

Influence of the western Pacific warm pool and East Asian climate on late Holocene typhoon activities affecting Taiwan

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ABSTRACT

Reconstructing paleo-typhoon activity in East Asia is essential for understanding long-term changes in cyclone frequency and intensity under ongoing anthropogenic warming. This study investigates high-resolution laminated sediments from Core MD18-3574, retrieved from the western levee of the Gaoping submarine canyon (southern Taiwan), using hyperspectral imaging, XRF core scanning, grain-size analysis, bulk mineralogy, and radiocarbon dating to reconstruct typhoon events over the past 4200 years. The core displays alternating dark and light laminae. Dark laminae consist of coarser, quartz- and feldspar-rich sediments with lower clay content and low log(Fe/Ca) ratios, showing upward fining and asymmetric sorting, consistent with deposition by hyperpycnal flows within the canyon associated with extreme river floods mainly attributed to typhoon-related events. A total of 2404 dark laminae are interpreted mainly as deposits induced by the most intense typhoon events. The frequency of the most intense typhoons in southern Taiwan varies between ~8 and 40 events per 40 years, with reduced activity during the periods 3300–2500 and 1800–400 cal yr BP, which coincide with time intervals with enhanced El Niño relative to La Niña-like conditions. In contrast, relative increases of La Niña-like conditions favor more frequent typhoons in southern Taiwan. Typhoon intensity remained stable until ~1800 cal yr BP, then increased, likely in response to elevated western tropical Pacific SSTs. Comparison with regional typhoon records reveals ENSO-driven spatial patterns. El Niño conditions shift cyclone genesis eastward inducing an increasing tendency for typhoon tracks to recurve northward reducing frequency in southern Taiwan but increasing it in southern Japan and Korea. La Niña conditions promote westward genesis and zonal typhoon trajectories inducing higher frequency of less intense typhoons in the SCS. Overall, these results indicate a decoupling between typhoon frequency and intensity in southern Taiwan, controlled by interactions between ENSO and SST variability. They also provide new insights into past tropical cyclone behavior and contribute to the forecasting of typhoon hazards under changing climate conditions.

1. Introduction

Approximately 80 tropical storms form each year at tropical and subtropical latitudes of the ocean (Emanuel, 2003). Tropical cyclones,

referred to as typhoons in the western North Pacific, are the most intense tropical storms, accounting for more than 50% of the yearly events (Emanuel, 2003). Tropical cyclones have significant impacts on human societies and economic activities, causing annual losses of about 43.9

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billion US dollars in the United States and 28.7 billion yuan in China (Zhang et al., 2009; Smith, 2020). In Taiwan, rainfall associated with the 3–4 typhoons that occur each year leads to destructive processes on land, such as landslides and floods, which cause considerable damage and casualties (Shieh et al., 2010; Lo et al., 2014; Deng et al., 2016; Yang et al., 2018; Tsai et al., 2021, 2022). Particularly strong typhoons, such as Morakot (2009), can produce rainfall and sediment loads sufficient to trigger deep-sea hyperpycnal flows in deep-sea canyons and damage submarine infrastructures, including submarine telecommunication cables to the south of Taiwan (Su et al., 2012a; Gavey et al., 2017).

Climate variability in Taiwan and the western Pacific is largely controlled by the East Asian monsoon system and El Niño–Southern Oscillation (ENSO) (e.g., Wang et al., 2001, 2005, 2014, 2015; Dykoski et al., 2005; Yu et al., 2016; Zhang et al., 2018). The interactions between the monsoon system and the ENSO conditions of the tropical Pacific Ocean determine the pattern of moisture distribution in the region (Elsner and Liu, 2003; Lin et al., 2008; Liu et al., 2017; Zhu et al., 2017). The southern continental shelf of Taiwan is narrow, and the head of the Gaoping submarine canyon is directly connected to the Gaoping River mouth (Liu et al., 2016a) (Fig. 1b). Because of this land-sea configuration, the transport of sediment within the Gaoping submarine canyon is mainly controlled by hyperpycnal flows deriving from floodwaters of the Gaoping River (Zhang et al., 2018). Hyperpycnal flows exert a strong erosional impact, truncating the deposition sequences in the submarine canyons (Mulder et al., 2003; Chiang and Yu, 2006). When these flows overflow the submarine canyons, their reduced density and turbidity generate weaker gravity-driven processes, thereby limiting erosion on the levees of the Taiwan margin (Lehu et al., 2015).

Data from a mooring system located on the levee 490 m above the canyon thalweg has shown that 4 typhoon-driven hyperpycnal flows occurred per year between 2013 and 2016 (Zhang et al., 2018). During this monitoring period, about 70% of the turbidity currents observed on the levee were triggered by high sediment river discharge induced by typhoon events (Zhang et al., 2018). The Gaoping submarine canyon rapidly transports sediments from the Gaoping River catchment to the deep basin of the South China Sea (SCS) through hyperpycnal flows (Milliman and Syvitski, 1992; Liu et al., 2009; Zhang et al., 2018).

The Gaoping River and the surrounding small rivers transport large volumes of fine sediments (mainly fine silt and clay). At the river mouth, these sediments are transported across the slope and the submarine canyon and settle by decantation along the southern margin of Taiwan (Stow and Tabrez, 1998; Stow and Smillie, 2020). During typhoon events, intense rainfall and enhanced runoff generate strong physical erosion, leading to a significant increase in sediment discharge from the Gaoping River to the SCS (Dadson et al., 2003; Xu et al., 2018; Wang et al., 2020). In such conditions, the concentration of suspended-sediment in the river plume on the slope and canyon head can be high enough to generate nepheloid layers along the slope and turbulent hyperpycnal flows within the canyon (Milliman and Syvitski, 1992; Dadson et al., 2003; Mulder et al., 2003; Poppe et al., 2008; Liu et al., 2009, 2010a, 2012, 2016a,b; Hsu et al., 2014; Zhang et al., 2018; Tian et al., 2022). Attention has been already paid to the highly dynamic environments surrounding Taiwan in order to investigate turbiditic systems and flood events associated with paleoclimatic changes over different time scales (Yu et al., 2017; Wang et al., 2019; Hsiung et al., 2021). Sediment deposits on the levee of the Gaoping submarine canyon, located along the southern margin of Taiwan, therefore constitute an ideal archive to reconstruct past changes in major paleo-flood events of the Gaoping River, mainly attributed to typhoon activity (Anschutz et al., 2002; Hess et al., 2005; Babonneau et al., 2013; Yu et al., 2017; Zhang et al., 2018).

In recent decades, developments in scanning methods, such as X-ray fluorescence (XRF) core scanning and hyperspectral imaging, have brought new insights in the geosciences through non-destructive, high-resolution analyses spectra (from millimeter to micrometer scales). XRF core scanning has been widely used to investigate relative geochemical compositions in lacustrine (Arnaud et al., 2016; Wang et al., 2019; Rapuc et al., 2020) and marine sedimentary sequences (Xie et al., 2014; Xu et al., 2018; Yu et al., 2017; Hsiung et al., 2021; Bozyigit et al., 2022). Sediment cores have also been scanned using hyperspectral imaging in conjunction with XRF core scanning to reconstruct paleoclimatic and environmental changes in lacustrine drainage basins (Butz et al., 2015; Jacq et al., 2020, 2022a). Hyperspectral imaging has also been used to determine occurrences of past flood events in lacustrine and fluvial systems (Jacq et al., 2019, 2022b; Ghanbari et al., 2020; Rapuc et al.,

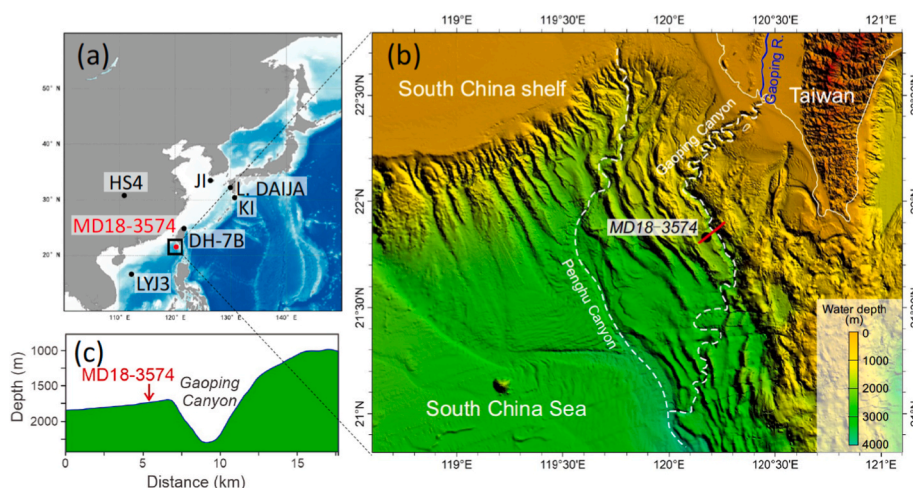


Fig. 1. (a) Regional map of East Asia showing the locations of the study area and the typhoon activity records discussed in this study: LYJ3 - coral reef destruction in northwestern SCS (Yue et al., 2019); DH-7B - typhoon activity records inferred from grain-size variations in a lacustrine sediment core from northern Taiwan (Chen et al., 2012); HS4 - paleoflood record derived from speleothems in central China (Zhu et al., 2017); L. Daija - extreme coastal flooding (overwash frequency) record from the coastal lake Daija in southwestern Japan (Woodruff et al., 2015); KI - storm surge-driven inundation reconstructed from coastal lake sediments on Kamikoshiki Island (southwestern Japan) (Woodruff et al., 2009); JI - heavy rainfall record from lake sediments of the Sara Oreum volcanic cone, Jeju Island, South Korea (Lim et al., 2023); (b) Bathymetric map of the northeastern SCS, showing the location of Core MD18-3574 (black dot) on the western levee of the Gaoping Canyon, as well as the location of the bathymetric profiles (red line) shown in Fig. 1c. The Gaoping River and the submarine canyons (Penghu Canyon and Gaoping Canyon) are also indicated; (c) Bathymetric profiles showing the distances and elevation of Core MD18-3574 relative to the thalweg of the Gaoping submarine canyon. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2020). Although interest in hyperspectral imaging for the study of finely laminated sediments in continental environments is increasing, this analytical method remains rarely utilized in the study of marine sedimentary sequences.

