

## Chemical weathering in Malay Peninsula and North Borneo: Clay mineralogy and element geochemistry of river surface sediments

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Received February 8, 2010; accepted August 27, 2010; published online January 10, 2011

Weathering products of silicate rocks are particularly useful for evaluating the continental chemical weathering on the Earth's surface and its mechanism. Clay mineralogy and major-element geochemistry of surface sediment samples collected in major rivers of Malay Peninsula and North Borneo in the tropical Southeast Asian region are used to study the present chemical weathering process and its controlling factors of tropical regions. The results indicate that the clay mineral assemblage in Malay Peninsula consists dominantly of kaolinite (average 80%) and minor illite (average 17%), almost without chlorite and smectite, whereas in North Borneo it consists mainly of illite and chlorite, with minor amounts of kaolinite (average 14%) and no smectite. Total contents of illite and chlorite in both Northwest and Northeast Borneo are 84% and 87%, respectively. Major-element geochemical results of both bulk and clay-fraction sediments show intensive chemical weathering degree for both areas. Relatively, the chemical weathering degree is gradually strengthened from Northeast Borneo, Northwest Borneo, to Malay Peninsula, and it is extremely intensive in Malay Peninsula. Our results indicate that, in the tropical Southeast Asian region exemplified by Malay Peninsula and Borneo, climatic condition of tropical warm temperature and East Asian monsoon rainfall is the first-order controlling factor on the chemical weathering, resulting in intensive chemical weathering throughout tropical areas, and tectonic activity and lithology of parent rocks are subordinate factors, which still have an important impact on the weathering products, forming completely different clay mineral assemblages between Malay Peninsula and Borneo.

**clay minerals, major elements, fluvial sediments, chemical weathering, Malay Peninsula, Borneo**

**Citation:** Wang H, Liu Z F, Sathiamurthy E, et al. Chemical weathering in Malay Peninsula and North Borneo: Clay mineralogy and element geochemistry of river surface sediments. *Sci China Earth Sci*, 2011, 54: 272–282, doi: 10.1007/s11430-010-4158-x

Weathering products of silicate rocks are particularly useful for evaluating the continental chemical weathering on the Earth's surface and its mechanism, because their geochemical composition and mineral assemblage can reflect the information of climate condition and tectonic activity during the weathering process [1–4]. Continents and islands in Southeast Asia have the highest denudation rate in the world [5, 6] and their annual suspended sediment discharge

accounts for as much as 70% of total sediments of the world oceans [7, 8]. Therefore, the region of Southeast Asia is ideal to study the chemical weathering and its controlling factors.

Studies of chemical weathering based on river sediment geochemistry have been previously done in numerous rivers in the Southeast Asian region, including the Yangtze and Yellow Rivers in East Asia [9], the Pearl, Red and Mekong Rivers in South China and Indochina [3], the Ganges River in South Asia [10, 11], mountainous rivers in Taiwan Island

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[2, 12], and small rivers in Luzon, Philippines [4]. These studies show that not only tectonics, landform, and climatic conditions [3, 12] but also lithology of parent rocks in drainage basins play an significant role in the weathering processes [4, 11]. The control of long-term climatic conditions can produce intensive chemical weathering (e.g., the Pearl River drainage basin) [3], the combined effect of tectonics and climate can form moderate chemical weathering (e.g., the Red and Mekong Rivers in Indochina Peninsula and mountainous rivers in Taiwan Island) [2, 3, 12], and the lithology-dominated control usually produces low chemical weathering (e.g., rivers in Luzon and the Ganges River) [4, 11]. However, the results mentioned above are based on studies of the drainage basins in subtropical and temperate regions of Southeast Asia, and few were carried out in tropical regions [13].

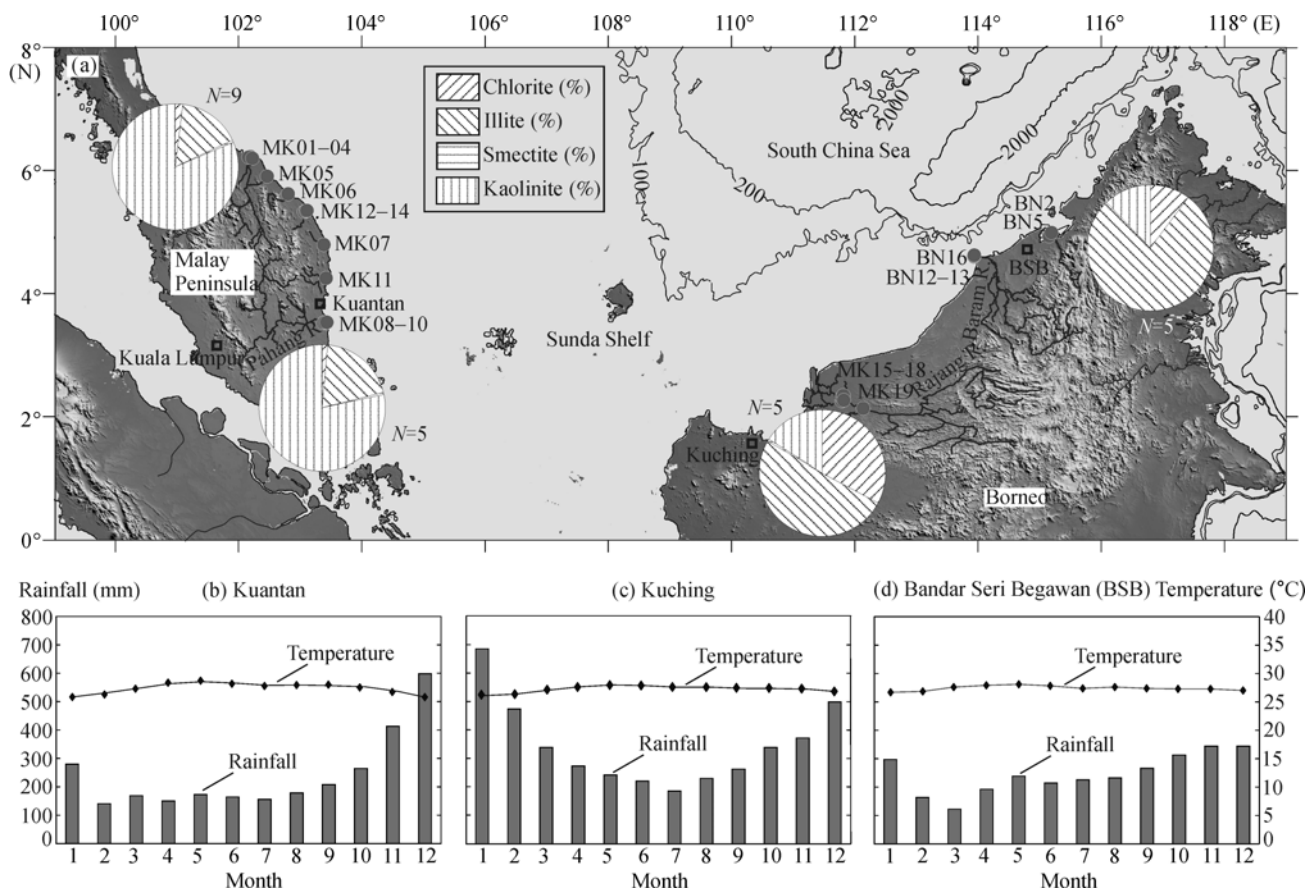
In this paper, clay mineralogy and major-element geochemistry have been investigated on surface sediments from major rivers in Malay Peninsula and North Borneo of the tropical region, in order to study modern processes of the tropical chemical weathering. Malay Peninsula and North Borneo have completely different lithological and tectonic settings, but both are affected by the similar East Asian monsoon climate. This study will help understand the controlling factors on tropical weathering by comparing the chemical weathering processes in the two tropical regions.

