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Tectonic – Geomorphology and its relation to geo-hazards in the Southwest region of Vietnam

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ABSTRACT

This study investigates tectonic geomorphology in the Southwestern region of Vietnam to clarify the relationship between tectonic factors and geological hazards using an integrated approach that combines geological data synthesis, multi-temporal remote sensing (RS), digital elevation models (Topo DEM), and field surveys in key areas such as Ca Mau, Rach Gia, and Ha Tien. The results identify three main geomorphic groups, including erosional landforms developed on magmatic and sedimentary rocks, karst landforms characterized by limestone, cave systems, and sea-level markers, and depositional landforms, which dominate the region and were formed from fluvial, marine, and mixed sediments from the Pleistocene to late Holocene. Geodynamic analysis reveals a dense system of active faults trending NE–SW, NW–SE, and sub-meridional directions, which strongly control coastal morphology, river patterns, and the formation of large depressions such as the Long Xuyen Quadrangle. The Ca Mau cape is particularly affected by fragmentation and subsidence, with average rates of about 11 mm/year and locally exceeding 3 cm/year. Major geological hazards include widespread land subsidence and severe coastal erosion, reaching up to 67 m/year in Ca Mau, resulting from the combined effects of natural subsidence, tectonic activity, and excessive groundwater extraction. Field evidence, including damaged seawalls and subsiding coastal infrastructure, further supports the role of active faults in destabilizing the delta. These findings provide a scientific basis for hazard zoning, coastal spatial planning, and sustainable adaptation strategies to climate change and sea-level rise in the Mekong Delta.

Keywords: *Tectonic-geomorphology, Mekong delta, subsidence, geo-hazards.*

1. Introduction

The Southwestern region of Vietnam, an important part of the Mekong Delta, is a low-land with young sedimentary formations, facing extremely complex geological and environmental changes. With an area of approximately 40,578 km², this region is primarily composed of alluvial deposits from the Mekong river system, which overlie an erosional surface formed during the Late Pleistocene (Nguyen V.L, Ta T.K.O, Tateishi M. 2000). In the context of global climate change, the southwestern coastal region is severely impacted by sea-level rise, posing a direct threat to territorial stability and the livelihoods of over 17.7 million people as of 2022.). The latest topographic model (Topo DEM) indicates that the average elevation of the entire delta is only about 0.8 m above sea level, much lower than previous estimates, making it highly vulnerable to erosion and flooding.

One of the most pressing geo-hazards in the region today is widespread land subsidence. Initial studies using InSAR technology and GPS monitoring have confirmed a dominant downward trend with an average rate of 7.4 to 11.8 mm/year, and in some urban "hot spots" such as Ca Mau and Rach Gia, the subsidence rate can exceed 3 cm/year (Erban et al., 2014). To date, most published results have focused on explaining the causes of subsidence based on anthropogenic factors such as excessive groundwater extraction, building loads, and the natural compression of loose sedimentary layers. However, although subsidence has been shown to vary across different geological blocks, the role of neotectonic activity remains insufficiently assessed and is often considered a minor factor in environmental change scenarios.

In reality, the geological structure of the southwestern coastal region is strongly fragmented by a network of active neotectonic faults trending northwest-southeast, northeast-southwest, and sub-meridional. These fault systems not only ontrol the development of the straight coastline and the angular bends of rivers, but also directly create large depressions such as the Long Xuyen Quadrangle and the Ca Mau Cape region. The lack of detailed tectonic structural diagrams and quantitative data on the modern movement of geological blocks has led to limitations in accurately predicting hazards such as severe coastal erosion (in some places reaching 67 m/year) and the fracturing of coastal infrastructure. Furthermore, existing geological data still has many shortcomings in linking the history of stratigraphic development with modern tectonic activity phases.