In this study, we conducted high-resolution, non-destructive hyperspectral imaging and XRF core scanning, combined with radiocarbon dating, X-ray diffraction (XRD), bulk mineralogical analyses, and laser grain size measurements on laminated sediments from Core MD18-3574, collected from the western levee of the Gaoping submarine canyon (Fig. 1). The objectives of this study are (1) to constrain the sedimentary processes responsible for the deposition of the laminations and (2) to reconstruct the frequency and intensity of typhoons affecting southern Taiwan over the past 4200 yrs. The studied levee is located ~600 m above the thalweg of the Gaoping submarine canyon (Fig. 1c), close to the mooring system site investigated by Zhang et al. (2018), who identified the occurrence of several typhoon-driven hyperpycnal flows per year. The fine laminations therefore have great potential to yield a continuous record of turbidites resulting from typhoon-driven hyperpycnal flows, allowing reconstruction of the intensity and frequency of typhoons during the late Holocene.

2. Environmental setting

At the present time, the climate of Taiwan is largely driven by the East Asian monsoon system and typhoons (Webster et al., 1998; Wu and Kuo, 1999; Chen and Chen, 2003; Wang et al., 2003; Su et al., 2012; Liang et al., 2017; Zhang et al., 2018). In southern Taiwan, the mean annual rainfall is about 2500 mm/yr, with nearly 80% of the total precipitation occurring during the summer season (Chen and Chen, 2003; Henny et al., 2021). The East Asian monsoon is characterized by a seasonal reversal of wind direction associated with changes in the land-ocean thermal gradient and a concomitant latitudinal shift of the Intertropical Convergence Zone (ITCZ), which together control moisture transport over East Asia (e.g., Webster et al., 1998). During the summer, southwesterly monsoon winds transport warm, moisture-rich air from the adjacent oceans toward Taiwan, while northward displacement of the ITCZ (20–35°N) further enhances regional moisture availability (Wang et al., 2003). In contrast, during winter, northeasterly monsoon winds originating from the Asian continental interior bring cooler and drier air masses to Taiwan, leading to the relatively dry winter conditions. At the same time, the ITCZ shifts southwards from 0 to 20°S (Chen and Chen, 2003; Wang et al., 2003).

The tropical and subtropical western North Pacific, spanning roughly 10°N to 27°N, represents the most active region globally for typhoon genesis (Elsner and Liu, 2003). Taiwan occupies a key position within this major cyclonic corridor, often described as a global “choke point” for tropical cyclone activity (Sampe and Xie, 2007). In this region, typhoon tracks generally diverge, alternating between westward-moving systems that cross southern Taiwan into the South China Sea and northward-recurving tracks that make landfall in southern Japan or Korea. The typhoon season mainly spans from July to November, with approximately 3 to 4 typhoons hitting Taiwan yearly, contributing up to nearly 50% of its total annual rainfall (Wu and Kuo, 1999; Su et al., 2012; Zhang et al., 2018). In modern times, mean rainfall intensity during typhoons is about 20 mm/h, and the most extreme events can produce up to the average yearly total rainfall (e.g., Herbs ~1800 mm in 1996 and Morakot >3000 mm in 2009) (Wu and Kuo, 1999; Chien and Kuo, 2011; Su et al., 2012).

The Gaoping River, with a length of about 170 km, is one of the largest drainage basins in Taiwan (area of about 3260 km²). It extends from the river's source near Yu-shan (Jade Mountain), in the Central Hsuehshan Range at an elevation exceeding 3000 m above sea level, to its mouth in the northeastern SCS (Liu et al., 2009). The high runoff (~2500 mm/yr), combined with the steep topography of the Gaoping River basin, result in high erosion rates (3–6 mm/yr) and sediment discharges to the SCS (~49 Mt/yr) (Dadson et al., 2003; Liu et al., 2009).

Approximately 80% of the supplied sediments are delivered to the SCS through the Gaoping canyon, whereas only about 20% are deposited along the Gaoping slope (Huh et al., 2009). The Gaoping canyon is ~260 km long, with the vertical relief between the thalweg to the levee ranging from ~130 to 800 m, before merging into the Manila Trench (Chiang and Yu, 2006, 2011).

3. Material and methods

3.1. Material

The Calypso Core MD18-3574 (21°50.42'N, 120°10.67'E; 22.52 m long; 1171 m water depth) was collected on the western levee of the Gaoping submarine canyon during the *HYDROSED* cruise aboard the *Marion Dufresne* in 2018 (Fig. 1b and c). The sediment core exhibits continuous, well-preserved millimeter-to centimeter-scale laminations throughout its entire length and consists of two different units, corresponding to greenish light-gray homogenous hemipelagic mud and fine pluri-millimetric heterogeneous dark-gray silt layers. No visible evidence of piston effects, sediment stretching, or sediment disturbance were observed in Core MD18-3574 which was recovered using the Calypso coring system.

For this study, the core was scanned using hyperspectral imaging and XRF core scanning at high resolutions. A total of 450 samples were collected at a 2 mm sampling resolution from selected core intervals of 1365–1385 cm and 2100–2170 cm. These samples were subjected to laser grain size analyses and 10 of them were additionally used for XRD bulk mineralogy analysis.

3.2. Chronological framework

Radiocarbon dating was undertaken at the UMS-ARTEMIS Facility (CNRS-CEA Saclay, France) using a Pelletron 3 MV AMS on 8 mg of well-preserved calcareous test samples of planktonic foraminifera (pluri-specific samples of *G. ruber*, *G. sacculifer*, *O. universa*) within the >150 µm size fraction (Table 1). The radiocarbon ages were calibrated using Bacon Package (Blaauw and Christen, 2011). A local delta R value of -133 ± 33 yr BP has been used (Yoneda et al., 2007; Hirabayashi et al., 2019).

The ¹⁴C dates range from 4050 cal yr BP at 2247.5 cm to 130 cal yr BP at 56 cm (Table 1; Fig. 2b). The mean sedimentation rate of Core MD18-3574 is very high (520 cm/kyr), with an average of 550 cm/kyr before 2216 cal yr BP and 490 cm/kyr thereafter (Fig. 2a). The linear sedimentation rate displays a slight increasing trend from 2600 to 1300 cal yr BP, followed by a period of lower sedimentation rate from 1300 to 550 cal yr BP, before increasing toward the present.

Table 1
Core MD18-3574 chronological framework. AMS¹⁴C dates obtained on pluri-specific samples of *G. ruber*, *G. sacculifer*, *O. universa* and calibrated to calendar age using Bacon Package (Blaauw and Christen, 2011).

Sample ID	Depth (cm)	¹⁴ C age (yr BP)	Calendar age (cal yr BP)	Error (1σ, ± yr)
65568	53.5–58.5	540 ± 30	130	85
65569	178–183	705 ± 30	322	84
69689	275–280	1080 ± 30	608	60
65570	385.5–390.5	1300 ± 30	817	75
69690	615–620	1895 ± 30	1425	76
69691	815–820	2260 ± 30	1843	87
65572	1003.5–1008.5	2535 ± 30	2204	86
69692	1300–1305	2850 ± 30	2601	92
69693	1600–1605	3310 ± 30	3144	94
69694	1920–1925	3750 ± 30	3673	96
65573	2245–2250	4035 ± 30	4050	97

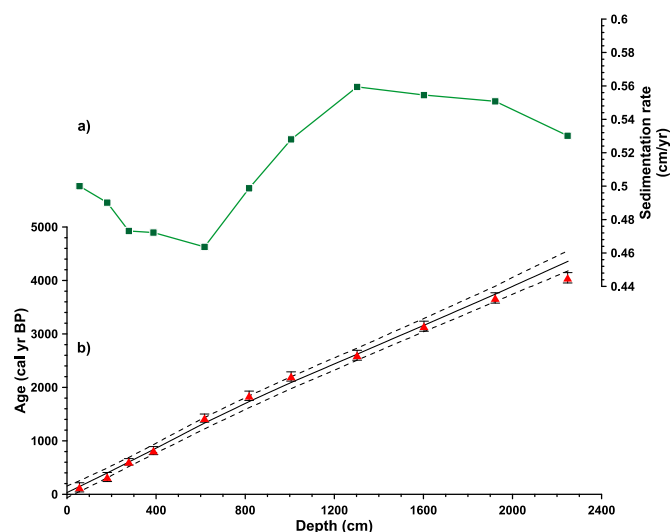


Fig. 2. Variations in sedimentation rate (cm/yr) for Core MD18-3574 (a); Age–depth model for Core MD18-3574 based on AMS ^{14}C dates obtained from planktonic foraminifera (*G. ruber*, *G. sacculifer*, *O. universa*). Black solid and dotted lines represent the mean ages and the 95% confidence interval, respectively (b).

3.3. Hyperspectral imaging

Hyperspectral imaging was performed at the M2C laboratory, Université Rouen-Normandie, using two hyperspectral camera sensors covering the Visible and Near InfraRed (VNIR) and Short Wave-InfraRed (SWIR) spectral range of 400–2500 nm. The data collection followed hyperspectral image acquisition protocols from Butz et al. (2015) and Jacq et al. (2020, 2022). The sediment core surface was smoothed and flattened as much as possible to reveal sedimentary structures masked by oxidation and to eliminate sediment surface variations that might distort the signal. The calibration table, illumination unit and camera heights were adjusted to obtain relevant images for our study (VNIR pixel size: 40 μm ; SWIR pixel size: 150 μm). Camera focus and parameters (integration time, frame rate) were optimized in order to capture a sharp image. Black (shutter closing, instrumental noise, 0% reflectance) and white (white spectra reference, 100% reflectance) were recorded to normalize the spectra of the sediments in terms of percentage of reflectance. After pre-processing settings (exposition time, calibrating noise), reflectance spectra information was captured and detrended to correct and normalize the spectra from a baseline following Jacq et al. (2020, 2022).