## 1 Geological and climatic settings

The bedrock of Malay Peninsula consists mainly of Paleozoic-Mesozoic granite and granodiorite and Paleozoic sedimentary rocks, dominated by Triassic granite and granodiorite, and Middle-Late Triassic and late Paleozoic sedimentary rocks [14]. The late Paleozoic sedimentary rocks mainly contain mudstone, sandstone, and limestone, interbedded with andesitic-rhyolitic volcanic rocks [15, 16]. Minor Mesozoic (mainly Jurassic-Cretaceous) sedimentary rocks and sparse basic volcanic rocks develop in the northern part of Malay Peninsula and other local areas. Quaternary sands-dominated loose sediments are distributed in the coastal plain areas of Malay Peninsula [14]. North Borneo is dominated by Paleozoic-Mesozoic sedimentary rocks, including sandy shale, sandstone, arenaceous shale interbedded with coal beds, and carbonate rocks [14, 17]. Scattered Tertiary basic volcanic rocks and Mesozoic basic-ultrabasic intrusive rocks developed only in curved tectonic belts, and late Tertiary acid volcanic rocks are scattered in early Tertiary sedimentary rocks [17]. Besides, Quaternary loose sediments are widely distributed in the coastal plain and delta regions of North Borneo. As a part of the Sundaland, Malay Peninsula is tectonically stable since the Mesozoic without any strong tectonic activity [16]. However, Borneo is tectonically active since the Mesozoic with frequent regional events including subduction of the Australian Plate

and spreading of the South China Sea, with the strongest Oligocene-Miocene tectonic uplift during the Cenozoic [17, 18]. The volcanic rocks with K-Ar ages ranging 6–10 Ma at Mount Kinabalu (4218 m) [19], the highest mountain of Southeast Asia in the northeastern Borneo, indicate that the rapid uplift during the late Miocene controlled the final mountain landscape of North Borneo, becoming one of major controlling factors on the chemical weathering. There is no significant difference in geological settings (bedrock lithology and tectonic activity) between Northeast and Northwest Borneo, but with the mountain landscape mainly distributed in the northeastern region and relatively low relief mainly in the northwestern region.

Climatic conditions in Malay Peninsula and Borneo are similar. Both are in the East Asian monsoon-influenced tropical region at the southern margin of the South China Sea, without seasonal temperature variation, but with an obvious difference between dry and humid seasons. Here, we take three cities as examples: Kuantan in the eastern Malay Peninsula, Kuching in Northwest Borneo, and Bandar Seri Begawan in Northeast Borneo (Figure 1). All the annual average temperature in the three regions is 27°C, with a monthly difference of less than 1.1°C. However, the rainfall is seasonal in all three regions: the rain season in Kuantan is from November to following January with the three-months rainfall of 1290 mm, accounting for 45% of its annual rainfall (2890 mm); the rain season in Kuching spans from December to following February, with the three-months rainfall of 1550 mm, accounting for 38% of its annual rainfall (4120 mm); the rain season in Bandar Seri Begawan is not very clear, generally from October to following January, with the four-months rainfall of 1284 mm, accounting for 44% of its annual rainfall (2913 m) (<http://www.worldweather.org>). The most prominent features of climatic conditions in Malay Peninsula and North Borneo compared with those in other regions surrounding the South China Sea [3, 4] include: (1) as a common tropical aspect, the temperature is consistent without a seasonal variation in Malay Peninsula and North Borneo, while other subtropical regions have the highest temperature during June–August (South China and Indochina) or April–June (Luzon) and the lowest one generally during November to following February [3, 4]; (2) affected by directions of East Asian monsoon winds, the rain season in Malay Peninsula and North Borneo is formed during October–November to following January–February by the greatly increased precipitation, resulting from southward transport of water vapor of the South China Sea brought by southward winter monsoon winds, whereas the rain season in other regions occurs during May–October, resulting from northward transport of water vapor of the south transported by northward summer monsoon winds [3, 4]. Furthermore, the annual rainfall is significantly higher in Malay Peninsula and Borneo than in other regions surrounding the South China



**Figure 1** Locations of river surface sediments and distribution of average clay mineral assemblages of major drainage basins in Malay Peninsula and North Borneo. (a) Locations of river surface sediments and distribution of average clay mineral assemblages.  $N$  = number of surface samples. (b) Rainfall and temperature distribution at Kuantan in the eastern Malay Peninsula. (c) Rainfall and temperature distribution at Kuching in Northwest Borneo. (d) Rainfall and temperature distribution at Bandar Seri Begawan in Northeast Borneo. See Table 1 for detailed GPS positions and clay mineral proportions. Monthly average rainfall and temperature data between 1971 and 2000 were obtained online through the World Weather Information Service (<http://www.worldweather.org>).

Sea, especially in Northwest Borneo which is generally twice as high as that in other regions, forming the rainforest vegetation that is typical in the tropical area.

## 2 Materials and analytical methods

A set of 24 river surface samples were collected at the downstream and estuary of 10 major rivers in Malay Peninsula and North Borneo, including 14 samples from 7 rivers in Malay Peninsula and 10 samples from 3 rivers in North Borneo (Figure 1, Table 1). Considering that surface argillaceous sediments on river beds can approximately present the components of suspended particles in river water [3, 4], we collected sediment samples directly either on a river beach near water or on a river bottom below shallow water with depth <1 m. The sampling sites were chosen in the river downstream and estuary to make mineralogical and geochemical compositions of sediments, representing the average effect of the entire drainage basin. Fieldworks were carried out mainly in February 2009, except for a sampling

of January 2006 to the Trusan and Baram Rivers in the northeastern Borneo [13]. Both sampling seasons are rainy periods of January and February, making the consistence of mineralogical and geochemical compositions of sediments. Sampling sites were also chosen to avoid contamination from riverbank sediments and potential man-made pollution. All samples were analyzed for clay minerals (<2  $\mu\text{m}$ ) and major elements in both bulk (<63  $\mu\text{m}$ ) and clay-fraction (<2  $\mu\text{m}$ ) particles.

