

PROVENANCE OF TERRESTRIAL SEDIMENT IN THE ANDAMAN SEA

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Received: January 07, 2019; Revised: July 24, 2019; Accepted: July 31, 2019

Abstract

Clay mineralogy of surface samples throughout the Andaman Sea and surrounding fluvial drainage basins were investigated to reveal the sources and determine the transport patterns of detrital fine-grained sediments. A total of 61 samples were obtained from the Irrawaddy delta shelf (IDS), Myanmar and the eastern continental shelf (ECS) of the Andaman Sea, Thailand and analyzed for clay mineralogy by X-ray diffraction (XRD). Clay mineralogy of the IDS and ECS revealed varying compositions. Clay minerals of the IDS comprised smectite (44%), illite (23%), chlorite (16%), and kaolinite (17%) with all showing high chemical weathering. ECS clay minerals were high in kaolinite (47%), smectite (23%), illite (18%), and chlorite (11%). Provenance analysis revealed that smectite was found in the IDS due to terrestrial sediment input supplied by the Irrawaddy and Salween Rivers. In contrast, kaolinite composition in the ECS was similar to clay mineral analysis of sedimentary samples obtained from the Malay Peninsula and Sumatra. Results confirmed that terrigenous sediments in the Andaman Sea resulted from mixing provenance sources. Although, the terrigenous material in the Andaman Sea sediments is mainly composed of the Irrawaddy River and Salween River the findings revealed different clay minerals in a west to east transect of the IDS area, indicating varying provenance and weathering processes of the parent rocks. Results confirmed that the west IDS was underlined by the Irrawaddy River delta input, while the east was supplied by input from the Salween River.

Keywords: Andaman Sea, clay mineral, provenance, X-ray diffraction

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Introduction

The Andaman Sea is part of the Northeast Indian Ocean and extends from ~5 to 15°N and ~93 to 98°E (Figure 1). The northern and eastern coastlines and the eastern section of the sea are bounded by Myanmar, the Malay Peninsula, and the Malacca Strait, respectively (Rodolfo, 1969a). The western section of the sea is connected to the Bay of Bengal through three main passages as the north (between Myanmar and the Andaman Islands), the middle (between the Andaman and Nicobar Islands), and the south (between the Nicobar Islands and Sumatra) (Cao *et al.*, 2015; Chatterjee *et al.*, 2017). The northern and eastern parts of the Andaman Sea are about 500 m deep and relatively shallow compared to the Western Andaman Sea where maximum depths reach 4,400 m (Rodolfo, 1969b) (Figure 1). Sediments supplied to the Andaman Sea are mainly transported by two major rivers in Myanmar as the Irrawaddy and Salween Rivers (Rodolfo, 1969b; Colin, 1998; 1999; 2006, Awashi *et al.*, 2014; Ali *et al.*, 2015, Cao *et al.*, 2015). The Irrawaddy River is the large delivers about 360 Mt/year of suspended solids into the Northern Andaman Sea (Ramaswamy *et al.*, 2004; Robinson *et al.*, 2007). Lower amounts of sediments are delivered by the Salween River at about 180 Mt/year (Robinson *et al.*, 2007). Sediments are also supplied by short and narrow rivers in the Malay Peninsula, Sumatra, and the Andaman and Nicobar Islands and exchanged with the Bay of Bengal but volumes are slight and less important compared to the Irrawaddy and Salween River systems (Keller and Richards, 1967; Rodolfo, 1969b; Ali *et al.*, 2015; Cao *et al.*, 2015).