To consider the spectral variation of the sample, the Rmean indicator for average reflectance was used for both cameras (Rmean VNIR and Rmean SWIR) (Trachsel et al., 2010). VNIR and SWIR spectra show specific absorptions of certain compounds at specific wavelengths (Krupnik and Khan, 2019; Viscarra Rossel and Behrens, 2010). To model them, a simple approach is to consider the reflectance value at this wavelength. It is also possible to use reflectance ratios or derivatives to correct for some effects (matrix, moisture, texture, other compounds). Thus, for the study of clays that absorb around 2200 nm (Madejová et al., 2017), the Clay R2200 index was used. Similarly, organic matter absorbs around 1650 nm (Viscarra Rossel and Behrens, 2010) and the OM R1650 index was used. To consider the effect of hydroxyl bonds induced by moisture and by clays or organic matter, the Moisture R1935 and Hydroxyl R1450 indices were created, as well as their R1935/R1450 ratio (Viscarra Rossel and Behrens, 2010).

3.4. Relative geochemical composition analysis

XRF core scanning was performed on Core MD18-3574 at two

different resolutions (1 mm and 1 cm). The core surface was cleaned, flattened, and smoothed to prevent perturbations and its center covered with an Ultralene film (4 μm thick). The core was firstly scanned at a resolution of 1 mm using an Itrax XRF core scanner at the Second Institute of Oceanography, Ministry of Natural Resources (Hangzhou, China) to obtain relative geochemical variations at the laminar scale. The Itrax XRF core scanner parameters were set to a 10 s exposure time at 60 kV and 45 mA. Under these analytical conditions, only Ca and Fe could be reliably measured. Other elements such as Al, Si, K, Ti and Br were not detected from the background noise due to the relatively low exposure time of sediments to X-rays. Consequently, these elements were excluded from the millimetric dataset (not shown in this study). To overcome this limitation, the core was also scanned at a resolution of 1 cm at the State Key Laboratory of Marine Geology, Tongji University (Shanghai, China), using an Avaatech XRF core scanner set at a 30 s exposure time with 10 kV, 30 kV, and 50 kV to measure intensities of the elements from Al to Fe. The relative abundances of each element were reported versus total counts per second (cps), which were proportional to the chemical concentrations of a specific element. Fe and Ca intensities display similar variations at both 1 mm and 1 cm resolutions (Fig. S1). At a resolution of 1 cm, longer X-ray exposure time allows reliable detection of Al, Si, K, Ti and Br. Therefore, in this study, Fe and Ca are considered at a millimetric resolution, whereas Al, Si, K, Ti and Br are considered at a centimetric resolution.

3.5. Grain size analysis

Grain-size distribution measurements of the detrital fraction of the core sediments were carried out using a Beckman-Coulter LS230 laser diffraction particle-size analyzer, which measures particle sizes ranging from 0.02 to 2000 μm . Prior to the grain-size measurement, organic matter was removed by adding 5 mL of 10% H_2O_2 to the sample. The solution was gently shaken for several days, after which the sediments were rinsed with deionized water. Carbonates were subsequently removed by adding 10 mL 0.5% hydrochloric acid (HCl). After the decarbonation, the residual HCl was removed by rinsing the samples three times with deionized water. The prepared suspension was then introduced into the Beckman-Coulter LS230 to carry out the grain size analysis. Measurements were performed in two successive acquisitions; the second acquisition, which was generally more stable, was selected.

3.6. Bulk mineralogy analysis

Bulk mineralogy was determined on ten samples collected from laminae (five dark and five light laminae samples). Approximately 0.5–1 g of dried sediments were first pre-ground and then finely ground (<1 μm) using a Retsch XRD-Mill McCrone equipped with agate balls and ethanol. Bulk mineral compositions were analyzed using X-ray diffraction (XRD) performed with a PANalytical X'Pert PRO diffractometer. As the fine grinding process with ethanol potentially may have affected the smectite, the samples were put in a 1M CaCl_2 solution to saturate the samples in calcium and to reconstitute the 001 smectite peak at $\sim 15^\circ$. A second XRD analysis was then performed and compared with the untreated samples to determine the presence or absence of smectite. The diffractograms were treated using the open-source Profex software to identify and semi-quantify the minerals.

3.7. Principal Component Analysis

Principal Component Analysis (PCA) was performed using R (version 4.6.0) through the prcomp(.) function from the base stats package. The primary objective of this analysis was to reduce the dimensionality of the dataset while preserving as much variance as possible, allowing for the identification of underlying patterns and relationships among the variables. Prior to the PCA, all proxy records were interpolated onto a consistent depth scale of 2 mm to standardize measurements across

different proxy record analyses at different depth resolutions. All variables were standardized to z-scores to ensure that each variable contributes equally to the analysis, preventing variables with larger ranges from disproportionately influencing the PCA results. The standardized dataset was then analyzed using PCA to extract principal components, which represent linear combinations of the original variables that capture the maximum variance in the data.

4. Results

4.1. Relative geochemical composition and hyperspectral imaging

For Core MD18-3574, Br and OM R1650 intensities remain relatively

stable from 2250 to 1250 cm and then increase upwards to the core top (Fig. 3d and e). Terrigenous elements (Al, Si, Ti and K) display similar long-term variations and exhibit trends that are opposite to those of Clay R2200 and OM R1650 (Fig. 3 and Fig. S2). Their intensities remain relatively stable from 2250 to 1250 cm, followed by a continuous decrease above 1250 cm (Fig. 3 and Fig. S2). The OH R1450 index is characterized by higher values before 800 cm and a decrease thereafter (Fig. 3b). The shift observed at 800 cm in this index is also visible in the Rmean image, where it corresponds to a markedly dark deposit (Fig. 3a). This pattern is further supported by the RGB image of the core, which shows a grayish interval between 2250 and 800 cm, followed by a transition to a more brownish color with specular reflection (white pixels), indicating a slightly higher water content.

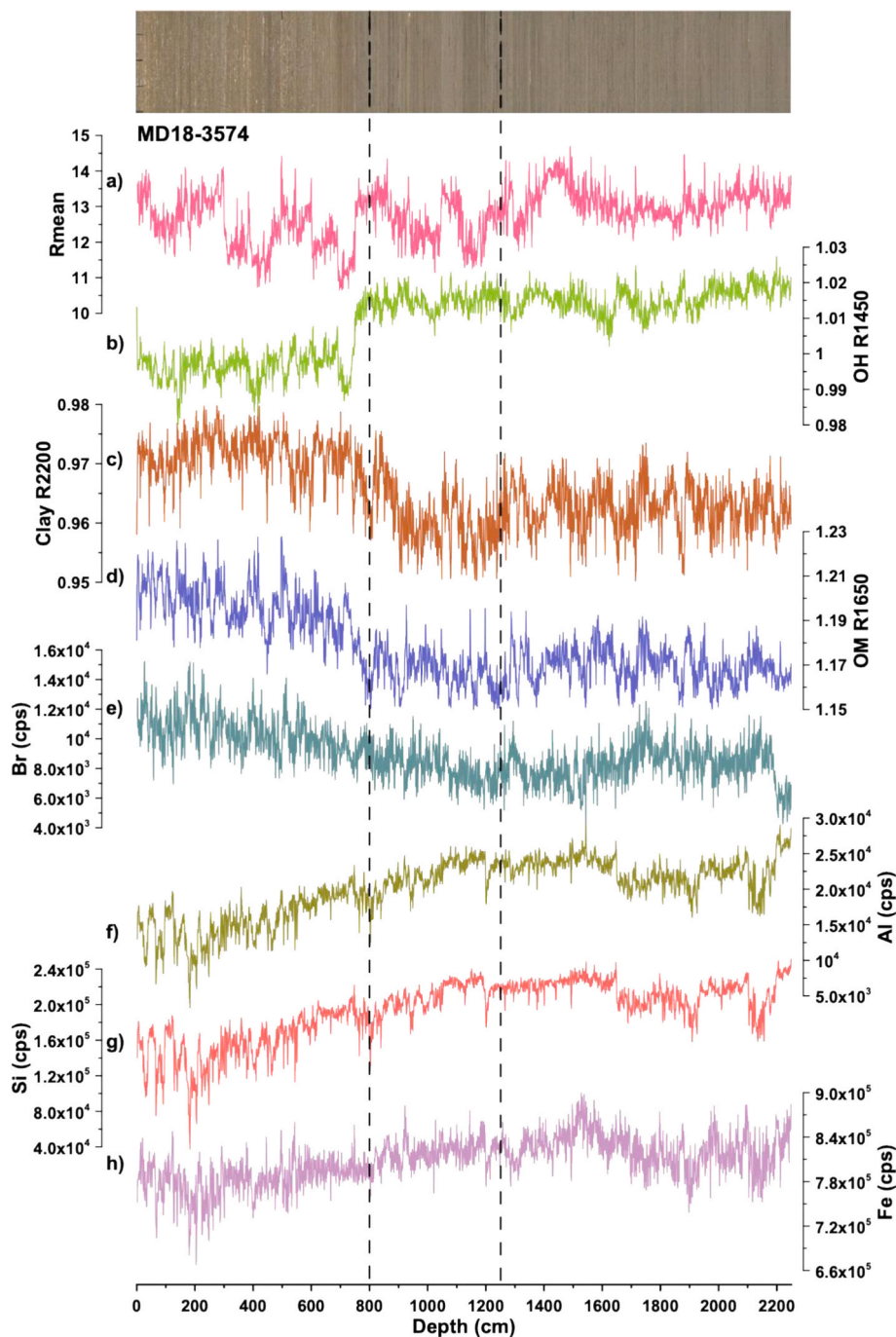


Fig. 3. Downcore variations in hyperspectral imaging indices, including Rmean (a), OH R1450 (b), Clay R2200 (c), OM R1650 (d), and XRF core-scanned elemental intensities, including Br (e), Al (f), Si (g) and Fe (h), for Core MD18-3574.

4.2. Laser grain size

Grain size variations for the 2100–2170 cm depth interval are reported in Fig. 4, whereas those for the 1365–1385 cm depth interval are shown in Figure S3. The mean grain sizes of the two depth intervals (2100–2170 cm and 1365–1385 cm) display variations ranging from 9.1 to 20.4 μm (mean of 13.4 μm) and from 10.5 to 17 μm (mean of 14.1 μm), respectively and exhibit similar laminated variations (Fig. 4 and Fig. S3). We have selected the 0–4 μm (clay fraction), 4–63 μm (silt fraction), and >63 μm (sand fraction) terrigenous sediment fractions for the following discussions. The sediments are mainly composed of silt (from 67% to 79%) with a moderate proportion of clay (from 15% to 30%) and very little or no sand (<4%) (Fig. 4). Sediments consist of an alternation of fine and coarse laminations, the thicknesses of which vary from about 2 to 25 mm. Fine sediment laminates (mean grain size of 10–12 μm) are mainly composed of silt (75%), dominated by the fine silt population, with a minor clay fraction (up to 15%) and no sand. Coarse sediment laminates are composed of a slightly higher proportion of silt (90%), with less clay fraction (9%) and a small proportion of sand (2%) (Fig. 4). The largest coarse levels display asymmetric sorting and are characterized by a rapid mean grain size increase followed by a gradual decrease, reflecting changes in the relative contribution of different grain size populations.

