mafic dyke. (*b*) – W-E fault plane 14<78°, slickenside P=42°, dip to the west, with thrust right-lateral slip. (*c*) – stereographic diagram of the fracture data and the principal paleo-stress field: σ_1: 340<18°; σ_2: 91<47°; σ_3: 235<38°. It shows the thrust–strike-slip stress field and the NNW-SSE compression. (*d*) – W-E-trending fault system. Large red arrows show compression.

Рис. 10. Из-за СЗ-ЮВ сжатия широтные разломы рассекли и сместили дайку основного состава в формации Деока с формированием правостороннего сдвига (обнажение NT50 к востоку от горного перевала Деока, координаты: 109°26’29”В и 12°52’58”С. См. рис. 5). (*а*) – широтный разлом рассек и сместил дайку основного состава. (*b*) – сместитель широтного разлома 14<78°, зеркало скольжения P=42°, падение на запад, правосторонний сдвиго-надвиг. (*c*) – стереодиаграмма трещиноватости и поле основных палеонапряжений: σ_1: 340<18°; σ_2: 91<47°; σ_3: 235<38°. Показано поле напряжений сдвиго-надвига и сжатие в ССЗ-ЮЮВ направлении). (*d*) – система широтных разломов. Крупные красные стрелки показывают направление сжатия.

Oligocene–Miocene tectonic sub-phase (25–23 Ma BP). This tectonic phase is closely related to sea floor-spreading expansion toward the southwest. The SW sub-basin of EVS had been developing under the NW-SE extension stress, and its development differed from the eastern sub-basin that experienced the N-S extention. An unconfomity on top of Oligocene was formed. Above this unconformity, the Tertiary basins of the Viet Nam continental margin were sealed by the carbonate build-up. Later on, the EVS region was, on the one hand, related to the left-lateral strike-slip of RRFZ in the north and, on the other hand, was affected by indentation of the southern plates via the Borneo subduction [*Rangin et al., 1995*].

Abundant evidence of the Oligocene–Miocene tectonic sub-phase was discovered in SCVN. In Quang Nam, Binh Đinh, Phu Yen, and Khanh Hoa provinces, we found gentle N-S-trending thrust faults (e.g. outcropt NT68 located east of Qui Nhon city: 109°15’13.2”E, 13°48’58”N; outcrop NT71 in Chu Lai in Quang Nam province: 108°38’55.3”E, 15°24’19.2”N). A well-developed NE-SW fault system was observed from Nha Trang City and its vicinity towards the SW. In the granite massive of the Suoi Mia outcrop (Ninh Thuan province), the NE-SW fault plane and clear slickensides showing the right-lateral slip were discovered (Fig. 11).

Late Neotectonic phase (since 17 Ma BP to Present). The Late Neotectonic phase took place after cessation of the EVS spreading (17±1 Ma BP) and change in the direction of displacement along RRFZ from left- to right-lateral due to change in the dynamic correlation between the Indosinian and China geoblocks. This made the stress field in the subsequent period of Cenozoic change its maximum compression axis direction by up to 90 degrees.

The SCVN and the adjacent continental margin were affected by sub-meridian compression, but local stress orientation could change to NNE-SSW or NNW-SSE [*Phung Van Phach et al., 2014a, 2014b*]. The role of EVFS was also important. In this period, the right-lateral strike-slip movement of EVFS facilitated considerable subsidence of the Phu Khanh basin, and the shallow-water environtment was gradually replaced with the deep-sea conditions.

During this phase, the Indosinian plate and the adjacent area experienced large-scale basalt eruption (Fig. 12), that formed onshore basalt plateaus. In total, the basalt cover amounts to~25000 km^2 and its thickness