The Irrawaddy River is 2,210 km long and originates from the confluence of the Nmai and Mali Rivers in the Himalayas (Lupker *et al.*, 2013). The Nmai and Mali River catchment basins are composed of late Precambrian and Cretaceous - Eocene metamorphosed basic - ultrabasic rocks of the eastern Himalayan syntax (Awasthi *et al.*, 2014; Ali *et al.*, 2015). The Irrawaddy River is in Kachin State, Northeast Myanmar and runs

in a north-south direction. The river flows through a basin that consists of the Cretaceous - Cenozoic flysch and the Eocene-Miocene-Quaternary sediments in the Indo-Burma-Arakan ranges and the central plain of Myanmar, respectively (Licht *et al.*, 2013; Robinson *et al.*, 2014; Awasthi *et al.*, 2014; Ali *et al.*, 2015). Salween River, which is about 2800 km long, is longer than Irrawaddy River and originated in Tibetan Plateau (Rodolfo, 1969a). The catchment rocks of the Salween consist of magmatic rocks and the Precambrian to Tertiary sedimentary, igneous and metamorphic rocks of the Shan Plateau (Brown, 2007).

Short and narrow rivers flowing into the western and eastern areas of the Andaman Sea deliver relatively low amounts of suspended solids compared to the Irrawaddy and Salween Rivers in the north (Ali *et al.*, 2015). The Andaman/Nicobar Islands in the western are almost entirely made up of mafic and ultramafic rocks of the Cretaceous ophiolite

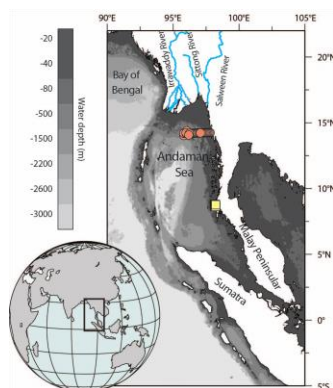


Figure 1. Location of the Andaman Sea with a bathymetric map showing 1) area of surface sediments from the Irrawaddy delta shelf (IDS), Myanmar; the eastern continental shelf (ECS) of the Andaman Sea is shown as orange and offshore of Phang Nga Province, Thailand as yellow, 2) main tributaries flowing into the Andaman Sea are shown as blue lines

suite as the origin of the sedimentary rocks (Ali *et al.*, 2015). Moreover, bedrock of the Malay Peninsula consists mainly of Paleozoic-Mesozoic granite and granodiorite and Paleozoic sedimentary rocks, minor Mesozoic (mainly Jurassic-Cretaceous) sedimentary rocks and sparse basic volcanic rocks in the central part of the Malay Peninsula. In addition, Sumatra is mainly covered by Quaternary intermediate to basic volcanic rocks as mountainous ranges and by late Tertiary sedimentary rocks in the plains (Liu *et al.*, 2012).

Sediment transportation in the Andaman Sea is mainly controlled by the Indian Monsoon and surface water (Rodolfo, 1969b; Rao *et al.*, 2005; Robinson *et al.*, 2007). The summer monsoon drives westerly surface currents from the Bay of Bengal to the Andaman Sea via the northern passage (Brown, 2007; Cao *et al.*, 2015). The portion of prevailing westerly current moves toward the Mataban Canyon then swings southward along the Malay Peninsula and eventually reaches the Malacca Strait. This current transports riverine sediment toward the east along the inner shelf of the Andaman Sea (Rodolfo, 1969b; Ramaswamy *et al.*, 2004; Rao *et al.*, 2005). The remaining surface water moves in a clockwise direction and eventually leaves the Andaman Sea through the middle and south channels (Brown, 2007; Cao *et al.*, 2015). Meanwhile, the Northeast monsoon strengthens southeasterly currents from the Malacca Strait and produces clockwise circulation in the Andaman Sea (Brown, 2007; Cao *et al.*, 2015). Consequently, the Andaman Sea outflow through the middle and south channels significantly intensifies during winter. These seasonal cycles of surface water circulation are highly dependent on monsoon intensity which can vary significantly year by year (Joussain *et al.*, 2016). Monsoon-dependent surface current variations play a significant role in creating different sediment provenances in the Andaman Sea (Ahmed *et al.*, 2005; Awasthi *et al.*, 2014).