4.3. Bulk mineralogy

The bulk mineralogy of Core MD18-3574 mainly consists of abundant proportions of muscovite/illite (33–41%, mean 38%) and quartz (32–40%, mean of 36%), moderate proportions of chlorite (12–15%, mean of 13%) and plagioclase (8–10%, mean of 9%), and low

proportions of calcite (2–3%, mean of 2%) and microcline (2–3%, mean of 2%) (Supplementary data Table 1). Darker and lighter laminae display slightly different mineralogical compositions. Lighter laminae are composed of higher proportions of foliated minerals with muscovite/illite (mean of 41%) and lower proportions of quartz (mean of 34%), plagioclase (mean of 8%), and calcite (mean of 2%). Inversely, darker laminae consist of higher proportions of quartz (mean of 38%), plagioclase (mean of 10%) and calcite (mean of 3%) and less important proportions of muscovite/illite (mean of 35%).

5. Discussions

5.1. Characteristics of laminae and associated depositional processes

Core MD18-3574 is highly laminated and composed of an alternation of light and dark laminae. To better understand the processes responsible for the deposition of these coupled laminae, the high resolution and non-destructive hyperspectral imaging and XRF core scanning were coupled with grain size analyses and XRD bulk mineralogy.

Fig. 5A presents the mean grain size variations and clay contents (0–4 μm) of the 2100–2170 cm depth interval compared to hyperspectral imaging proxies (clay contents from Clay R2200 and reflectance from Rmean) and XRF-derived geochemical ratios, including log(Si/Al) ratio obtained at a resolution of 1 cm and log(Fe/Ca) ratio obtained at a resolution of 1 mm. In general, the mean grain size closely covaries with these different proxies. Each increase in the mean grain size is consistently associated with lower Rmean values (indicating darker sediments), higher log(Si/Al) ratios, higher Clay R2200 values (indicating lower clay-sized fraction contents), and lower log(Fe/Ca) ratios (Fig. 5A).

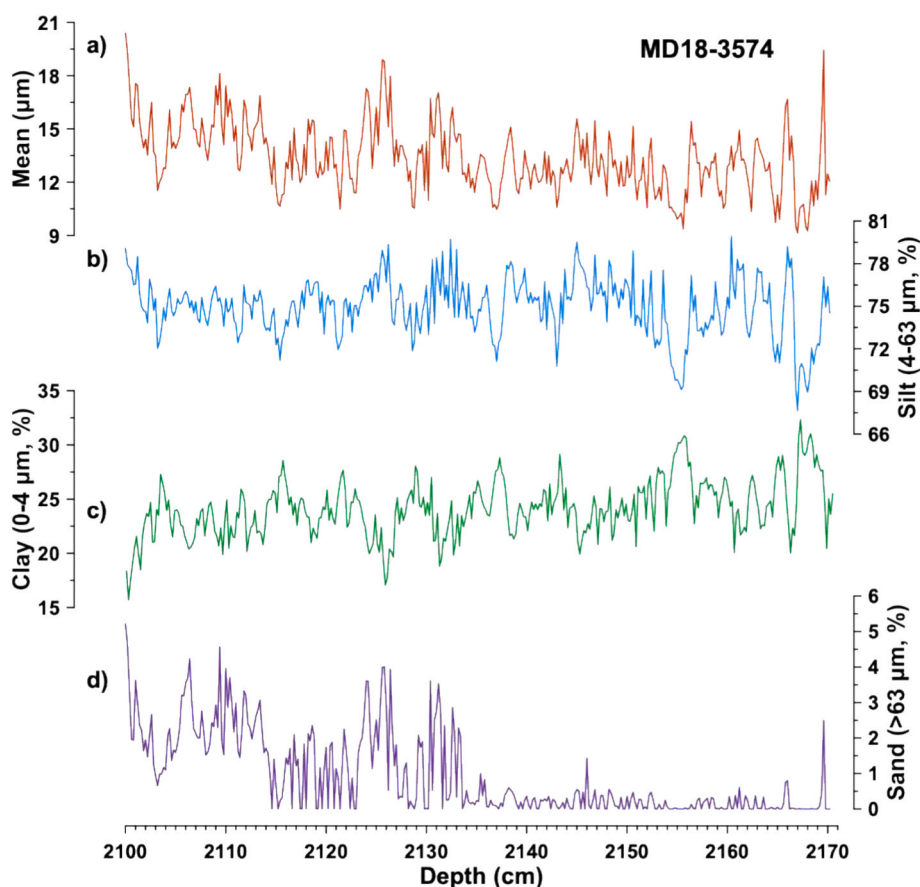


Fig. 4. Downcore variations in mean grain-size (μm) (a) and contents (%) of silt (4–63 μm , %) (b), clay (0–4 μm , %) (c) sand (>63 μm , %) (d) fractions within a 70 cm sediment interval (2100–2170 cm core depth) from Core MD18-3574, located along the Gaoping submarine canyon.

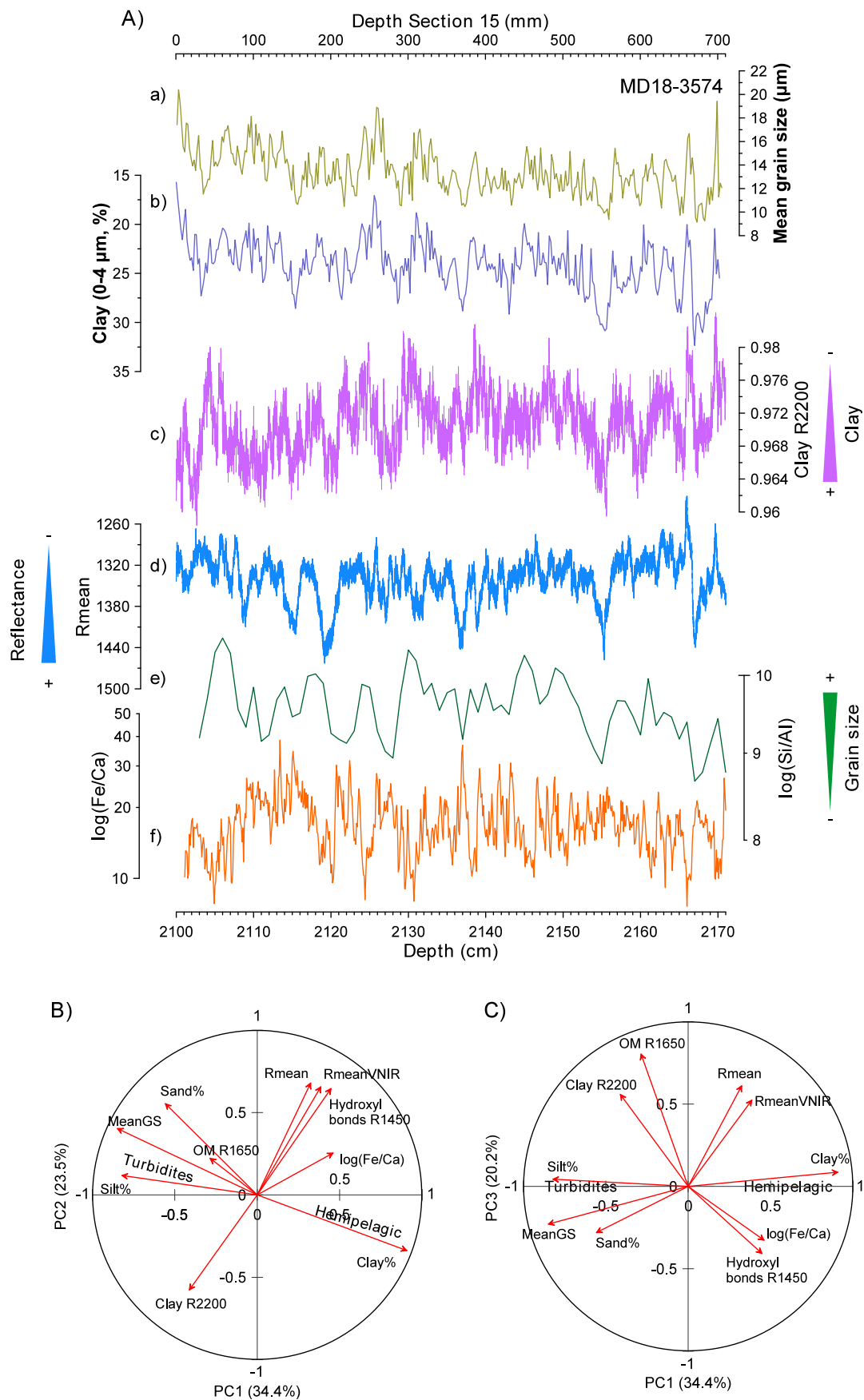


Fig. 5. Core MD18-3574: (A) Downcore variations in mean grain size (μm) (a), clay fraction content (0-4 μm , %) (b); Clay R2200 (proxy for clay content) (c), Rmean (proxy for sediment reflectance) (d), $\log(\text{Si}/\text{Al})$ ratio (e) and $\log(\text{Fe}/\text{Ca})$ ratio (f); (B, C) Principal component analysis (PCA) of grain size, hyperspectral indices, and relative geochemical composition, with PC1-PC2 (B) and PC1-PC3 (C) illustrating the characterization of laminations.

