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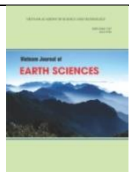

Quaternary stratigraphy of southern Vietnam continental margin

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ABSTRACT

This study investigates the stratigraphic architectures of the South Vietnam continental margin (SVCM) from the Pliocene to the recent period. We have utilized high-resolution seismic data and sediment core data to achieve this. The study reveals that the Quaternary sequences on the continental margin are bounded by composite erosional surfaces, which were formed due to sub-aerial erosion during periods of sea level fall and subsequent reworking processes during sea level rise. The Quaternary sequence can be divided into two subsequences: the Early Pleistocene and the Middle Pleistocene-Holocene. The Middle Pleistocene-Holocene sequences can be subdivided into six fourth-order sequences, each lasting approximately 100 to 120 thousand years. These sequences are well-preserved on the outer shelf at a modern water depth of around 100 to 120 meters. Seismic stacking patterns indicate that regressive deposits predominantly dominate the Quaternary stratigraphy of the SVCM. This means that sediment deposition during the Quaternary period was more pronounced during periods of sea-level fall. The outer shelf margin of the modern continental margin shows a south-to-southeastward migration of prograding clinoforms, indicating sediment progradation in these directions. The thick Quaternary regressive deposits preserved on the outer shelf are attributed to various factors. These factors include the low shelf gradient, tectonic subsidence, regional hinterland uplift, monsoon strengthening, and high sediment supply from the Palaeo-Mekong Delta during sea-level fall. The interaction of these factors facilitated the accumulation of thick sedimentary deposits during falling sea levels. The mid-late Pleistocene stratigraphy of the SVCM shows similarities to many other continental margins worldwide. These margins are mainly shaped under the influence of asymmetric 4th order Milankovitch cycles. These cycles are driven by variations in Earth's orbital parameters and are characterized by longer phases of relative sea-level fall followed by shorter periods of stabilization and rise.

Keywords: Sequence stratigraphy, Quaternary, Vietnam continental shelf, East Vietnam Sea, Seismic.

1. Introduction

The Southern Vietnam continental margin (SVCM) is located on the southwestern continental margin of the East Vietnam Sea (EVS), which is one of the largest marginal seas on the western edge of the Pacific Ocean (Fig. 1). Throughout the Quaternary period, the SVCM experienced fluctuations in sea level, leading to differential states of exposure and flooding on the continental shelf. These variations resulted in cycles of regressive and transgressive phases, significantly influencing

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the shelf's sedimentary architecture. The interactions between sediment supplies, hydrodynamic conditions, and sea-level changes played a crucial role in shaping sedimentary patterns. This region's characteristic sedimentary pattern of the Quaternary margins records rapid ice melting phases compared to more extended periods of ice growth (Lisiecki and Raymo, 2005). The cycles with a periodicity of approximately 100-120 thousand years significantly impacted the stratigraphic architecture of the Quaternary margins over the past 800,000 years (Lobo and Ridente, 2014). These Middle-Late Pleistocene cycles are asymmetric, characterized by prolonged periods of relative sea-level fall followed by short periods of stabilization and rise (Waelbroeck et al., 2002).

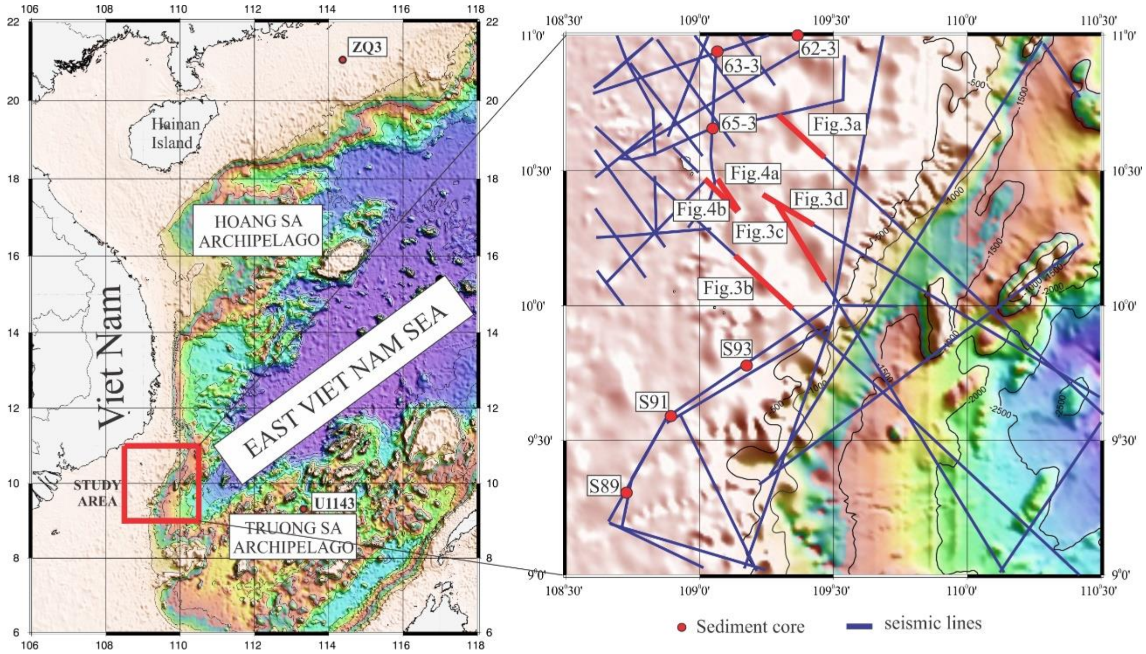

Figure 1. Map of the South East Vietnam Shelf with seismic profiles (lines), shallow sediment cores (circles) and two reference wells (ZQ3 and ODP 1143) used in this research

While there have been numerous studies on the Oligocene to Late Miocene tectono-stratigraphy in the SVCM, as it is an essential target for petroleum exploration (Matthews et al., 1997; Li et al., 2013; Tuan et al., 2016; Bui et al., 2018), the understanding of the Pliocene-recent seismic stratigraphy and the Middle Pleistocene-Holocene interval remains limited in this area. Pliocene-recent seismic stratigraphic successions of the southern Vietnam shelf, including the Cuu Long and Nam Con Son Basins, have been analyzed and subdivided into nine sequences based on petroleum industry seismic data (Yarbrough, 2006). Previous research in the region mainly focused on the last deglacial Holocene evolution and modern asymmetric sand waves (Schimanski and Stattegger, 2005; Kubicki, 2008; Bui et al., 2009; Tjallingii et al., 2010; Bui et al., 2013; Nguyen et al., 2021). Detailed studies on late Quaternary sequence stratigraphy have been carried out on the nearby central Sunda Shelf, and the narrow continental shelf off central Vietnam (Hanebuth et al., 2000, 2003, 2009; Hanebuth and Stattegger, 2004; Bui et al., 2014), but the specific characteristics of the Quaternary stratigraphy in the SVCM have not been thoroughly investigated.

