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Late Quaternary tectonics and seismotectonics along the Red River fault zone, North Vietnam

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ABSTRACT

A study of active tectonic development in Vietnam is of great importance. Right lateral strike-slip offsets along the Red River fault during the Pliocene-present are determined by analyzing tributaries, Quaternary alluvial fans, river valley from Landsat, SPOT images, detailed topographical maps and field observation. Along the SW fault of the Red River, right lateral offsets of stream channels range between 150 and 700 m (mean offsets of 300 m). Drainage offsets (170–450 m) are found on the eastern branch. Assuming the major phase of incision is visible in this area which is close to the Red River delta due to the onset of Riss glaciation. Using the average length of offset channels and a minimum rate of 100–150 mm/yr for river propagation, we estimate the horizontal slip rates of 2.9 ± 1.7 mm/yr for Song Chay fault, 2.3 ± 1.5 mm/yr for Red River left side fault and 2.1 ± 1.5 mm/yr for Red River left side fault. Several active faults associated with it are observed in Son La area. The Phong Tho-Nam Pia fault is clearly seen in the geomorphology which separates Tu Le and Song Da rift zones. In normal fault segments striking NW–SE, SW dipping is observed clearly from SPOT images. In the field, triangular facets indicate typical dip slip displacement. Based on different data, vertical slip rate of Phong Tho-Nam Pia fault is estimated to be 0.2–0.4 mm/y for Pliocene-present, 0.5–3 mm/y for Quaternary-present and 0.6–1.7 for the present time. Based on various methods, maximum credible earthquakes for different fault segments in Vietnam were estimated.

Contents

1. Introduction

A study of active tectonics in Vietnam and its surrounding areas is important not only for understanding tectonic development in Southeast Asia but also for the mitigation of seismic hazards in this region (Fig. 1). In particular, the study of active tectonic development of the Red River fault zone is of greatly scientific and practical significance. The mechanism of deformation of the lithosphere is currently a topic discussed by many international research groups. The first point of view suggests that due to the collision between the Indian continental block and the Asian block, the deformation is mainly found at the contact of the collision which is characterized by the compression and thickness of the lithosphere. This model believes that the extrusion is not significant and if any, it would be absorbed by the sub-meridian fault zone like the Shansuihe fault in Yunnan, China (Houseman and England, 1986, 1993). According to this model, the Asian block was not extruded by the collision. The second view is that the Indian block is a rigid one and the Asian block is deformed following an indentation mechanism (Tapponnier et al.,

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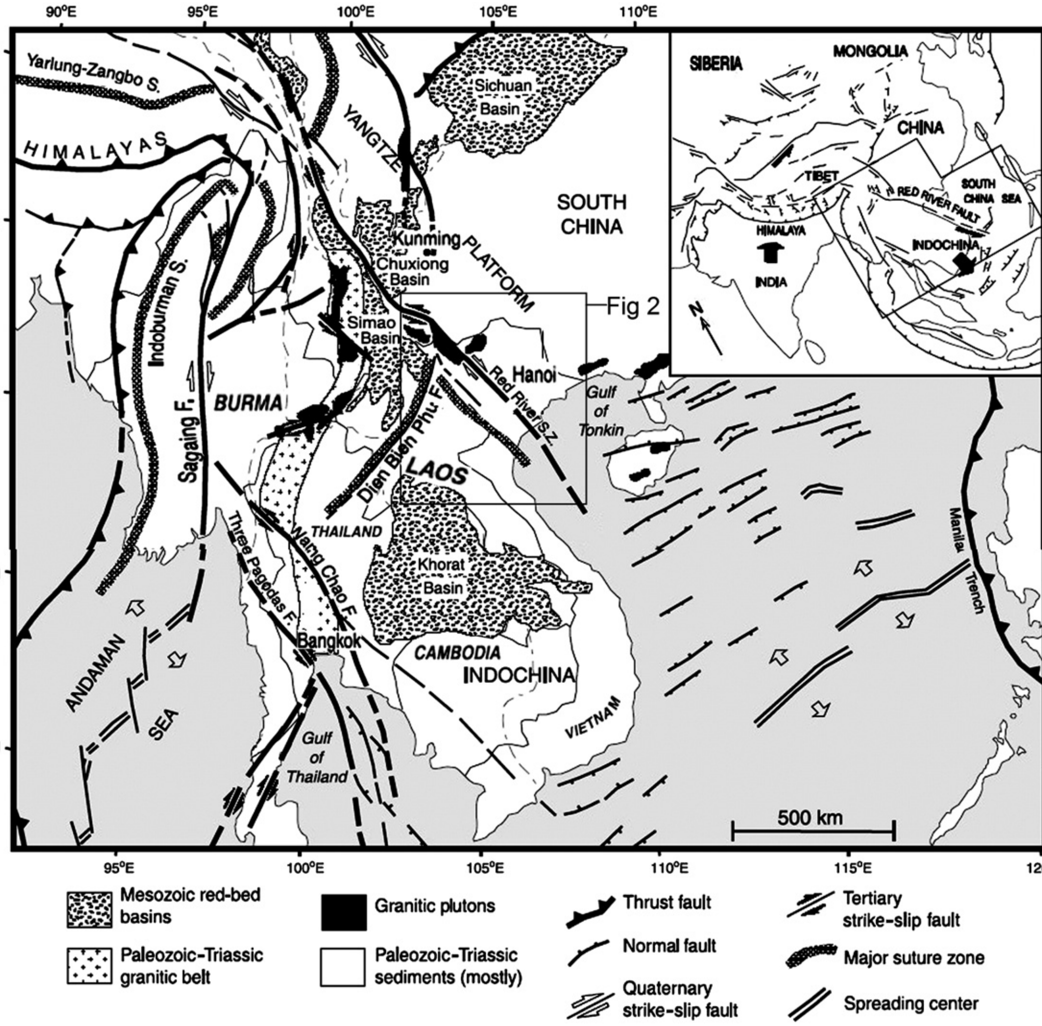

Fig. 1. Geologic and tectonic map of Southeast Asia.
Modified after Leloup et al. (1995).