Clay mineralogy and element geochemistry were analyzed on carbonate-free particles. In order to avoid potential significant effects of coarse grains on geochemical compositions of a sediment sample, we use particles <63  $\mu\text{m}$  to represent bulk suspended sediments [4]. Therefore, the sediment sample was firstly wet sieved using a 63  $\mu\text{m}$  sieve, and the resulting <63  $\mu\text{m}$  particles were reacted with 1% HCl to remove carbonate components, following by successive washing with deionized water to neutral solution. Then, the sample was divided into two parts after fully mixed. The first part was used for analysis of clay minerals (<2  $\mu\text{m}$ ) and

**Table 1** Geographic locations and clay mineral assemblages of surface sediments in Malay Peninsula and North Borneo

No.	Sample	River	Latitude	Longitude	Smectite (%)	Illite (%)	Chlorite (%)	Kaolinite (%)	Illite chemistry index
Malay Peninsula									
1	MK01	Kelantan River	06°12.052'N	102°12.264'E	0	17	1	82	0.41
2	MK02	Kelantan River	06°11.651'N	102°13.257'E	1	18	0	81	0.45
3	MK03	Kelantan River	06°11.100'N	102°14.103'E	0	13	1	85	0.49
4	MK04	Kelantan River	06°12.067'N	102°10.423'E	0	22	1	77	0.38
5	MK05	Jerteh River	05°53.463'N	102°28.547'E	4	12	1	83	0.54
6	MK06	Besut River	05°36.204'N	102°48.872'E	0	16	1	82	0.48
7	MK07	Dungun River	04°46.561'N	103°23.607'E	0	24	1	74	0.45
8	MK08	Pahang River	03°30.321'N	103°23.406'E	1	16	2	81	0.49
9	MK09	Pahang River	03°30.129'N	103°25.077'E	1	16	2	81	0.44
10	MK10	Pahang River	03°30.796'N	103°26.378'E	1	18	0	81	0.39
11	MK11	Kemaman River	04°13.819'N	103°25.908'E	0	25	1	74	0.48
12	MK12	Terengganu River	05°18.375'N	103°05.301'E	0	11	8	81	0.55
13	MK13	Terengganu River	05°19.775'N	103°06.009'E	0	17	1	81	0.52
14	MK14	Terengganu River	05°20.117'N	103°07.099'E	0	19	1	80	0.48
Northwest Borneo									
15	MK15	Rajang River	02°14.235'N	111°48.504'E	0	50	32	18	0.38
16	MK16	Rajang River	02°16.916'N	111°48.821'E	1	52	31	16	0.36
17	MK17	Rajang River	02°19.649'N	111°50.028'E	1	51	32	16	0.41
18	MK18	Rajang River	02°14.849'N	111°50.069'E	0	52	38	9	0.37
19	MK19	Rajang River	02°06.375'N	112°09.464'E	1	47	31	21	0.43
Northeast Borneo									
20	BN2	Trusan River	04°59.305'N	115°10.477'E	0	71	13	16	0.23
21	BN5	Trusan River	04°54.16'N	115°09.212'E	0	85	5	10	0.20
22	BN12	Baram River	04°35.765'N	113°57.195'E	0	75	13	12	0.23
23	BN13	Baram River	04°35.992'N	113°56.988'E	0	76	11	13	0.20
24	BN16	Baram River	04°35.58'N	113°57.085'E	0	81	9	10	0.28

of element geochemistry of clay-fraction (<2  $\mu\text{m}$ ) particles, and the second part was used for element geochemical analysis of bulk (<63  $\mu\text{m}$ ) particles after drying. The sample used for clay mineral and clay-fraction geochemical analysis was continuously washed with deionized water to help the deflocculation of clays. The particles less than 2  $\mu\text{m}$  were separated following the Stokes' Law [20] and were concentrated using a centrifuge. A small part was used for making oriented mounts for clay mineral (<2  $\mu\text{m}$ ) analysis [3, 4], and the other part was dried for element geochemical analysis of clay-fraction (<2  $\mu\text{m}$ ) particles.

Clay minerals were identified by X-ray diffraction (XRD) using a PANalytical diffractometer at the Laboratoire IDES, Université de Paris XI with  $\text{CuK}\alpha$  radiation and Ni filter, under a voltage of 45 kV and an intensity of 40 mA. Three XRD runs were performed, following air-drying, ethylene-glycol salvation for 24 h, and heating at 490°C for 2 h. Identification and interpretation of clay minerals were made according to a comprehensive comparison of multiple X-ray diffractograms obtained under three measurement conditions [3, 4]. Semi-quantitative calculations of each peak's parameters were carried out on the glycolated curve by using MacDiff software [21]. The relative contents of each clay mineral species were estimated mainly according to areas of (001) series of basal reflections, i.e., smectite (001)

including illite/smectite random mixed-layers at 1.7 nm, illite (001) at 1 nm, and kaolinite (001) and chlorite (002) at 0.7 nm [20]. Kaolinite and chlorite were discriminated according to the relative proportions given by a ratio of the 0.357 nm and 0.354 nm peak areas. Additionally, illite chemistry index was determined on the glycolated curve by a ratio of the 0.5 and 1.0 nm peak areas. Ratios above 0.40 are found in Al-rich illites (muscovites), which are released following strong hydrolysis; when Mg and Fe substitute Al in illite's crystal lattice, ratios decrease accordingly; ratios below 0.15 represent Fe-Mg-rich illites (biotites), which are characteristic of physical erosion [22, 23].

Major elements were measured by inductively coupled plasma optical emission (ICP-OES) using an IRIS Advantage at the State Key Laboratory of Marine Geology, Tongji University on bulk (<63  $\mu\text{m}$ ) and clay-fraction (<2  $\mu\text{m}$ ) particles [4]. About 30–40 mg oven-dried sediments were heated at 600°C to achieve the loss of ignition (LOI). The sample was then dissolved using a mixture solution of  $\text{HNO}_3$  + HF on a hot plate. The eluted sample was diluted 1000 times with 2%  $\text{HNO}_3$  for the major-element measurement. Replicate analyses of GSR-5, GSR-6, and GSD-9 reference samples during the study gave an accuracy of 4% for major elements. Replicate analyses of selected samples gave a precision of  $\pm 2\%$  ( $2\sigma$ ).

### 3 Results and discussion

#### 3.1 Clay mineral assemblage and its distribution

Clay mineral assemblages of river surface sediments in Malay Peninsula and North Borneo are significantly different, and can be easily grouped into three blocks: Malay Peninsula, Northwest Borneo, and Northeast Borneo (Figure 1, Table 1). The clay mineral assemblage of 14 samples from 7 rivers in Malay Peninsula is similar, with dominant kaolinite (74%–85%, average 80%), minor illite (11%–25%, average 17%), and very little chlorite (average 2%) and smectite (average 1%). The clay mineral assemblage of five samples from the Rajang River, the largest river in Northwest Borneo, is also similar with each other, with dominant illite (47%–52%, average 51%) and chlorite (31%–38%, average 33%), minor kaolinite (9%–21%, average 16%), and no smectite (~0%). For five samples from the Trusan and Baram Rivers in Northeast Borneo, the clay mineral assemblage consists dominantly of illite (71%–85%, average 77%), with minor kaolinite (10%–16%, average 12%) and chlorite (5%–13%, average 10%), and no smectite (0%) [13].

The resemblance of clay mineral assemblages in the three blocks is that all contain kaolinite and illite, almost without smectite. However, the kaolinite content is extremely high in Malay Peninsula, averaged up to 80%; whereas in North Borneo, the illite content is very high, averaged up to 77% in Northeast Borneo. Illite chemistry index of the samples in Malay Peninsula is generally larger than 0.40, with an average value of 0.47 (Table 1), representing intensive chemical weathering; however, values of the index decrease gradually in the samples of Northwest and Northeast Borneo, averaged to 0.39 and 0.22, respectively (Table 1), indicating decreased chemical weathering and increased physical erosion.

