








Neotectonic Activities and Its Significance to River-Course Evolution: Implication for the Cai River Catchment, Ninh Thuan Province, South-Central Vietnam

Hai Thanh Tran¹ , Chi Kim Thi Ngo¹ , Hau Vinh Bui¹ ,
Binh Van Nguyen¹ , Thao Thanh Nguyen¹ , Hien Thi Hoang²,
Nam Xuan Nguyen³, and Tu Do Ngo Hoang⁴

¹ Department of Geology, Hanoi University of Mining and Geology, Hanoi, Vietnam

tranthanhhai@hmg.edu.vn

² Department of Geology and Minerals of Vietnam, Division of Radioactive and Rare Minerals, Hanoi, Vietnam

³ Vietnam Institute of Geosciences and Mineral Resources, Hanoi, Vietnam

⁴ Faculty of Geography and Geology, Hue University of Sciences, Hue, Vietnam

Abstract. The Cai River catchment of the Ninh Thuan province locates in the South-central portion of Vietnam. This area is underlain by various rock types, including Mesozoic to Cenozoic sedimentary and volcanogenic sequences and a large volume of magmatic complexes. The Cenozoic sedimentary cover comprises thin units that are commonly deposited within small deltaic or fault-controlled alluvial basins, and along discontinuous narrow coastal plains. Pliocene-Quaternary basaltic bodies are locally covered part of the coastal zone or form small offshore volcanic islands. These assemblages are variably deformed and dismembered as consequence of long-lived tectonic movements. Recent tectonic activities are evident by numerous indicators, which include brittle fracture and fault systems straddling Quaternary sedimentary covers and recent weathering profiles, numerous fault scarps, abrupt local land uplift and/or subsidence, disruption of drainage systems, occurrence of earthquake, exposure of hot spring water and mud/sand volcanos. Other morpho-tectonic features such as the presence of Quaternary terraces, exposure and displacement of coral reef, and the development or significant modification of drainage patterns and modern basinal architecture have also resulted from active tectonic activities. Dating of the deformed materials, including fault gauge, uplifted, or subsided sediments reveal that the recent tectonic movements have taken place continually during the Late Holocene to recent. The combination of diverse lithologies, multiple tectonic fracturing and displacement of the rock units, tectonic uplift, and subsidence, in conjunction with the surface processes and sea action, have resulted in complex river course and coastal morphology. Active faulting and local tectonic movements have created long-term effects on the river flow pattern and coastal zone stability, including the shifting of flow direction, the formation of subsided or uplifted structures, sea-shore modification. Lateral tectonic movements, on the other hand, have led to the modification of the flow

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2021

D. Tien Bui et al. (Eds.): *Proceedings of the International Conference on Innovations for Sustainable and Responsible Mining*, LNCE 108, pp. 1–17, 2021.

https://doi.org/10.1007/978-3-030-60269-7_1

pattern, which consequently creates local complex flow patterns and associated hazards along the Cai River and its tributary.

Keywords: Recent tectonics · Change of river course · Subsidence and uplift · South-central Vietnam

1 Introduction

The Cai River catchment area of Ninh Thuan province locates in the south-central portion of Vietnam (Fig. 1). Geological works conducted previously [1–4] show that the basement of area is represented by numerous lithologies of differing composition, ages, and origins. These are overlain by fluvial-deltaic or marine aeolian deposits and subordinated volcanic rocks of the Tertiary-Quaternary in age. Both the basement assemblages and sedimentary cover have undergone poly-phases of neotectonic deformation that have taken place from the late Mesozoic to present. The strong tectonic activities have led to intense fracturing and dismemberment of both basement rocks and sedimentary cover. The neotectonic activities are currently active [5–9], which is indicated by numerous indicators including the occurrence of neotectonic/active faults and fractures, the deformation of Quaternary sedimentary cover, tectonic- controlled terrane uplift and subsidence, modification of morphological features such as abrupt change of flow direction. The interaction of many factors such as the variation in lithologies of the basement, faulting and fracturing, localized tectonic uplift and subsidence in combination with the influence of subaerial processes including climate, weathering, surface water flow, wave and marine actions [5, 6].

The drainage system along the Cai River catchment in the Ninh Thuan province is characterized by a unique and complicated pattern, which is controlled mainly by the tectonic features (Figs. 1, 2). The morphological feature and evolution of a river system have been demonstrated to be the consequence of endogenic elements such as the spatial occurrence and composition different lithological units, tectonic strain regime, crustal movements, coupled with exogenic activities under the heavy influence of tropical climate (e.g., [10–17]). In addition, geohazards along the river catchment as well as in the river mouth area are also common. Some studies in this area (eg., Tran, 2015 [5]; 2020 [6]) have pointed out that the endogenic processes such as extensive faulting and eustatic movement are essential factors for the hazards to take place in the study area. Furthermore, the combined effects of ground uplift and subsidence in the context of relative sea-level rise also create additional parameters that shape the morphology and evolution as well as related geohazards in the river catchment, especially in the lower course and coastal areas related to the river basin [11, 15, 18]. However, these important endogenic parameters in the evolution of the river and its related geohazards in the area have largely been ignored or inadequately addressed in previous studies.

To obtain a thoroughly understanding of the nature of the recent geological structures and their role in the evolution and related geological hazards in the middle and lower portions of the Cai River catchment area in Ninh Thuan province and establish a basis for

application in assessment of the role and effect of neotectonic activities to other catchment areas along the coastal zone of central Vietnam, a comprehensive interpretation of structural features and their relationship to the evolution of the river must be carried out.

This paper presents new evidences for neotectonic movements and assess their roles as regional controlling parameters in the evolution of the Cai River course and its morphological features using the combination of field mapping, structural and tectono-morphological interpretations, and age dating of the Quaternary deposits as well as fault-derived materials.