Principal component analyses (PCA) have been conducted on all proxies. They were analyzed at a resolution of 1–2 mm in order to statistically constrain the light and dark laminae (Fig. 5B and C). The first three principal components (PC1, PC2 and PC3) display two main end-members from all proxies (Fig. 5B and C). PC1 indicates two populations: the layers characterized by coarser grain size correspond to negative PC1 values, whereas positive values correspond to layers with finer grain size. The comparison of PC1 with PC2 and PC3 (Fig. 5B and C) highlights the differences between the two end-members. The coarse-grained laminae (high mean grain size, high sand% and silt%, and low clay%) are associated with high Clay R2200 values, indicating a low proportion of the clay-sized fraction content, and with low $\log(\text{Fe}/\text{Ca})$ ratio (Ca-rich sediments). These coarse-grained laminae also correspond to darker sediment layers, as indicated by lower Rmean values (Fig. 5B and C). In contrast, the fine-grained laminae (low mean grain size, low sand% and silt%, and high clay%) are associated with low Clay R2200 values, indicating a higher proportion of the clay-sized fraction, and with high $\log(\text{Fe}/\text{Ca})$ ratios. These fine-grained laminae correspond to lighter sediment layers, as is indicated by higher Rmean values (Fig. 5B and C).

Bulk mineralogy is also in close agreement with the relative geochemical composition obtained from light (fine-grained) and dark

(coarse-grained) laminae. Darker and coarser sediments contain slightly higher proportions of quartz (38%), feldspars (11%) and calcite (3%), and lower proportions of micaceous minerals (34%) compared to the lighter and finer sediments (33% quartz; 10% feldspars, 2% calcite and 40% muscovite and illite) (Table 1; Fig. 6). Quartz-, feldspar- and calcite-rich layers (Si, and Ca-rich) correspond to high $\log(\text{Si}/\text{Al})$ ratios and low $\log(\text{Fe}/\text{Ca})$ ratios, in contrast to the micaceous-rich layers, which are depleted in Si and Ca but enriched in Al, Fe, K, and Ti (Fig. 6). Thus, the dark and light laminae of Core MD18-3574 result from two different sedimentary processes.

The dark laminae, which are coarse-grained and rich in quartz, feldspar and biogenic calcite (Hsiung et al., 2021), are interpreted as overflow deposits resulting from turbidity currents of the Gaoping submarine canyon; present day mooring system observations show that these currents are capable of over-spilling the canyon and reaching the studied levee (Zhang et al., 2018). In contrast, the light silty clay layers, composed mainly of micaceous minerals with lower proportions of quartz, feldspar, and carbonate minerals, are interpreted as hemipelagic sediments derived from suspended sediments delivered by rivers draining southern Taiwan (Liu et al., 2010b, 2016b; Nayak et al., 2021). Several observations support this interpretation. First, the very high sedimentation rate of Core MD18-3574 (~520 cm/kyr), located on the

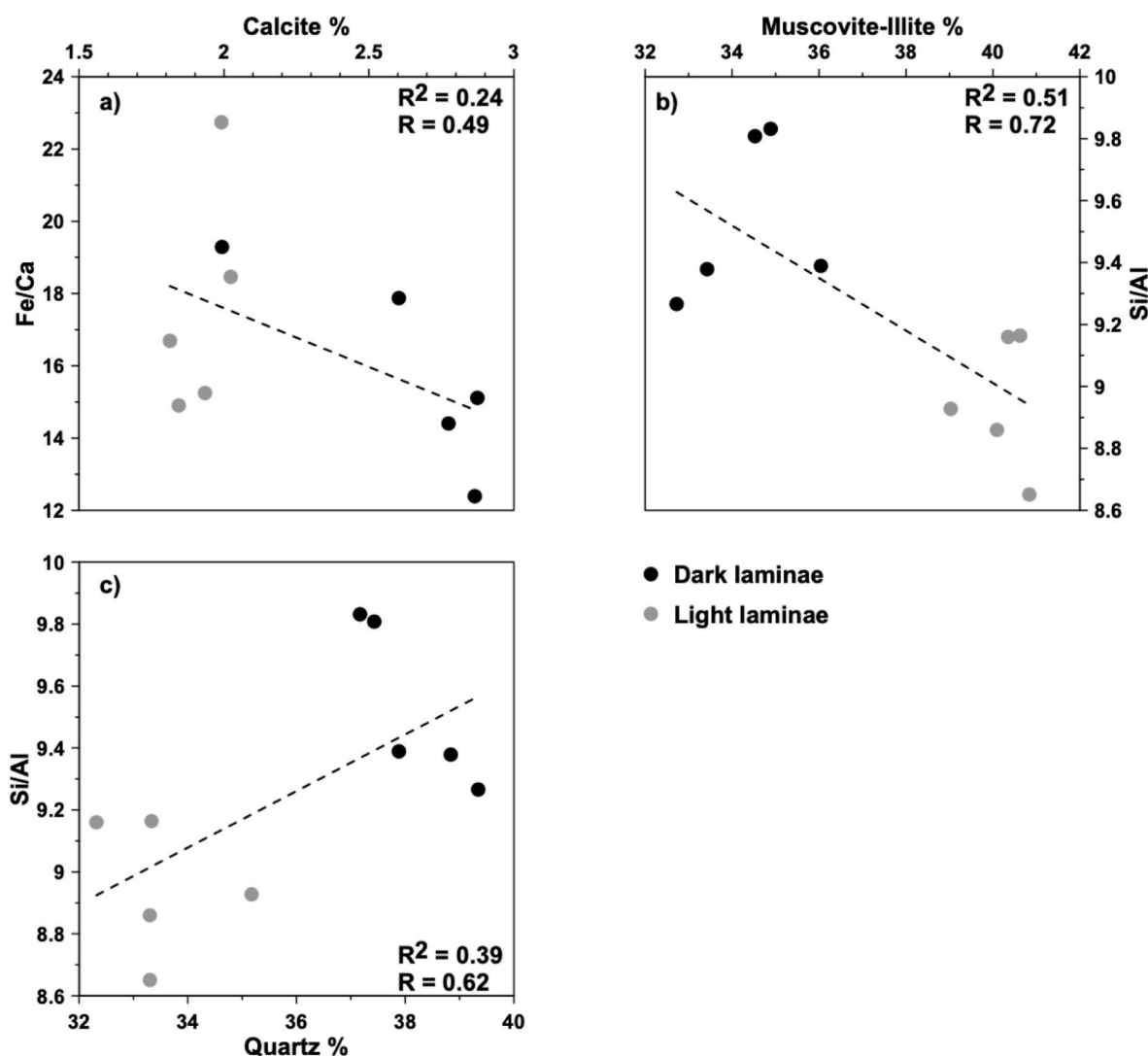


Fig. 6. Correlation plots between mineralogical composition and geochemistry for the light (gray dots) and dark (black dots) laminae of Core MD18-3574: Calcite (%) vs Fe/Ca (a), muscovite-illite (%) vs Si/Al (b) and quartz (%) vs Si/Al (c). Note that the number of analyses performed for each lamina type is small ($n = 5$), but it permits differences in their mineralogical and geochemical compositions to be identified.

Canyon levee, suggests a dominant sediment source from the Gaoping River. This interpretation is further supported by several cores recovered from the same levee, which exhibit similarly high sedimentation rates (between 130 and 560 cm/kyr) and turbidites of variable thickness and grain-size depending on their elevation relative to the canyon thalweg (Huang et al., 2026). Cores located closer to the thalweg contain thicker and coarser turbidites than those recovered at higher elevations than Core MD18-3574 (Huang et al., 2026). This is in contrast with sedimentation rates in cores collected outside the influence of the canyon turbidity system which are characterized by a sedimentation rate that is over ten times lower (e.g., Core MD18-3569; Bertaz et al., 2024; Huang et al., 2026). Second, the abrupt increase in grain size, together with the enrichment in quartz and feldspar, higher $\log(\text{Si}/\text{Al})$ ratios, and the typical classical fining-upward trend that characterizes the dark layers, suggest deposition mainly from turbidity currents (Bouma, 1962; Stow and Shanmugam, 1980) (Fig. 7). Although the Si/Al ratio was analyzed at a relatively low resolution (1 cm), it increases across most of the thick dark layers, indicating a relatively higher proportion of coarse quartz minerals relative to aluminosilicate minerals that dominate the clay-sized fraction. In contrast, the Fe/Ca ratio, measured at 1 mm resolution, decreases throughout most of the turbidites, reflecting a relatively higher carbonate content attributed to the presence of foraminifera. Similar increases in the Si/Al ratio and carbonate content have previously been used as reliable indicators of turbidite deposition in other systems, including the Bay of Bengal (e.g., Fournier et al., 2016; Joussain et al., 2016).

The absence of visible erosion surfaces, the limited thickness of the

deposits, and the low sand contents in the dark layers of Core MD18-3574 primarily reflect topographic filtering, as the studied levee lies ~600 m above the Gaoping submarine canyon thalweg (Fig. 1c), where the coarse-grained fraction remains largely confined to the canyon axis. The thickness and grain-size distribution of turbidite deposits are therefore controlled by the elevation of the levee relative to the canyon thalweg. Consequently, the sedimentary succession is dominated by the fine-grained upper part of turbidity currents that are capable of overspilling the canyon and reaching the elevated coring studied site. This setting also favors the preservation of a continuous sedimentary archive by limiting erosion during high-energy flow events. A similar sedimentary environment has previously been described along the eastern margin of Taiwan (Lehu et al., 2015).