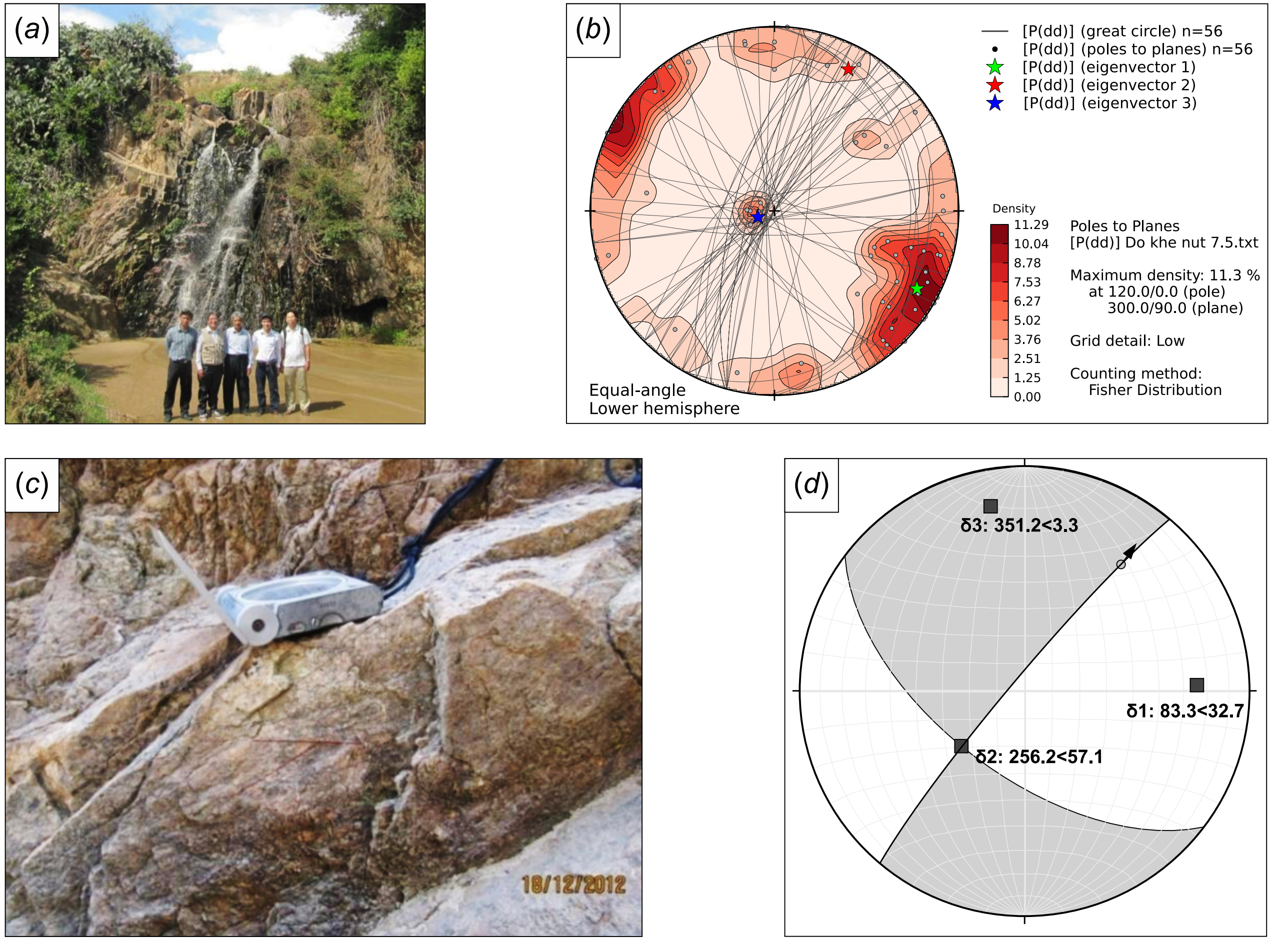


Fig. 11. Due to the W-E compression, the NE-SW faults cut and displaced the granite rock by the right-lateral slip (outcrop NT07 located at the Suoi Mia stream: 109°00' 19.3" E, 11° 26' 27.5" N, see in Fig. 5). (*a*) – Suoi Mia stream and the NE-SW-trending fault. (*b*) – stereographic diagram of fracturing. (*c*) – fault plane 312<70° and slickensides 12<24° (P=28°, dip to NE) showing strong right-lateral strike-slip. (*d*) – stereographic diagram of the fracture data and the principal paleo-stress field: σ_1: 83<32°; σ_2: 256<57°; σ_3: 351<3°.

Рис. 11. Из-за широтного сжатия (В-З) СВ-ЮЗ разломы рассекли и сместили гранитные породы с формированием правостороннего сдвига (обнажение NT07 у р. Суоимиа, координаты: 109°00'19.3"В и 11°26'27.5"С, см. рис. 5). (*a*) – р. Суоимиа и СВ-ЮЗ разлом. (*b*) – стереодиаграмма трещиноватости. (*c*) – сместитель 312<70° и зеркала скольжения 12<24° (P=28°, падение на СВ), сильный правосторонний сдвиг. (*d*) – стереодиаграмма трещиноватости и поле основных палеонапряжений: σ_1: 83<32°; σ_2: 256<57°; σ_3: 351<3°.