#### 3.2 Major element distribution and chemical mobility

Major-element compositions of bulk and clay-fraction surface sediments from major rivers in Malay Peninsula and North Borneo consist mainly of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub>, and their total content is up to ~80%. Concentrations of CaO, K<sub>2</sub>O, MgO, MnO, Na<sub>2</sub>O, P<sub>2</sub>O<sub>5</sub>, and TiO<sub>2</sub> are relatively low, with their total content of less than 6% (Table 2). By comparing bulk to clay-fraction major element compositions, one can find that clay-fraction sediments usually contain higher Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, and P<sub>2</sub>O<sub>5</sub>, and lower SiO<sub>2</sub> and Na<sub>2</sub>O than bulk sediments (Figure 2). Variation diagrams of these elements versus Al<sub>2</sub>O<sub>3</sub> (Figure 2) indicate relatively strong negative correlations of Al<sub>2</sub>O<sub>3</sub> with SiO<sub>2</sub> and Na<sub>2</sub>O, implying that along with an increase of Al<sub>2</sub>O<sub>3</sub>, i.e., the formation of clay minerals (Al-rich mostly), quartz particles (Si-rich mostly) reduce gradually, and contents of mobile alkaline elements (the most leachable element Na) decrease accord-

ingly. Enrichment of Fe<sub>2</sub>O<sub>3</sub> during the formation of clay minerals suggests that along with the strengthening of chemical weathering, Fe is easily enriched in weathering products to form red soils, which are widely distributed in the tropical region, and becomes the main source of river sediments. There is no reasonable correlation for other elements between bulk and clay-fraction element compositions, e.g., CaO, MnO, and TiO<sub>2</sub> (Figure 2). Variations of K<sub>2</sub>O and MgO in the three blocks present a clear difference, with consistent values in both bulk and clay-fraction sediments in Malay Peninsula, but presenting a positive correlation between MgO and Al<sub>2</sub>O<sub>3</sub> in two regions of Borneo. This indicates that along with the formation of clay minerals, K<sub>2</sub>O and MgO are enriched gradually. The enrichment of K<sub>2</sub>O is in contradiction with the character of the leachable alkaline element [4], but is in accord with the majority of illite (K-rich) in sediments of Borneo, and is especially in keeping with the low values of illite chemistry index (Mg-Fe-rich illite) of Borneo (Table 1).

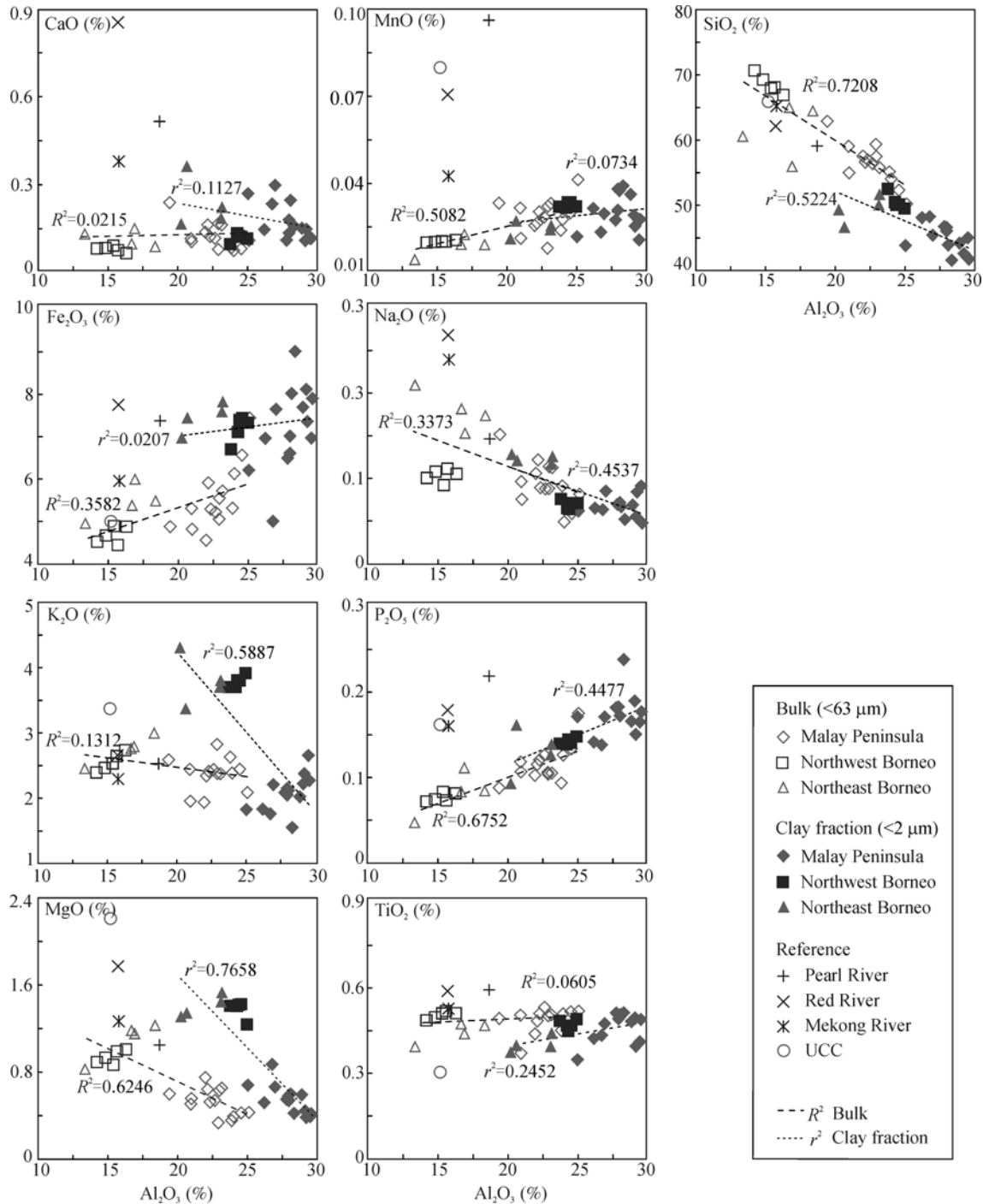
Through the comparison of major element results among the three blocks of Malay Peninsula, Northwest Borneo, and Northeast Borneo, it shows that samples of Malay Peninsula contain higher Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>, P<sub>2</sub>O<sub>5</sub>, and MnO, and lower SiO<sub>2</sub>, Na<sub>2</sub>O, K<sub>2</sub>O, and MgO than those of Borneo (Figure 2), indicating higher chemical weathering degree and absence of K- and Mg-rich clay minerals in Malay Peninsula. In addition, major element compositions of bulk sediments in the three blocks are quite different from those of UCC (upper continental crust) [24], Pearl, Red, and Mekong Rivers [3] (Figure 2). Apart from that, K<sub>2</sub>O, SiO<sub>2</sub>, and TiO<sub>2</sub> contents in the samples of North Borneo are close to those of UCC and the rivers mentioned above, other major elements in samples of North Borneo and all major elements in samples of Malay Peninsula are mostly lower than those of UCC and the reference rivers, indicating a strong leaching effect.

Chemical mobility of major elements is usually semi-quantitatively expressed by using an elemental ratio (wt%) of the content of element X respect to Al. The formula [10] is

$$\text{Elemental ratio (X)} = [X/\text{Al}_2\text{O}_3 (\text{rivers})] / [X/\text{Al}_2\text{O}_3 (\text{UCC})]. \quad (1)$$

The elemental ratio refers to the relative enrichment or depletion of the element X during weathering, i.e., >1 indicates enrichment, <1 indicates depletion, and =1 indicates no change in the relative abundance of the element.