To address this knowledge gap, the present study aims to investigate the Quaternary stratigraphic architecture of the SVCM (Fig. 2), with a particular focus on the Middle Pleistocene-Holocene period. We utilize high-resolution seismic data and available sediment core data to analyze the evolution of the stratigraphy in this area. By doing so, we hope to gain insights into the geological history, sedimentary processes, and sea-level fluctuations that have shaped the continental shelf of the SVCM during the Quaternary period.

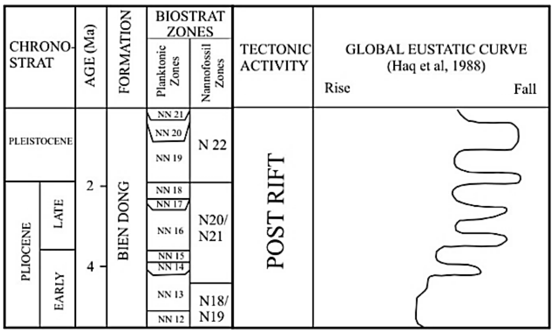

Figure 2. Chronostratigraphy of Pliocene to Pleistocene of the southern Vietnam shelf (Bui et al., 2018)

2. Geological setting and oceanographic conditions

The SVCM is bordered by a 600 km long coastline to the West, the EVS to the East, and the Sunda Shelf to the South (Fig. 1). Formation of the SVCM was associated with the Cenozoic rifting process that is suggested to be related to the opening of the EVS from 32 to 15.5 Ma. (Briais et al., 1993; Li et al., 2014). The SVCM is narrower to the North and becomes wider to the South and Southwest (Fig. 1). Previous studies suggested that two main rifting phases occurred in the SVCM during the Cenozoic (Matthews et al., 1997; Tuan et al., 2016; Bui et al., 2018). The first rifting phase was started during the Late Eocene and Early Oligocene by the N-S spreading of the EVS (Matthews et al., 1997; Tuan et al., 2016). The main NW continued the later rifting event-SE extension, and it ceased before a tectonic inversion in the Middle Miocene, which is evidenced by the presence of a regional unconformity (Matthews et al., 1997; Tuan et al., 2016; Bui et al., 2018). The late Miocene-present period is marked by thermal subsidence and eastward progradation of the Palaeo-Mekong River Delta (Matthews et al., 1997; Li et al., 2013; Bui et al., 2018). In addition, volcanism was widely active in the study area during the Late Miocene-Holocene Period, which is now identified by typical features of the seamounts (Li et al., 2013). On the modern seabed, numerous NE-SW striking sand waves were found at water depths of ~20-40 m, which suggests the activities of strong bottom currents (up to 0.8 m/s) (Bui et al., 2009). The seabed morphology (sand waves and sand ripples) detected from the hydroacoustic record and the grab samplers indicate that the shallow geology comprises a thick layer of loose sand within the study area (Kubicki, 2008; Bui et al., 2009). In this area, the most prominent shallow subsurface feature is the courses of the incised-channel systems (Bui et al., 2013). The channels extend eastward with an average width of ~5 km and incised depth of ~20 m. Those incised valleys are believed to be the traces of the palaeo-Mekong River during the Last Maximum Glaciation, filled with deglacial sediments (Tjallingii et al., 2010; Bui et al., 2013). The Mekong River is the most critical sediment source for the SVCM, which annually discharges ~160 million tons/Yr. of suspended sediment (Milliman and Syvitski, 1992; Nguyen et al., 2000; Pham 2003). The oceanographic conditions of the study area are strongly driven by the East Asian monsoon with reversal wind directions, which blow from northeast during winter (November to April) and from the southwest during summer (June to September) (Pham, 2003). Tide regime of the SVCM is semi-diurnal with maximum amplitude of 2.5-3.8 m (Pham, 2003).

3. Data and Methods

The study area covers a significant extent of the Southern Vietnam continental margin (SVCM), with approximately 3000 km of industrial and high-resolution 2D seismic profiles having been interpreted (Fig. 1). These seismic profiles were acquired through various cruises conducted along the Southern Vietnam Shelf. Using industrial and high-resolution 2D seismic data allows us to gain detailed insights into the subsurface geological structures and stratigraphy of the SVCM. Industrial seismic data typically involve larger-scale surveys for commercial or industrial purposes, such as petroleum exploration. On the other hand, high-resolution seismic data have a more focused and detailed resolution, which is valuable for studying finer geological features and sedimentary sequences. Different sound sources and bandwidths were used during the seismic data acquisition, which provides a comprehensive dataset capturing various aspects of the continental margin. The choice of sound sources and bandwidths can affect the resolution and penetration depth of the seismic data, allowing to investigate different layers and geological features within the subsurface.

The study employs several marine geophysical survey systems to gather data for investigating the geological features of the study area. Here are the central systems used:

(1) Parasound: This hull-mounted system combines a narrow-beam echosounder with a sub-bottom profiler. The system operates with a fixed primary frequency of 18 kHz and a secondary primary frequency of 20.5 to 23.5 kHz (Grant and Schreiber, 1990). Both primary frequencies are transmitted simultaneously in a narrow beam (~50 degrees), and their constructive interference generates a working frequency (secondary frequency) within the beam of 2.5 to 5.5 kHz. Parasound data collected with a secondary primary frequency of 22 kHz resulted in a secondary working frequency of 4 kHz.

(2) Boomer System (EG&G Uniboom): This single-channel system has a vast working frequency bandwidth ranging from 0.3 to 11 kHz. It effectively penetrates the seafloor to depths 20 to 100 meters below the seabed. Seismic traces are digitally recorded and displayed on a computer using NWC software.

(3) High-Resolution Reflection System (GeoResouces): This system is equipped with a sparker source, including a Geo-spark 1000 pulsed power supply, a Geo-Source 200 sparker, a Geo-Sense Mini-Streamers, and a Mini-Trace II acquisition module. The system is used for high-resolution reflection seismic surveys.

(4) Multichannel Seismic System (Geo Marine Survey Systems): This system includes a Geo-Spark 16 kJ revolutionary high-voltage (HV) power supply, a Geo-Source 1600 mega-sparker, and a Geo-Sense lightweight UHRS 48 Channel Streamer. It can collect data over a wide area and provides detailed information about subsurface structures.

By using these different marine geophysical survey systems, the study aims to obtain a comprehensive dataset to understand the geological features, stratigraphy, and subsurface structures of the Southern Vietnam continental margin. Each system has its specific advantages and capabilities, complementing each other and contributing to a more thorough understanding of the study area's geological setting.

The study utilizes gravity cores taken at selected sites in the study area (Fig. 1). These gravity cores are sediment cores that have been collected from the seabed using gravity-driven coring devices (Wiesner, 1999; Schimanski and Stattegger, 2005; Wiesner, 2006). The sedimentological and geochemical analysis of these gravity cores provides valuable information about the study area's sediment composition, sedimentary processes, and environmental conditions. Radiocarbon dating using accelerator mass spectrometry (AMS) is a powerful technique used to determine the age of organic materials in sediment cores. By analyzing the radiocarbon content of organic matter in the sediment, we can establish the age of the sediment layers and reconstruct the chronological sequence of sediment deposition. By combining sedimentological, geochemical, and radiocarbon dating analyses, the study aims to comprehensively understand the sedimentary history, environmental changes, and geological processes that have shaped the Southern Vietnam continental margin.