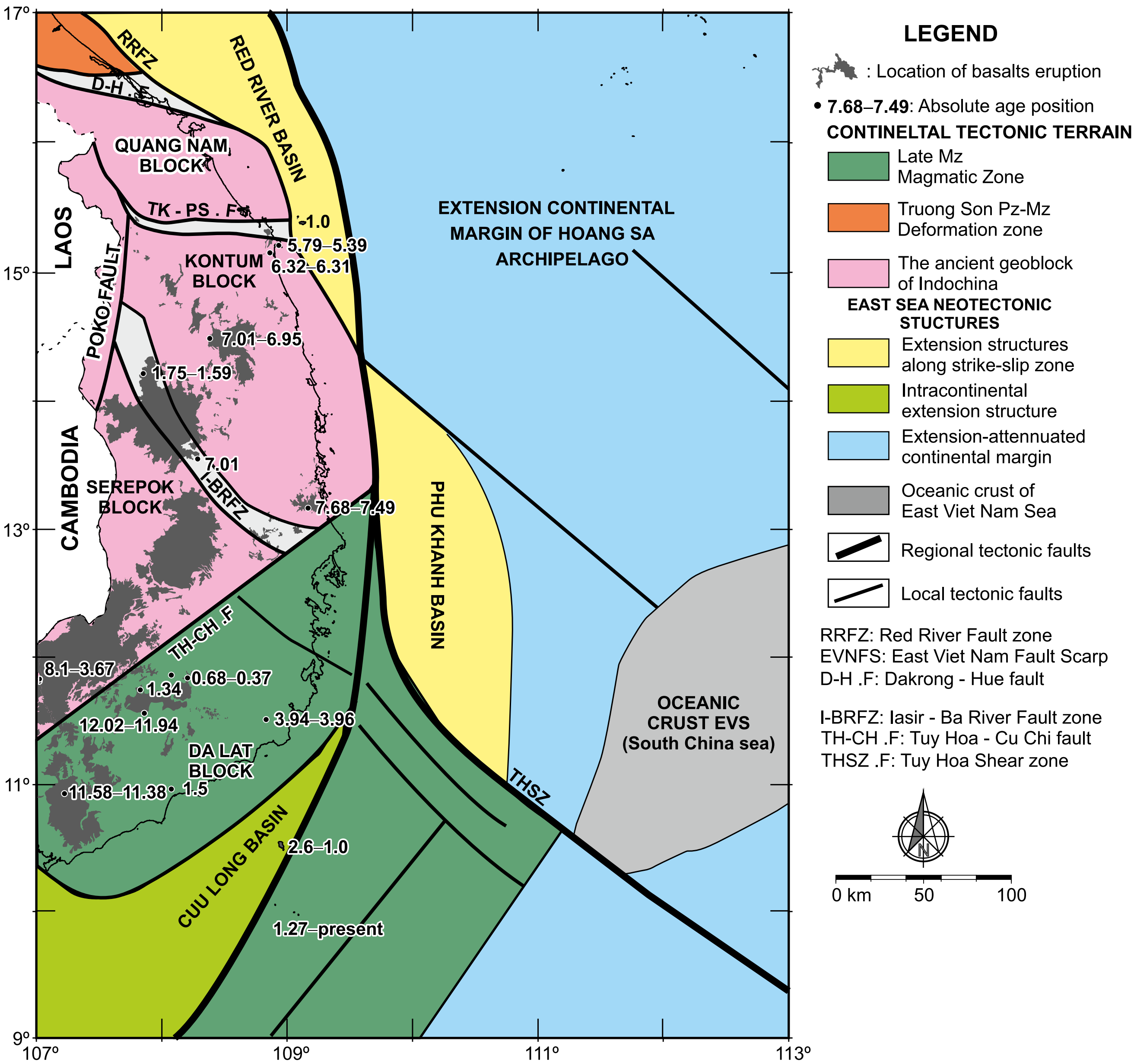


Fig. 12. Map of the Central and South Viet Nam showing basalt distribution and absolute ages [*Anh et al., 2017*].

Рис. 12. Карта распределения базальтов в Центральном и Южном Вьетнаме (показан абсолютный возраст) [*Anh et al., 2017*].

varies from 1–2 m to 500 m. Basalt is also widespread offshore. It was reported in [*Wang et al., 2013*] that 'mass transported deposits' (MTD) were discovered in the Hoang Sa Archipelago. The MTD strata formed due to basalt eruption in large amounts and strong uplifting of the Indosinian block, belonged to the upper Huangliu formation (8.2–5.5 Ma), and occupied ~28800 km^2 (~160 km W-E and ~180 km S-N). The maximum thickness reached 770 m.

In CSVN and the adjacent area, basalt eruption began after cessation of seafloor spreading, mainly after 6 Ma BP. The basalt eruption period can be roughly subdivided into three phases: (1) ~17–8 Ma BP, (2) 6–5 Ma BP, and (3) 2 Ma BP to present [*Anh et al., 2017*]. During the first phase, the basalt occurrence was limited to the Xuan Loc area, and tholeitic eruption is supposed to come from a shallow source (30–60 km). The second phase of basalt eruption was enormous and widespread in the Central Highland of Viet Nam occupying a large area. It formed large basalt plateaus in South Viet Nam: Pleiku, Buon Ho, Buon Ma Thuot, and Oranh. Mainly olivine basalt was erupted from deeper sources (60–100 km). During the third phase, basalt eruption was similar to the second phase, but its amount was limited, and the eruption events were solitary and usually formed conic-shape features. The

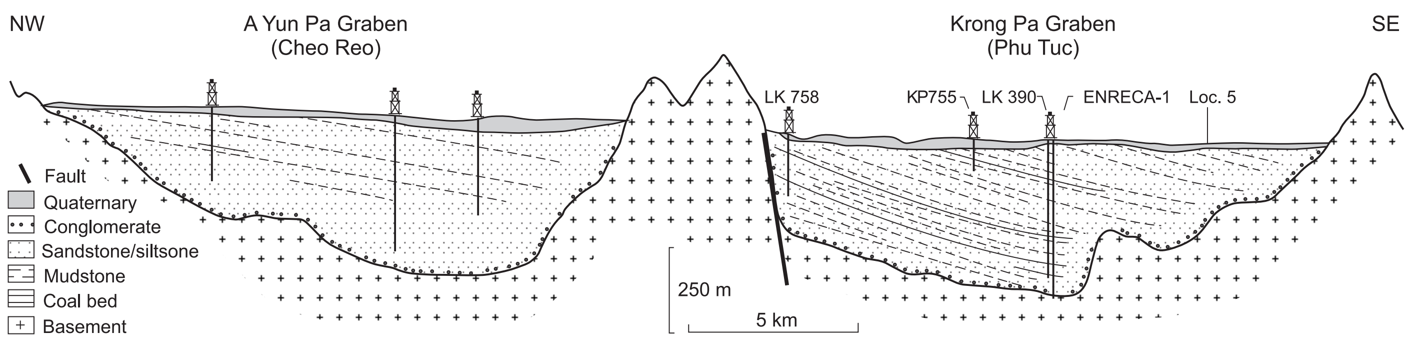


Fig. 13. The NW-SE section of the A Yun Pa (Cheo Reo) and Krong Pa (Phu Tuc) grabens along the axis of the Song Ba Rift. In the Krong Pa graben, true dip of the basin fill is mainly toward the SSW [*Nielsen et al., 2007*] (see the location in Fig. 5).

Рис 13. СЗ-ЮВ разрез грабенов Аюнпа (Чеорео) и Кронгпа (Футук) вдоль оси рифта Согба. В грабене Кронгпа отложения, заполняющие впадину, падают в основном на ЮЮЗ [*Nielsen et al., 2007*] (местоположение показано на рис. 5).

locations and distribution of volcanic mouths were generally controled by tectonic fault zones.

The Late Neotectonic phase also can be devided into two sub-phases: Late Early Miocene and Late Miocene-Pliocene.