The major elemental ratios of bulk and clay-fraction sediments in Malay Peninsula and North Borneo calculated from eq. (1) present a relative depletion for all major elements of clay-fraction sediments, and a similar depletion for most major elements of bulk sediments except Ti, but with a lower depletion than that of clay-fraction sediments (Figure 3). Through the comparison of major elemental ratios in these three blocks, we find that the chemical mobility of



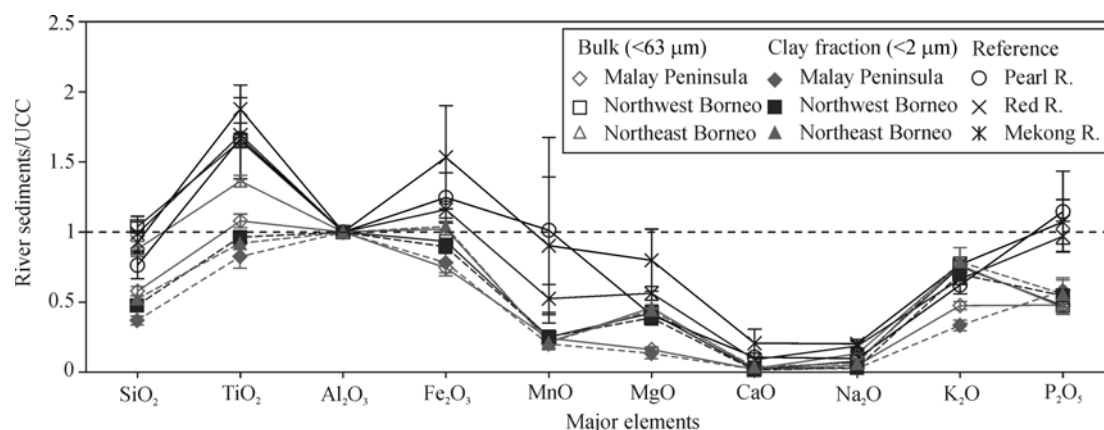
**Figure 2** Variation diagrams of major elements of bulk and clay-fraction surface sediments in major rivers of Malay Peninsula and North Borneo. Data of the Pearl, Red, and Mekong Rivers are from ref. [3]; data of UCC (upper continental crust) are from ref. [24].

major elements is the strongest in Malay Peninsula, moderate in Northwest Borneo, and relatively weak in Northeast Borneo. But all the major elements of these samples in the three blocks are more depleted than those of the Pearl, Red, and Mekong Rivers. The chemical mobility of Ti, Al, and Fe are mostly stable. Because Al is used to calculate the elemental ratio through eq. (1), the results cannot evaluate the chemical mobility of Al. However, although Ti in bulk

sediments is obviously enriched, Fe in bulk sediments is slightly depleted. Alkali element Na and alkaline element Ca show an extreme depletion, whereas alkali element K shows a moderate depletion. The K depletion is quite different between the sediments in Malay Peninsula and North Borneo, while the Mg depletion is similar in the two regions (Figure 3). The reason could be the majority of illite (K-rich) in sediments of North Borneo, especially with low values of

**Table 2** Major element compositions of bulk (<63  $\mu\text{m}$ ) and clay-fraction (<2  $\mu\text{m}$ ) surface sediments in major rivers of Malay Peninsula and North Borneo

No.	Sample	Al <sub>2</sub> O <sub>3</sub> (%)	CaO (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	K <sub>2</sub> O (%)	MgO (%)	MnO (%)	Na <sub>2</sub> O (%)	P <sub>2</sub> O <sub>5</sub> (%)	TiO <sub>2</sub> (%)	SiO <sub>2</sub> (%)	LOI (%)	CIA
Bulk sediments (<63 $\mu\text{m}$ )													
1	MK01	26.21	0.15	6.96	1.83	0.52	0.03	0.20	0.14	0.69	48.09	15.18	87
2	MK02	28.09	0.25	8.02	2.12	0.60	0.04	0.20	0.17	0.83	43.91	15.78	83
3	MK03	28.90	0.15	7.69	2.02	0.59	0.04	0.21	0.16	0.79	44.20	15.25	87
4	MK04	26.98	0.30	7.65	2.21	0.66	0.03	0.26	0.17	0.78	45.40	15.57	87
5	MK05	26.76	0.23	5.00	1.76	0.87	0.02	0.19	0.14	0.71	48.24	16.07	88
6	MK06	25.03	0.27	6.21	1.83	0.68	0.02	0.18	0.17	0.57	43.83	21.21	89
7	MK07	29.22	0.15	7.36	2.37	0.38	0.03	0.25	0.15	0.65	42.57	16.87	87
8	MK08	27.81	0.11	6.49	2.08	0.55	0.03	0.21	0.18	0.84	46.72	14.98	87
9	MK09	27.97	0.13	6.61	2.06	0.54	0.03	0.21	0.18	0.81	46.60	14.86	87
10	MK10	27.98	0.18	7.01	2.15	0.58	0.04	0.21	0.18	0.83	46.03	14.81	86
11	MK11	29.50	0.12	6.97	2.66	0.39	0.02	0.27	0.16	0.68	45.01	14.23	86
12	MK12	28.35	0.16	9.01	1.55	0.42	0.04	0.16	0.23	0.84	41.55	17.69	89
13	MK13	29.58	0.12	7.90	2.27	0.42	0.03	0.14	0.17	0.80	41.73	16.83	90
14	MK14	29.14	0.11	8.12	2.22	0.44	0.03	0.16	0.19	0.81	42.57	16.21	89
15	MK15	24.27	0.13	7.11	3.70	1.41	0.03	0.20	0.14	0.77	50.47	11.78	82
16	MK16	23.77	0.10	6.70	3.70	1.41	0.03	0.23	0.14	0.80	52.50	10.63	81
17	MK17	24.37	0.13	7.39	3.81	1.42	0.03	0.19	0.14	0.74	50.07	11.71	81
18	MK18	24.57	0.12	7.44	3.81	1.42	0.03	0.21	0.14	0.77	50.14	11.35	82
19	MK19	24.97	0.12	7.33	3.92	1.24	0.03	0.21	0.15	0.81	49.49	11.74	82
20	BN5	20.24	0.17	6.97	4.30	1.31	0.02	0.38	0.09	0.61	49.28	16.62	77
21	BN12	23.18	0.22	7.82	3.80	1.53	0.03	0.38	0.14	0.72	51.63	10.56	80
22	BN13	20.65	0.36	7.44	3.37	1.34	0.03	0.36	0.16	0.65	46.62	19.02	81
23	BN16	23.12	0.18	7.59	3.70	1.44	0.02	0.35	0.13	0.65	50.05	12.77	81
Clay-fraction sediments (<2 $\mu\text{m}$ )													
24	MK01	22.93	0.17	5.55	2.38	0.63	0.03	0.34	0.10	0.83	57.46	9.58	91
25	MK02	19.42	0.24	4.88	2.59	0.60	0.03	0.45	0.09	0.81	62.87	8.02	90
26	MK03	23.16	0.16	5.72	2.38	0.65	0.03	0.34	0.11	0.83	55.77	10.86	91
27	MK04	22.15	0.16	5.91	2.34	0.64	0.03	0.36	0.11	0.79	56.61	10.89	89
28	MK05	21.98	0.14	4.56	1.94	0.75	0.03	0.32	0.10	0.72	57.53	11.94	91
29	MK06	20.98	0.11	4.81	1.96	0.56	0.02	0.23	0.11	0.61	54.96	15.66	90
30	MK07	23.87	0.09	5.31	2.63	0.36	0.02	0.27	0.09	0.74	55.13	11.49	90
31	MK08	22.67	0.12	5.21	2.44	0.54	0.03	0.26	0.12	0.87	56.40	11.33	91
32	MK09	22.32	0.12	5.29	2.41	0.52	0.03	0.27	0.12	0.84	56.96	11.12	91
33	MK10	20.95	0.12	5.31	2.44	0.51	0.03	0.29	0.12	0.83	59.03	10.39	90
34	MK11	22.91	0.08	5.05	2.82	0.33	0.02	0.26	0.11	0.83	59.34	8.24	89
35	MK12	24.00	0.08	6.13	2.39	0.39	0.03	0.15	0.12	0.84	54.02	11.86	93
36	MK13	25.11	0.11	7.44	2.09	0.43	0.04	0.24	0.17	0.85	50.19	13.33	91
37	MK14	24.55	0.08	6.57	2.44	0.42	0.03	0.18	0.13	0.85	52.31	12.44	91
38	MK15	16.28	0.07	4.88	2.74	1.00	0.02	0.32	0.08	0.84	66.88	6.89	84
39	MK16	15.66	0.08	4.45	2.65	0.99	0.02	0.33	0.07	0.85	68.09	6.80	84
40	MK17	14.20	0.08	4.54	2.39	0.90	0.02	0.30	0.07	0.80	70.68	6.02	84
41	MK18	14.83	0.08	4.68	2.46	0.93	0.02	0.32	0.07	0.81	69.24	6.55	84
42	MK19	15.39	0.09	4.90	2.54	0.87	0.02	0.27	0.08	0.84	67.96	7.03	84
43	BN5	13.36	0.13	4.95	2.45	0.83	0.01	0.63	0.05	0.65	60.55	16.39	78
44	BN12	16.69	0.10	5.38	2.77	1.18	0.02	0.54	0.08	0.78	65.00	7.45	82
45	BN13	16.93	0.15	5.99	2.79	1.15	0.02	0.46	0.11	0.72	55.96	15.71	81
46	BN16	18.38	0.09	5.48	3.00	1.23	0.02	0.52	0.08	0.77	64.47	5.96	82