5.2. Records of the frequency and intensity of typhoon activity over the last 4200 yr

Each dark laminae can be attributed to a hyperpycnal flow from Gaoping submarine canyon. Based on mooring observations, Zhang et al. (2018) have shown that these hyperpycnal flows are triggered by extreme Gaoping River floods, approximately 70% of which are associated with a typhoon event. We therefore used the Rmean index to identify the coarser dark deposits corresponding to hyperpycnal flow deposits and we can thus reconstruct past variations in the frequency of extreme river floods which are mainly associated with typhoon-related events. First, the deposits were detected through the identification of local maxima and minima once the Rmean was enhanced by

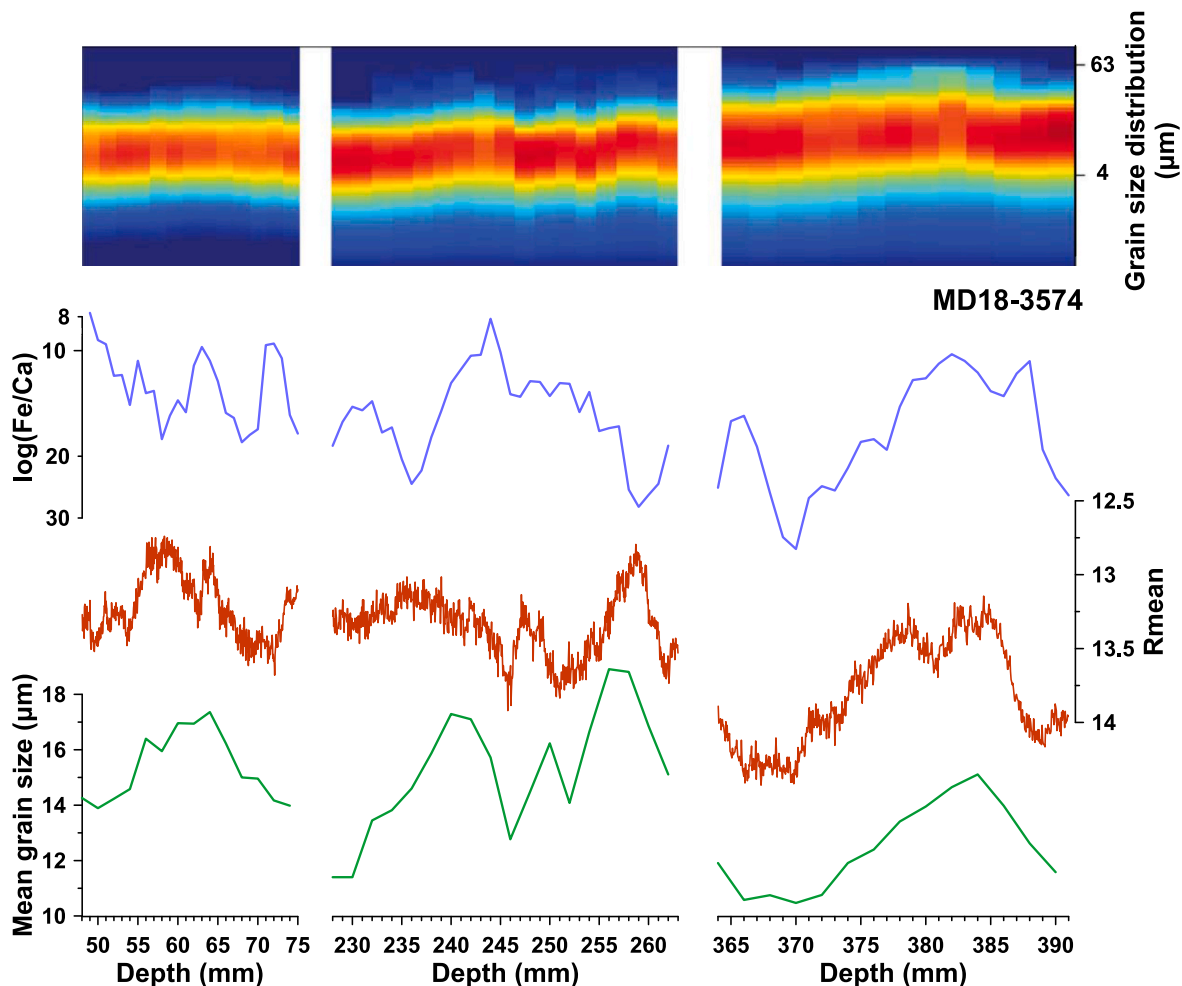


Fig. 7. Downcore variations in grain-size distributions, $\log(\text{Fe}/\text{Ca})$ ratio (reversed scale), Rmean SWIR (lower values indicate darker sediments; reversed scale) and mean grain size (μm), of three turbiditic laminae from Core MD18-3574.

contrast-limited adaptive histogram equalization (CLAHE) to maximize the differences between the deposits (Zuiderveld, 1994) and smoothed (Savitzky and Golay, 1964). The detection of local maxima and minima allowed the number of deposits to be determined but did not provide information on their thickness. Core MD18-3574 is composed of 2404 laminations consisting of an alternation of millimetric to pluri-centimetric light and dark laminae. To determine lamina thicknesses, it was necessary to identify the deposit boundaries, rather than their maxima or minima in the Rmean signal. Boundaries were identified by determining the local maxima or minima of the first derivative of the unenhanced Rmean curve between the previously identified coordinates. Lamina thickness was then calculated as the distance between two consecutive boundaries. To analyze variations in the number of deposits and their thicknesses over a given period, a sum and an average per time interval (40 years) were used.

The frequency and intensity of hyperpycnal-flow deposits are primarily controlled by extreme rainfall events, most of which are associated with typhoons. Consequently, these deposits can be used as a proxy for reconstructing the frequency and intensity of typhoon-related flooding, although a small proportion of hyperpycnal-flow deposits may also result from extreme rainfall events unrelated to typhoons. Furthermore, the study site is located ~600 m from the Gaoping submarine canyon thalweg, implying that the sedimentary sequence preferentially records extreme flood events, which are predominantly associated with the most intense typhoons (Zhang et al., 2018). In addition, we cannot totally exclude the possibility that the intensity of many typhoons may have fallen below a potential intensity threshold where the suspended-sediment concentration was insufficient to generate hyperpycnal flow in the Gaoping submarine canyon (Mulder et al., 2003) and thus would not be recorded on the studied levee of

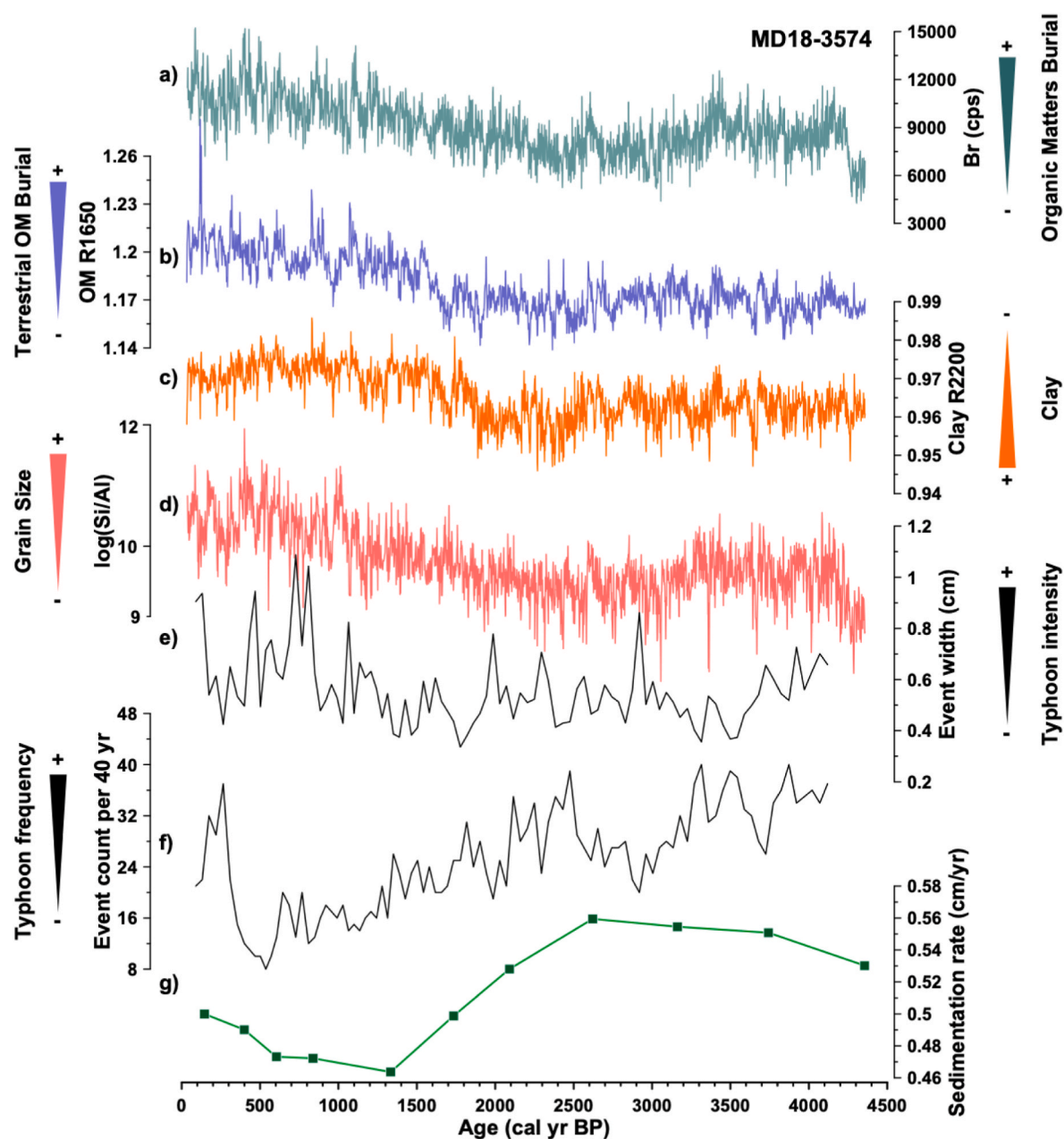


Fig. 8. Variations in organic matter proxies, including Br intensity (a) and OM R1650 (b); grain-size proxies, including Clay R2200 (c) and the log(Si/Al) ratio (d); typhoon intensity reconstructed from turbidite deposits, based on turbidite thickness (e) and frequency (number of events per 40 years) (f); and sedimentation rate (cm/yr) for Core MD18-3574 during the late Holocene.

the canyon. Therefore, in the following, we reasonably assume that the recorded events predominantly correspond to the most intense typhoon-related events.

The frequency of the most intense typhoon events affecting the Gaoping River basin displays variability since the mid-Holocene (Fig. 8f). Typhoon frequency peaked above 40 events per 40 years between 4200 and 3300 cal yr BP and again between 2500 and 2200 cal yr BP, with an interval of slightly lower frequency between 3300 and 2500 cal yr BP. Thereafter, typhoon frequency steadily decreased and reached fewer than 20 events per 40 years between 1400 and 500 cal yr BP. An abrupt increase in typhoon frequency occurred after 300 cal yr BP, reaching nearly 37 events per 40 years. The mean thickness of the laminae remained relatively stable from 4200 to 1800 cal yr BP with lamina thickness ranging from 0.3 to 0.7 cm (mean of 0.4 cm) (Fig. 8e). In contrast, from 1800 cal yr BP to the present, the mean thickness increased to an average of 0.6 cm and displayed greater variability, ranging from 0.3 to 1 cm. The thickness of hyperpycnal flow deposits depends on several factors (e.g., sediment delivery, soil recovery state, land use) (Page et al., 1994; Gomez et al., 2012), but is generally related to the total storm rainfall that triggers the hyperpycnal flow (Page et al., 1994). In addition, the increase in laminae thicknesses is associated with higher log(Si/Al) ratios and Clay R2200 values after 1800 cal yr BP, suggesting the deposition of slightly coarser detrital material (Fig. 8d and e). The greater lamina thickness observed in the upper part of the core cannot be attributed to burial compaction, as it coincides with lower sedimentation rates and an overall increase in grain-size, instead suggesting enhanced hyperpycnal flow activity. We therefore propose that variation in the thicknesses of the dark laminae reflects the intensity of typhoon induced rainfall, which triggers hyperpycnal flows in the Gaoping submarine canyon. Overall, the variations in the mean laminae thicknesses suggest that typhoon intensity was relatively low and stable from 4200 to 1800 cal yr BP, and became stronger and more variable after 1800 cal yr BP.