Clay mineral assemblages in marine sediments are a significant proxy to differentiate source possibility, propagation of

water masses and to investigate ocean systems. In addition, clay mineralogy is suggested to differentiate the source of terrigenous sediments and marine sediment and to demonstrate geological conditions such as weathering processes (Gingele *et al.*, 2001). The distribution in the main group of clay minerals (i.e., smectite, illite, kaolinite and chlorite) can be used to illustrate sedimentological processes. The clay minerals are generally produced from weathering of parent rocks, including physical weathering, which leads to rock fragmentation, and chemical weathering. The provenance of sediment, investigating the intensive chemical weathering is identified from different provenance from both clay mineralogical and geochemical results in the surface sediment (riverine) regardless of their various lithological and tectonic settings in the southern Andaman Sea (Liu *et al.*, 2012; Liu *et al.*, 2016). In addition, the chemical weathering intensity increases gradually suggested that the monsoon climatic condition with constant warm temperature and abundant precipitation throughout the year is the principal forcing factor on the chemical weathering (Liu *et al.*, 2012). The illite and chlorite fractions were considered as primary minerals which originated from intensive physical erosion and moderate chemical weathering of metamorphic and granitic parent rocks. These minerals could possibly be the product of reworked sedimentary rocks. Smectite and kaolinite are generally secondary minerals obtained by chemical weathering (Chamley, 1989). Smectite is mainly produced by chemical weathering of aluminosilicate and ferromagnesian silicate minerals under warm and seasonally contrasted climatic conditions (Chamley, 1989). In warm and humid climates, chemical weathering of alkali and alkaline minerals produces kaolinite (Liu *et al.*, 2009). Thus, clay minerals are generally weathering products which can be utilized to suggest the provenance of terrestrial sediments and investigate weathering processes.

However, this area is one of the poorly known areas with very few reports on sedimentological aspects. The previous study

reported that sediments supplied to the Andaman Sea are mainly transported by two major rivers in Myanmar as the Irrawaddy and Salween Rivers (e.g., Rodolfo, 1969b; Colin 1998; 1999; 2006, Awashi *et al.*, 2014; Ali *et al.*, 2015, Cao *et al.*, 2015, Jousain *et al.*, 2016) while the other sources are not well reported. This study reports for the first time to reveal an overview of sediments supplied to the Andaman Sea approach by clay mineralogy. Previously, the terrigenous sediment study especially clay mineralogy has rarely been conducted in the Andaman Sea. Therefore, a high-resolution study of clay mineralogy in the Andaman Sea would help to illustrate provenances of terrestrial sediment in the Andaman Sea.

Materials and Methods

A total of 39 and 22 sediment samples were taken from the Irrawaddy delta shelf (IDS) in Myanmar and the eastern continental shelf (ECS) of the Andaman Sea off Phang Nga, Thailand, respectively (Figure 1). The IDS samples were collected during an expedition to assess the environmental impact of a pipeline construction across the Gulf of Mataban in December 2009. The ECS samples were taken under the auspices of a Thai-German corporation project for paleo-tsunami investigation in December 2008. The samples were carefully wrapped in aluminum foil, placed in glass bottles, stored in an onboard refrigerator at about -4°C and subsequently transported to the State Key Laboratory of Marine Geology, Tongji University, Shanghai, China for analysis in 2013.

Clay mineral determinations were performed by X-ray diffraction (XRD) using a PANalytical diffractometer at the State Key Laboratory of Marine Geology, Tongji University, China. Non-calcareous clay-sized ($<2\text{ }\mu\text{m}$) samples were individually measured under three conditions of (i) air-drying, (ii) ethylene-glycol solvation for 24 h, and (iii) heating at 490°C for 2 h (Holtzapffel, 1985). Clay compositions were calculated for