**Figure 3** Elemental ratios of bulk and clay-fraction sediments in Malay Peninsula and North Borneo, calculated from average major-element concentrations were normalized to UCC. The error bar for each element refers to the standard deviation of all samples. Data of the Pearl, Red, and Mekong Rivers are from ref. [3].

illite chemistry index (Mg-Fe-rich illite) (Table 1), consistent with the results of major elements discussed above (Figure 2).

### 3.3 Formation of clay minerals and weathering trends

Clay minerals at the surface of the Earth originated mainly from weathering of parent rocks, including physical weathering leading to rock fragmentation and chemical weathering with subtraction of ions. Hydrolysis is by far the most efficient chemical weathering, which attacks rocks by low ionized water at medium pH conditions ( $5 < \text{pH} < 9.6$ ). Following an increase of hydrolysis intensity during chemical weathering, subtraction of ions from minerals in parent rocks statistically is concerned first with the more mobile ions, like Na, K, Ca, Mg, and Sr. The hydrolytic weathering process has been called bisialitization. Transitional elements tend to be expelled later (Mn, Ni, Cu, Co, and Fe). This process corresponds to monosialitization. Finally, Si tends to be leached completely when compared to Al, which is the less mobile element through the hydrolytic process. The final process of hydrolytic weathering is alitization [25].

Kaolinite is usually formed in monosialitized soil, representing the intensive hydrolysis climate. The parent rocks enriched with alkali and alkaline elements are easier to form kaolinite through chemical weathering. Granite, granodiorite, and intermediate-acid volcanic rocks that mainly developed in Malay Peninsula are easily and intensively weathered to form kaolinite. The stable tectonics since the Mesozoic and humid East Asian monsoon climate in Malay Peninsula allow sufficient time and condition for chemical reaction to form the monosialitization of kaolinite, resulting in as high as 80% of kaolinite in surface sediments of major rivers. Such a phenomenon also develops in the Pearl River drainage basin of South China [3, 26]. Therefore, the formation of kaolinite in Malay Peninsula is controlled by lithology of intermediate-acid rocks, warm and humid cli-

mate conditions, and stable tectonic setting. Illite and chlorite are very rich in river surface sediments in North Borneo. The sum of the two minerals is up to 84% in Northwest Borneo and 89% in Northeast Borneo, respectively (Figure 1). Illite and chlorite are primary minerals and they are formed through weak hydrolysis and/or strong direct erosion of bedrocks. Such environments usually include two situations: (1) under dry and cold climate conditions, the chemical reaction is short of temperature and moisture environments that can strengthen the hydrolysis; (2) under the setting with frequent tectonic activities, rapidly exposed fresh rocks are frequently washed and eroded without sufficient time for hydrolysis. Active tectonic setting and frequent volcanic activities in North Borneo since the Mesozoic, and especially the rapid uplift during Oligocene-Miocene, have resulted in extreme physical erosion of parent rocks. Along with lithological features of the major Mesozoic-Cenozoic sedimentary rocks (lack of intermediate-acid rocks that can form a large amount of kaolinite), numerous seasonal precipitations can strengthen the physical erosion to form clay mineral assemblages with a majority of primary illite and chlorite in North Borneo. Such clay mineral assemblages with primary illite and chlorite under warm and humid climate conditions also well develop in the modern Taiwan drainage basins [12]. Therefore, illite and chlorite in North Borneo represent active tectonics and precipitation-caused physical erosion capability, instead of dry and cold climate conditions that are often observed in other regions. Because the mountainous landscape is mainly distributed in Northeast Borneo, the large relief difference may promote stronger physical erosion, resulting in the highest content of illite in the region. Smectite occurs usually in bisialitized soils and indicates secondary products of chemical weathering of ferromagnesian aluminosilicates. Because intermediate-basic rocks are scarce in Malay Peninsula and North Borneo and only scattered Tertiary basic volcanic rocks and Mesozoic basic-ultrabasic intrusive



rocks developed in curved tectonic belts, smectite is almost absent in river surface sediments in this study.

Although the sediments of North Borneo are characterized by high contents of primary minerals (illite and chlorite), they are located in the warm and humid tropical region. And therefore, the chemical weathering is still very intensive, similar to the case of Malay Peninsula. We use the CIA (chemical index of alternation) to represent the degree of chemical weathering. The formula is [27]:

$$\text{CIA} = [\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O})] \times 100, \quad (2)$$