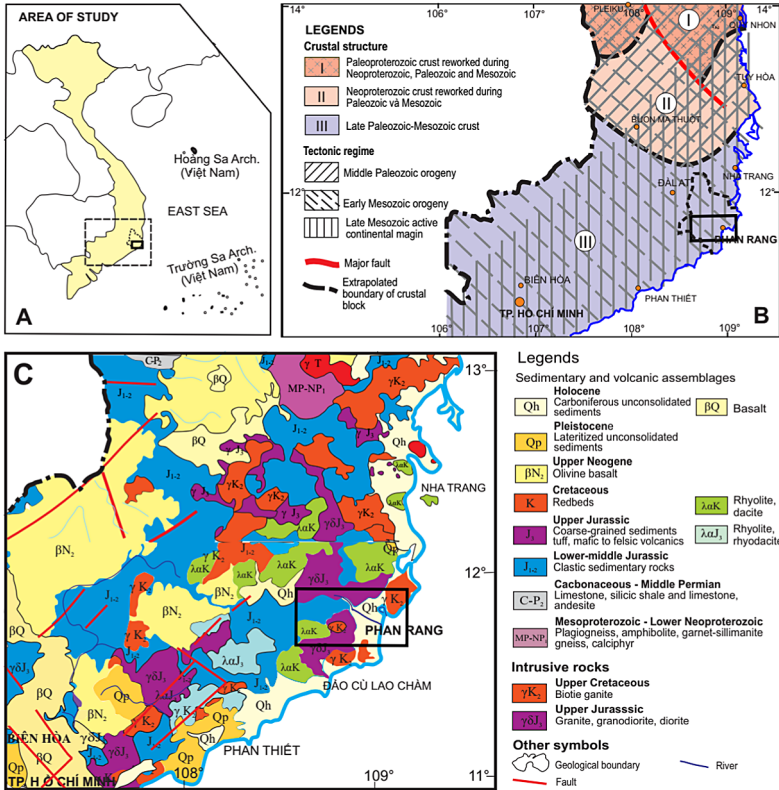


Fig. 1. A. General position of the Cai River catchment in the Ninh Thuan province, South-central Vietnam; dashed rectangle box is the area of B, area in dotted line is the approximate area of the Ninh Thuan province; small box is the location of this study; B. Generalized tectonic map showing the tectonic position of the study area in south-central Vietnam; rectangle box is the location of this study (modified after [19]); C. Generalized geological map of south-central Vietnam showing major lithologies of the underlying basement of the study area (modified from [4]); the area in the black box is the area discussed in this study.

2 Neotectonic Features of the Cai River Catchment, Ninh Thuan Province

2.1 Basement Rocks and Sedimentary Cover

a. Basement units

The Cai River catchment area occurs along the southeastern margin of Da Lat structural block, a tectonically complex terrane (Fig. 1B) comprising predominant Jurassic sedimentary units or intruded variably by numerous types of plutonic complexes (Fig. 1C; [1–4]). These are partly overlain by Cenozoic sediments and local volcanic layers that dominantly cover as well as shape the topography of the lower course and rivermouth portions of Cai River (Fig. 1C).

Within the area, oldest sedimentary units exposed are Mesozoic active continental margin assemblages including Lower to middle Jurassic volcanogenic clastic sedimentary units, which exposed in the western part of the area (Fig. 1C). These units are locally unconformably overlain by rhyolitic to dacitic volcanics of Cretaceous in age. In places, small outcrops of Neogene-Quaternary basalts are locally occurred. The Mesozoic rocks are largely intruded by numerous batholith-style felsic intrusive bodies of Late Cretaceous in age, which produced a region-wide basement of the study area (Fig. 1C).

b. Quaternary cover

Cenozoic sedimentary sequences cover dominantly the central part and along the coastal plain of the study area (Fig. 1C, 2). These consist of mostly Quaternary unconsolidated deposits of various origins and can be classified based of their age and origin [1–3]. Pleistocene deposits comprise marine, fluvial, alluvial and aeolian deposits that expose as the terraces, forming the foot-hill areas in the western part, whereas the aeolian-marine sediments commonly occur as remnants of dunes and plains along the eastern portion, particularly the coastal zone of the area. Poly-origin Holocene deposits consisting of alluvial, fluvial, lacustrine/lagoon, marine and aeolian sediments overlay the modern alluvial vales along the Cai River catchment and coastal area (Figs. 1C, 2).

2.2 Structural Features

The area has experienced strong neotectonics activities. All lithological units and Quaternary deposits in the area are variably deformed, indicated by fracturing, partly dismembering, and/or displacing that are caused by many phases of regional deformation [5, 6, 19]. Field mapping and structural interpretation have identified numerous paleo- and neotectonic structures, including faults and fracture zones of differing orientations and ages (Fig. 2). Many of fault systems appear to be multiple reactivated and are remained active throughout the Quaternary.

a. *Paleotectonic structures*

The Paleotectonic faults and fractures, which are considered to be predated 5 Ma in age (eg., [6, 20]), are widely documented within pre-Quaternary lithotectonic assemblages. These comprise numerous cross-cutting systems, including northwest-southeast, northeast-southwest, longitudinally, and trending [5, 6]. They can be identified by numerous evidences including large zones of brecciation, slickensides, and systematic distribution of fractures [5, 6]. Kinematic indicators identified from the faults and fracture zones as well as the cross-cutting relationship between different systems indicate that the movement history along the paleotectonic faults are complex, including reverse, strike-slip or oblique-slip (Fig. 2). Many fault systems are multiple reactivated, which are indicated by the presence of several generations of overprinting and cross-cutting fault-generated products.

b. *Neotectonic structures*

In the Cai River catchment area, numerous neotectonic fault and fracture systems, which are postdated 5 Ma in age (eg., [6, 20]), have been recognized (Fig. 2). Field mapping and structural interpretation have recorded many evidences demonstrating the occurrence of the neotectonic structures, especially active fault zones. These include the widespread exposure of brittle slickensides, unconsolidated fault gouge, and numerous open-spaced, systematic fractures that straddle and dismember the Quaternary deposits and/or weathering profiles/regoliths (Fig. 3). Furthermore, many tectono-geomorphological markers resulted from neotectonic and active movements such as linear distribution of triangular facets, fault scarps, uneven occurrence of drainage systems, colluvial cones and alluvial fans, or abrupt change of flow direction of flows, local zones of fault-controlled uplift or subsidence (eg., [11, 15, 21] and references herein) are also widely recognized within the study area (Figs. 2, 3, 4 [5, 6, 19]). In many places, the paleotectonic structures are overprinted or reactivated during neotectonic movements, which have locally created zones of multiple displacements during the Quaternary. In such zones, the overprinting of contrasting slip directions identified on the slickensides points towards a unstable neotectonic regime with opposing movements that has strongly affected the architecture as well as the spatial occurrence of the Quaternary sediments along the Cai River course and its tributary (Figs. 2, 3, 4).