The seismic data in the study were interpreted based on the seismic/sequence stratigraphic concept, which is a widely used approach for analyzing the geological and stratigraphic relationships within seismic data (Mitchum and Vail, 1977; Vail, 1987; Catuneanu, 2002; Catuneanu et al., 2009). This concept involves identifying seismic packages and sequence boundaries, which are essential horizons for defining sequence stratigraphy and associated systems tracts.

The boundaries between seismic packages were picked along surfaces of reflection termination, such as onlap, down lap, top lap, erosional surfaces, and correlative conformities. These surfaces are crucial for identifying sequence boundaries, which mark significant changes in sedimentary processes and represent important stratigraphic boundaries. The seismo-stratigraphy was divided into acoustic units that generally correspond to seismic sequences. These sequences are packages of sedimentary strata that share similar seismic characteristics and are bounded by sequence boundaries. Seismic facies techniques were employed to characterize the units identified within the seismic data. These techniques involve analyzing reflection characteristics, such as amplitude, continuity, and frequency, and reflection configurations, such as well-stratified, chaotic, parallel, and reflection-free patterns. These analyses help understand the seismic sequences' sedimentary architecture and depositional processes. Since the seismic data were recorded in the time domain, TWT-depth conversion was used to convert the two-way travel time (TWT) to depth. This conversion requires knowing the average sound velocity in seawater and the Quaternary stratigraphy. The formula used for this conversion is $D = (\text{Velocity} \times \text{TWT})/2$, where D represents the depth.

To determine the age and formation of the sequence boundaries, we calibrated and correlated the seismic data with oxygen isotope curves and available dating constraints (Waelbroeck et al., 2002). Oxygen isotope curves often proxy global sea-level changes, providing valuable age control for the identified sequence boundaries.

By using this comprehensive approach, the study aims to gain a detailed understanding of the stratigraphy, sedimentary processes, and geological history of the Southern Vietnam continental margin.

3. Results

3.1. Quaternary Seismic stratigraphy

Based on the results of seismic interpretation, we identified a distinct erosional surface (referred to as SB7) that separates the Quaternary sedimentary succession from the underlying Pliocene formation. This separation was observed in the multichannel seismic profiles (Figs. 3 and 4). The Quaternary formation was further divided into seven subsequences. The detailed analysis helps to identify and distinguish these individual sequences based on their seismic reflection patterns and characteristics. Additionally, the top of the Pliocene formation (referred to as SB1) was also clearly identified in the seismic data. This boundary marks the transition between the underlying Pliocene sedimentary layers, which exhibit low amplitude and frequency, and the overlying Quaternary sedimentary layers, characterized by solid amplitude, high frequency, and continuous seismic reflectors.

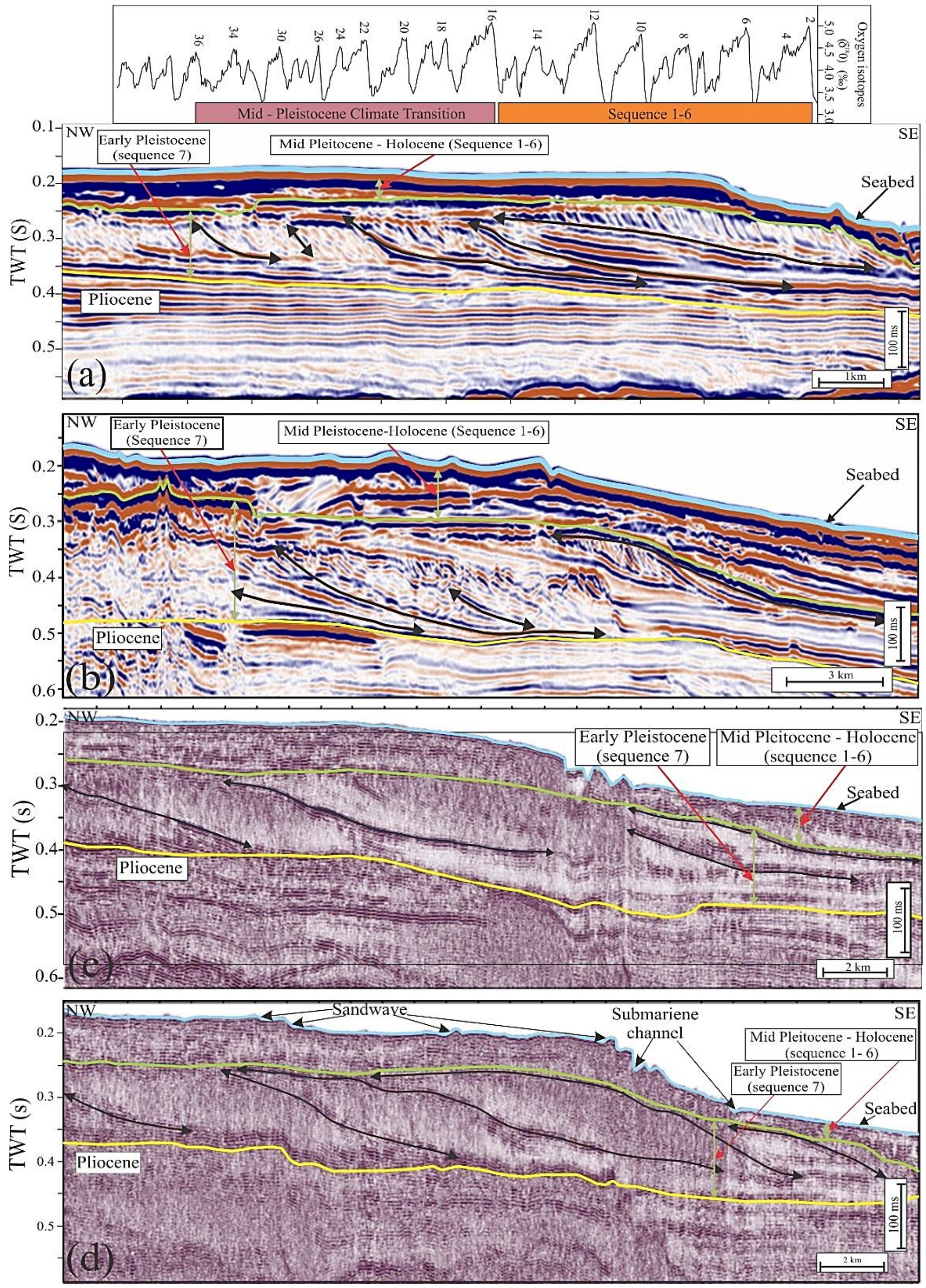

Figure 3. Example of Quaternary deposits is recorded by seismic data on the SE VN shelf. The Quaternary megasequence includes two sub-sequences, bounded by a clear erosional truncation surface. This sequence boundary is probably related to the end of mid-Pleistocene climate transition (MPT)