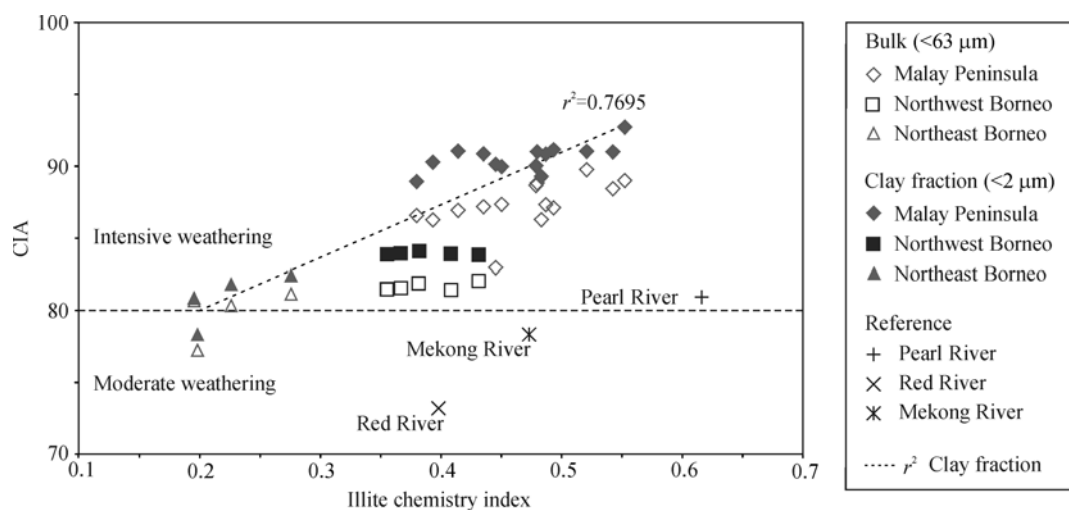
where major elements are in molecular ratios;  $\text{CaO}^*$  represents  $\text{CaO}$  associated with the silicate fraction of the sample. Because the samples used in this study were removed for calcium carbonate (the main content of carbonate rocks) during the preparation, the analyzed values of  $\text{CaO}$  can be used to calculate the CIA directly. With the progress of chemical weathering, alkali and alkaline elements such as Na, K, and Ca are leached gradually and values of CIA increase accordingly. Fresh basalts have CIA values between 30 and 45, granites and granodiorites have values between 45 and 55, kaolinite has values close to 100, while UCC has an average value of 46. In general, CIA values between 45 and 55 mean no weathering; values less than 60 indicate weak chemical weathering, values between 60 and 80 shows moderate chemical weathering, and values more than 80 represent intensive chemical weathering.

CIA values of bulk and clay-fraction sediments in Malay Peninsula and North Borneo and their linear correlations to illite chemistry index (Figure 4) shows the gradually strengthened chemical weathering degrees from Northeast Borneo, Northwest Borneo, to Malay Peninsula. Averages CIA values of bulk sediments are 80, 82, and 87, respectively, and average CIA values of clay-fraction sediments are 81, 84, and 91, respectively, all corresponding to the intensive chemical weathering. At the same time, all illite

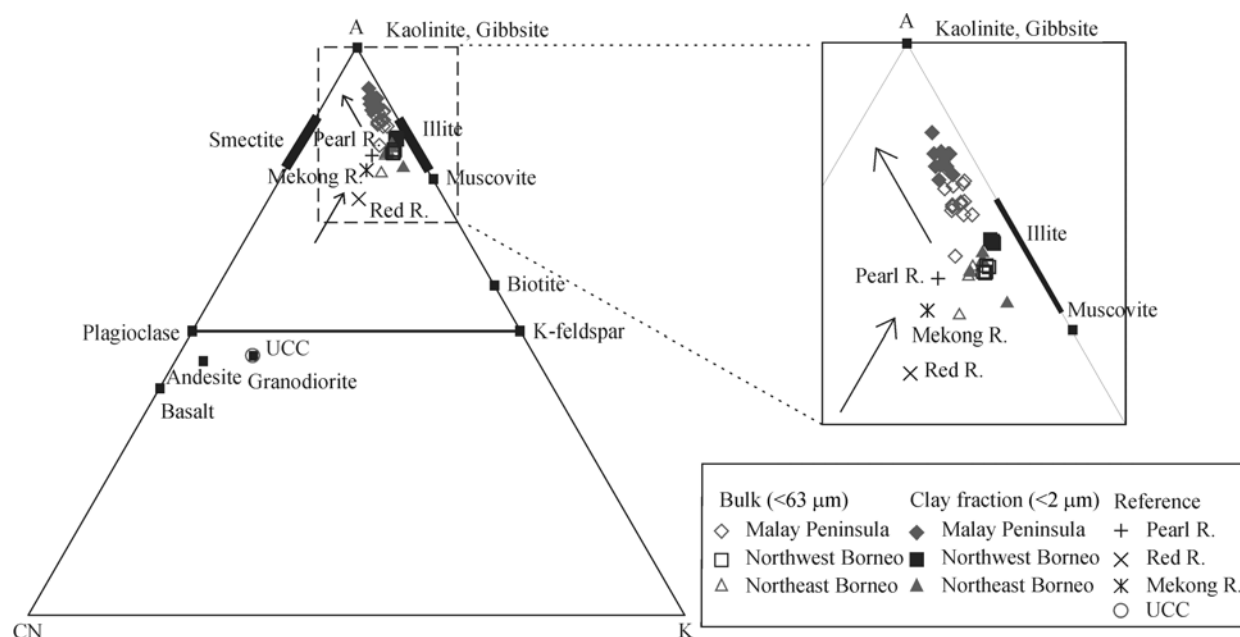
chemistry indices of the three blocks are larger than 0.15, with an average value of 0.22 in Northeast Borneo, 0.39 in Northwest Borneo, and 0.47 in Malay Peninsula, respectively, also indicating the gradually strengthened chemical weathering (Figure 4). The degree of chemical weathering intensity is definitely stronger in Malay Peninsula and North Borneo than in other regions surrounding the South China Sea (e.g., South China and Indochina). For example, the chemical weathering degree in Northeast Borneo with relatively weak weathering among the three blocks reaches that of the Pearl River drainage basin.

Due to the intensive chemical weathering, Na and Ca in samples of Malay Peninsula and North Borneo are almost leached out (Figure 3), and the chemical weathering trend is to leach K and other elements gradually. Observed on A-CN-K ( $\text{Al}_2\text{O}_3$ - $(\text{CaO} + \text{Na}_2\text{O})$ - $\text{K}_2\text{O}$ ) ternary diagrams (major elements as molecular ratios) [28, 29] (Figure 5), the samples of Malay Peninsula and North Borneo are plotted parallel to the A-K line, indicating gradually leaching K, unlike samples of the Pearl, Red, and Mekong Rivers that the plot parallels to the A-CN line with an indication of preferential leaching Na and Ca. The clay-fraction samples have a stronger depletion than the bulk samples, and the Malay Peninsula samples have a higher depletion ability than the North Borneo samples, indicating the very intensive chemical weathering.

To sum up, despite that clay mineral assemblages in weathering products and controlling factors on the formation of clay minerals are completely different in Malay Peninsula and North Borneo, because both areas are situated in the warm and humid tropical region, the major-element geochemical results of both bulk and clay-fraction sediments indicate the intensive chemical weathering. Relatively, the chemical weathering intensity is gradually strengthened from Northeast Borneo, Northwest Borneo, to Malay Peninsula, and it is extremely intensive in Malay



**Figure 4** CIA of bulk and clay-fraction sediments and their correlation with illite chemistry index in major rivers of Malay Peninsula and North Borneo. Data of the Pearl, Red, and Mekong Rivers are from ref. [3].



**Figure 5** Weathering trends from A-CN-K ternary diagrams of bulk and clay-fraction sediments in major rivers of Malay Peninsula and North Borneo. A =  $\text{Al}_2\text{O}_3$ ; CN =  $\text{CaO} + \text{Na}_2\text{O}$ ; K =  $\text{K}_2\text{O}$ ; major elements as molecular ratios; data of the Pearl, Red, and Mekong Rivers are from ref. [3]; data of UCC from ref. [24]; arrows indicate weathering trends.

Peninsula. Therefore, in the tropical Southeast Asian region represented by Malay Peninsula and Borneo, climatic condition of tropical warm temperature and East Asian monsoon rainfall is the first-order controlling factor on the chemical weathering, and tectonic activity and lithology of parent rocks are subordinate factors, which still have an important impact on the degree of chemical weathering.