This study aims to comprehensively assess the geomorphological and neotectonic characteristics by integrating multi-temporal remote sensing, geographic information systems (GIS), and field verification surveys in key areas such as Ha Tien, Rach Gia, and Ca Mau. The research results not only clarify the close relationship between active fault zones and modern geological hazards but also provide a crucial scientific basis for spatial planning, land resource management, and the proposal of sustainable solutions to address the challenges of natural disasters in the Southwest region of Vietnam.

2. Research methods

The study was designed using an integrated multi-methods approach to ensure objectivity, systematic approach, and high accuracy in assessing geological changes. This approach allows for a shift from large-scale spatial analysis to detailed verification in key areas.

2.1. Document Synthesis and Analysis Method

This process focuses on collecting and systematizing data from reputable scientific databases such as ScienceDirect, MDPI, and ResearchGate. The documents analyzed include geology, tectonics, plain evolution during the Holocene epoch, and climate change scenarios. In particular, the study inherits and modifies data from 1:200,000 and 1:500,000 scale geological and mineral maps to establish a Quaternary stratigraphic framework and identify the main fault systems controlling the structure of the Southwest region of Vietnam.

2.2. Remote Sensing and Geographic Information Systems (GIS)

Multi-source remote sensing and geospatial data were integrated in this study. Multi-temporal Landsat imagery (5, 7, 8, and 9) from 1984 to 2022 (30 m resolution) was used to analyze long-term geomorphic trends, complemented by Sentinel-2 (10 m resolution) and SPOT data for detailed mapping of coastlines and vegetation cover. Sentinel-1 radar data were further utilized for their cloud-penetrating capability and effectiveness in flood detection under tropical conditions. Image processing was conducted using ENVI software, including

geometric (UTM-WGS84) and radiometric corrections, with 5-4-1 (R-G-B) pseudo-color composites applied to distinguish land cover types. Supervised classification using the Maximum Likelihood algorithm was employed to quantify geomorphic units. Coastal changes were analyzed using the Digital Shoreline Analysis System (DSAS) in a GIS environment to calculate erosion and accretion rates and identify hazard hot spots in Ca Mau and Kien Giang. In addition, InSAR processing of Sentinel-1 data enabled mapping of subsidence velocity fields with millimeter-level accuracy, allowing differentiation between natural compaction, groundwater extraction, and neotectonic influences. Finally, digital elevation models (Topo DEM), corrected to local tidal benchmarks, were used to identify elevation gradients and low-lying areas highly vulnerable to sea-level rise. Fieldwork was conducted to validate interpretations derived from remote sensing data and to collect direct geological evidence in key areas, including Ca Mau, Ha Tien, and Rach Gia. Geomorphological verification involved measuring paleo sea-level indicators preserved in limestone formations (e.g., Hang Ca Sau and Da Dung) to determine former marine transgression levels (0.5 m, 2.5 m, 5 m, and 25 m), as well as identifying marine erosion surfaces (wave-cut benches) and Pleistocene–Holocene depositional terraces surrounding residual limestone hills. Neotectonic structures were investigated through detailed mapping of active fractures and fault zones exposed in magmatic rocks (such as granite in the Bay Nui and Hon Soc areas) and sedimentary formations, with fault orientations, strike, and dip systematically recorded. In addition, sediment, peat, and attached organisms (e.g., oysters and barnacles) were collected for radiocarbon (^{14}C) dating, while field observations documented subsidence and structural damage to coastal infrastructure in relation to inferred fault zones. The integration of remote sensing data with field-based evidence has produced a consistent and comprehensive dataset, allowing for a robust interpretation of the relationship between neotectonic activity and present-day geological hazards in the region.