reflections of smectite, chlorite, illite, and kaolinite content as relative proportions of the total clay assemblage. These oriented mounts were prepared following the method described by Liu *et al.* (2004). Semi-quantitative estimates of peak areas of basal reflections for the main clay mineral groups of smectite ($14\text{-}17\text{\AA}$), illite ($10\text{\AA}$), and kaolinite/chlorite ($7\text{\AA}$) were carried out on anethylene glycol saturated curve using MacDiff software (Petschick, 2000). Relative proportions of kaolinite and chlorite were determined from the area ratios of the (002) peak of kaolinite ($3.57\text{\AA}$) and the (004) peak of chlorite ($3.54\text{\AA}$). Calculations of clay proportions were performed as the overlap of (001) reflection of kaolinite and (002) reflection of chlorite of the diffractogram in glycolated mode representing the layer thickness. Relative error at $\pm 5\%$ (Holtzapffel, 1985) and precision of replicate samples were analyzed at $\pm 2\%$ (2σ) (Liu *et al.*, 2010).

Clay content results were used to differentiate the source of terrigenous and marine sediments and refer the provenance input from source variations through the illite chemistry index. Illite chemistry index was calculated from XRD diagrams and corresponded to the ratio of $5\text{\AA}$ and $10\text{\AA}$ illite peak areas (Esquevin, 1969). Ratios above 0.40 are found in Al-rich illites (muscovites) with higher chemical state of illite (high illite chemistry index) (Esquevin, 1969), released following hydrolysis when Mg and Fe substitute Al in the illite crystal lattice as a result of chemical weathering (Liu *et al.*, 2012). Meanwhile, ratios below 0.15 represent Fe-Mg-rich illites (biotites), which are characteristic of physical erosion (Esquevin, 1969; Petschick *et al.*, 1996). The illite chemistry index has previously been used to estimate sediment weathering states (Liu *et al.*, 2007; Colin *et al.*, 2010) and constrain sedimentary sources (Liu *et al.*, 2004; 2010; Ehrmann *et al.*, 2007). In addition, illite chemistry index was identified because they could be used to track sediment source and transport paths (e.g., Liu *et al.*, 2008, 2010; Wan *et al.*, 2010).

Table 1. Average clay mineral assemblages and illite chemical index of surface sediments from the two sample sites [Irrawaddy delta shelf (IDS) and the eastern continental shelf (ECS)] compared with different provinces surrounding the Andaman Sea based on the normalizing method of Holtzapffel (1985)

Regions	Sample Number	Averages contents (%)				Illite chemistry index	References
		Smectite	Kaolinite	Illite	Chlorite		
Surface sediment							
Ganges-Brahmaputra	13	12	52	29	7	-	Phillips <i>et al.</i> (2014)
Krishna-Godawari	16	75	13	8	5	-	Phillips <i>et al.</i> (2014)
Mahanadi	20	36	16	24	23	-	Phillips <i>et al.</i> (2014)
Irrawaddy delta	48	79	13	5	3	-	Rodolfo (1969b)
Irrawaddy delta shelf*	39	44	17	23	16	0.437	This study
The eastern continental shelf**	22	23	47	18	11	0.303	This study
Malay Peninsula	12	0	80	18	2	0.469	Wang <i>et al.</i> (2011)
Sumatra	14	18	66	8	7	0.701	Liu <i>et al.</i> (2012)
Core top sediment							
Bay of Bengal***	-	53	9	17	9	-	Joussain et al. (2016)
Andaman/Nicobar Island****	27	89	5	1	5	-	Ali <i>et al.</i> (2015), Colin <i>et al.</i> (1999)

Irrawaddy delta shelf* - IDS

The eastern continental shelf** - ECS

Bay of Bengal*** - average from MD12-3412, MD77-178, MD77-179, MD77-181, MD77-183, RC12-340, RC12-341 of Joussain *et al.* (2016)

Andaman/Nicobar Island**** - average from NGHP Site 17 of Ali *et al.* (2015), MD77-176, MD77-186, and MD77-169 of Colin *et al.* (1999)

Results and Discussion

The 61 sediment samples obtained from the IDS and ECS were analyzed for clay mineral assemblages to reveal the sources and determine the transport patterns of detrital fine-grained sediments to the Andaman Sea. Average clay mineral assemblages for the four main contents, illite chemistry index of IDS and ECS samples, and the surrounding provinces in the Andaman Sea based on the normalizing method are listed in Table 1.