#### 4 Conclusions

Clay mineralogy and major-element geochemistry of surface sediments collected in major rivers of Malay Peninsula and North Borneo are used to study chemical weathering and its controlling factors in tropical regions for the first time. It is concluded that:

(1) The clay mineral assemblage of river surface sediments in Malay Peninsula consists of dominant kaolinite (74%–85%) with an average content of 80%, minor illite (11%–25%), and little chlorite and smectite. However, in North Borneo it consists of dominantly illite and chlorite, and minor kaolinite (9%–21%) without smectite. In Northeast and Northwest Borneo, the average content of illite is 77% and 51%, respectively, and the average content of chlorite is 10% and 33%, respectively.

(2) The formation of kaolinite in Malay Peninsula is controlled mainly by lithology of intermediate-acid rocks, warm and humid climatic conditions, and stable tectonic setting, whereas the formation of illite and chlorite in Borneo is caused mainly by active tectonic setting and heavy precipitations. Among them, mountainous landscapes dis-

tributed in Northeast Borneo may promote stronger physical erosion and result in the highest content of illite in the region.

(3) The major-element results of both bulk and clay-fraction sediments indicate intensive chemical weathering in Malay Peninsula and North Borneo. Relatively, the chemical weathering degree is gradually strengthened from Northeast Borneo, Northwest Borneo, to Malay Peninsula. Our results indicate that, in the tropical Southeast Asian region represented by Malay Peninsula and Borneo, climatic condition of tropical warm temperature and East Asian monsoon rainfall is the first-order controlling factor on chemical weathering, and tectonic activity and lithology of parent rocks are subordinate factors, which still nevertheless have an important impact on the degree of chemical weathering.

We thank Joseph Anak Bidai, Sunny Goh Eng Giap, and Noor Azhar M. Shazili from the Institute of Oceanography, University Malaysia Terengganu for fieldwork assistance and discussion, and Peijun Qiao and Lei Shao from the State Key Laboratory of Marine Geology, Tongji University for technical help during the laboratory analysis. We specially thank Haijin Xu, other two anonymous reviewers, and an expert in the editorial board for their constructive and detailed reviews on the early version of this paper. This work was supported by National Natural Science Foundation of China (Grant Nos. 40925008, 40876024, and 40776027), National Basic Research Program of China (Grant No. 2007CB815906), Shanghai Shuguang Program (Grant No. 07SG23), and Shanghai Subject Chief Scientist Program (Grant No. 10XD1406300).

- Galy A, France-Lanord C. Weathering processes in the Ganges-Brahmaputra basin and the riverine alkalinity budget. *Chem Geol*, 1999, 159: 31–60

- 2 Selvaraj K, Chen C-T A. Moderate chemical weathering of subtropical Taiwan: Constraints from solid-phase geochemistry of sediments and sedimentary rocks. *J Geol*, 2006, 114: 101–116
- 3 Liu Z, Colin C, Huang W, et al. Climatic and tectonic controls on weathering in South China and the Indochina Peninsula: Clay mineralogical and geochemical investigations from the Pearl, Red, and Mekong drainage basins. *Geochem Geophys Geosyst*, 2007, 8: Q05005. doi: 10.1029/2006GC001490
- 4 Liu Z, Zhao Y, Colin C, et al. Chemical weathering in Luzon, Philippines from clay mineralogy and major-element geochemistry of river sediments. *Appl Geochem*, 2009, 24: 2195–2205
- 5 McLennan S M. Weathering and global denudation. *J Geol*, 1993, 101: 295–303
- 6 Summerfield M A, Hulton N J. Natural controls of fluvial denudation rates in major world drainage basins. *J Geophys Res*, 1994, 99: 13871–13883
- 7 Milliman J D, Meade R H. World-wide delivery of sediment to the oceans. *J Geol*, 1983, 91: 1–21
- 8 Milliman J D, Syvitski J M P. Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. *J Geol*, 1992, 100: 525–544
- 9 Yang S, Jung H S, Li C. Two unique weathering regimes in the Changjiang and Huanghe drainage basins geochemical evidence from river sediments. *Sediment Geol*, 2004, 164: 19–34
- 10 Singh M, Sharma M, Tobschall H L. Weathering of the Ganga alluvial plain, northern India: Implications from fluvial geochemistry of the Gomati River. *Appl Geochim*, 2005, 20: 1–21
- 11 Singh P. Geochemistry and provenance of stream sediments of the Ganga River and its major tributaries in the Himalayan region, India. *Chem Geol*, 2010, 269: 220–236
- 12 Liu Z, Tuo S, Colin C, et al. Detrital fine-grained sediment contribution from Taiwan to the northern South China Sea and its relation to regional ocean circulation. *Mar Geol*, 2008, 255: 149–155
- 13 Liu Z, Zhao Y, Li J, et al. Late Quaternary clay minerals off Middle Vietnam in western South China Sea: Implications for source analysis and East Asian monsoon evolution. *Sci China Ser D-Earth Sci*, 2007, 50: 1674–1684
- 14 Commission for the Geological Map of the World. Geological World Atlas, scale 1:10,000,000. U N Educ Sci and Cult Org, Paris, 1975
- 15 Sultan K, Shazili N A. Distribution and geochemical baselines of major, minor and trace elements in tropical topsoils of the Terengganu River basin, Malaysia. *J Geochem Expl*, 2009, 103: 57–68
- 16 Hutchison C S. Dating tectonism in the Indosinian-Thai-Malayan orogen by thermoluminescence. *Geol Soc Am Bull*, 1968, 79: 375–386
- 17 Hutchison C S. *Geology of North-West Borneo: Sarawak, Brunei and Sabah*. Amsterdam: Elsevier Science, 2005. 444
- 18 Hall R. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: Computer-based reconstructions, model and animations. *J Asian Earth Sci*, 2002, 20: 353–431
- 19 Rangin C, Bellon H, Benard P, et al. Neogene arc-continent collision in Sabah, Northern Borneo (Malaysia). *Tectonophysics*, 1990, 183: 305–319
- 20 Holtzapffel T. *Les Minéraux Argileux: Préparation, Analyse Diffractométrique et Détermination*. Soc Géol Nord Publ, 1985, 12: 1–136
- 21 Petschick R. MacDiff 4.2.2. 2000. <http://servermac.geologie.un-frankfurt.de/Rainer.html>
- 22 Esquevin J. Influence de la composition chimique des illites sur leur cristallinité. *Bull Cent Rech Pau S N P A*, 1969, 3: 147–153
- 23 Petschick R, Kuhn G, Gingele F. Clay mineral distribution in surface sediments of the South Atlantic: Sources, transport, and relation to oceanography. *Mar Geol*, 1996, 130: 203–229
- 24 Taylor S R, McLennan S M. *The Continental Crust: Its Composition and Evolution*. Malden: Blackwell, 1985. 312
- 25 Chamley H. *Clay Sedimentology*. Berlin: Springer, 1989. 1–623
- 26 Liu Z, Colin C, Huang W, et al. Clay minerals in surface sediments of the Pearl River drainage basin and their contribution to the South China Sea. *Chin Sci Bull*, 2007, 52: 1101–1111
- 27 Nesbitt H W, Young G M. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature*, 1982, 299: 715–717
- 28 Nesbitt H W, Young G M. Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. *Geochim Cosmochim Acta*, 1984, 48: 1523–1534
- 29 Nesbitt H W, Young G M. Formation and diagenesis of weathering profiles. *J Geol*, 1989, 97: 129–147