Besides, the existence of active seismic activities [22], which has been recorded systematically recently [6, 8, 9], as well as the evidence for a recent volcanic eruption in nearby areas, both onshore and offshore, and presence of numerous hot springs, are direct accounts for strong active tectonics in the area (see Tran, 2020 [6] for detailed data).

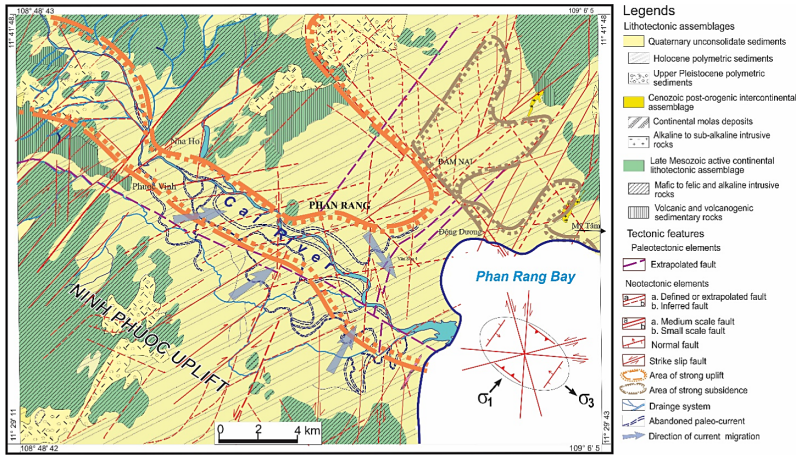


Fig. 2. Generalized neotectonics map of the middle-lower courses of Cai River, Ninh Thuan Province constructed based on various data sources (see [1–3, 5, 6]). Insert show the general distribution of fault systems and their approximate relationship to local stress-field during the Quaternary. Note that the main flow of the Cai River was migrated from the southwest to the northeast of the study area during the recent time, indicated by numerous evidences for the abandoned currents of the Cai River that are widespread in the area and can be used to delineate and restore at least parts of the paleo-flows (Fig. 2). The widespread of the bending and sudden change of flow direction is related to the lateral movement of many active faults, whereas subsided areas are commonly related to the fault-controlled, pull-apart style basin (e.g., Dam Nai area, Fig. 2). The dominant northeasterly-directed migration of the flows is considered the consequence of a major uplifting of the crust in the south of the rea (eg., the Ninh Phuoc Uplift).

2.3 Morphological Variation Related to Neotectonics Movements in the Cai River Area

The current geomorphology and landscape along the middle and lower courses of the Cai River area in Ninh Thuan has derived from the development of a number type of landform [1, 2] that are controlled by a combination of neotectonic endogenic and exogenic processes [11–16, 21, 23]. This includes the occurrence and spatial distribution of various type of lithologies, their internal structures and physical property, tectonic structures, seismicity activities, water activities, sedimentary transportation and deposition, wind and sea/wave actions, weathering and erosion and other climatic elements.

Based on the examination of the comprehensive relationship between tectono-morphological features with basement architecture, neotectonic endogenic and subaerial exogenic processes, a number of genetic morphological types have been categorized in the study area [1, 2, 5, 6], consisting of erosional, fluvial, marine, lagoonal, aeolian, and composite landforms. The landforms related to erosion commonly occur above the exposed lithologies and within the uplifted terranes. The fluvial-derived landforms consist of valleys and plains developed along the drainage systems, which commonly create flood plains, terraces or channels that formed by the combination of subsidence or uplift coupled with the influence of faulting and fracturing of the basement (Figs. 3 and 4). In many cases, the morphology and spatial distribution of the surface flows are governed

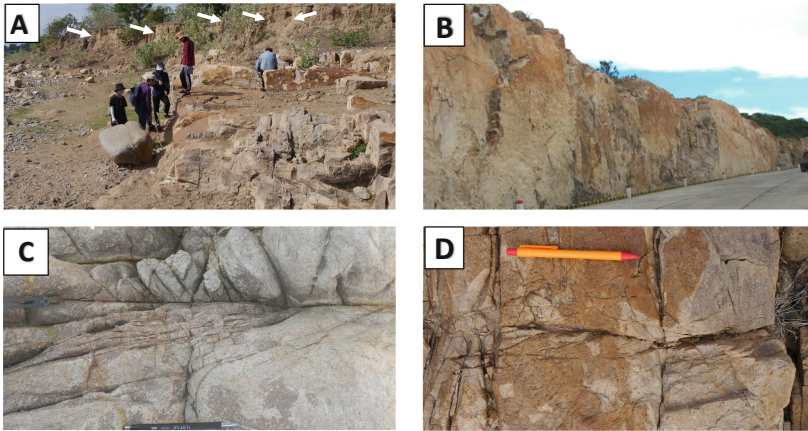


Fig. 3. Examples of field occurrence of neotectonic structures in the middle and lower course portion of the Cai River, Ninh Thuan province: A. A large fault zone developed in intrusive rocks and Quaternary cover crops out in the Nha Trinh area. Note the white arrows point to the fracture zones as parts of the fault straddle the Quaternary sedimentary units; B. A slickenside as part of a large, longitudinally trending fault exposed at the Dinh Co Pass, northeast of the area (After Tran, 2017 [5]); C. A Riedel-style brittle fault zone in granitic rocks in Nha Trinh Dam area; D. Multiple cross-cutting faults, which produced complete fracture zones and dismemberment of the rock bodies seen at Nha Trinh Dam; E. A NE-SW trending fault crosses cut the Neogene-Quaternary basaltic layers observed along the left bank of Cai River in Nha Ho area; F. An angular unconformity in Quaternary deposits exposed in Nha Ho area: dotted yellow line is the trace of unconformity, dashed white line is trace of bedding; G. A large outcrop of folded and faulted Quaternary deposits seen in My Tan, east of the study area (see Tran, 2020 [6]): dashed yellow line is the trace of folded bedding, dashed red lines are the fault zone; rectangle boxes are location of figs H and I; H. Part of a fault zone in G, red arrow indicates the width of fault zone in the picture; I. part of G being sampled for radiocarbon and TL dating (after Tran, 2020 [6]).

by the underlying neotectonic structures, particular large fault and fracture zones (eg., [11, 15, 21]; Figs. 2, 3, 4). The lagoonal and marine derived landforms including marine terraces, coastal plains, lagoons and beaches occurring along the lower course and river-mouth portion of the study area (Figs. 3, 4). The aeolian landforms are widespread in the eastern portion of the area and comprises both depositional and erosional types: the earlier comprises dunes, barchan dunes, and locally thin loess layers that are locally formed elongated sand hills adjacent to the shoreline in the southeastern portions of the area (Fig. 2), whereas the later commonly occurs as ventifacts, yardings and pans in the high-relief, bed rock-exposed areas along the coastal zone of study area.