Late Early Miocene tectonic sub-phase (17±1 Ma BP). During the Late Early Miocene tectonic sub-phase, one of the most significant unconformities was formed in EVS and adjacent area. It was named the end-rifting unconformity (ERU), and the stratigraphic hiatus lasted for 2–2.5 Ma [*Hutchison*, *2007*]. Generally, ERU marks the boundary between the below strongly deformed strata and the upper less deformed tectonic strata. Its age is ~17–16 Ma and slightly differs from one basin to another. This boundary is related to cessation of seafloor spreading in the entire EVS and ending of left-lateral strike-slip of RRFZ (17±1 Ma BP). After a significant period of quescence, RRFZ activated again as right-lateral slip. Such movement marked a new tectonic sub-phase, which lasts to the present day [*Tapponnier et al., 1986; Fyhn et al., 2009; Kasatkin et al., 2017*]. According to [*Tapponnier et al.*, *1986*], due to continuous movement of the India continent, the sense of slip along RRFZ changed from left- to right-lateral because the China block began to move faster to the east, while the Indosinian block remained stable. The Ba River-Tuy Hoa Shear zone became active during this sub-phase, and the lacustrine sediments of the Miocene-Pliocene were deposited in the Ba River valley [*Rangin et al.*, *1995*]. During this tectonic sub-phase, SCVN experienced regional uplifting, while subsidence took place in the neighboring continental margin. *Nielsen et al.* [*2007*] reconfirmed that the Song Ba Rift was strongly reactivated in the Middle Miocene, and the A Yun Pa (Cheo Reo) and Krong Pa (Phu Tuc) grabens were filled with more than 500 km thick deposits. The basal graben fill consists of thin fluvial sandstone layers interbedded with well-oxygenated lacustrine siltstones in the basin centre, while very coarse-grained fluvial sandstones and conglomerates dominate at the basin margins (Fig. 13).

In this period, the Ba River-Tuy Hoa shear zone was characterized by right-lateral strike-slip with trans-extention component. Outcrop SB18 (location: 108°51′7.9′′E and 13°2′5.1′′N, see in Fig. 5) at Ba River bank can be taken as an example. On that site, we discovered the NW-SE-trending fault, which length amounted to several dozen meters (Ba River fault) (Fig. 14).

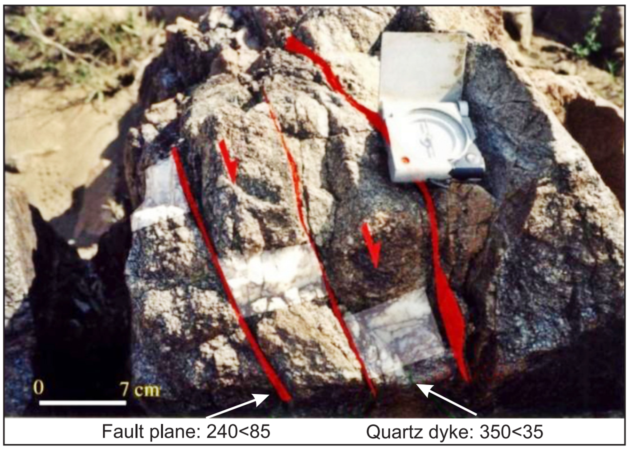


Fig. 14. Right-lateral slip with normal component of the Ba River fault (outcrop SB18): N–S compression; E–W extension. Fault plane 240<85° cut through quartz and diabase dykes and displaced them right-laterally, with normal component [*Phung Van Phach, 2014b*].

Рис. 14. Правосторонний сбросо-сдвиг разлома Ба-Ривер (обнажение SB18): меридиональное сжатие; широтное растяжение (В-З). Сместитель 240<85° рассек кварцевые и диабазовые дайки с формированием правостороннего сбросо-сдвига [*Phung Van Phach, 2014b*].