1986, 1990). A part of the deformation in the Asian block was absorbed by the thickness of the lithospheres. Another part of the deformation is seen along strike-slip fault zones. The left lateral displacement occurred along the Antyl-tag fault and the right lateral movement seen along the Red River fault made the South China Block extrude toward the east (Tapponnier et al., 1982, 1986; Peltzer and Tapponnier, 1988). Since 1982, basing on plasticine experiments and field observations followed by detailed laboratory analyses, Tapponnier and his colleagues proposed that a large fraction of Asian deformation was taken up by successive extrusions of large continental masses along great strike-slip faults (Tapponnier et al., 1982, 1986). Such a point of view has been challenged by the one which believed that the Asian continent responded to the deformation as a viscous fluid (Houseman and England, 1986, 1993). Another point of view confirms that surface faults only separate upper crustal blocks whose relative motion is driven by lower crustal distributed flow, along a great N–S dextral discontinuity at the eastern margin of India. Therefore, the Red River fault zone is the key for verification of the models of lithosphere deformation. Besides the question about the direction of the lithosphere slip, one pays attention also to the size and slip rate of different blocks. At present, there is a big contradiction between active fault slip rate calculated from GPS and that calculated according to the geologic data (Allen et al., 1984, 1991; Weldon et al., 1994; Peltzer and Saucier, 1996; King et al., 1997; Duong Chi Cong and Feigle, 1999; Wang and Burchfiel, 2000; Replumaz et al., 2001; Schoenbohm et al., 2004a, 2004b; Shen et al., 2005; Simons et al., 2007). Studies of earthquake movement provide a precise understanding of the present deformation of continents. In Asia, slip rates on the largest active faults on the order of centimeters per year indicate that movements along a few narrow zones absorb much of the present-day convergence between India and Eurasia (Armijo et al., 1989; Avouac and Tapponnier, 1993). Studies of active faults also lead to more quantitative bounds on the relative importance of shortening mechanisms such as strike-slip faulting and over thrusting. The slip rates on faults in the western Tibet and the Tien Shan, for instance, suggest that 30–50% of the present-day convergence between India and Siberia is taken up by strike-slip faulting along the northern and southern edges of Tibet (Avouac and Tapponnier, 1993).

However, present-day tectonic styles and rates cannot be extrapolated for long into the past. Because the deformation of Asia started with the onset of collision, prior to ~50 Ma, instantaneous rates derived from earthquake moment tensors concern at most ~2.1–4% of the collision span, while rates deduced from morpho-tectonic studies characterize only the last few percent of that span. A full, quantitative understanding of the finite strain induced by collision evidently requires analysis of pre-Quaternary movements and deformation.

The value of slip rate of Altyl-tac shear calculated from seismic moment is several ten times smaller than that determined by the geomorphologic–geologic observed data. The GPS measurement showed that the South China Block and Indochina block are slipping eastward with a speed of more than 30 mm/yr (Michel et al., 2000, 2001; Iwakuni et al., 2004; Shen et al., 2005; Simons et al., 2007). If taking into account the ability of the South China Block to turn anti-clock wise, one can forecast that strike slip rate of the Red River fault zone is larger than 10 mm/yr (Peltzer and Saucier, 1996). This forecast seems to be contradicted with the fact that large earthquakes have not occurred along the Red River fault zone. Besides the research on directions and slip rate of the Red River fault zone, we need to clarify the timing of this process. This research plays an important role in examining the possibility of the existence of pedeplene surfaces in Vietnam and evaluating the erosion rate in this region.

Study of active tectonics of Vietnam has another practical importance in mitigation of earthquake disasters. The Red River fault and some other active faults are located closely to Hoa Binh, Thac Ba and Son La hydropower dams. Assessments of earthquake hazard must base on the faults' characteristics, segment sizes and their slip rate at a given time.

2. Tectonic setting

Vietnam and its surrounding areas are affected intensively by Tertiary tectonics. Opening the East Vietnam Sea (South China Sea) is related to the left lateral movement of the Red River fault zone (Refs). The Red River fault zone is a major geological discontinuity that separates South China from Indochina (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Peltzer and Tapponnier, 1988; Wang and Burchfiel, 1997, 2000). At present, strong right-lateral displacement along this fault spans over 900 km recorded at four narrow, less than 20 km wide, high-grade gneiss ranges together forming the Ailao Shan–Red River (ASRR) metamorphic belt — the Day Nui Con Voi in Vietnam and the Ailao, Diancang and Xuelong Shan in Yunnan, China (Leloup et al., 1995, 2001). The Ailao Shan, the longest, is fringed to the south by a strip of low-grade schists embedding several ultramafic bodies. The ASRR belt has been viewed as a suture. A detailed study of the Ailao and Diancang Shan shows that the gneiss cores of the ranges are composed of strongly foliated and lineated mylonitic gneisses. The foliation is usually steep and the lineation nearly horizontal, both being almost parallel to the local trend of the gneissic cores (Leloup et al., 1995). Numerous shear criteria, including asymmetric tails on porphyroclasts, C–S or C′–S structures, rolling structures, asymmetric foliation boudinage and asymmetric quartz axis fabrics indicate that the gneisses have undergone intense, progressive left-lateral shear. P–T studies show that left-lateral strain occurred under amphibolite-facies conditions (3–7 kb and 550–780 °C) (Leloup and Kienast, 1993). In both ranges, high-temperature shear was coeval with emplacement of leucocratic melts. Such deformed melts yield U/Pb ages between 22.4 and 26.3 Ma in the Ailao Shan and between 22.4 and 24.2 Ma in the Diancang Shan indicating that shear occurred in the Lower Miocene. The mylonites in either range rapidly cooled to 300 °C between 22 and 17 Ma before the end of the left-lateral motion (Schaerer et al., 1990, 1994; Tapponnier et al., 1990). The similarity of deformation kinematics, P–T conditions and crystallization ages in the aligned Ailao and Diancang Shan metamorphic cores, indicates that they represent two segments of the same Tertiary shear zone: the Ailao Shan–Red River shear zone. The field observations confirm the idea that the Ailao Shan–Red River shear zone was the site of major left-lateral motion, as Indochina was extruded toward the SE as a result of the India–Asia collision. The absence of metamorphic rocks within the 80 km long "Midu gap" between the gneissic cores of the two ranges results from sinistral dismemberment of the shear zone by large-scale boudinage followed by uplift and dextral offset of parts of that zone along the Quaternary Red River fault. Additional field evidence suggests that the Xuelong Shan in northern Yunnan and the Day Nui Con Voi in Vietnam are the northward and southward extensions respectively of the ASRR shear zone.

These results significantly improve the quantitative understanding of the finite deformation of Asia under the thrust of the Indian collision. While being consistent with a two-stage extrusion model, they demonstrate that the great geological discontinuity that separates Indochina from China results from Cenozoic strike-slip strain rather than more ancient suturing. Furthermore, they suggest that this narrow zone acted like a continental transform plate boundary in the Oligo-Miocene, governing much of the motion and tectonics of adjacent regions.

South and east of the Ailao Shan, the Day Nui Con Voi stretches for about 300 km along the north bank of the Red River. With a width of 10–15 km, it forms the southernmost massif of the ASRR metamorphic belt. In southern Yunnan the belt nearly merges with the Ailao Shan, being separated from it by the active Red River valley fault near the Yunnan–Vietnam border. This fault splays into two roughly parallel strands, the Chay River and Red River faults, which bound the Day Nui Con Voi to the north and south, respectively. Currently, both fault-strands appear to slip mostly right-laterally, with variable components of normal slip (Phan Trong Trinh et al., 1994).