After 1800 cal yr BP, both grain-size proxies (log (Si/Al) ratio and clay-sized content) suggest that more intense typhoon events enhanced the transport and deposition of detrital material on the levee through intensified hyperpycnal flows within the Gaoping submarine canyon (Fig. 8). This interval is also characterized by a concomitant increase in Br counts and OM R1650 values suggesting a higher proportion of organic matter preserved in these deposits. However, because the origin of the organic matter was not investigated in this study, Br variations cannot be unequivocally attributed to an increased input of terrestrial organic matter transported by hyperpycnal flows. An alternative, or complementary, explanation is that Br records changes in the production of marine organic matter associated with the late-Holocene strengthening of the East Asian Winter Monsoon (Kang et al., 2020). In our studied region, stronger winter monsoon conditions may have enhanced nutrient availability through increased Asian dust deposition and/or more vigorous upper-ocean mixing, thereby increasing surface marine productivity. The increase in Br and OM R1650 during the last ~2000 years is consistent with trends reported by Fenies et al. (2024) from the northwestern Philippine Sea, east of Taiwan, suggesting that these variations may reflect a broader regional increase in marine productivity linked to the intensification of the East Asian Winter Monsoon. Additional geochemical analyses, such as $\delta^{13}\text{C}_{\text{org}}$ and TOC/TN measurements, will be required to distinguish between terrestrial and marine sources of organic matter and to better assess the relationship between organic matter deposition and the intensity and/or frequency of hyperpycnal flows reaching the studied levee. Such analyses would also help determine whether these flows primarily enhance the delivery of terrestrial organic matter and/or favor better preservation of marine organic matter within the sediment.

The linear sedimentation rate (LSR) of Core MD18-3574 displays a trend similar to that of hyperpycnal flow frequency, which mainly reflects the frequency of the typhoons (Fig. 8g). Before 2200 cal yr BP, a relatively high sedimentation rate (>0.52 cm/yr) is associated with a

higher frequency of hyperpycnal flow events (up to 40 events per 40 yr). In contrast, after this period the sedimentation rate decreases to a minimum of ~ 0.45 cm/yr, concomitant with a marked decline in hyperpycnal flow frequency (~ 10 events per 40 yr) (Fig. 8f). These observations suggest that the levee aggradation of the studied area depends more on the frequency of hyperpycnal flow events than on the thickness of turbidite deposits themselves.

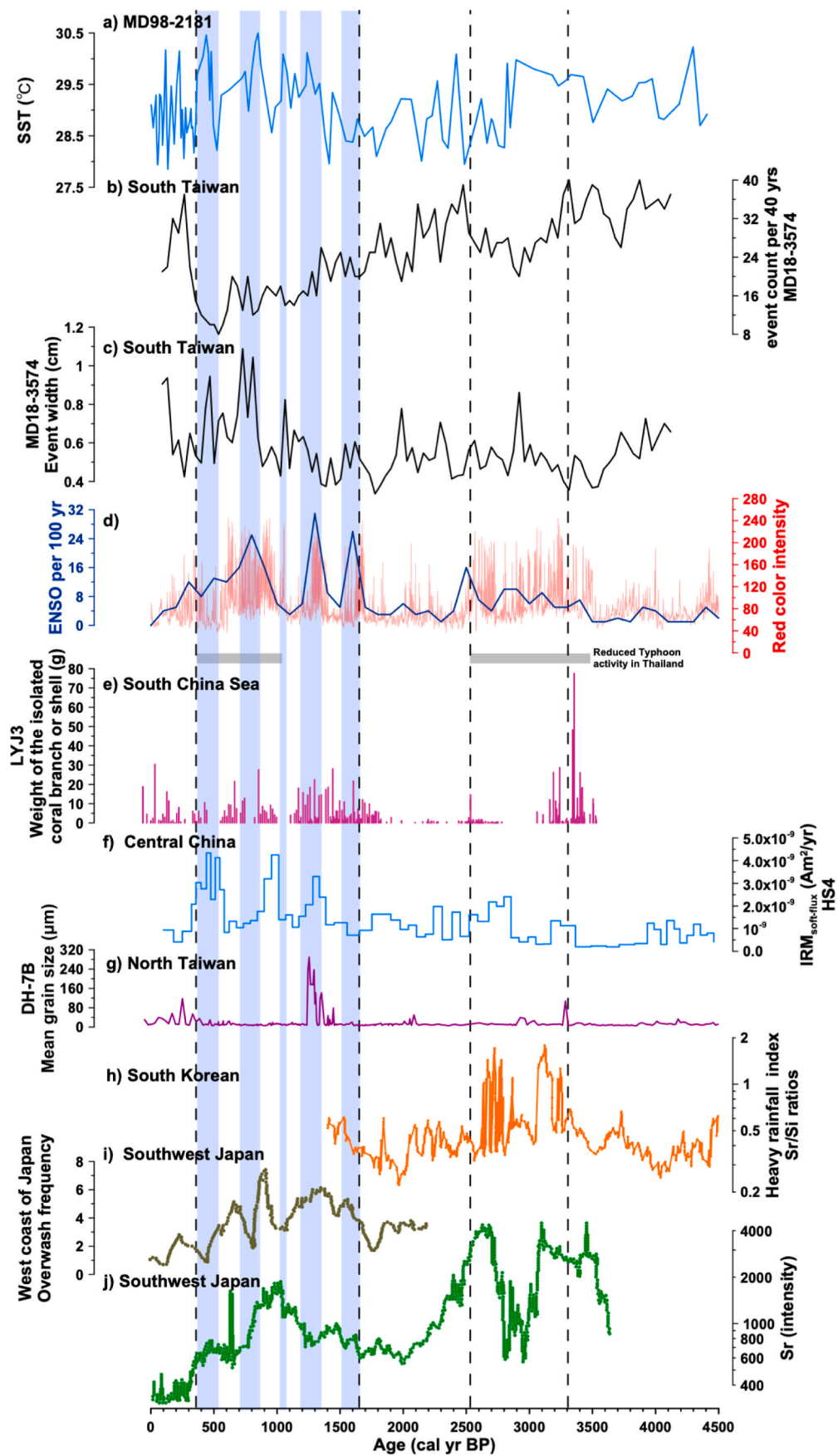
5.3. Regional comparison of typhoon activity records in East Asia

Previous reconstructions of Holocene typhoon activity in East Asia, based on evidence from coral reef destruction in central China (Yue et al., 2019), lagoonal and coastal environments in southern Japan and western Korea (Lim et al., 2019, 2023; Woodruff et al., 2009, 2015), and speleothems in central China (Zhu et al., 2017), primarily document the occurrence of the most intense storms (Fig. 1a). In contrast, our new records, which comprise 2404 dark layers, most of which are interpreted as deposits associated with typhoon events with landfall in southern Taiwan, provides insights into both the intensity and frequency of past typhoon activity. All these records offer an opportunity to better constrain the spatial distribution of typhoon activity across the East Asian region. Nevertheless, such comparisons should be interpreted cautiously, as the available typhoon records are based on different sedimentological proxies and depositional environments, each characterized by distinct sensitivities and preservation potentials with respect to typhoon-related processes.

In the western central SCS, increased coral destruction on the reefs of the Xisha Islands has been linked to enhanced typhoon intensity and frequency during the time intervals 3500–3100 and 1800–0 cal yr BP (Yue et al., 2019) (Figs. 1a and 9e). Several peaks in the high-resolution coral destruction record match with our reconstructed curve of typhoon intensity, which indicates an overall increase with several maxima after 1800 cal yr BP (Fig. 9c). In contrast, this time interval is associated with a significant decrease in typhoon frequency in southern Taiwan (Fig. 9b). Our new results suggest that coral destruction in the Xisha Islands should be more strongly related to periods of increased typhoon intensity rather than to increased typhoon frequency, at least during the late Holocene.

In addition, a magnetic record (IRM_{soft-flux}) obtained from speleothems in central China (Heshang cave) reveals an increase in extreme paleoflood events, such as storms, after 1500 cal yr BP, with several maxima centred at 1300, 900, and 400 cal yr BP (Figs. 1a and 9f) (Zhu et al., 2017). This extreme storm events record derived from speleothems is further supported by previously published histories of flood deposits preserved in the middle reaches of the Yangtze Rivers (Zhu et al., 2017). Taking into account the uncertainty associated with age models, these extreme paleoflood events (Fig. 9f) coincide with several maxima in our reconstructed record of typhoon intensity (Fig. 9c). In addition, grain size variations in a lacustrine sediment core from northern Taiwan have been associated with a marked period of typhoon activity from 1450 to 1250 cal yr BP (Fig. 9g; Chen et al., 2012) which closely matches with periods of increased typhoon intensity affecting the Gaoping river basin during the 1400–1100 cal yr BP time interval (Fig. 9c). In addition, two periods of reduced typhoon frequency (3500–2500 and 1100–400 cal yr BP) have been identified in southern Thailand (Williams et al., 2016), which are also contemporaneous with the two intervals of decreased typhoon frequency observed in our new record from southern Taiwan (Fig. 9). Thus, a regional pattern emerges in the southern latitudes (SCS and Taiwan) in which more important typhoon frequency occurs around 4200–3300 cal yr BP, 2500–1800 cal yr BP and after 400 cal yr BP. The 1800–0 cal yr BP time interval is associated with more intense typhoons affecting southern Taiwan and the northern SCS (Fig. 9).