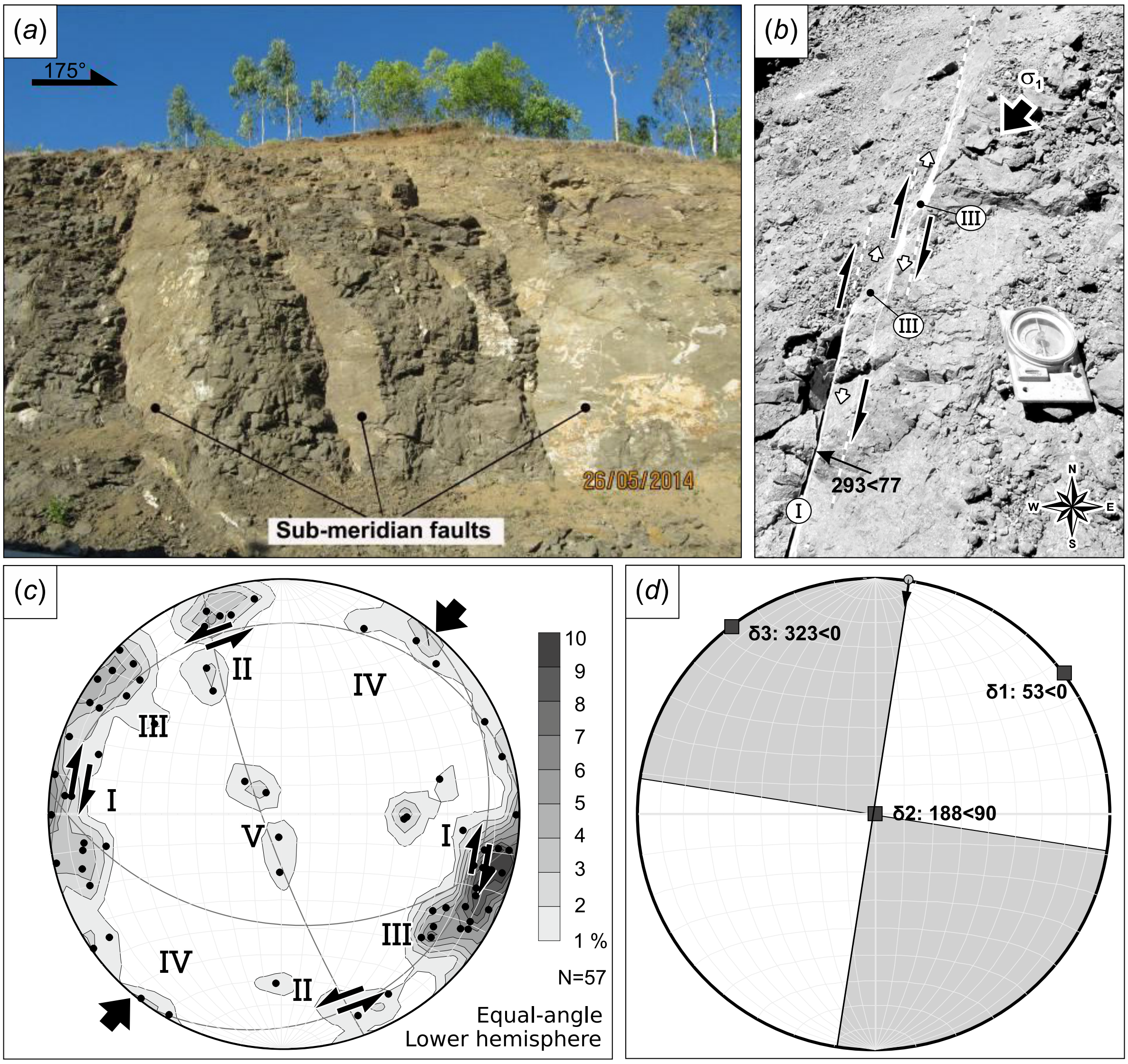


Fig. 15. Doc Suc outcrop NT85 (location: 109°15' 14.4"E, 13°12' 9.5"N, see in Fig. 5) at the foot of the Van Hoa plateau (Phu Yen province) (see Fig. 14, *a*). (*a*) – sub-meridian faults in the Miocene-Pliocene basalts. (*b*) – NNE-SSW fault system and related microstructures showing right-lateral strike-slip and NE-SW compression. (*c*) – stereographic diagram of fracture data. (*d*) – paleostress field calculated from fault plane 98<90° and almost horizontal slickenside (P~0°): σ_1: 53<0°; σ_2: 188<90°; σ_3: 323<0° [*Phung Van Phach et al., 2014a*].

Рис. 15. Обнажение Доксук NT85 (координаты: 109°15' 14.4"В и 13° 12' 9.5"С, см. рис. 5) у подножия плато Ванхоа (провинция Фуйен) (см. рис. 14, *a*). (*a*) – субмеридиональные разломы в миоцен-плиоценовых базальтах. (*b*) – система ССВ-ЮЮЗ разломов и микроструктуры, свидетельствующие о правостороннем сдвиге и СВ-ЮЗ сжатии. (*c*) – стереодиаграмма трещиноватости. (*d*) – поле палеонапряжений согласно расчетам по сместителю 98<90° и практически горизонтальному зеркалу скольжения P~0°): σ_1: 53<0°; σ_2: 188<90°; σ_3: 323<0° [*Phung Van Phach et al., 2014a*].

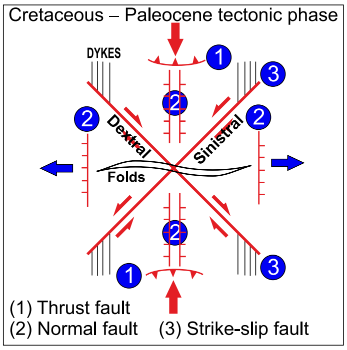
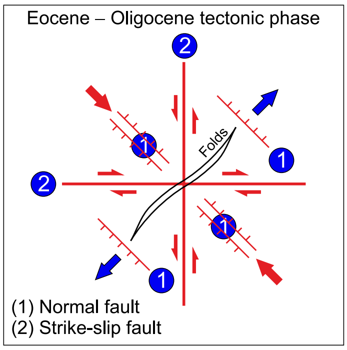
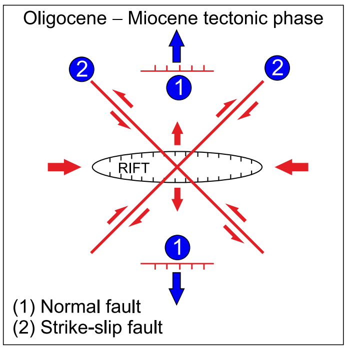
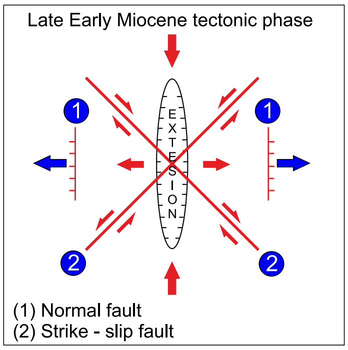
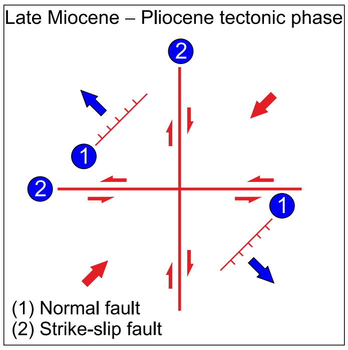
Late Miocene-Pliocene sub-phase (6.0–5.2 Ma BP). Late Neogene uplifting was related to the uplift of Central and South Viet Nam and subsidence of EVS. Olivine basalt eruption was voluminous during this sub-phase. The Miocene-Quartenary basalts are widespread in Viet Nam and the adjacent area and compose the major high plateaus (Pleiku, Buonho, Buonmathuot, Oranh, and Xuan Loc). Besides, there are basalt concentration locations of smaller sizes, such as Van Hoa and Konplong plateaus.