As for the Ailao Shan, the Day Nui Con Voi metamorphic rocks are mapped as Proterozoic (Phan Trong Trinh et al., 1994). South of the Ailao Shan terminates in the reportedly Paleogene Fansipan granite massif is the Day Nui Con Voi gneisses across a complete section and outside that section shows that most rock types are mylonitic with a well-defined foliation, striking nearly parallel to the belt, as in the Ailao Shan. NE of the Red River fault, Paleozoic granite–Chay River massif was deformed at the border in Cenozoic (Roger et al., 2000). Along the Bao Yen section, the foliation is generally steep, dipping either toward the SW or NE. The stretching lineation is everywhere well defined and nearly horizontal. Shear criteria are left-lateral irrespective of the foliation dip. U/Pb and $^{39}Ar/^{40}Ar$ radiometric dating yields Eocene–Oligocene ages (Leloup et al., 1995, 2001). We interpret the Day Nui Con Voi to be part of the ASRR shear zone, which brings this narrow belt of Tertiary, left-laterally sheared, metamorphic rocks to a total outcrop length of 900 km, almost to the shore of the South China Sea (Leloup et al., 1995; Phan Trong Trinh et al., 1997; Leloup et al., 2001). In the metamorphic cores of the ASRR, the left-lateral shear that was ongoing at high temperatures pursued during cooling of these ranges (Leloup and Kienast, 1993; Leloup et al., 1993; Leloup et al., 2001). P–T estimates based on garnet chemical zoning and garnet–biotite and garnet–sillimanite–plagioclase–quartz thermobarometry show that left-lateral strain occurred in the Day Nui Con Voi, Ailao Shan and Diancang Shan ranges under a very high geothermal gradient, from amphibolite facies (3–7 kb and 550–780 °C) to greenschist facies (<3.8 kb and 500 °C) conditions (Leloup and Kienast, 1993; Leloup et al., 1995, 2001).

The cooling history of the whole shear zone, based on more than one hundred $^{40}Ar/^{39}Ar$ ages, shows that the four ranges forming the ASRR, have their own cooling histories. However, all these cooling histories show two main episodes of rapid cooling separated by a period of slower cooling: cooling (I) from peak metamorphism during left-lateral shear, and cooling (II) from greenschist conditions during right-lateral reactivation of the ASRR (Leloup et al., 1993, 2001). The timing of cooling (I) differs in the different ranges (32 Ma in the XLS, 24 Ma in the DCS and 28 Ma in the DNCV) and is diachronic along strike in the Ailao Shan (from 28 to 18 Ma) (Harrison et al., 1992; Schaerer et al., 1994; Harrison et al., 1996; Zhang and Scharer, 1999; Leloup et al., 2001; Gilley et al., 2003). During cooling, denudation rates were 0.4 mm/yr (Diancang Shan) and 1.6 mm/yr. We propose a kinematic model termed "zipper tectonics" explaining how and when cooling (I) took place (Briais et al., 1993; Phan Trong Trinh et al., 1994; Leloup et al., 2001).

The Northwest region of Vietnam was affected by intensive deformation in the Tertiary. Over thrusting was widely developed in many areas such as Hoa Binh arc, Sapa marble and Phong Tho Limestone (Phan Trong Trinh et al., 1997). It should be noted that Triassic limestone overthrusts Yen Chau stratum system. This can be observed directly at Moc Chau plateau (Findlay and Phan Trong Trinh, 1997). At 10 km from Yen Chau to the North, on the way from Ban Dan to

Ban Ngop, one can observe directly Triassic limestone overthrusting upper Yen Chau formation with inverse bedding of Yen Chau beds. Triassic limestone displacing over red sediments (Findlay and Phan Trong Trinh, 1997; Lacassin et al., 1998) made both limestone and sediments deformed strongly. At the contact place, limestone and clay slab can be found to be tumbled alternatively. Further from the contact zone toward the Yen Chau formation, shale, laminated conglomerate, crumpled folds and cracks with chaotic displacement direction are observed. In many places, the bedding of Yen Chau conglomerate layer is steep raised or inverted, and then changed into bedding more gently, or rather gently when running for ways of the contact place. At about 10 km from Yen Chau toward Son La, inverse bedding of the Yen Chau formation can be observed (Phan Trong Trinh, 1993). From various field observations, the bedding direction of Da river fault zone is inclining toward the southwestward and expressing thrusting and over thrusting activities of deformation after Cretaceous (Phan Trong Trinh et al., 1999). The left slip phase of the Red River fault still continued after 19–17 Ma. Basing on the data of brittle deformation (cracks and small faults), we have defined tectonic stress state for a series of places in the Northwest Vietnam (Phan Trong Trinh, 1994). In this period, the Dien Bien–Lai Chau fault zone operated like a right lateral strike-slip fault. Analysis of difference of structure zones along both sides of Dien Bien fault zone shows the right lateral shear along this fault zone reaching 170–200 km. Rocks along the Dien Bien fault zone is laminated and milonised strongly. On the road from Lai Chau to Phong Tho, at 30 km west from Phong Tho, strongly deformed gneiss can be met (Phan Trong Trinh et al., 2002). After 15 Ma, left lateral slip displacement along the NW fault system has been reduced step by step, but uplifting is continuing. Perhaps, there was a rest phase of 12 to 5 Ma (Leloup et al., 1995). In the present tectonic plan, a series of fault zones show their activities in Pleistocene and continue up to present time. The clearest manifestation is the Red River fault, Chay River fault and Dien Bien–Lai Chau fault zones.

3. Active tectonics

Brittle micro tectonic analysis indicates that, since the Miocene, two main tectonic phases have affected the Northwest Vietnam. For each of these two phases, the state of stress was transpressive in the Northwest and extensive in the Hanoi basin (Phan Trong Trinh et al., 1994). The stress field of phase 1 is compatible with the left-lateral shear along the Red River fault zone and with the sea floor spreading in the South China Sea between 35 and 16 Ma. The stress field of phase 2 associated active tectonic features of Vietnam (right-lateral strike-slip along the Red River, N–S compression, E–W extension), probably began in the Pliocene. Several active faults associated with phase 2 are recognized in North Vietnam from the analysis of TM and SPOT satellite images. Among these, two main zones exhibit a relatively fast movement: the Red River fault zone and the Dien Bien Phu fault (Lacassin et al., 1994; Phan Trong Trinh et al., 1994; Phan Trong Trinh, 1995) (Fig. 2).