3. 3.1. Geomorphological and Quaternary Sedimentary Characteristics Results and discussion

Through the combination of multi-temporal remote sensing image interpretation, digital elevation modeling (Topo DEM), and field surveys, the study established the geomorphological structure of the Southwest region of Vietnam as comprising three main groups of units: erosional landforms, karst landforms, and depositional landforms. Erosional landforms develop mainly on magmatic rock masses (granite, rhyolite) scattered on some coastal islands in the Rach Gia area, concentrated into mountain masses in the Bay Nui region (An Giang), while erosional landforms on clastic sedimentary rocks are common on Phu Quoc and Nam Du islands. This landform group is characterized by steep, heavily dissected mountain slopes with a relatively thick ferralitic weathering crust, including ancient leveled surfaces (peneplains) on high peaks such as Nui Cam - Cam Mountain (~705m), evidence of long tectonic stabilization cycles before significant uplift. Karst landforms are concentrated in the coastal strip of Ha Tien – Kien Luong with tower karst limestone formations, or some isolated mountain blocks in the middle of the plain. Field surveys at Crocodile Cave have recorded a very distinct system of eroded sea level marks cut by faults. Studies have identified three levels of sea level marks at elevations of +0.5m; +2.5m and +5m, reflecting the stages of sea level rise from the late Pleistocene to the middle Holocene. Notably, the discovery of a layer of barnacles clinging

tightly to the limestone cavities at an elevation of 2.1 – 2.2m is direct evidence of a sea level rise during the middle Holocene.

Accumulated landforms dominate the area, formed on a deep tectonic subsidence depression, evidenced by the thickest and most complete Quaternary stratigraphic column in Vietnam. This stratigraphic structure is divided into three major sequences: the Lower Pleistocene span (Binh Minh and Ca Mau formations) at depths of hundreds of meters; the Middle-Upper Pleistocene span at depths of 60-80m, which also creates terraces of +10 to +15m high clinging to the edges of mountain ranges in the Bay Nui area; and the Holocene span covering the current low plain surface. These accumulated surfaces include ancient coastal beach ridges 2-5m high at Tan Hiep and Cai Lay, reflecting the process of sea regression and deposition of mixed fluvial-marine sediments over the past 3,000 years. In the Rach Gia and Ha Tien areas, marine accumulation surfaces (mQ_2^2, mQ_2^3) and coastal swamps (bQ_2^3) are interspersed, composed of fine, organic-rich clayey mud, creating a weak geological foundation sensitive to surface changes.

3.2. Neotectonic Activity and Modern Fault Network

Remote sensing and geodynamic data analysis show that the Southwestern region of Vietnam is strongly dissected by an active neotectonic fault network along the main directions: Northwest-Southeast (NW-SE), Northeast-Southwest (NE-SW), and sub-meridional. The NW-SE fault system controls the northern edge of the delta and cuts through Rach Gia, playing an important role in the formation of the Gulf of Thailand and large depression zones such as the Long Xuyen Quadrangle. Notably, the sub-meridional fault running along the western coast is highly active, causing the offshore portion to subside, creating the characteristic straight and sharp coastline.

In the Ca Mau Cape area, Landsat and Google Earth satellite imagery has depicted a complex geological picture where a dense network of small faults running parallel to the northeast "splitting" the peninsula. This fragmentation causes the Ca Mau Cape area to subside faster than the northern areas and controls the angular, tortuous morphology of tidal channels and river systems such as the Ong Trang River. Field evidence at Thach Dong (Ha Tien) and Hon Chong has confirmed the existence of northeast-southwest fault slip surfaces with dip angles up to 80 degrees, showing a clear shift between limestone layers. At Hon Soc, research has documented a fissure zone up to 50m wide, extending along the sub-meridional direction, cutting through the granite massif, reinforcing the hypothesis that modern tectonic movements are still occurring slowly but distinctly. Synthesis of data from geodynamic studies shows that the subsidence trend is overwhelmingly dominant over an area of more than 36,000 km² with tectonic subsidence rates ranging from 7.4 to 11.8 mm/year.