The basalt Van Hoa Plateau (1.8–5.3 Ma BP) is located in the zone of dynamic influence of EVFS. At the foot of this plateau, we investigated Doc Suc outcrop NT85 (location: 109°15'14.4"E, 13°12'9.5"N) and observed abundant steeply-dipping rectilinear ruptures with horizontal slickenside (P~10°). Sliding grooves were found ubiquitously (Fig. 15).

According to [*Phung Van Phach et al., 2014a*], the structural paragenesis including the NNE right-lateral and ENE left-lateral slip shows the NE (40°)-trending

Table 2. **Tectonic phases and correspondent tectonic stress fields**

Таблица 2. **Тектонические фазы и соответствующие поля тектонических напряжений**

<table>
<tr><th>No.</th><th>Tectonic phases</th><th>Tectonic stress fields</th></tr>
<tr><td>1</td><td>Cretaceous–Paleocene tectonic phase (~70–65 Ma BP)
Rifting in the continental margin</td><td>
</td></tr>
<tr><td>2</td><td>Eocene–Oligocene tectonic sub-phase (45–32 Ma BP)
Uplifting, break-up unconformity, and cessation of rifting in the Northern, Eastern and Southern EVS</td><td>
</td></tr>
<tr><td>3</td><td>Oligocene–Miocene tectonic sub-phase (25–23 Ma BP)
Uplifting, erosion, and cessation of rifting in the SCVN continental margin</td><td>
</td></tr>
<tr><td>4</td><td>Late Early Miocene tectonic sub-phase (17±1 Ma BP)
Cessation of seafloor spreading in the entire EVS. Cessation of the left-lateral strike-slip along RRFZ (17±1 Ma BP). Middle Miocene unconformity (MMU)</td><td>
</td></tr>
<tr><td>5</td><td>Late Miocene–Pliocene tectonic sub-phase (6.0–5.2 Ma BP)
Commencement of the right-lateral strike-slip along RRFZ. Uplifting of the SCVN landmass, and subsidence of EVS. Onset of basalt eruption</td><td>
</td></tr>
</table>

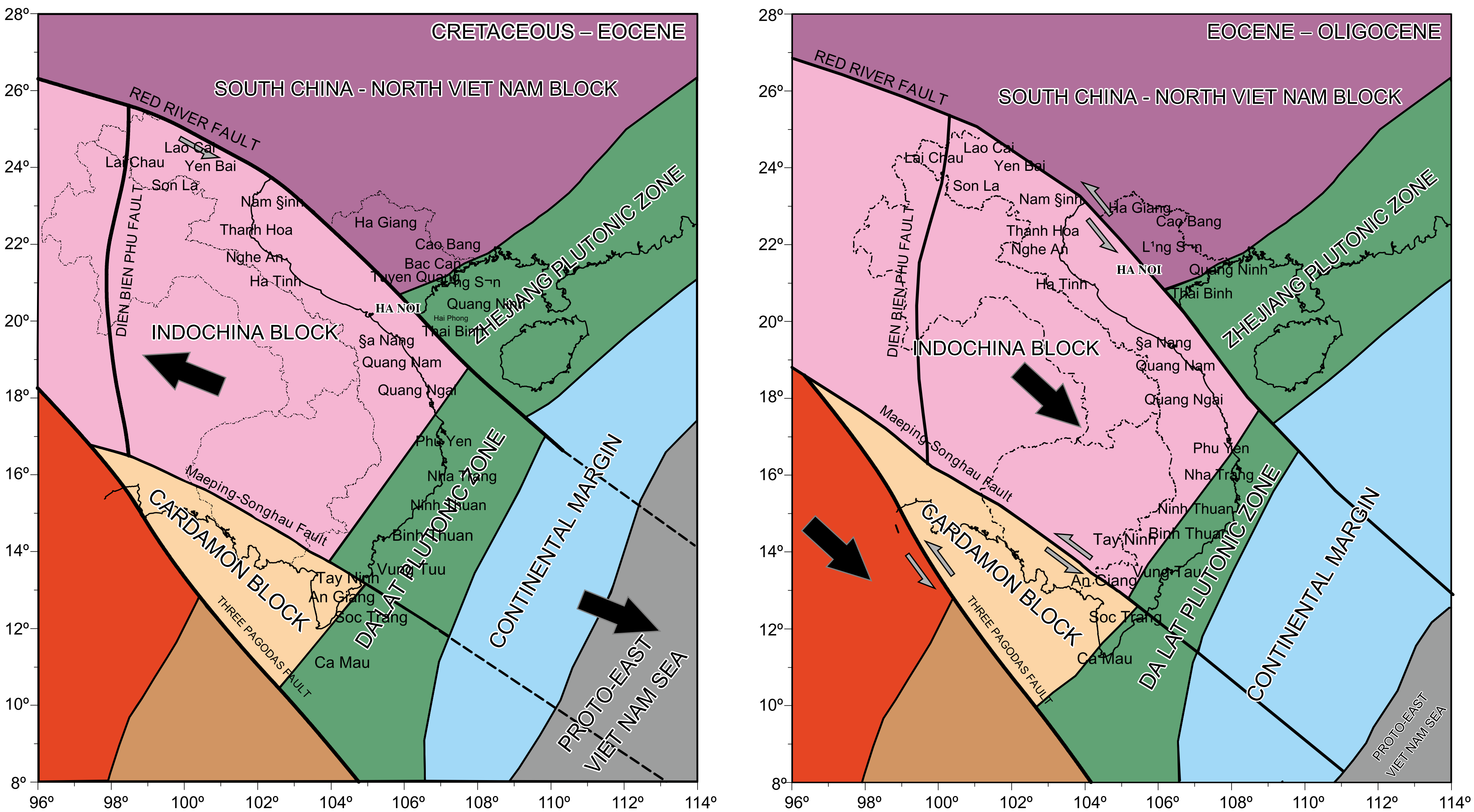


Fig. 16. Model showing the tectonic evolution of the South Central Viet Nam and the adjacent area during the Cenozoic era.