In North Vietnam, the Red River fault zone prays into two major active fault branches. The Red River branch, representing the SW limit of the Day Nui Con Voi metamorphic massif, follows the Red River valley. The Song Chay River branch, which is very clear on Landsat and SPOT images and in its geomorphology, is located NE of Day Nui Con Voi. Toward the SE, the Red River itself splays into several faults. The two major ones are located NE and SW of the Red River. Right lateral strike-slip offsets of these faults are determined by analyzing tributaries, stream channels, Quaternary alluvial fans and river valleys on Landsat and SPOT images, on detailed topographical maps, and by field observations. The fresh geomorphologic appearance of the faults under these intensely erosive conditions demonstrates that these faults are very active. Along the SW fault of the Red River, right lateral offsets of stream channels range between 220 and 700 m (mean offset 313 m) (Fig. 4). Drainage offsets (358 ± 109 m) are found on the NE branch. Geomorphology and topographical offsets suggest that these strike-slip movements are combined with normal slip. Along the Song Chay branch, right lateral offsets of rivers range between 250 and 1000 m (mean value 566 m). Toward the Southeast, the Red River fault branch splits up into several faults. One of them bends toward Hoa Binh, striking N–S. The kinematics of this fault change from right lateral strike-slip to normal dip slip to form the Quaternary Hoa Binh graben (Phan Trong Trinh, 1995). Clear evidence of the active strike-slip movement is also found on the conjugate Dien Bien Phu fault. The measured left lateral offsets of tributaries, river and drainage channels range between 270 and 790 m. The rapid uplift of the Fansipan massif can explain the displacement of some normal fault segments striking NW–SE and NNW–SSE. On the side of the Red River fault zone, a SW dipping normal fault striking NW–SE (parallel to the Red River fault zone) is clearly observed in TM and SPOT images. In the field, triangular facets of the escarpment following the SW Tam Dao massif indicate a typical dip slip displacement. In Northeastern Vietnam, the Cao Bang Tien Yen fault is recognized as a right lateral strike-slip fault. This fault terminates in the Bac Bo gulf. The islands to the NE side of the fault can be considered as the recent anticline that resulted from the termination of the right lateral fault. The Mau Son massif, more than 2000 m high, located beside the Cao Bang-Tien Yen fault may be considered a Quaternary anticline, striking E–W. The uplift of the Yen Tu massif, striking E–W and bounded by two faults, results from the N–S compression. To identify the young faults, we have used the method of remote sensing, geological and geomorphographic observations. The satellite Landsat and SPOT images, aerophotographs and 1:50,000 scale topographic maps had been used to identify the position and geometry of the faults. In the Yunnan region, the Red River fault appears as a straight line going from Mindu to the Sino-Vietnamese border. They separate into two branches: one follows the Red River valley, right lateral displacement, the other appears as a normal fault (Allen et al., 1984). The right lateral displacement of the Red River fault zone was estimated as 3–8 mm/yr (Allen et al., 1984). Although the Red River fault stretch from Mindu to the Sino-Vietnamese border has been clearly seen in terms of geomorphology, however over the past several hundred years, there has not been any earthquake, thus causing two possibilities. First, the Red River fault has been sliding in Crip form where the deformation has only concentrated along the fault. The sliding friction has been small, and the energy has not accumulated. That's why earthquake has not occurred. Second, the fault has been locked at the current time, the strain has been accumulated along the fault, but slip in the area adjacent to the fault has not been significant. In this case, potential big earthquakes could occur along the fault.

On Vietnamese territory near Lao Cai Province, the Red River fault zone splits into two main faults surrounding two sides of the metamorphic Con Voi Mountain range, and are called Red River fault zone and Chay River fault zone. The Chay River fault follows the NE side of the metamorphic range, stretching into a straight line linking Lao Cai and Viet Tri. On the satellite Landsat and SPOT images, the fault is clearly seen (Phan Trong Trinh, 1995; Phan Trong Trinh et al., 2002). The green spectrum means that humidity here is higher than that of the surrounding areas. Geomorphologic observations in the field showed that the fault follows a narrow valley which is observed as a V-shape. The Chay River fault is clearly presented in the Luc Yen region. Analyzing the deviation across the fault of the stream network, we can suggest that the offset of the right lateral displacement of the stream is 150–700 m, average offset is 150 m. This offset varies depending on the size of the stream that is cut across by the fault. The older the stream is, the higher the offset is.

The Chay River fault is running along the SW border of the Thac Ba hydro power reservoir. The line-shape of the fault is easily identified on satellite images as well as by field observations. Attention should be paid to the fact that the Chay River fault cuts across dam no. 9 of the Thac Ba Reservoir. Dam no. 9 is located 1 km far from the main

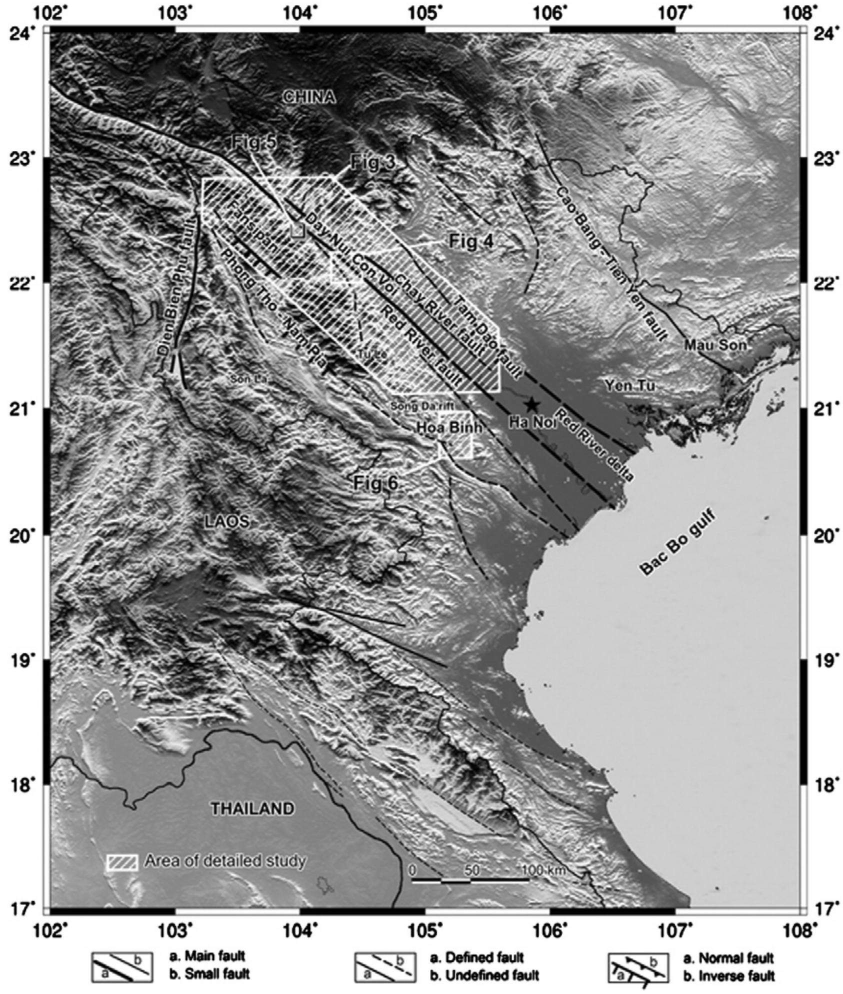

Fig. 2. Active faults in North Vietnam and details of the studied area.

dam to the southwest. From dam no. 9 up to the Viet Tri town, the Chay River fault is clearly presented in topography stretching along a narrow valley and also is clearly presented in the SPOT images.