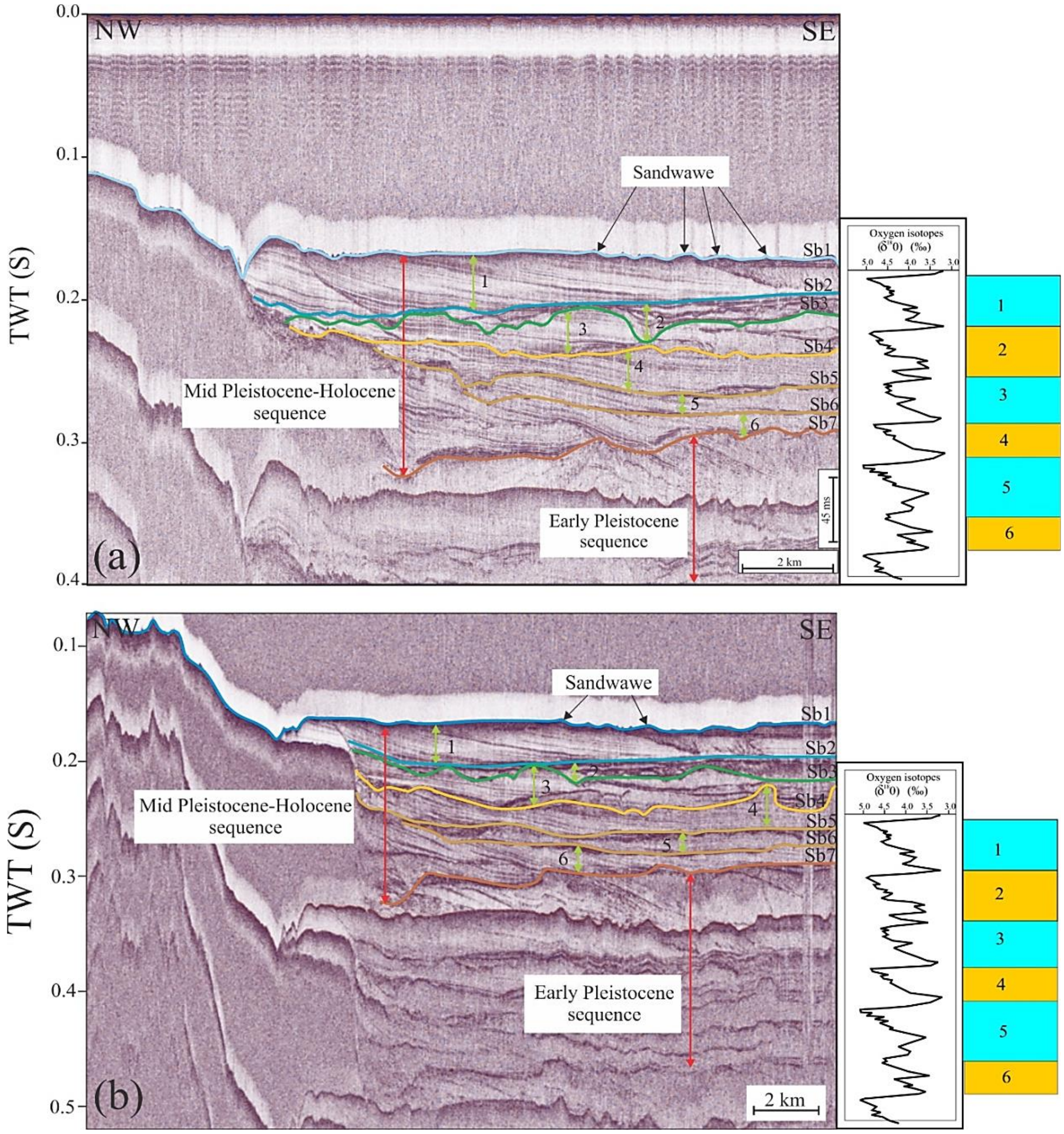

Figure 4. Example of Mid-late Pleistocene sequences (1-6) recorded by high resolution seismic data on the SVCM. Sequence boundaries are tentatively correlated with the marine isotope stages (Waelbroeck et al., 2002) with the most pronounced sea level fall. The base of sequence 6 is probably related to the end of mid-Pleistocene climate transition (MPT)

We identified multiple wedge-shaped units on the seismic profiles in the lower part of the Quaternary deposits. These units are characterized by top-lap and off-lap seismic terminations. Toplap refers to the geometry of sedimentary layers that appear to overlap one another in an upward direction, while offlap occurs when sedimentary layers terminate in a downward direction. These wedge-shaped stratal units mostly exhibit eastward to southeastward progradation, indicating that the sedimentary deposits were extending in those directions. The progradation is observed together with top lap termination under the SB7 unconformity, suggesting that these deposits were laid down during sea-level fall, forming an unconformity surface (SB7) on the outer shelf of the study area.

The thickness of the Lower Pleistocene sequence, which lies between the SB7 unconformity and the top of the Pliocene surfaces, is substantial, measuring approximately 0.2 seconds of two-way travel time (TWT), which corresponds to around 160 meters (Figs. 3 and 4).

In the upper part of the Quaternary deposits, the seismic reflections mostly appear parallel to sub-parallel, exhibiting low to moderate frequency (Fig. 3). This suggests that the sedimentary layers in this section have a relatively uniform and continuous character. The thickness of this upper part, referred to as the subsequence, varies from approximately 0.1 to 0.15 seconds of two-way travel time (TWT), corresponding to a depth of about 80-120 meters (Figs. 3 and 4). This subsequence extends from the SB7 unconformity (the boundary between the Lower Pleistocene and Pliocene deposits) to the seabed surfaces.

On high-resolution single-channel seismic profiles, the subsequence can be further subdivided into six distinct seismic units, and these units are bounded by seven unconformities (labeled from SB1 to SB7) (Fig. 4). The presence of these unconformities indicates periods of non-deposition or erosion that occurred during the deposition of the upper part of the Quaternary deposits. Most of these unconformities are recognized on the high-resolution seismic data by the presence of top lap terminations (overlapping reflections) or channel incisions (indicating erosional channels) (Fig. 4). These features suggest that during specific periods, sediment deposition was interrupted. Erosion or sediment reworking processes took place, resulting in the formation of unconformities.

3.2. Sedimentary characteristics and age control of Quaternary deposits

In the study area, direct sediment core control for the Holocene sequence is limited (Fig. 5). However, we obtained significant age constraints from the radiocarbon dating of a sediment core collected at a water depth of 156 meters. This core reached the upper part of the lowstand wedge and was dated to approximately 24.33 thousand years (kyr) before the present (Bui et al., 2013). This age provides valuable information about the timing of sediment deposition during the late Pleistocene to early Holocene period. Other studies in the region have also provided age constraints for sedimentary deposits. An earlier study on the outer Sunda Shelf indicated an age range of 25-30 kyr for the late Pleistocene soil surface (Hanebuth and Stattegger, 2004). The ages of seaward dipping clinoforms, located at water depths of 80-126 meters below the Last Glacial Maximum (LGM) paleosol surface on the Sunda Shelf, were dated to a range of 50 to 30 kyr (Hanebuth et al., 2003; Hanebuth and Stattegger, 2004).