Clay mineral determinations of the IDS samples suggested dominance of the smectite fraction at 40-55%. However, illite, chlorite and kaolinite concentrations varied as 15-30%, 10-22%, and 14-20%, respectively. Kaolinite fractions remained constant at about 14%. The most abundant clay mineral in the surface samples obtained from the ECS was kaolinite which varied from 30 to 60%. The smectite fraction, as the dominant clay mineral assemblage in the IDS, was about 22% and distinctively varied from <5 to >50%. Illite and chlorite concentrations varied from 12 to 22% and 7 to 15%, respectively with the illite chemistry index ratio at about 0.3. Clay

mineral assemblages of sediment samples obtained from the IDS and ECS were compared with other published results derived from the Bay of Bengal (Joussain *et al.*, 2016), the Andaman/Nicobar Island (Colin *et al.*, 1999; Ali *et al.*, 2015), the Myanmar shelf (Phillips *et al.*, 2014), the Irrawaddy delta (Rodolfo, 1969b), the Malay Peninsula (Wang *et al.*, 2011) and Sumatra (Liu *et al.*, 2012). Clay mineralogical data were recalculated following the procedure of Holtzapffel (1985).

Clay mineral compositions in terrestrial sediments showed a difference between the western and eastern parts of the IDS. Concentration of smectite gradually increased between 42 and 54% from west to east of the IDS transect (Figure 2). By contrast, illite and chlorite components declined from 25 to 18% and from 18 to 12%, respectively. The illite chemistry index increased from 0.4 to 0.5 in the west and east of the IDS. An increase in smectite indicated that chemical weathering was more prevalent in the east IDS. Since both areas fall under similar climatic conditions of the Indian Monsoon, these discrepancies could be simply explained by the different riverine sediments transported to the west and the east IDS. These areas are near to the Irrawaddy

River delta and the Salween River mouth, west to east respectively. Thus, terrestrial sediments in the Andaman Sea were considered to be transported by the Irrawaddy and Salween Rivers which have different rock catchments areas (Colin *et al.*, 1998; 1999; Robinson *et al.*, 2014; Awasthi *et al.*, 2014; Ali *et al.*, 2015). Higher chemical weathering in the west IDS corresponded well with the Irrawaddy rock catchment area that is mainly composed of aluminosilicate and ferromagnesian silicate minerals in magmatic, igneous and metamorphic rocks (Awasthi *et al.*, 2014), while the Irrawaddy rock catchment area as Eocene-Miocene-Quaternary sediments agreed well with the more dominant physical weathering in the west IDS (Awasthi *et al.*, 2017). In addition, increase in the illite chemical index also suggested more prevailing mafic minerals in the eastern IDS rock catchment area than in the western part (Ramaswamy *et al.*, 2008).

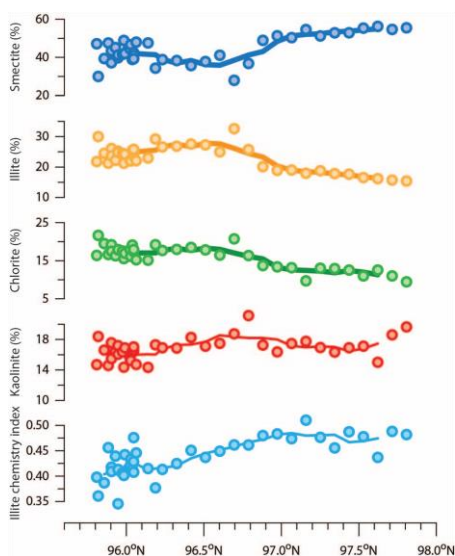


Figure 2. Plots of clay mineral assemblages showing the percentages of kaolinite, chlorite, illite, smectite, and the illite chemistry index versus longitude (degree N). Clay mineral determinations for 39 individual samples were composed of longitude data from west to east of the Irrawaddy delta shelf (IDS), Myanmar.