The Red River active fault is running along the SW side of the metamorphic belt of Day Nui Con Voi matching with the Red River fault traditionally described in the geologic documents. On Landsat images, it

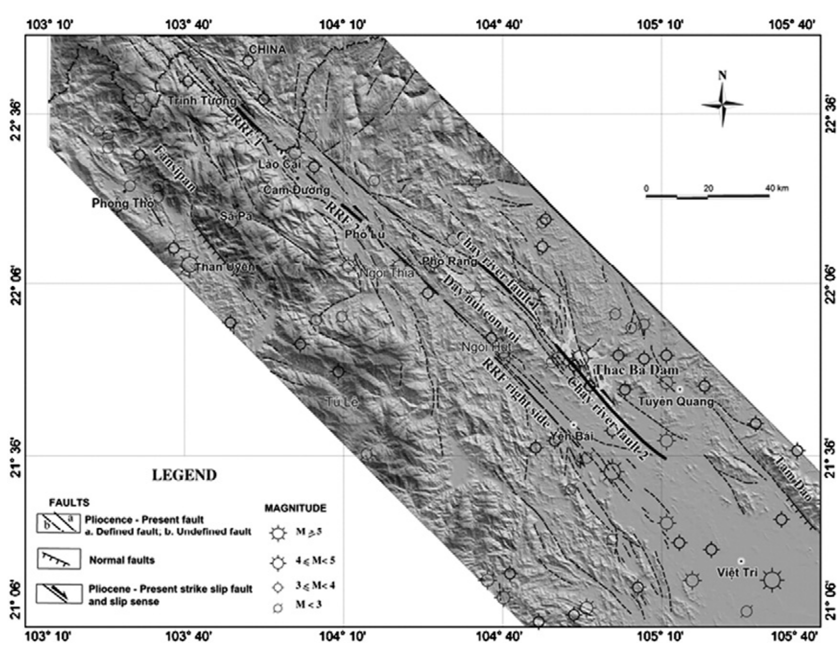

Fig. 3. Active fault segments along Red River faults and Chay River fault.

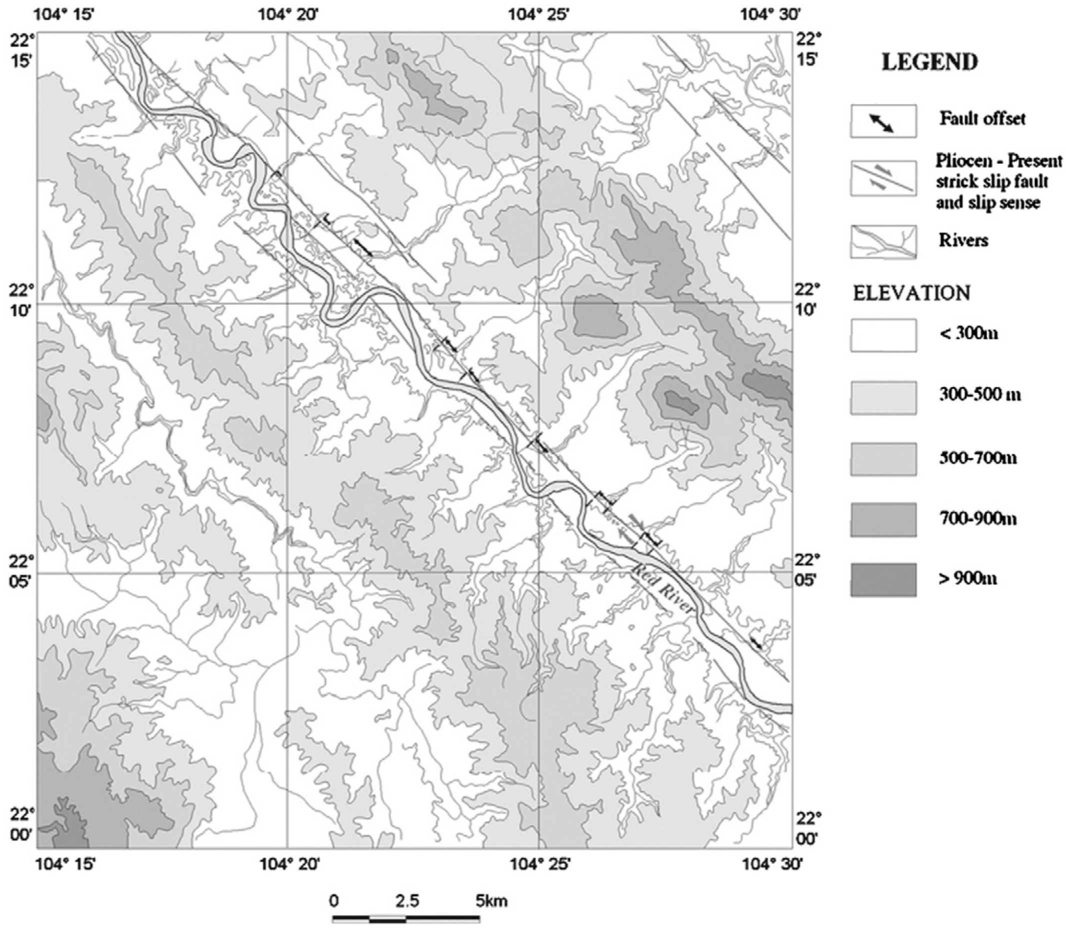

Fig. 4. Right lateral offset of drainages along the Red River fault show in same time sense of active movement and amplitude of displacement along active faults.

is presented as a unique fault running along the Red River valley. However, detailed analyses demonstrated that the Red River actual fault is presented by two main faults running along both right and left sides of the Red River. They are not continuously prolonging but are divided into individual stretches.

In Lao Cai, the left side fault is presented clearly on aerophotographs as plane slip fault. The right shore fault is divided into many levels composing of small faults having a sign of dip slip displacement.

In Bao ha area, offset of right slip of streams could be identified as oscillating between 150 and 250 m along the Red River left shore fault, while the right side fault is divided into many short fault segment. At the Red River left shore sign of critical sliding was observed.