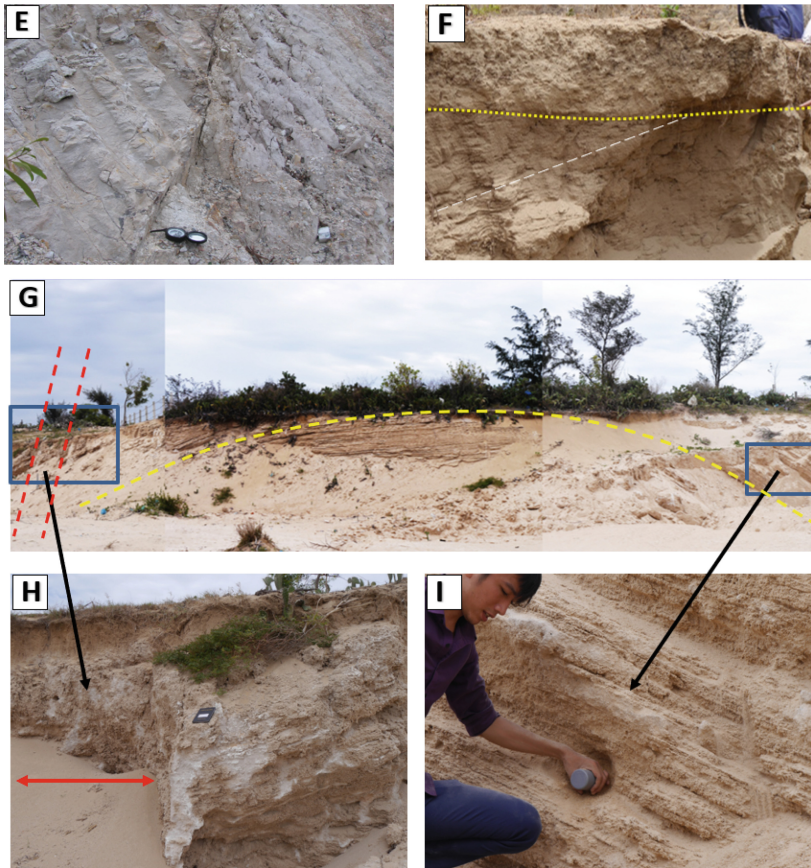


Fig. 3. (continued)

3 The Controls of Neotectonic Activities on the Flow of the Cai River and Its Tributary

In general, neotectonic activities act as a major factor in controlling the morphology of one area, which has been well documented in the literature (eg., [11, 12–17, 22–28]). The neotectonic movements that include uplifting, subsidence or lateral transportaiton along the neotectonic faults, are the most important factors governing the formation or migration of the flow and its morphology, the spatial distribution of drainage networks, evolution of river valley, plain, and terrace and other features. The spatial occurrence of flow networks in the study area, on the other hand, could also be the consequence and therefore reflects the nature of neo- and active-tectonic movements (e.g., [15, 25]).

In the study area, the the discharges and major flows the Cai River tributary are either oriented along the neotectonic faults or fracture zones or being offset and diverted the flow direction due to the displacement of the active faults or being influenced by the local uplift/subsidence (Figs. 2, 5). In many places, the sudden change in flow direction



Fig. 4. Examples of tectonic morphology in the study area: A. Residual fault scarps with triangular facets of a large scale, NE-SW trending fault zone observed in Khanh Son area (photo looking SW). The dashed red line is the approximate trace of the fault, whereas thick red arrows point towards the hanging wall block. The subsidence of the hanging wall block led to the formation of the flood-plain wetland (the front part of the picture); B. A section of residual fault scarp with triangle facets seen in the NW Son Hai area. The dashed red line indicates the piedmont scarp (after [19]); C. Linear valley developed along a fault zone; D. A trough developed along a fault the wall on the left is a scarp (slickenside) of the fault with slickenside on the surface. The red arrow indicates the direction of the striation. The formation of trough or valley in C and D also indicates strong tectonic uplift, which led to the rising of the base-level and incision to form straight and steep-slope valleys and/or troughs; E. A mountain slope consists of linear, steep-side troughs and exposed granitic rocks, which formed by the erosion of the rocks along the fracture zones and rapid uplifting of the area; F. Different marine terrace levels seen in An Hải area, the numbers II-IV equivalent to 2nd to 4th level respectively (after [19]); G. Remnant of the first (I) and second (II) marine terraces observed in Vinh Hai area, in which the 2nd terrace occurs as remnant eroded surface on top of granitic rocks; H. A platform-type coral reef exposed either due to relative sea level fall or uplifting of the sea bottom seen in Thai An area (Ninh Hai); I. Two levels of coral reefs exposed in the Nui Chua area in which the level (0) is the younger reef that uplifted recently, 1st level (I) is older reef has been uplifted about 5 m above current sea level. Yellow dots indicated the position for radiocarbon dating samples (after Tran, 2015 [5]).

commonly coincides with the location of fault transect, and the shift of flow direction is controlled by the movement of the fault walls (Figs. 2, 5). The cross-cutting and opposing movements of the fault sets have led to the complex zig-zag shape of the flow in many places along the Cai River and its branches (Fig. 2, 5).