Moreover, the predominance of smectite fractions in the IDS corresponded well with chemical analyses of core top sediments in the Bay of Bengal (Joussain *et al.*, 2016), and the Andaman/Nicobar Islands (Ali *et al.*, 2015; Joussain *et al.*, 2016). The similarity of clay mineral concentrations between the Bay of Bengal and the IDS possibly occurred because they both originated from similar provenances. In addition, sediment samples obtained from the Andaman/Nicobar Islands were almost entirely composed of smectite at about 89%, while other clay minerals were found in very low concentrations. This can be explained because the Andaman/Nicobar Island arches are almost entirely composed of low weathering resistant mafic and ultramafic rocks (Ali *et al.*, 2015). Moreover, the significant prevalence of this clay mineral in the deeper parts of the Andaman Sea was possibly caused by the higher salinity of seawater increasing the flocculation and deposition of smectite as showing at the core top sediments from the Andaman/Nicobar Island. This relationship was also found in other studies which investigated the Niger River (Porrenga, 1967), the Amazon River (Patchineelam and de Figueiredo, 2000), and the Mekong River (Szczeniński *et al.*, 2013; Xue *et al.*, 2014).

Kaolinite was recorded as a minor fraction in surface samples derived from the other sites in the Andaman Sea because of abundance in the sediments obtained from the ECS (Figure 3). Kaolinite concentration in these samples was about 47%. The smectite fraction as the most dominant component in sediments obtained from the IDS was only about 24% in the ECS, with illite and chlorite concentrations at 17.4 and 11.4%, respectively. The dominance of kaolinite fractionation concurred with the clay mineral analysis of sedimentary samples obtained from the Malay Peninsula and Sumatra (Keller and Richards, 1967; Liu *et al.*, 2012; Cao *et al.*, 2015; Liu *et al.*, 2016). However, kaolinite concentration was more significant in the Malay Peninsula and Sumatra sediments at about 80 and 67%, respectively. Dominance of the kaolinite fractions agreed well with those obtained from

the Malacca Strait but concentrations of this clay mineral fraction decreased with increasing water depth (Keller and Richards, 1967). The significance of the kaolinite fraction in the sediment could be explained by the high chemical weathering of the parent rocks enriched in alkali and alkaline elements in the Malay Peninsula, and the upper Tertiary sediments of the Quaternary volcanic rocks in Sumatra (Keller and Richards, 1967; Liu *et al.*, 2012; Cao *et al.*, 2015; Liu *et al.*, 2016).

Regarding, clay minerals in sediments are generally formed from physical and chemical weathering of the parent rock, with deduction of ions (Liu *et al.*, 2012) under transport from land to sea. Investigation of clay mineral distribution depends on the mineral composition of the source rock, mixing of water masses and chemical modification (Chamley, 1989). The relationship between weathering processes, geological settings and climate conditions can be explained by Velde's ternary diagram (Velde, 1985) (Figure 4).

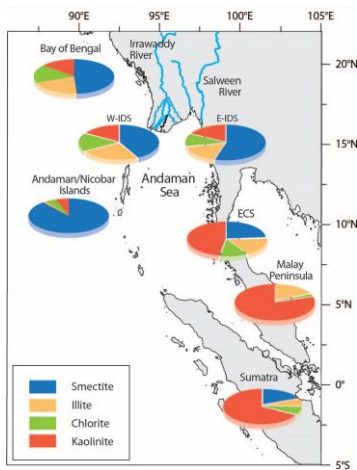


Figure 3. Distribution of the average four main clay mineral assemblages (%) in various areas of the Andaman Sea indicated by different colors as smectite (blue), illite (yellow), chlorite (green), and kaolinite (red). Data from various provinces are listed in Table 1 based on the normalizing method

Findings indicated that clay minerals of the IDS in Myanmar were under lithological control while the ECS clay minerals were controlled by climate and lithology of the source rock. Results confirmed that the Andaman Sea receives potentially terrestrial materials from the Bay of Bengal, the Irrawaddy River delta - Salween River, the Malay Peninsula, and Sumatra through the weathering of their parent rocks as showing in the difference clay mineral assemblages of each provenance. Moreover, our results suggested that clay mineral deposition surrounding the ECS area originated from sediments derived from the adjacent land sources which were then transported by surface circulation under the climatic setting of the Indian Monsoon.