Рис. 16. Модель тектонической эволюции южной части Центрального Вьетнама и прилегающей территории в кайнозое.

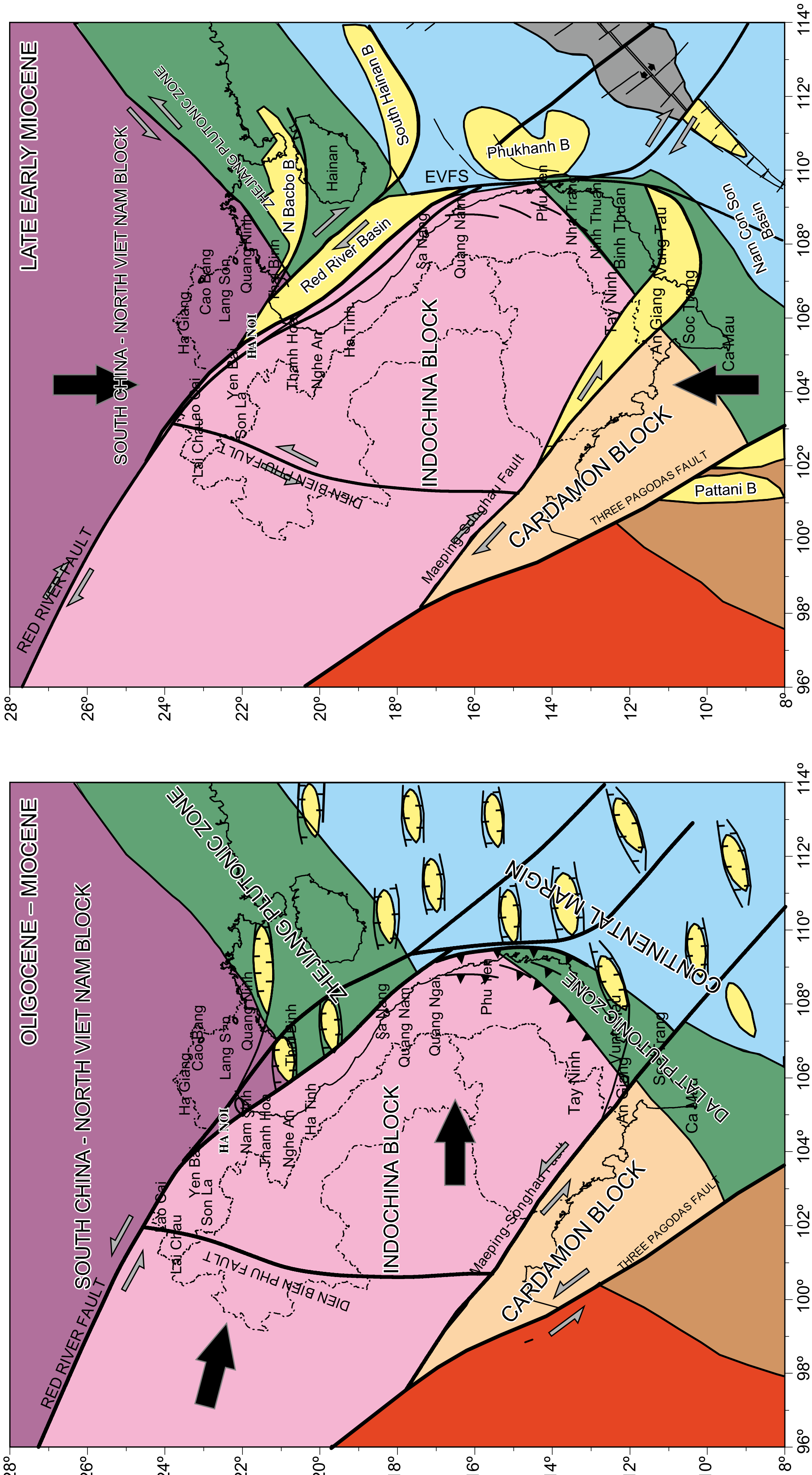


Fig. 16 (continuation).

Рис. 16 (продолжение).