The uplift due to neotectonic activities commonly results in the base-level rise, which leads to vertical incision and vertical erosion that consequently straightens the river course and development of V-shape river valleys, angular and antecedent flow networks, exposure of marine or river terraces, and sea-wards expansion of the deltaic



Fig. 4. (continued)

plain and river mouth (eg., [14, 15, 25]). The uplifting walls of the faults also create systematic residual fault scarps that are abundant in the area (Figs. 2, 3, 4 and 5). In contrast, subsided areas are localized and commonly occurred within the graben or half-graben caused by pull-apart or horse-tail portion of the strike-slip faults [29], or along the hanging walls of the normal faults (Fig. 4A, B). The subsidence also leads to the rise of base-level, lateral erosion of the riverbanks and formation of meanders, marsh, oxbow lake, flood-plain, and lagoon in the lower portion of the river. The general model for interrelationship between neotectonic faulting and movements to river shape and morphology is presented in Fig. 6.

4 Timing of Neotectonic Movements Along the Cai River Area and Environs

As described above, the evidence for neotectonics movements is abundant in along the Cai River catchment, including the uplifting or subsidence and movements along the fault. Some works recently have focused on the dating of neotectonic events to precisely define the exact timing of recent tectonic movements [5, 6, 30, 31]. Michelli (2008) [30] had used $\delta 180$ and $\delta 13C$ isotopes dating for beachrocks, and beach ridge has determined the fluctuations of sea-level from mid-Holocene to recent in which the coastal zone of Ninh Thuan area has experienced a sea level highstand during the period from 6721 to

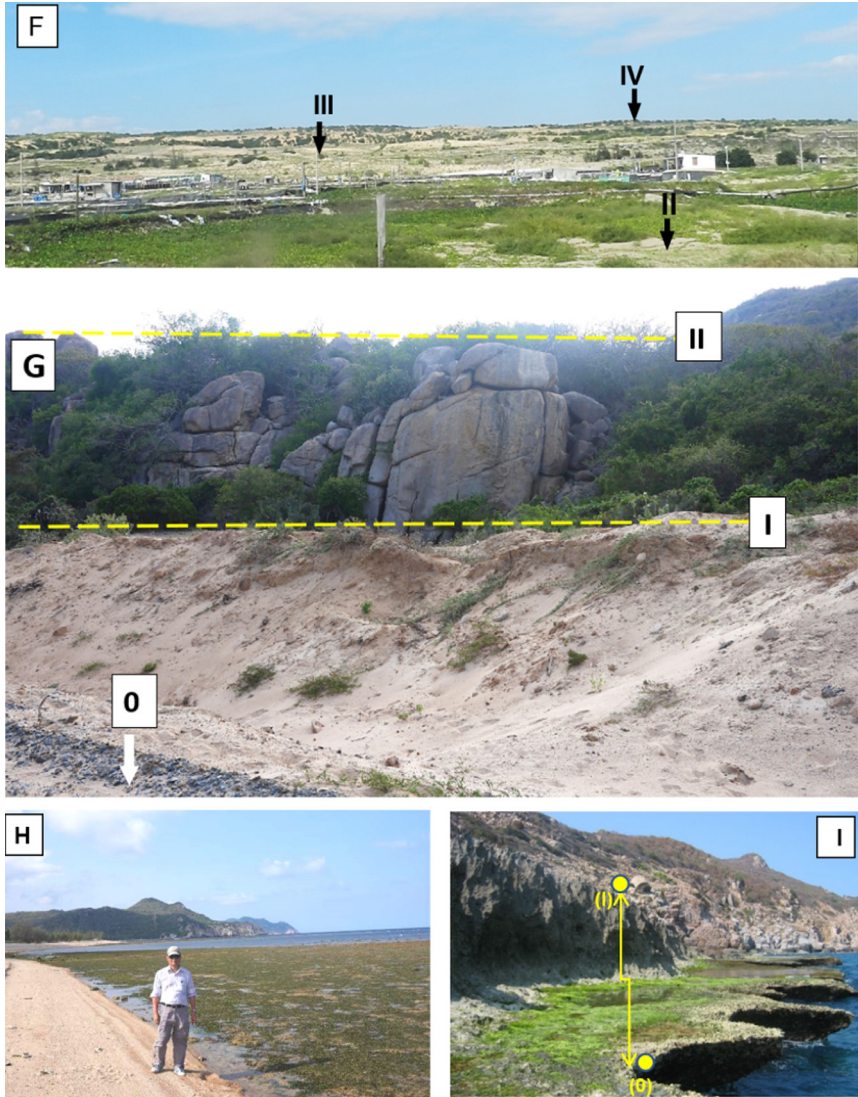


Fig. 4. (continued)

5869 cal yr BP that followed by a period of sea level rise from 5687 to 5377 cal yr BP. This was continued by a sea-level fall period starting after the 5377 cal yr BP until recent time. Statterger, et al. (2013) [31] used AMS 14C dating methods for beachrocks, beach ridge, washover and backshore deposits along the coastal zone including Ninh Thuan area have argued that the area was influenced by Holocene sea-level fluctuations that caused by eustatic and isostatic movements, including a final phase of sea-level rise due to deglaciation from -5 to $+1.4$ m during the period of 8.1 to 6.4 ka, followed by the mid-Holocene, slightly above $+1.4$ m sea level highstand between 6.7 and 5.0 ka and