At a higher latitude, Woodruff et al. (2009) reconstructed storm surge-driven inundation from coastal lake sediments on Kamikoshiki Island (southwestern Japan) (Figs. 1a and 9j), revealing



(caption on next page)

Fig. 9. Temporal variations in SST ($^{\circ}\text{C}$) from Core MD98-2181 in the western tropical Pacific (Stott et al., 2017) (a); records of typhoon frequency (event per 40 yr) (b) and intensity (c) derived from turbidite sequences of Core MD18-3574 (this study); El Niño reconstructions from Laguna Pallacocha, Ecuador (Moy et al., 2002), with blue line representing the number of events per 100 yr (d); Record of typhoon activity inferred from coral destruction on the Xisha Islands reefs (western SCS; Yue et al., 2019) (e); Record of extreme paleoflood events associated with increased extreme precipitation frequency, reconstructed from magnetic properties (IRM_{soft-flux}) of speleothems (HS4) from Heshang Cave, Central China (Zhu et al., 2017) (f); typhoon activity reconstructed from grain size variations in a lacustrine sediment core of northern Taiwan (Chen et al., 2012) (g); Heavy rainfall index (Sr/Si ratio) from the Sara volcanic cone, Jeju Island, South Korea (Lim et al., 2023) (h); Record of overwash frequency (extreme coastal flooding, events per 100 yr) from the coastal Lake Daija, southwestern Japan (Woodruff et al., 2015) (i); Paleo-typhoon record (Sr intensity of core NK15) reconstructed from coastal lake inundation on Kamikoshiki Island, southwestern Japan (Woodruff et al., 2009) (j). The time interval of reduced typhoon frequency in southern Thailand is also reported (Williams et al., 2016). The vertical blue lines between 1800 and 300 cal yr BP correspond to maximum of event width per 40 yrs from core MD18-3574. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

barrier-breaching episodes since the mid-Holocene. A 2000-year record of extreme coastal flooding (overwash frequency) from the coastal lake Daija, located in southern Japan, confirms this pattern (Figs. 1a and 9i) (Woodruff et al., 2015). Both records obtained in southern Japan indicate higher typhoon frequencies in the 3500–2500 cal yr BP and 1800–500 cal yr BP time intervals. In addition, enhanced typhoon activity has been observed between 3400 and 2600 cal yr BP based on heavy-rainfall records obtained on lake sediments from a volcanic cone (Sara Oreum) on Jeju Island (Korea) (Figs. 1a and 9h) (Lim et al., 2023). Taken together, all these studies show that enhanced typhoon frequency in southern Japan and Korea aligns with a decrease in typhoon frequency in southern Taiwan.

5.4. Influence of climatic (ENSO) and oceanographic (SST) variability on typhoon activity

Instrumental observations undertaken since 1945 AD show that the El Niño–Southern Oscillation (ENSO) strongly modulates tropical cyclone activity (Lander, 1994; Elsner and Liu, 2003; Camargo and Sobel, 2004; Trenberth et al., 2007). To evaluate the influence of ENSO on typhoon activity and its potential latitudinal distribution through time, we compare all typhoon records reported in Fig. 9 with an annually resolved El Niño proxy record from Laguna Pallacocha, Ecuador (Moy et al., 2002) (Fig. 9d). The Laguna Pallacocha record, derived from clastic sediments deposited during intense rainfall events associated with moderate to strong El Niño phases relative to La Niña-like conditions, remains the only continuous, high-resolution archive for the mid-to late Holocene. A record of the SSTs from the western equatorial Pacific is also presented in Fig. 9a as they have been shown to potentially control the intensity of typhoons.

Comparison of typhoon records from different latitudes with the Pallacocha record indicates that intervals characterized by enhanced El Niño relative to La Niña-like conditions coincides with reduced typhoon frequency in southern Taiwan (3300–2500 and 1800–400 cal yr BP) (Fig. 9b). In contrast, these intervals correspond to increased typhoon activity and frequency in southern Japan and Korea (Woodruff et al., 2009, 2015; Lim et al., 2023) (Fig. 9h, i, 9j). Such latitudinal patterns in typhoon activity support the hypothesis that the strongest El Niño conditions induce an eastward shift of the genesis region of tropical cyclones over the western North Pacific as has been observed at modern time (Lander, 1994). Under these conditions, Pacific Walker circulation is also weakened, and the formation of typhoons occurs farther east, making them more likely to follow recurving tracks northward toward higher latitudes under the combined influence of the large-scale atmospheric circulation and the Coriolis effect (Elsner and Liu, 2003). As a result, the probability of landfalls increases in regions such as southern Japan and Korea. These longer, northward, typhoon trajectories over the warm waters of the western Pacific lead to tropical cyclones with longer lifetimes and consequently higher intensity (Camargo and Sobel, 2004) as this is observed in Japan and Korea during the 3300–2500 and 1800–400 cal yr BP time intervals. This northward trajectory of typhoons is in agreement with the reduced typhoon frequency reconstructed for southern Taiwan. In contrast, during periods of dominant La Niña-like conditions, the Pacific warm pool expands horizontally but

shrinks in vertical depth, and the Pacific Walker circulation strengthens (Barr et al., 2019). Such oceanic and atmospheric configurations may have shifted the typhoon genesis region westward with more latitudinal typhoon tracks. During the 4200–3300 and 2500–1800 cal yr BP time intervals and after 400 cal yr BP, the dominant La Niña conditions therefore led to a higher probability of landfall of more low-to-moderate intensity typhoons in southern Taiwan and the central SCS (Chen et al., 2012; Zhu et al., 2017; Yue et al., 2019; Wang et al., 2021).

The western tropical Pacific SST record indicates higher values between 1800 and 400 cal yr BP (Fig. 9a) associated with decreased frequency and increased intensity of typhoon landfall in southern Taiwan (Fig. 9b). Several peaks in the SST record are coeval with enhanced typhoon intensity suggesting that western tropical Pacific SST variations may control typhoon intensity in southern Taiwan. Lower SSTs likely inhibit the formation and/or weaken the intensity of locally formed typhoons (Dong et al., 2021) as conditions are close to the threshold SST (26–27 $^{\circ}\text{C}$) for typhoon genesis (Dare and McBride, 2011; Tory and Dare, 2015). Accordingly, the increase in SST after 1800 cal yr BP was accompanied by more intense typhoon landfalls in southern Taiwan, whereas typhoon frequency declined, indicating that late Holocene SST variations primarily influenced storm intensity rather than occurrence.

The time interval from 1800 to 400 cal yr BP was also characterized by increased typhoon intensity across the SCS, as reflected by increased coral destruction on the reefs of the Xisha Islands (central SCS; Fig. 8e) (Yue et al., 2019), higher frequency of extreme precipitation events in central China (Fig. 8f) (Zhu et al., 2017) and a period of typhoon surges in northern Taiwan (Fig. 8g) (Chen et al., 2012). This time interval, associated with higher SSTs and dominant El Niño-like conditions, would have favored a decrease in typhoon exposure but an increase in intensity in the SCS while at the same time leading to increased exposure in the East China Sea, including the Korean Peninsula and Japan, and parts of eastern China.

Overall, our results indicate a decoupling between typhoon frequency and intensity in southern Taiwan, largely controlled by interactions between ENSO and SST variability in the western tropical and subtropical Pacific. These findings provide new insights into the potential future evolution of regional typhoon activity in response to forecasted climate changes (Tan et al., 2019). Climate projections from CMIP5 models and observational data suggest that tropical expansion associated with global warming could lead to a potential eastwards shift in the genesis of western North Pacific tropical cyclones (Kossin et al., 2016; Tan et al., 2019). This pattern is consistent with the long-term record of typhoon tracks over recent decades, which show an increasing tendency for typhoons to recurve northward (Kossin et al., 2014, 2016; Oey and Chou, 2016) and to move more slowly. This has been attributed to warming of the Indo-Pacific tropical-subtropical oceans, occurring in phase with a reduced land-sea thermal gradient and a weakening trend in the Asian summer monsoon (Liang et al., 2017).

6. Conclusions

In this study, high-resolution non-destructive hyperspectral imaging and XRF core scanning, combined with laser grain-size analysis, bulk mineralogy and radiocarbon dating, were investigated on laminated

sediments from Core MD18-3574, which was collected on the western levee of the Gaoping submarine canyon. The objectives were (1) to constrain the sedimentary processes responsible for laminae deposition, and (2) to reconstruct by indirect sedimentary proxies that need further quantitative calibrations the frequency and intensity of the most intense typhoon events affecting Taiwan over the past 4200 yrs. We conclude that.

1. Core MD18-3574 consists of an alternation of dark laminae, composed of relatively coarser sediments enriched in quartz, feldspar, and calcite, and light laminae, composed of finer sediments enriched in mica. Dark laminae display a characteristic upward decrease in grain size, implying deposition from turbidity currents capable of overspilling the Gaoping submarine canyon and mainly triggered by typhoon events. In contrast, light laminae correspond to hemipelagic sedimentation. A total of ~2400 dark laminae, most of which are interpreted as recording typhoon-related events, have been identified for the last 4200 yrs.
2. Typhoon frequency and intensity recorded in southern Taiwan appear to be decoupled. Since the mid-Holocene, typhoon frequencies vary between ~8 and 40 events per 40-yr. Periods of increased El Niño intensity, relative to La Niña intensity, particularly during the 3300–2500 and 1800–400 cal yr BP time intervals, coincide with a reduction in typhoon frequency in southern Taiwan. In contrast, typhoon intensity remained relatively stable between 4200 and 1800 cal yr BP, but increased after 1800 cal yr BP, with several peaks coeval with higher SST in the western tropical Pacific.
3. Comparison of typhoon records across different latitudes reveals a clear ENSO-driven spatial pattern. Periods of enhanced El Niño intensity relative to La Niña (3300–2500 and 1800–400 cal yr BP) are associated with decreased typhoon frequency in southern Taiwan, but increased frequency and intensity in south Japan and south Korea. This pattern reflects an eastward shift of tropical cyclone genesis and a weakening of the Pacific Walker circulation. These changes promote more frequent recurving tracks, longer lifetimes, and higher storm intensity at higher latitudes. In contrast, La Niña-like conditions shift genesis regions westward and favor more zonal trajectories. As a result, they increase the likelihood of more frequent but lower-intensity typhoon landfalls in Taiwan and the central South China Sea.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2026.110282>.

Data availability

All data and/or code is contained within the submission.

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