In the Yen Bai area, two main faults are divided into many smaller faults. Faults prolong along the Red River right side that appears relatively clear. The slip rate is difficult to identify. The Red River fault branches could also be observed in the Phu Tho area. They continue to divide into smaller stretches, and continue to prolong toward the Red River delta. It is noteworthy that the fault branch bends over gradually turning toward SN direction, stretching to the Hoa Binh Town. Other branches continue to go toward NW–SE. In Dong Mo-Ngai Son region, a sign of young fault is still observed.

Besides the Red River fault system comprising the Red River fault and the Chay River fault, Lo River fault is located at the NE of the Red River fault zone. The Lo River fault parallels the Red River fault system. The Lo River fault mainly appears as a right strike-slip, in Tuyen Quang area. The offset is reflected in the deviation of 2.5 km of Lo River at the place where the fault cut across Lo River. But, along the SW side of Tam Dao Mountain, the fault mainly appears as a normal fault. Triangle facets appeared clearly both on satellite images and field observations.

Table 1 presents offsets received from the mapping and measurement of river–stream network where the fault cuts across. The minimum strike-slip offset relates to streamlets, while the maximum strike-slip offset relates to large streams with lengths of several tens of kilometers.

An important problem is the evaluation of the slip rates of the main faults of the Red River fault zone. The difficulty is that we do not know the topographic age as well as the age of the river–stream network. In previous works, based on the assumption of the age of rivers and streams, some authors estimated the slip rates of the Red River fault in Yunnan, China as 3–8 mm/yr (Allen et al., 1984) or several mm/yr (Lacassin et al., 1994). Based on the geodetic measurements from 1960 to 1980, geodesists evaluated slip rates of the Red River fault in current period. The strike-slip rate of the whole Red River–Chay River fault zone was evaluated at about 23 mm/yr or deformation rate of 1.2 ± 0.2 rad/yr with respect to the rate of 12 ± 2 mm/yr, along the distance of 10 km of both main faults of the Red and Chay

Table 1
Strike-slip offset of the Red River faults and Chay River faults.

Fault name	Minimum strike-slip offset (m)	Maximum strike-slip offset (m)	Average value (m)
Chay River fault	220 ± 40	2000 ± 50	560
Red River left side fault	170 ± 40	450 ± 50	360
Red River right side fault	150 ± 40	700 ± 50	300
Lo River fault		2500 ± 50	

Rivers (Duong Chi Cong et al., 1994). Based on the results of GPS supplement measurements, having used previous geodetic measurements, the slip rate was evaluated, with 95% probability, not over 0.6 rad/yr with respect to slip rate of 6 mm/yr along the distance of 10 km (Duong Chi Cong and Feigle, 1999). It is noted that all the values of evaluated deformation rates fell within the range of error. This explains the reason why the results of geodetic measurements were quite different, although the data used are from the same sources.

In order to evaluate the average slip rate of the fault in the late Quaternary, we try to evaluate two following scenarios. These scenarios were based on the two methods of estimation of river–stream network age within the region.

Scenario 1: The age of small streamlets would be able to estimate if the streamlet development rate over the time were known. However, there was no study on rate of streamlet development in our studied region. Therefore we have to use the data calculated for the stream system in California: at least 100 mm/yr and add 50% of its value, taking into account the conditions of tropical humid area, thus getting the figure of 100–150 mm/yr. After measuring the length of the stream where the fault cut across, using the above mentioned figure, we estimate the age of the stream, then calculate the fault slip rate. Results of calculation were presented in Table 2.

Scenario 2: Because the studied area is at the altitude of less than 100 m, it was strongly impacted by the change of the sea level. Any global change can influence the development of river–stream network in the region. According to the regional research documents, Vietnam in particular, and South East Asia in general, all suffered from the influences of the cycles of glaciation such as Wurm Glacial Cycle which occurred 12,000–18,000 years ago. Assuming that the streamlets were formed during the Wurm Glacial Cycle, we identify the strike-slip rates of faults (given in Table 3.1).

Before the Wurm Glacial Cycle, the South East Asia was under strong impacts of Riss Glacial Cycle. Assuming that the streamlets network was formed after the Riss Glacial Cycle which occurred 55,000–150,000 years ago, we can have estimates of fault slip rates (given in Table 3.2). To compare the results from the Scenario 1 and those of Table 3.2, we see that basically the figures match with each other, among them, the strike-slip rate of the Chay River fault and Red River right side fault calculated following the Scenario 1 were smaller than the respective values given in Table 3.2 (following Scenario 2); while the slip rate of the Red River left side fault is bigger.

It is obvious that the results given in Tables 3.1 and 3.2 were quite different. Therefore we must choose one of the two. We incline to the estimates given in Table 3.2 (Scenario 2), based on the following reasons:

(1) Wurm Glacial Cycle happened in a short period of time while the Riss Glacial Cycle had occurred in a longer period, thus having greater impact on the development of river–stream network.

(2) Estimate on strike-slip rates given in Table 3.2 (Scenario 2) is compatible with results identified by Scenario 1. Estimates given by Table 3.2 quite agrees with the respective estimates of the average slip rates in Quaternary–Pliocene while estimates given in Table 3.1 were many times bigger than the average values in Quaternary Pliocene.

Table 3.1
Average fault slip rates, based on Scenario 2 (12,000–18,000 years ago).

Fault name	Average sliding rate (mm/yr)
Chay River fault	15.5 ± 5.5
Red River left side fault	12.4 ± 5.2
Red River right side fault	11.0 ± 4.9

(3) Estimates given in Table 3.2 show much more agreement with the respective average strike-slip rates given by the geodetic measurements.

A fault is referred to be an active fault if it is shown with clear signs on satellite images and aerial photos. We also checked at outcrop points, in trenching sites to identify facets, stream offsets. In the Lao Cai–Yen Bai area, RRF is not continuous but separates into different-length fault segments. Digital elevation modeling suggests that the active fault lies along the Red River valley. However, analyzing satellite images and geomorphologic observation in detail indicated that the Red River active fault is subdivided into two smaller faults located on the left side and right side. They do not extend continuously but segmented into some discrete units. We defined two seismogenic segments (RR1 segment and RR2 segment), both of them are possible to generate earthquakes and they are used to estimate maximum earthquake. RR2 is represented distinctly on satellite images, aerial photos and DEM. It extends 10 km long from Pho Lu to Cam Duong. It is confirmed to be a strike-slip fault. Basing on Quaternary stream sedimentary displacements, the offset of dextral strike-slip is 150–250 m. To the right, the RR2 segment is a zone of many smaller subsidiary faults. The RR1 segment initiates from NW Lao Cai and running along the Red River. This segment is 11.94 km long and the amount of displacement is about 150 m (Sinh Quyen copper deposit, and 3 km NW of Trinh Tuong). Along Ngoi Hut and Ngoi Thia, some subsidiary segments of the Red River fault to the right have both vertical displacement and horizontal strike-slip components. Segments to the left are relatively unclear. In Yen Bai, the Red River fault is also manifested by some similar small segments. Segments to the right bank are more apparent than the left. Nonetheless, the displacement offset is difficult to estimate. The Red River fault continues to branch off into smaller segments when it reaches to the Red River delta. The active Chay River fault is located NE of the Con Voi range and stretches linearly from Lao Cai to Viet Tri. On Landsat and SPOT images, the fault is a sharply green narrow band characterizing strongly fault ruptures with higher moisture than the surrounding area. In the field, the Chay River fault situates in a narrow V-shape valley rupture. Elevation differences cannot be distinguished between two fault walls as well as features of vertical displacement in the Chay River fault. Along the fault it could be referred to be a strike-slip fault that composes of two main segments (CR1 and CR2 segments) (Fig. 3). CR1 segment has a length of 17.74 km exposed in Luc Yen. Along the SW edge of Thac Ba hydropower reservoir, it is prominently expressed on satellite images, topographic map and in the field. The CR2 segment is 51.36 km long. From Ha Noi–Yen Bai road, turning to Thac Ba road we found out a lot of evidence proving the existence of small shear zones in gneisses. These shear zones cause