3.3. Coastal Changes and Subsidence Hazards from a Remote Sensing Perspective

Observation results using Digital Shoreline Analysis System (DSAS) tools and satellite imagery series from 1984 to 2022 show a serious reversal of coastal zone dynamics. More than 50% of the total 720 km of the Southwest Vietnam coastline is currently experiencing severe erosion. At Ca Mau Cape, the average erosion rate reaches over 50m/year, with some sections experiencing erosion up to 67m/year. Conversely, sedimentation only occurs locally at some large river mouths such as the Cai Lon River and the tip of Ca Mau Cape, where sediment from the Mekong River system is transported along the coast westward by ocean currents. However, the total area of land loss still far exceeds the area of sedimentation, causing the delta to gradually shrink.

Land subsidence has been identified as the most urgent problem, with InSAR data from 2014-2019 recording subsidence rates in urban areas such as Ca Mau, Rach Gia, and Can Tho commonly at 1-4 cm/year. This rate is more than 10 times higher than the current average annual sea level rise rate. Remote sensing analysis also indicates that the most severe subsidence areas are often associated with areas of excessive groundwater extraction and urbanization "hot spots" on the bQ23 swamp sediment. Human impact (anthropogenic topography) is evident in the 77% reduction in the area of the Ha Tien mangrove delta to make way for infrastructure and the disappearance of limestone massifs in Kien Luong due to industrial cement production. Field surveys in Rach Gia have recorded serious infrastructure subsidence and cracking within coastal embankments and the complete destruction of concrete embankment sections at Hon Chong, right at the point where a fault line cuts through.

3.4. The relationship between geomorphology, neotectonics, and geological Hazards

The synthesis of research results allows for in-depth discussion of the causal relationship between endogenous structure and modern hazards. A key finding is that the locations of areas of severe subsidence do not completely coincide with natural low-lying areas, suggesting that uneven neotectonic movement along geological blocks plays a fundamental role. Active fault zones not only control the river network but also fracture the structure of young sedimentary layers, facilitating the inland erosion of riverbanks and coastlines by ocean currents and waves.

The low terrain with an average elevation of only about 0.8m makes the area extremely vulnerable to the combined effects of subsidence (with an amplitude of cm/year) and sea level rise. Tectonic subsidence zones such as the Long Xuyen Quadrangle (~80% of the area has an elevation of 0-0.6m) are becoming "funnels" attracting saltwater, exacerbating saltwater intrusion and tidal flooding. In the Ba The mountain area, archaeological sites belonging to the Oc Eo culture (such as Go Cay Thi) were found at a depth of 1m below the current delta surface, providing historical evidence of modern tectonic subsidence and continuous sedimentation over thousands of years. Furthermore, in the remaining mountains, tectonic activity combined with weathering has caused landslides at the foot of the mountains, directly threatening cultural relics and residential areas along the mountain slopes.

In short, evidence from remote sensing and field verification has clarified that geological hazards in the Southwest region of Vietnam are a multi-factorial consequence, in which neotectonic activity plays an indirect but a significant role. Identifying key areas in Ca Mau, Rach Gia, and Ha Tien not only helps to understand the geological evolutionary history but also provides an essential basis for mapping risk zones, guiding infrastructure planning, and proposing sustainable adaptation solutions in the context of increasingly complex climate change.

Figure 1. Riverbank erosion in Nguyen Van Thoi commune, Ca Mau province. (Photo: N.X.Nam, 2025)

Figure 2. Erosion destroys concrete seawall along the coast of Kien Luong, An Giang. (Photo: N.X.Nam, 2025)