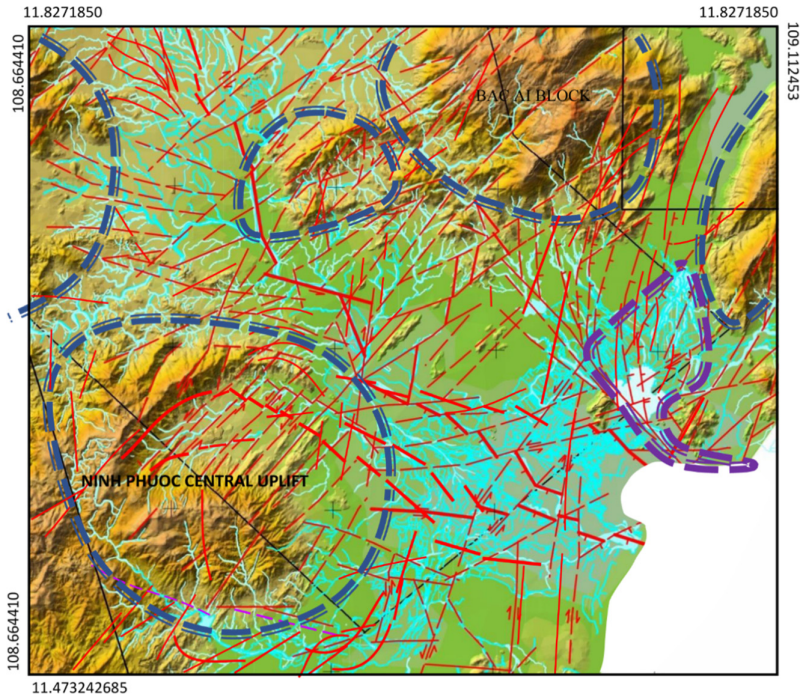


Fig. 5. DEM model and photo-lineament maps showing the relationship between the distribution of the drainage systems and their relationship to the neotectonic lineaments, many are neo- and active faults along the Cai River catchment. Red lines are topographic lineaments, which in many cases, are neotectonic fault traces. The areas within blue dashed lines are strong uplifting; the areas within the purple dashed lines are strong subsided; red lines are defined or extrapolated neotectonics faults that affect the formation or modify the flow pattern of the drainage systems. In many places, the uplifting or subsidence governs the flow pattern (e.g., such as Ninh Phuoc Central Uplift), whereas the faults control the direction and/or the (abrupted) change of the flow direction. The movement along with conjugate, strike-slip fault systems generally lead to the formation of the Z or S shape; zig-zag flows along the river; the development of horse-tail and or pull apart, or imbricate structures along the fault zones commonly lead to the formation of the fault-controlled grabens and/or hosts along the river catchment.

reached to maximum of +1.5 m at 6.0 ka. These followed by a post 5.0 ka sea-level fall linearly below +1.4 m at a rate of 0.24 mm/year, which lasted until 0.63 ka and at +0.2 m.

These studies, however, did not count for the effects of local neotectonic movements on such sea level variation in the studied areas but considered the sea level changes were a consequence of eustatic and globally glaciation. On the basis of the identification of the deformation and/or displacement of the Quaternary deposits or weathering profiles that are widely occurred in the area, Tran (2015, 2020) [5, 6] have attempted to date the Quaternary tectonic movements using several modern methods including (radiocarbon,

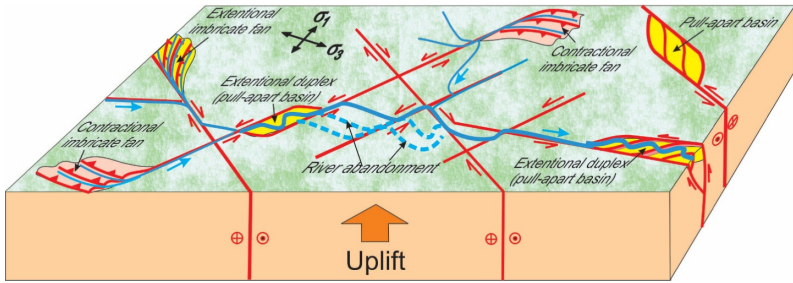


Fig. 6. The general model summarizes the interrelationship between flows and neotectonic elements in the middle and lower courses of the Cai River catchment, Ninh Thuan province.

ESR, TL and OSL techniques (eg., [11, 15, 32]) for different materials collected from the study area. Tran (2015) [5] has dated the fault gouge collected from fault zones in Ninh Hai area, east of this study area using ESR method and obtained the ages for latest phase of fault movement including ca. 13,30 ka and 33.1 ka for a fault gouge zone (eg., at coordinator: 11 42 05832 N and 109 11 2.9256 E) and $32,60 \pm 3,20$ ka for another sample (at coordinator: 11 42 01908 N and 109 11 23028 E). This indicates that the latest phase of movement along the studied faults could have been at ca. 13 ka (eg., see [5] for detail). In addition, on the basis of identification of the uneven distribution and displacement of the Quaternary terraces that were caused by a large active fault in the Nha Ho area on the left bank and Phuoc Vinh area on the right bank of the Cai River, west of this study (Figs. 2, 7), Tran (2015) [5] has also dated the Holocene units that were truncated and displaced by the fault (Figs. 7A and B) by OSL technique. The results show that the same unit with similar ages occurred on opposing walls are significantly displaced (Fig. 7B). The dating results also show a complex movement history of the fault with opposing sense of movement, in which the earlier phases taken place from ca. 6.3 ka to 3.0 ka had controlled the deposition of sedimentary layers with a NW-side down relatively producing beds with greater thickness compare to those in the SE side, whereas the latest phase took place after ca. 2.6 ka, truncated all sediments with a northeast side-down, sinistral oblique movement (see Figs. 7A and B).

Furthermore, on the basis of the discovery of a pronouncedly deformed Quaternary sedimentary unit in the My Tan area, east of this study, which led to the significant folding and faulting of the sedimentary layers (see Fig. 4G–I), Tran (2020) [6] has collected samples for $\delta^{13}\text{C}$ radiocarbon dating of the remnants of *in situ* materials (eg., shells and roots collected within the sedimentary layers) and got the ages ranging from ca. 5.9 to 4.89 ka for older and younger beds within the stratigraphic sequence, respectively (Fig. 8). Based on the bedding configuration and ages of the beds within the sedimentary unit, Tran (2020) [6] has extrapolated the youngest age of the sedimentary layers in the studied location is at ca. 2.2 ka. However, as the exposed beds in the outcrop (Figs. 4G, 8) is not the top of the sequence, this means that the top of the sedimentary unit in this area may be younger than 2.0 ka and therefore the deformation of these beds, including folding and subsequent faulting (Fig. 8) must have taken place at least after the age of ca. 2.0 ka (Fig. 8).