Table 2
Evaluated average strike-slip rates of faults (Scenario 1).

Fault name	Average rate (mm/yr)
Chay River fault	2.5 ± 1.5
Red River left bank fault	4.0 ± 1.8
Red River right bank fault	1.7 ± 1.5

Table 3.2
Average strike-slip rates, based on Scenario 2 (55,000–150,000 years ago).

Fault name	Average sliding rate (mm/yr)
Chay River fault	2.9 ± 1.7
Red River left side fault	2.3 ± 1.5
Red River right side fault	2.1 ± 1.5

shearing and displacing gneiss weathering layers. Fault in this area is manifested by flower structures, which could be formed in compressive tectonics. In the field, we observed shear zones in weathered sediments, direction of shear zones coincides with the RRF direction (300–330°). The width of shear zones varies from some centimeters in the Yen Bai bridgehead to tens of meters in the Lao Cai new residential area.

Similar active shear zones are also exposed in some other areas along the Red River fault and CR fault. In the SW bank these shear zone type is quite common. For example in the Yen Bai bridgehead (road from Yen Bai to Nghia Lo) active shear zones left well-persevered features in Neogene thin sandstone, gravestones. Their fault plane has a dip angle of 85° and an azimuth of 225° and slickenside in siltstones have a rake of 25° and an azimuth of 135°. In Lao Cai City, we recognized many shear zones that developed in Neogene sediments as well as in altered layers (Fig. 5).

At 6 km SE of the Lao Cai center, a shear zone 1.2–2 m wide and hundreds of meters long is cross-cut and cause displacing Neogene sandstones and gravestones and its ten meters weathered layers. Fault planes have azimuth of 270°, dip angle of 70–75°, slickenside have azimuth of 140° and rake of 20–25°. Remarkably silt materials were compressively foliated (azimuth 320°) and segmented by sublatitude shear cracks. This shear system is a dextral strike-slip (Fig. 5).

These systems are also commonly developed in some other areas to the right bank of the Red River such as Bao Yen, some sites between Pho Rang and Cam Duong and some other sites between Bat Xat and Amuxung. Along road No. 70, in Khanh Hoa commune (Bao Thang, Lao Cai province), one can observe a similar shear zone with a direction of 300°, greater than 15 m long exposed from gray, dark-gray porous altered materials of Neogene formations that are foliated and oriented coinciding with the fault direction. A similar phenomenon is also observed in 40–60 cm-thick weathering Neogene gravestones at Pho Rang domain. In other sites of RRFZ, many modern shear zones differentiated by their size and orientation left slickenside in silt-clays layers or iron–gel with dextral or sinistral strike-slip components matching with strike-slip mechanism of the overall RRFZ. The boundary between Neogene formations and recent terraces is cropped out prominently in An Lac (Bac Cuong-Lao Cai). Two tensile crack systems related to prehistoric earthquakes are well retained. Their azimuths are 275° and the amount of normal strike-slip displacement is 2–4 cm. These numbers were concordant with the one of fault planes of RRF but the amount of displacement is much smaller than the one of RRF (30–45 cm). The first system is filled with light gray soft fine materials. The second is filled with reddish brown materials of modern depositions. The material compositions in these shear

Fig. 5. Active fault observed in weathering cover of Neocene sediments, 6 km SE of Lao Cai city.

zones are relatively porous-plastic and there are iron–gel layers. It is correlated displacing of the RRFZ with age of weathering crushes developing in Neogene formations, some signs above seem to be in Holocene. In some sites to the SW, sublatitude, the NW–SE tensional crack system having an amount of 2–5 cm normal strike-slip displacement is also filled with soils and terrace materials (upper part of weathering). They could be cracks related seismically to the fault zones.

In the northwest area, the Phong Tho-Nam Pia fault is bounded regionally by the Tule volcanic zone and the Da river zone. This fault is developed as an active normal fault. Triangular facets dipping toward the southwest are recognized clearly in SPOT images and digital elevation models. On the topographic map, the height of the triangle reaches 300–500 m. The fault changes direction from NW–SE to a sub-meridian direction on the western side of the Tule volcano zone. The slip rate of sub-meridian trending fault is not clearly manifested. In the segment from Muong La to Bac Yen, the fault changes again, to the trend of NW–SE. Extensional activity on the fault is manifested in this segment: the fault is divided into two segments, Muong La 1 and Muong La 2. From Bac Yen to Phu Yen, the fault changes its direction. The nature of this fault segment changes mainly into right lateral strike-slip.