While direct sediment core control is limited in the study area, we could refer to core data and age constraints from the nearby ODP (Ocean Drilling Program) well 1143 and other areas in the northern EVS where such data are available (Figs. 6, 7). These additional data sources help to provide a more comprehensive understanding of the Quaternary deposits in the study area, even in the absence of direct sediment core control for the Holocene sequence. By using these age constraints and integrating data from nearby regions, we can establish a more robust chronological framework for the Quaternary deposits in the SVCM. This information is crucial for accurately reconstructing the geological history and understanding the environmental changes in this region over time.

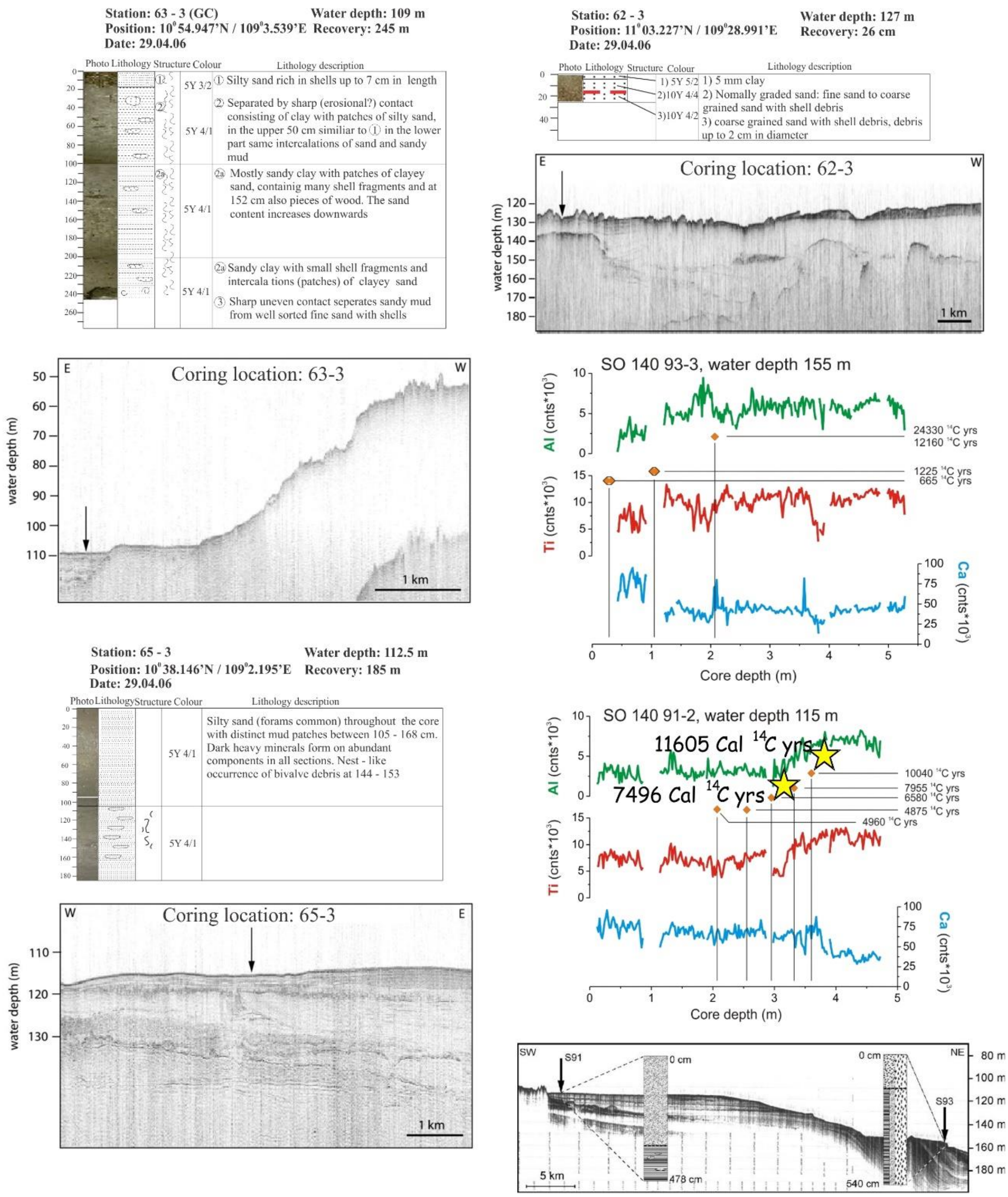

Figure 5. Available sediment core and sub-bottom profiles data are on the SVCM. Sediment age controls are only limited for late Pleistocene-Holocene sequence (Wiesner, 1999; Schimanski and Stattegger, 2005; Wiesner, 2006). Location of sediment cores is shown on Fig. 1

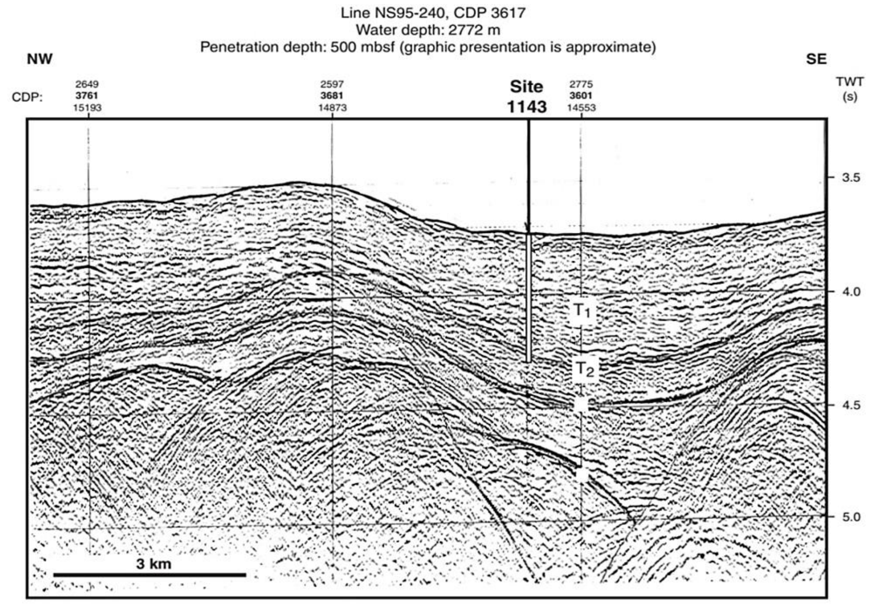

Figure 6. Sediment core of ODP well 1143 penetrates to Pliocene sequence on the outer SVCM. T2: Top of Middle Miocene; T1: Top of Late Miocene (Ocean Drilling Program Site 1143 of Leg 184). *Location of ODP well is shown on Fig. 1*