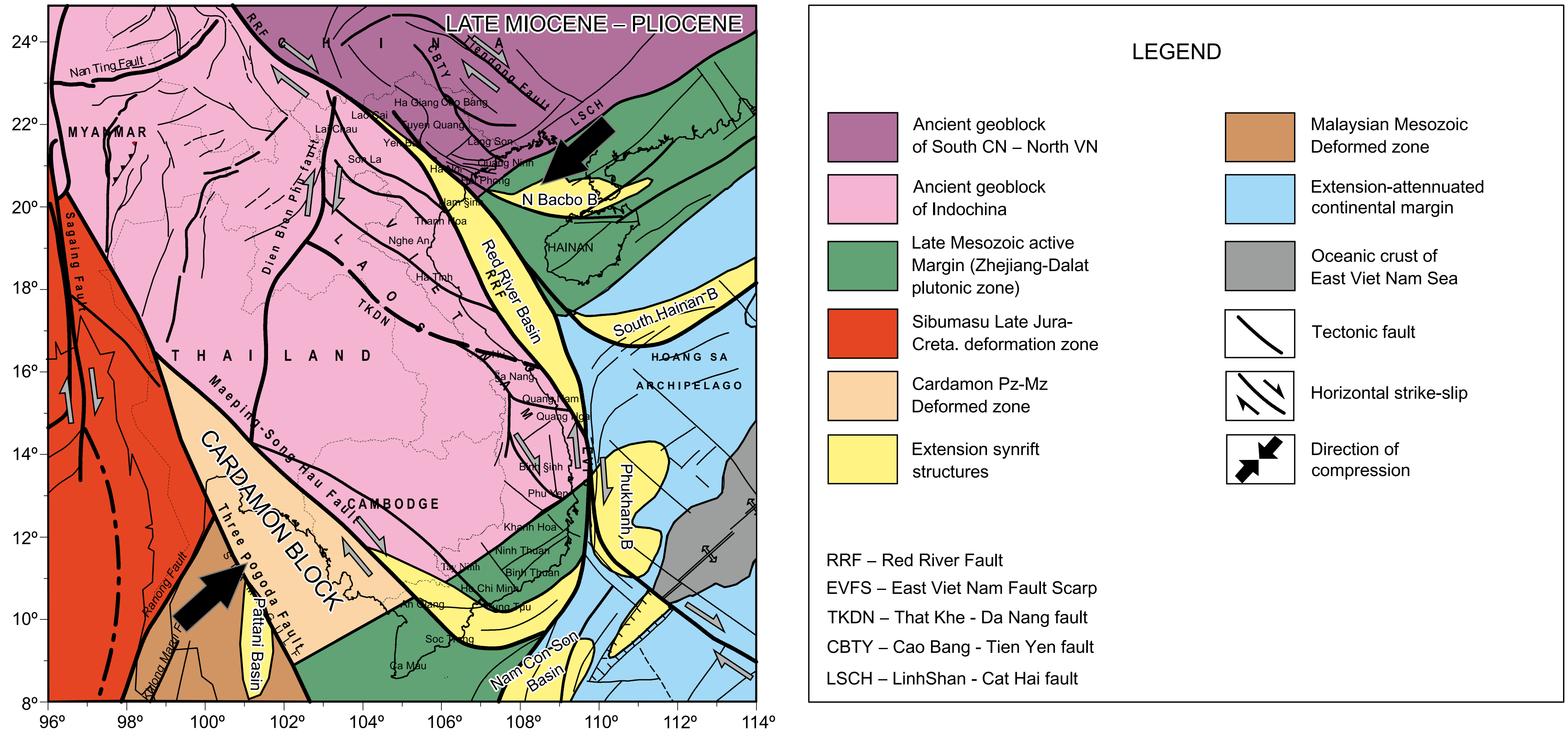


Fig. 16 (e n d).

Рис. 16 (о к о н ч а н и е).

compression and, correspondingly, the right-lateral displacements along EVFS in the Late Cenozoic. This compression was probably local and manifested itself in the area of co-fault extension at the non-co-axis dynamic interaction during the right-lateral displacements against the background of the submeridional regional compression.

The right-lateral slip with extension component was observed in some outcrops along the Ba River trough, e.g. strike-slip in the section of Pliocene strata near the Le Bac Bridge.

Table 2 shows the tectonic evolution of the study region, the characteristic features of the tectonic phases, and order of their occurrence.

5. Model of the tectonic evolution of the southern part of Central Viet Nam and the adjacent area

As described above, it is possible to establish five major periods of tectonic activity in the tectonic evolution of SCVN and the adjacent area. The Red River fault plays an important role as a boundary between two major terrains in the study area: the South China – North Viet Nam terrainconsidered stable during the Cenozoic (Neotectonic period), and the mobile Indochina terrain (SW flank of RRF).

In our opinion, the movements that disturbed the stable status of the Indosinian and the adjacent region in the Early Cenozoic were caused by commencement of the Neotectonic phase, which was maniftested by the onset of rifting in the entire region. The characteristics of the pioner rift formation at the bottom of the sediment basins suggest that rifting in the continental margin of Viet Nam started in the Eocene–Oligocene.

According to some data, the Indochina terrain moved to the SE for a distance of 500 km and rotated clockwise 15° [*Richter, Fuller, 1996, Hall, 2002*]. We assume that the amounts of displacement and rotation were divided equally between the tectonic phases.

In the Quaternary–recent time, vertical movement dominated in SCVN and the adjacent area. It caused, on the one hand, episodic uplift of SCVN and, on the other hand, fast subsidence of the offshore Phu Khanh basin. The Cenozoic basins considerably expanded, and the rate of Quaternary sediment deposition was high. In Quaternary period, the tectonic stress field of the region changed significantly, and the direction of compression (σ_1) changed to NNW-SSE, according to the GPS and seismic data.

Based on the above results, we propose a model showing the tectonic evolution of SCVN and the adjacent area (Fig. 16).

6. Conclusion

In the tectonic evolution of SCVN and the adjacent area since the Late Mesozoic to the present, we establish the following main phases that are closely related to interactions between the plates in the study area.

(1) Cretaceous–Paleocene tectonic phase: N–S compression and E–W extension; formation of numerous mafic and felsic dykes; in Paleocene, rifting in the continental margin of the Proto-East Viet Nam Sea.

(2) Early Neotectonic phase: extention, rifting, and seafloor spreading. This phase includes two sub-phases:

- Eocene–Oligocene tectonic sub-phase: NW–SE compression, and the right-lateral strike-slip along the sublatitudinal faults;
- Oligocene–Miocene tectonic sub-phase: E–W compresion, and widespread left-lateral strike-slip along the NW-SE faults.

(3) Late Neotectonic phase, including into two subphases:

- Late Early Miocene tectonic sub-phase: N–S and NE (40°)-trending compression, right-lateral displacements along EVFS, and intensive subsidence of the Phu Khanh basin;
- Late Miocene–Pliocene tectonic sub-phase: dominating vertical movements manifested by: (i) series of basaltic eruptions that are widespread all over the territory of the Indosinian plate and the adjacent area, and (ii) episodic uplifting of the onland terrains, and subsidence of the offshore Phu Khanh basin.

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