Conclusions

Clay mineralogy was investigated for 61 surface sediment samples from the Irrawaddy delta shelf (IDS), Myanmar and the eastern continental shelf (ECS) of the Andaman Sea, off Phang Nga, Thailand. Clay mineral compositions and transport of detrital fine-grained sediments to the Andaman Sea were investigated.

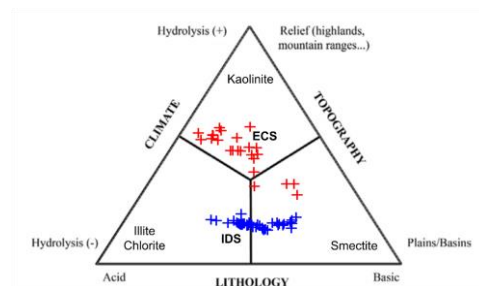


Figure 4. Ternary diagram representing the clay mineral assemblages (Velde, 1985). Interpretation of control factors influencing the clay mineral assemblages in surface samples obtained from the Irrawaddy delta shelf (IDS) (west and east) and the eastern continental shelf (ECS) are plotted in blue and red colors, respectively

Clay minerals of the IDS samples consisted dominantly of smectite 44% (40-55%) with moderate illite 23% (30-15%), chlorite 16% (22-10%), and kaolinite 17% (20-14%). Provenance analysis revealed the smectite was found in the IDS due to terrestrial sediment input supplied by the Irrawaddy and Salween Rivers. ECS clay minerals were high in kaolinite 47% (30-60%), smectite 23% (<5 to >50%), illite 18% (12-22%), and chlorite 11% (7-15%). By contrast, clay minerals in the ECS were dominantly kaolinite, similar to the clay mineral analysis of sedimentary samples obtained from the Malay Peninsula and Sumatra. The significance of the kaolinite fraction in the sediment could be explained by high chemical weathering of the parent rocks in the Malay Peninsula and Sumatra. Results confirmed that terrigenous sediments in the Andaman Sea resulted from mixing provenance sources. Terrestrial sediments in the Andaman Sea were considered as mixed sources from the surrounding continental shelf which then underwent oceanic transport by surface circulation. Findings revealed that major provenances were from the Bay of Bengal and the Irrawaddy and Salween Rivers, with minor provenance from the Malay Peninsula, Sumatra, and the Andaman/Nicobar Islands.

Although, the terrigenous material in the Andaman Sea sediments is mainly composed of the Irrawaddy River and Salween River the findings revealed different clay minerals in a west to east transect of the IDS area, indicating varying provenance and weathering processes of the parent rocks. The IDS sediments revealed an increasing illite chemical index from the west to the east, indicating that chemical weathering was more prevalent in the east IDS. These disparities corresponded well with the different rock catchments; the west IDS as the Irrawaddy rock catchment, and the east as the Salween rock catchment. In addition, the increasing illite chemical index also suggested the prevailing higher prevalence of mafic minerals in the eastern part of the IDS rock catchment than in the western part. Furthermore, the ECS sediment

variation could be explained by high chemical weathering of the parent rocks.

Acknowledgements

This work was supported by Research Scholarship of the CU. Graduate School Thesis Grant from Chulalongkorn University. This work materials were supported by Distinguished Research Professor grant under project “Tsunami deposits in near-shore and coastal waters of Thailand (TUNWAT)” under Thai-German corporation project and “Environmental Impact Assessment for the Myanmar Block M9 Production Development and Offshore Gas Transmission Pipeline”. The laboratory work funded by Pro. Dr. Zhifei Liu, Tongji University.

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