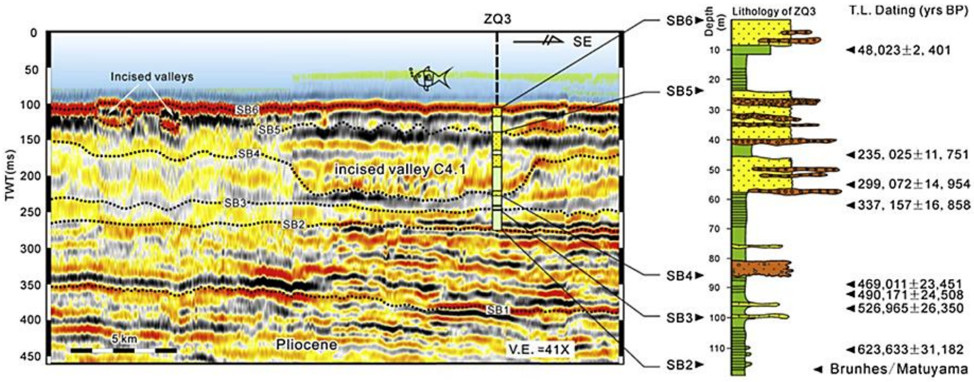

Figure 7. Correlation between major Quaternary sequence boundaries and the shallow borehole ZQ3 in the Northern EVS (Zhuo et al., 2015)

ODP well 1143, located in the eastern part of the study area at a water depth of 2772 meters, provides valuable sedimentary data for the region. The sediments drilled at Site 1143 represent continuous hemipelagic sedimentation of fine-grained terrigenous material and pelagic carbonate, covering a time from the late Miocene (T1) to the present. The Pleistocene sediments at Site 1143 consist mainly of various clayey nannofossil mixed sediment, clay with nannofossils, and clay with different color variations such as olive, greenish, light grey-green, and greenish-grey. Minor lithologies are found at various depths, including ash layers, turbidities (sediments deposited by underwater landslides or turbidity currents), and green clay layers. The carbonate content of this interval varies but averages around 18%. Both calcareous nannofossils and planktonic foraminifers are abundant and well-preserved in these sediments. The sedimentation rate at Site 1143, calculated based on biostratigraphic data, is estimated to be approximately 54 meters per thousand years (m/my) during the Pleistocene. This means that, on average, about 54 meters of sediment were deposited at this location every thousand years during the Pleistocene period.

4. Discussions

4.1. Quaternary evolution of the SVCM

Quaternary formation has been divided into seven subsequences in the study area, as shown in Figs. 3 and 4. Among these sequences, Sequence 7 is identified as the Early Pleistocene, while the other six sequences are subdivisions of the Middle Pleistocene-Holocene section.

Unfortunately, sediment thickness maps are available only for the Early Pleistocene (Sequence 7) and the Mid Pleistocene-Holocene sequences (including all sequences from 1 to 6). These maps are presented in Fig. 9. However, the sediment thickness of each sequence from 1 to 6 could not be mapped due to the limited availability of high-resolution seismic data.

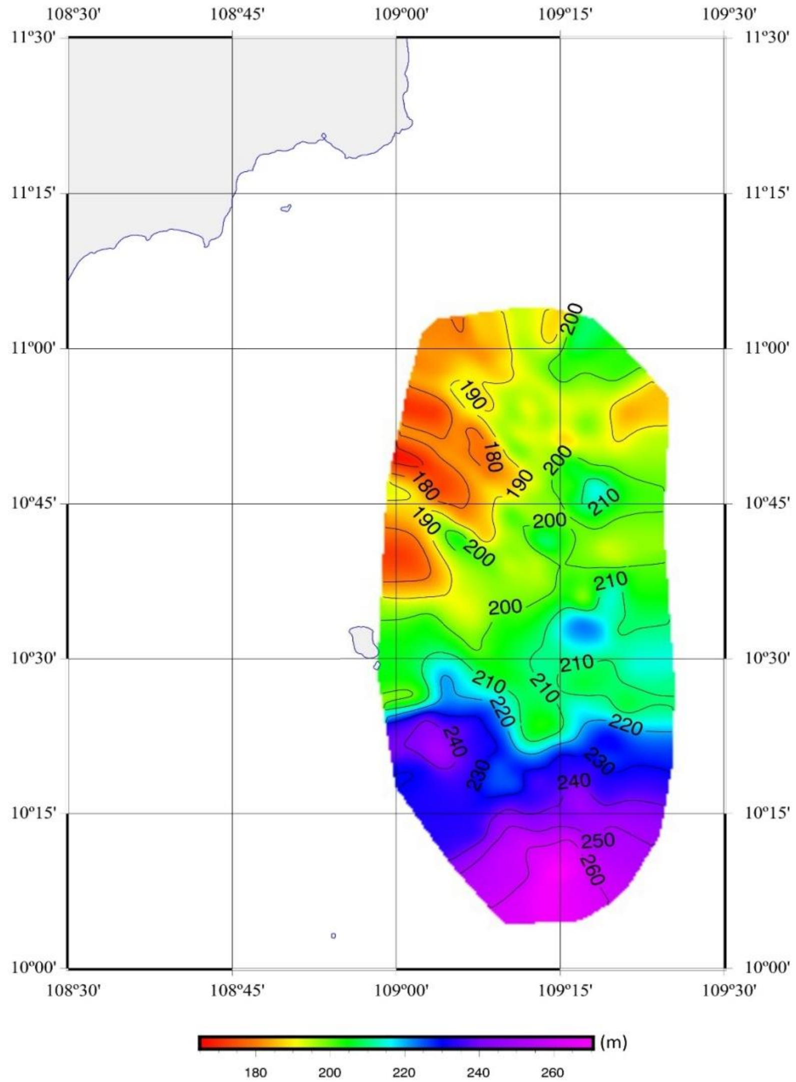

Figure 8. Topographic map of Early Pleistocene sequence boundary (SB7)