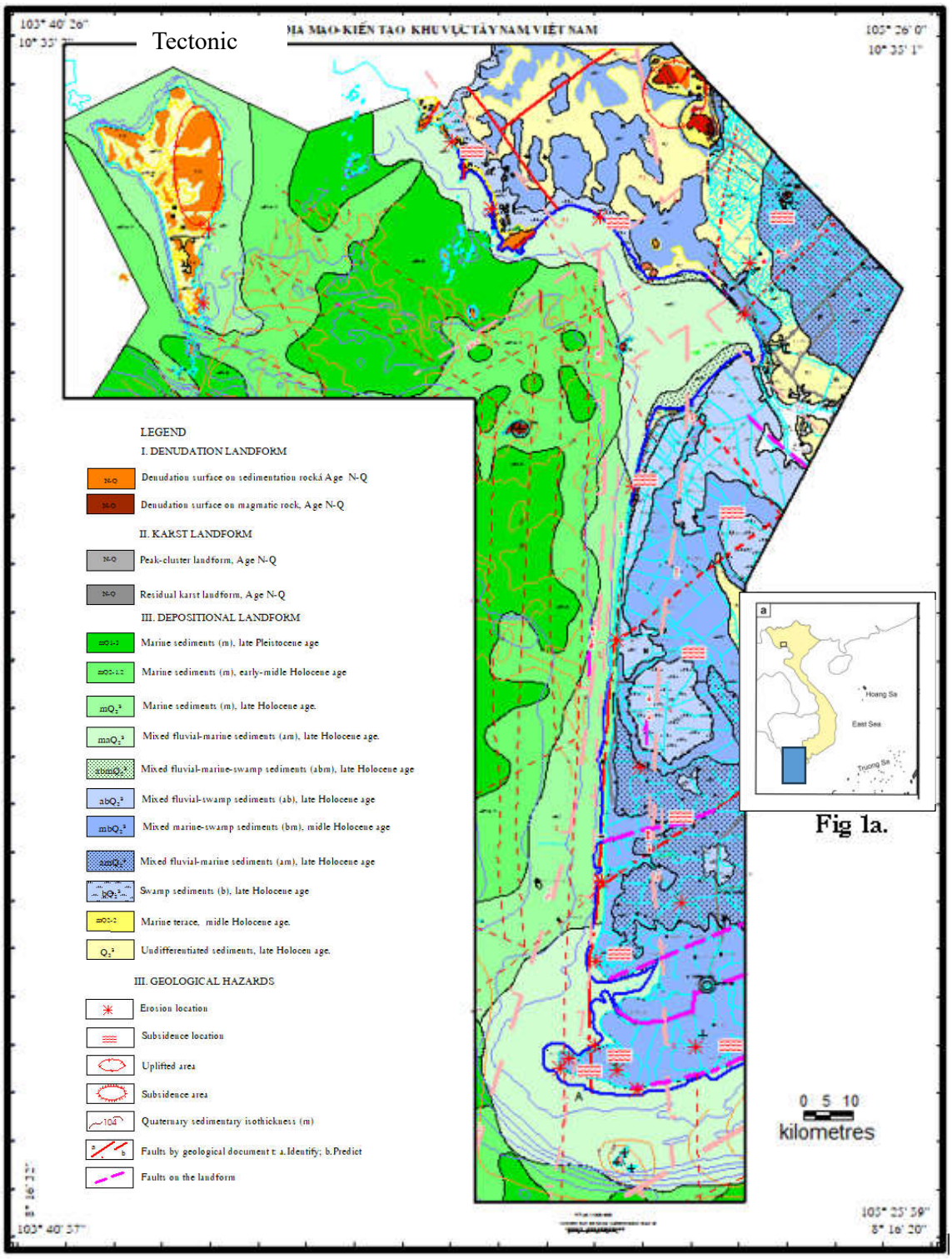

Figure 3. Tectonic geomorphology map in the southwestern region of Vietnam; Figure 1a. Location of the study area on the map of Southeast Asia

4. Conclusion

The Southwestern region of Vietnam is a young, sensitive delta, strongly affected by an active fault network. Its geomorphological characteristics, with alluvial landforms on weak soil, increase its vulnerability to subsidence and erosion. Remote sensing and field evidence confirm that widespread erosion is not only due to sediment shortages or climate change but also

significantly contributed by the uplift and subsidence movements of geological structures. Integrating geomorphological-neo-tectonic models into urban planning and resource management is necessary for sustainable risk mitigation.

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