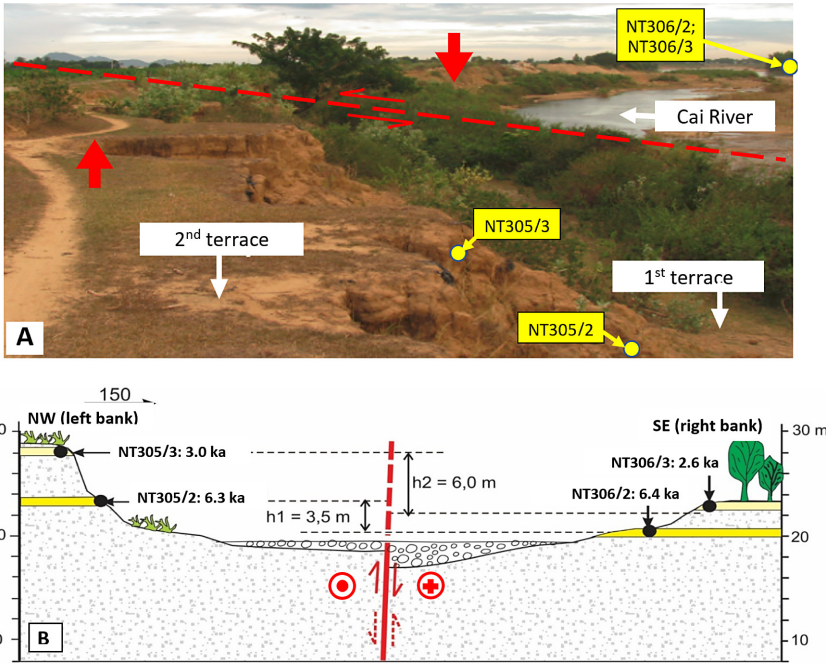


Fig. 7. A. The relationship between terrace, river and fault movement in Nha Ho - Phuoc Vinh area: red dashed line is the trace of a fault straddling the Cai River; arrows indicate senses of strike-slip movement; thick red arrows indicate the vertical movement direction of the uplifted and subsided walls of the fault respectively. Yellow dots and numbers in yellow boxes are sample collection locations for OSL dating in Fig. 7B (after Tran, 2015). View of the picture looking east; B. A northwest-southeast cross-section straddles the left and right banks of the Cai River, from Nha Ho (NW) to Phuoc Vinh (SE) modified after [5, 19], showing the relationship between the active fault and the distribution of Quaternary sediments and their ages. Dating of the marker beds reveals complex movement history along the faults, which resulted in the variation in thickness and height of the sediments in the NW and SE walls of the fault. The latest phase of the fault is oblique, NW side-up sinistral strike-slip. Approximate locations for sample NT305/2 and NT 305/3 are: 11.6293631 N; 108.8830180 E, for samples NT 306/2 and NT 306/3 are: 11.6293631 E and 108.8712300 E. See Tran, 2015 [5] and Tran 2017 [9] for details of sample locations, dating methods and discussion of results.

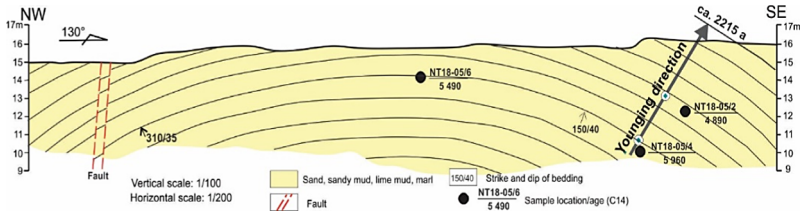


Fig. 8. Generalized cross-section sketched from the outcrop in Fig. 4G, showing the relationship between deformation and age of the Quaternary sedimentary beds in My Tan area, east of the study area (cordinator: 15.8511014N, 108.3827994E). The age of the beds was obtained by $\delta^{13}\text{C}$ isotopes dating of the remnants of shells collected within each bed that expressed in year BC (see Tran, 2020 [6] for detail of sampling and dating). The data shows that the dated layers occur in the middle of the stratigraphic sequence, and the top layer of the sequence has not been dated. However, based on the age data of 3 successive layers have been dated (e.g., ca. 5960, 5490, 4890 ya, from lower to upper part of the sequence, respectively) and the defined younging direction of the sequence, the average age of the top layer in the section can be extrapolated to be at least ca. 2.2 ka. This indicates that the age of the youngest beds of the sequence (which extend far to the southeast of the outcrop) should be equivalent to at least ca. 2.0 ka. In this case, the pronounced folding and later faulting events in the area had taken place after 2.0 ka.

5 Conclusion

Systematic field mapping and structural interpretation of the geological parameters and their interrelationship to the surface flow networks along the middle and lower courses of the Cai River and its tributary, Ninh Thuan province have shown a complicated regional structural pattern that was created by long-lived regional neotectonic evolution, which are remain active. Active tectonism has acted as a controlling factor in producing the geomorphology and landscape of the study area. The neotectonic overprints, caused by many phases of deformation that produce non-penetrative, open-spaced brittle fracture and fault zones, have not only cross-cutted the basement rocks but also disrupted the Quaternary cover. This consequently led to both vertical and horizontal displacements, including local uplift and subsidence, tilting, or dismemberment of both undercover lithologies, the Quaternary deposits as well as the Cai River and its tributaries.

The combined effects of all structural elements within a framework of neotectonic endogenic and exogenic activities have produced the unique morphology of the Cai River and its tributary in the study area. Localized vertical movements within generally fault-controlled block has led to local rise or fall of base level and consequently the formation of braided or meandered flows, uplifted blocks or subsided basins within area of generally regional uplift or subsidence, respectively. In addition, many basins and and/or uplifting areas along the Cai River are also products of fault movement and the relationship between faults and fractures within a system in the form of extensional fans/pull-apart basins or contractional imbricate structures. Moreover, the local uplifting and tilting of the basement has also greatly influenced the abandonment and migration of the river courses from the uplifting, higher base-levels to the areas of lower-base levels. The widespread cross-cutting and lateral displacement along active structures, on the other hand, have led to deformation and redirection of the flow direction, enhancing

the affects of exogenic processes including vertical and lateral erosion that have resulted in the modification of the riverbanks and its related coastal area of the Cai River in Ninh Thuan.

Dating of the neotectonic generated elements have revealed that the study area is currently tectonically activated and the recent movements, both vertical and lateral, contribute significantly to the formation and evolution of the modern morphology including the drainage system in the study area.

Thus, neotectonic structures and activities, especially those were formed recently are critical parameters for the shaping of current morphology, landscape, and spatial distribution of the drainage networks in the middle and lower courses of Cai River catchment in Ninh Thuan province. Therefore, detailed structural interpretation, including adequately documentation of all structural events, their relative timing, especially for those have been originated or activated by neotectonism are therefore very important and, as such, must be carried out systematically and detailedly in any geological works aimed to understand the nature of a river course, especially in assessment and prediction of the evolution of river and its associated natural hazards.

Acknowledgments. This work is partly supported by the Ministerial Project B2019-MDA-562–15 to Hai Thanh Tran. We thank two anonymous reviewers for their constructive comments and corrections, which have helped to improve the quality of this work.