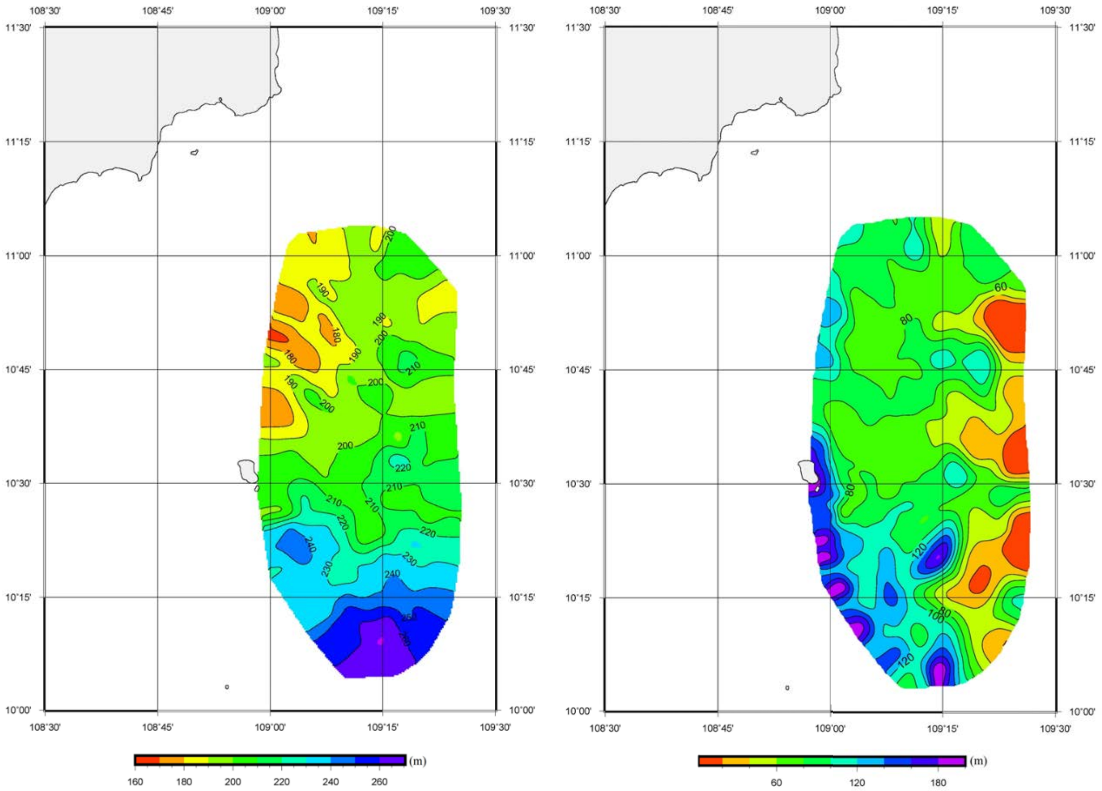

Figure 9. Thickness map of Early Pleistocene (sequence 7) (left) and Mid Pleistocene-Holocene sequences (sequences 1-6) (right)

The sediment units observed between the top of the Pliocene formation and the SB7 seismic surface, characterized by off-lapping strata on multichannel seismic profiles, have been interpreted as stacked falling-stage wedges formed during regression (Fig. 3). These wedges are indicative of periods of sea-level fall, during which sediments were deposited as the shoreline migrated seaward. Since no direct age control is available for this specific unit in the study area, we have used information from nearby regions to make age assignments. Similar stacked regression deposits observed in the northern EVS were assigned to be Early Pleistocene deposits in a previous study by Zhuo et al., 2015. Therefore, based on this correlation, it is likely that the sediment units observed in the study area may also be Early Pleistocene in age.

Furthermore, the large magnitude of incisions observed along the SB7 seismic surface on the SVCM indicates a relatively long erosional hiatus related to subaerial processes (Figs. 3, 4). This suggests a significant period of erosion and non-deposition, which may have been caused by changes in sea level and climate during the Middle Pleistocene Transition (MPT) event. The Mid-Pleistocene Transition (MPT) is a period in the Quaternary glaciations, occurring from approximately 41 thousand years to 100 thousand years ago, marked by a change in the behavior of glacial cycles (Head et al., 2008). The formation of the SB7 surface on the SVCM is believed to be related to the end of this Middle Pleistocene climate transition event, which occurred around 1.2-0.6 million years ago (Ma) (Clark et al., 2006; Li et al., 2008; Zhuo et al., 2015). Therefore, the age of the SB7 surface in the study area is likely to be around this time frame and is possibly equivalent to another surface (SB2 surface) observed in the northern EVS, according to the previous study by Zhuo et al., 2015. These age correlations and interpretations help to provide a temporal context for the sedimentary deposits and understand the geological history and climatic changes that have influenced the SVCM during the Pleistocene period.

In the study, the upper sediment units bounded between the SB7 seismic surface and the seabed have been tentatively assigned to be Middle-Late Pleistocene age. The Middle-Late Pleistocene period includes varying lengths of glacial and interglacial cycles. The average cycle length during this time is estimated to be around 100-120 thousand years (kyr) after the Mid-Pleistocene Transition (MPT) event (Head et al., 2008).

To correlate the sequence boundaries (SB1 to SB6) observed on the seismic profiles with specific glacial-interglacial intervals, we have related them to marine isotope stages (MIS) characterized by significant sea-level falls (Fig. 4). MIS is defined based on variations in the isotopic composition of marine sediments, which are influenced by changes in global ice volume and sea level. The suggested correlation of the sequence boundaries (SB1 to SB6) with glacial-interglacial intervals is as follows:

(1) SB1 is correlated with the Last Glacial Maximum (LGM), representing a time of extensive glaciation and lower sea levels.

(2) SB2 is correlated with MIS 6, another glacial period characterized by lower sea levels.

(3) SB3 is correlated with MIS 8, indicating another glacial-interglacial cycle.

(4) SB4 is correlated with MIS 10, representing a period of lower sea levels during a glacial stage.

(5) SB5 is correlated with MIS 12, indicating another glacial period.

(6) SB6 is correlated with MIS 14, representing a time of lower sea levels during a glacial stage.

These correlations provide valuable information about the timing and durations of glacial and interglacial intervals that occurred during the Middle-Late Pleistocene period in the study area. The sea-level falls associated with these sequence boundaries are suggested to have formed regional fluvial incisions, implying that significant changes in sea level had an impact on the geomorphological features of the continental shelf (Posamentier, 2001). Understanding the relationship between the sequence boundaries and the glacial-interglacial intervals helps to reconstruct the paleoenvironmental conditions and sea-level fluctuations during the Middle-Late Pleistocene, contributing to a better understanding of the geological history and sedimentary processes on the SVCM.

4.2. Comparison between Quaternary stratigraphy of the SVCM to worldwide continental margins

The Pliocene to recent strata of the southern Vietnam shelf exhibits distinct characteristics in terms of seismic reflectors and sediment accumulation patterns. On the inner-middle shelf, the strata are characterized by horizontal to sub-parallel seismic reflectors, indicating relatively uniform and continuous sediment deposition in this area. In contrast, on the outer shelf, prograding clinoforms are observed. Clinoforms refer to the sloping sedimentary layers in submarine environments, and their presence on the outer shelf suggests sediment progradation seaward, possibly due to sediment supply from river systems or other sediment sources.

Fluvial incision, the cutting of river channels into the underlying strata, appears to be more dominant in the upper Pliocene to recent strata. This increased fluvial activity is attributed to the influence of high glacio-eustatic sea-level fluctuations across the low-gradient shelf. As sea levels rise and fall during glacial and interglacial periods, the coastal rivers respond by cutting down into the shelf sediments, leading to fluvial incisions.

The high accumulation rate of the Pliocene to recent strata observed in the SVCM is consistent with similar patterns observed in other areas within the EVS. Previous studies have documented these patterns (Matthews et al., 1997; Clift and Sun, 2006; Fyhn et al., 2009, 2019). The high accumulation rates are likely linked to enhanced Southeast Asian weathering, triggered by regional hinterland uplift and Pliocene to Holocene monsoon intensification. The regional hinterland uplift exposes more land areas to weathering processes, increasing the supply of sediments to the coastal regions. Additionally, the intensification of the monsoon during the Pliocene to Holocene periods may have contributed to increased rainfall and runoff, further enhancing sediment transport to the shelf and subsequent accumulation. Overall, the sedimentary characteristics and accumulation patterns of the Pliocene to recent strata in the southern Vietnam shelf provide insights into the geological processes that have shaped the region's sedimentary architecture over time. Factors such as sea-level fluctuations, fluvial activity, and climate-driven changes in sediment supply all significantly influence sediment deposition in this area.

After the end of the MPT period, transgression-regression cycles continued to repeat during the Middle-Late Pleistocene on the SVCM. These cycles were controlled by high-frequency sea-level fluctuations (Figs. 3, 4). Each sequence observed in the sedimentary record shows an overall pro-gradational stacking pattern, reflecting the characteristic 100-kyr asymmetric periodicity. This means that the sequences were formed under the influence of Milankovitch cycles, with long phases of relative sea-level fall followed by shorter periods of stabilization and rise (Waelbroeck et al., 2002).

The pro-gradational stacking patterns suggest that sediment deposition occurred primarily during falling sea level periods when shorelines migrated seaward. As sea levels rose again, sedimentation would stabilize or slow down. This cyclic pattern results from the interplay between glacial-interglacial cycles and their influence on sea levels.

During the Pliocene to recent times, the south-to-southeastward migration of the shelf edge complex indicates that the Palaeo-Mekong River System was the dominant sediment source for the study area (Yarbrough, 2006). During the Pliocene to recent periods, the Mekong River likely contributed a significant amount of sediment to the continental shelf through its deltaic system. Additionally, sediment may have been transported alongshore from the northern shelf of Vietnam, which serves as another sediment source for the region (Bui et al., 2013, 2019).

The dominance of the Palaeo-Mekong River System and the potential alongshore sediment transport from the northern shelf of Vietnam played vital roles in shaping the sedimentary architecture and depositional patterns observed on the SVCM during the Pliocene to recent periods.

The thick Middle Pleistocene-Holocene regressive deposits, with a depth range of 100-150 meters, preserved on the SVCM, result from the interaction between various factors during periods of sea-level lowstand.

One of the key factors contributing to the preservation of these regressive deposits is the low shelf gradient. The gentle slope of the shelf allows sediments to accumulate and build up during lowstand phases when sea levels are lower and shorelines recede seaward. This leads to the deposition and preservation of significant sediment on the continental shelf.

Tectonic subsidence also plays a role in creating accommodation space for sediment deposition. Subsidence refers to the downward movement of the Earth's crust, and in this case, it helps create deeper basins on the continental shelf where sediments can accumulate.

The monsoon intensification during sea-level lowstand also increases sediment supply to the continental shelf. The monsoon brings heavy rainfall and increased river discharge, enhancing sediment transport from the land to the sea. The Palaeo-Mekong River, a primary regional river system, likely served as a significant sediment source, transporting large amounts of sediment to the shelf.

During long periods of sea-level lowstand, most inner and middle shelves were exposed, with shorelines far inland compared to the present. This prolonged exposure led to erosion and non-deposition on the inner-middle shelf and morphological highs (elevated features on the shelf). However, regressive sequences were locally preserved on the outer shelf, where sediment accumulation was more favorable due to the low shelf gradient.

The combination of these factors, including the low shelf gradient, tectonic subsidence, monsoon intensification, and high sediment supply from the palaeo-Mekong River, led to the formation and preservation of the thick Middle Pleistocene-Holocene regressive deposits on the SVCM.

The review of Quaternary Milankovitch cycles on worldwide modern continental shelves highlights the general and specific characteristics of the middle-upper Pleistocene sequences formed under the influence of composite 100 and 20 kyr Milankovitch cycles (Lobo and Ridente, 2014). These cycles refer to periodic changes in Earth's orbital parameters that influence climate and sea-level fluctuations. The overall stacking patterns of Middle Pleistocene-Holocene deposits on the SVCM appear to be very similar to those observed in other Quaternary margins worldwide, where the 100-kyr cycle has become dominant over the last 500-800 kyr (Ruddiman et al., 1986; Shackleton et al., 1990; Rabineau et al., 2005; Ridente et al., 2008). This suggests that the sedimentary sequences on the SVCM were influenced by similar climatic and sea-level fluctuations observed in other regions during the middle-upper Pleistocene period. The dominant retrogradation stacking patterns observed in late Quaternary sequences have been documented in various areas worldwide. Examples include the Tyrrhenian offshore Northern Latium and Northern Sicily in the Mediterranean region, as well as the Adriatic basin (Chiocci, 2000; Pepe et al., 2003; Trincardi and Correggiari, 2000; Ridente and Trincardi, 2002; Maselli et al., 2010). Similar patterns have also been described in the Gulf of Lion, Alboran Sea, and Gulf of Cadiz (Rabineau et al., 2005; Lobo et al., 2008; Hernández-Molina et al., 2000). Overall, the asymmetric 4th-order Milankovitch cycles are identified as the primary control on the variation of the mid-late Pleistocene-Holocene sequences in these regions. These cycles of sea-level fluctuations, driven by variations in Earth's orbital parameters, significantly impact sedimentation patterns and the formation of stacked sequences on the continental shelves. Recognizing these global and regional patterns helps us understand the broader geological implications of the Middle Pleistocene-Holocene sequences observed on the SVCM. It provides valuable context for the sedimentary processes, climate variability, and sea-level changes that have shaped the sedimentary architecture in this area, contributing to a more comprehensive understanding of the region's geological history.

5. Conclusions

Overall, the combination of seismic data interpretation and age correlation with global sea-level fluctuations has provided valuable insights into the geological history and sedimentary processes of the SVCM. These findings contribute to a broader understanding of the regional and global factors that have shaped the sedimentary architecture of this area over time. Based on the results obtained from high-resolution single/multichannel seismic interpretation and age correlation to global sea-level fluctuations, the following conclusions can be drawn about the Quaternary stratigraphy of the SVCM:

- Seismic stacking patterns indicate that the Pliocene to present SVCM stratigraphy is characterized by the continental shelf's East to southeastward progradation. This suggests that sediment deposition has been mainly driven by sediment transport and accumulation in these directions.

- The study reveals six Middle Pleistocene-Holocene fourth-order sequences on the outer SVCM at a water depth of approximately 120 meters. These sequences represent sedimentary deposits formed during distinct sea-level changes.

- The ages of these sequences are determined by correlating them with the global oxygen isotope curve, which provides a way to establish the timing of sea-level changes. The correlation indicates that each sequence records a fourth-order cyclicity of sea-level change, approximately 100-120 thousand years.

- The sequence boundary SB7, identified in this study, is likely related to the end of the MPT period, which occurred around 1.2-0.6 million years ago and marked a significant change in glacial cycle behavior.

- The thick middle Pleistocene-Holocene regressive deposits, with a depth range of 100-150 meters, preserved on the Southeast Vietnam Shelf, result from the interaction between the shelf gradient, tectonic subsidence, and sediment supply during sea level fall. These factors created favorable conditions for sediment accumulation and preservation during periods of low sea level.

- The Quaternary stratigraphy of the SVCM exhibits similarities to many other continental margins around the world. These margins are mainly formed under the influence of asymmetric 4th order Milankovitch cycles, characterized by longer phases of relative sea-level fall followed by shorter periods of rise.

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