References

1. Phuong, H., Nguyen, N.S., Trinh, N.T.: Geological and Mineral Resources map of Phan Rang-Thap Cham Urban area scale 1:25.000. Department Geology and Minerals of Vietnam Achieves, Hanoi (1999)
2. Stepanek, P., Ty, H.T.: Report on mineral geological mapping at Phan Rang-Cam Ranh at 1:50,000 scale. Archived at the Center for Information & Archives of Geology, Hanoi (1986)
3. Thang, N.D. (ed.): Report on surveying and mapping of Geology and Minerals in Phan Rang-Nha Trang area at 1:200,000 scale. Archived at the Center for Information & Archives of Geology, Hanoi (1988)
4. Tran, V.T., Vu, K.: Geology and Natural Resources of Vietnam. Natural Sciences and Technology Publishing House, Hanoi (2011)
5. Tran, T.H.: Research on and evaluation of active tectonics in central Vietnam coastal area and its role for the natural hazards for predicting and mitigation of natural hazards in the climate change condition (Vietnamese). Final Report of National Project BDKH 42 (2015)
6. Tran, T.H.: Research on the impacts of neotectonic on the modification of main courses of river catchment in Central Vietnam for the protection of river, applied for Vu Gia - Thu Bon catchment (Vietnamese). Final Report of National Project BDKH 13/16-20 (2020)
7. Pham, V.H.: Characteristics of neotectonic faults in South Central Vietnam. Ph.D. thesis, Geological Institute, Academy of Science and Technology of Vietnam, Hanoi (2002)
8. Nguyen, H.P.: Map of earthquake dangerous rate in Vietnam and the East Sea. *J. Sci. Earth* **26**(2), 97–111 (2004). (in Vietnamese with English abstract)
9. Nguyen, H.P., Pham, T.T.: Probabilistic seismic hazard maps of Vietnam and the East Vietnam Sea. *J. Mar. Sci. Technol.* **15**, 77–90 (2015)
10. Easterbrook, D.J.: Principles of Geomorphology. McGraw-Hill Book Company, New York (1969)

11. National Research Council (NRC): *Active Tectonics: Impact on Society. Study in Geophysics* (1986)
12. Hurtrez, J.E., Lucazeau, F., Lavé, J., Avouac, J.P.: Investigation of the relationships between basin morphology, tectonic uplift, and denudation from the study of an active fold belt in the Siwalik Hills, central Nepal. *J. Geophys. Res. Solid Earth* **104**, 12779–12796 (1999)
13. Pidwirny, M.: The drainage in concept. In: *Fundamentals of Physical Geography*. Physical Geography.net (2006)
14. Huggett, R.J.: *Fundamentals of Geomorphology*. Taylor & Francis E-library (2007)
15. Burbank, D.W., Anderson, R.S.: *Tectonic Geomorphology*. Wiley, Hoboken (2011)
16. Whitney, B.B., Hengesh, J.V.: Geomorphological evidence for late quaternary tectonic deformation of the Cape region, coastal west central Australia. *Geomorphology* **241**, 160–174 (2015)
17. Lawrie, K., Brodie, R.S., Gibson, D., Halas, L., Magee, J.: Inter-disciplinary approaches to mapping neotectonic intra-plate fault systems & their hydrological effects in Australia's floodplain landscapes. In: Lawrie, K. (ed.) *Neotectonics on the Australian Plate: New Science for Energy, Mineral and Groundwater Systems, and Hazard Assessment (Abs)*, p. 31 (2016)
18. McGuire, B., Maslin, M.A.: *Climate Forcing of Geological Hazards*. Wiley-Blackwell, Oxford (2013)
19. Tran, T.H.: *Active tectonics in the coastal zone of Central Vietnam and its impacts on the geohazards*. Science and Technics Publishing House, Hanoi (2017). 218 pp.
20. Moores, E.D., Twiss, R.J.: *Tectonics*. Freeman and Company, New York (1995)
21. Molnar, P., Anderson, R.S., Anderson, S.P.: Tectonics, fracturing of rock, and erosion. *J. Geophys. Res.* **112**, F03014 (2007). <https://doi.org/10.1029/2005TF000433>
22. Keller, E.A., Pinter, N.: *Active Tectonics: Earthquakes, Uplift, and Landscape*. Prentice Hall, Upper Saddle River (2001)
23. Ritter, M.E.: *The physical environment: An introduction to physical geography*. http://www.earthonlinemedia.com/ebooks/tpe_3e/title_page.html (2006)
24. Ritter, D.F., Kockel, R.C., Miller, J.R.: *Process Geomorphology*. Waveland Press, Inc., Long Grove (2002)
25. Schumm, S.A., Dumont, J.F., Holbrook, J.M.: *Active Tectonics and Alluvial Rivers*. Cambridge University Press, Cambridge (2000)
26. Malik, J.N., Mohanty, C.: Active tectonic influence on the evolution of drainage and landscape: geomorphic signatures from frontal and hinterland areas along the Northwestern Himalaya, India. *J. Asian Earth Sci.* **29**, 604–618 (2007)
27. Keil, M., Neubauer, F.: Neotectonics, drainage pattern and geomorphology of the orogen-parallel Upper Enns Valley (Eastern Alps). *Geologica Carpathica* **62**(3), 279–295 (2011)
28. Vita-Finzi, C.: River history. *Philos. Trans. R. Soc. A* **370**, 2027–2263 (2012)
29. Wu, J.E., McClay, K., Whitehouse, P., Dooley, T.: 4D analogue modelling of transtensional pull-apart basins. *Mar. Pet. Geol.* **26**, 1608–1623 (2009)
30. Michelli, M.: *Sea-level changes, coastal evolution and paleoceanography of coastal waters in SE-Vietnam since the mid-Holocene*. Ph.D. thesis, Christian-AlbrechtsUniversität Kiel, Germany (2008)
31. Statterger, K., Tjallingii, R., Saito, Y., Michelli, M., Nguyen, T.T., Wetzele, A.: Mid to late Holocene sea-level reconstruction of Southeast Vietnam using beachrock and beach-ridge deposits. *Glob. Planet. Change* **110**(Part B), 214–222 (2013)
32. Walker, M.: *Quaternary Dating Methods*. Wiley, Hoboken (2005)