To estimate the slip fault rate, we based on the following events: Metamorphic and slip-shear zones in the Ye Yen Sun granite have ages of 23 million years and a formation depth of at least 4–10 km. In order to reach the present day topographic height (3 km) it must have been uplifted 7–13 km. The present surface thus is not a trace of a Paleocene surface, but only one of a late Miocene surface. The time interval from 15 to 5 million years can be seen as sufficient to allow the formation of a relatively smooth surface due to accumulation of fine material containing coal in Hang Mon. The highest peaks on the present topographical surface are traces of surfaces existing just before the Pliocene. The Red River metamorphic zone, Hoang Lien Son zone and Tule volcano zone showed strong uplift from the Pliocene to present. The Da river zone was also uplifted, but at a lower rate. The strongest uplift is represented by the Fansipan mountainous region; with average uplift rates of about 1.4–2.6 mm/year from the Pliocene up to now (uplift amplitude is 7–13 km within 5 million years). In a similar way, the average height of 2000 m reached in the Tu Le zone was also caused by an uplift during this time with a rate of 0.93–1.73 mm/year, with the peak average height of 900 m in the Da River zone showing an average uplift rate of 0.4–0.8 mm/year. From this, the relative displacement rate between the Da river zone and Tule volcano block can be calculated with 0.53–0.93 mm/year. In order to determine the relative displacement rate of both the Tu Le and Da River zones through the Phong Tho fault, attention should be paid to the block displacement of the two main zones through the main Phong Tho-Nam Pia fault zone. Rectifying vaulted displacement and that caused by other small faults in the zone with 1/3 of total displacement amplitude, we estimate the average uplift rate of the northwest part relative to the southwest wing as 0.35–0.62 mm/year for the Phong Tho-Nam Pia fault from the Pliocene up to now. In order to estimate the slip rate of the Phong Tho-Nam Pia fault for a shorter time interval, we have used two other approaches. The first uses SPOT images, geomorphologic and geological documents, and the second is based on geodetic measuring data over 20 years. The triangle facets are clearly observed on SPOT images. The difference in amplitude between two fault sites is 300 m (for the clearest triangular facets) and 500 m (for less clear triangular facets). Assuming that the present surface is of early Quaternary age (1 million years), we can estimate the displacement as 0.3–0.5 mm/year. If this surface is related to the process of forming the present topographical surface, related to the Wurm Glacial Cycle of 10,000 years of age, we estimate the rate as 35 mm/year. It may be more reasonable to assume that the surface difference of 500 m corresponds to the early Quaternary, in which we can estimate the rate as 0.5 mm/year, and the surface difference of 300 corresponds to the surface 100,000 years ago, in which slip rate is estimated as 3 mm/year. Therefore, the average displacement rate of the Phong Tho-Nam Pia fault estimated on the base of geomorphology is about 0.5–3 mm/year.

4. Seismotectonics and earthquake evaluation

Basing on study of active tectonics, we determine active fault segments and estimate maximum earthquake by using different methods of seismotectonics.

Although RRF is sharp in topography, earthquake data of the Seismological International Center from 1913 to 1999, China earthquake catalog (prior to 1999) and Vietnam earthquake catalog (prior to 2003) recorded no earthquake greater than 5.5 in RRFZ and adjacent areas. Accordingly, greatest earthquake related to RRFZ in Vietnam was the one that occurred in 1285 in Hanoi and another in 1984 in Luc Yen with a magnitude recorded at 5.5. This presents us a question if those earthquakes showed maximal magnitude or whether they occurred during an interseismic period between two peaks of an earthquake cycle. On the basis of geomorphologic studies in Yunnan province, Allen et al. (1984) proved that a great earthquake of 8.1–8.3 or so occurred in this region. He estimated that a recurrence interval between two big earthquakes is 1000 years. Lacassin et al. (1994) based on field works concluded that earthquake with magnitude as high as 7.5 could occur in the Vietnam territory. Using Gumbel's extreme theory Nguyen Dinh Xuyen and Tran Thi My Hanh (1996) estimated a limitation magnitude of 6.1. In this study, we use seismogenic segments as represented above to assess maximum earthquake by seismotectonic methods, integrating many approaches according to fault length, rupture area and earthquake moment. On earthquake moment approach, the amount of maximum displacement is unknown. Nonetheless, it could be estimated by continuous approximate solution deduced by a formula of maximum displacement according to Well and Coppersmith (1994). We assign coefficient 1 for fault length approach, 2 for rupture area approach, and 3 for earthquake moment approach. Earthquake moment approach accounts for about 50% of the overall method because it contains the highest physical senses. Calculating is an iterative process. In the first step, the amount of maximum displacement is evaluated based on the data acquired from assessing maximum earthquake according to different approaches, from which we estimate seismic moment. After calculating the means of the main numbers and normalizing errors, the amount is deduced from Well–Coppersmith's formula. In the second step, from maximum earthquake moment, maximum earthquake magnitude is determined and this process is iteratively operated until acquired results are stable. Calculation showed that the acquired results have very little difference. We show an example of the calculation of maximum earthquake, displacement and rate for CR fault, segment 2 (CR2) in Table 4. The estimation of earthquake for 4 fault segments RR1, RR2, CR1, CR2 are presented in Table 5.

In the result table, the first line is filled with input results gained from the latest calculation in the order of (left to right) fault length, fault depth, fault dip, and amount of maximum displacement and sense of displacement. For example, in Table 5 of CR2 maximum earthquake assessment, fault length is gained from a topographic map, dip angle 90° (because of strike-slip fault), the amount 0.15 m (acquired from repeatedly calculating), and sense of displacement 2 (in convention normal fault 1, strike-slip 2, reverse 3). The final results indicated that RRFZ in Lao Cai–Yen Bai area have maximum earthquake magnitude from 6.2 to 7.0 depending on different regions. These results are in accordance with earlier results. In spite of no earthquake reaching to this number recorded over the last 1000 years, the result is still remarkable. Therefore, in construction we should refer to this number. It is imperative to continue studying this problem.

The method used in this study is that of Slemmons' (1982) while Well–Coppersmith and Slemmons' method was used for the first

Table 4
The results of the calculated maximum earthquake magnitude for CR2.

Length (km)	Width (km)	Dip angle	Displacement (m)	Sense of slip
51.36	15.00	90	1.27	Strike slip
Magnitude by using Slemmons' (1982) method for fault length:				6.9
Magnitude by using Well–Coppersmith's method for fault length:				7.1
Magnitude by using Well–Coppersmith's method for rupture area:				6.9
Magnitude by using Wyss' (1979) method for rupture area:				7.0
Magnitude by using Woodward-Clyde Consultants' (1983) method for rupture area:				7.0
Magnitude by using Hanks–Kanamori's method for seismic moment				6.9
Displacement (m) by using Slemmons' (1982) method:				0.83
Rate (mm/y) by using Woodward-Clyde Consultants' (1983) method:				0.67
Maximum displacement (m) by using Well and Coppersmith's (1994) method:				1.27
Average displacement (m) by using Well and Coppersmith's (1994) method:				0.82

time in Vietnam in UNDP's Project for the assessment of earthquake hazard of the Hoa Binh dam (Winter et al., 1994). In our study, the methods used to calculate the maximum magnitude which is based on the fault surface area are from Well and Coppersmith (1994), Wyss (1979), Woodward-Clyde Consultants (1983) and Hanks and Kanamori (1979). To combine the various methods, we take the average value by weight number, whereby the method based on earthquake moment applies coefficient 3, the method based on fault surface area uses coefficient 2, and methods based on destroyed fault length employ coefficient 1. In order to get an average value, the method based on seismic moment is used (coefficient 3) due to its highest confidence. To evaluate seismic hazard in the Son La hydropower dam area, we focused on the fault systems with considerable size and closeness to the dam. The fault length is measured from SPOT images, and controlled by geophysical and geomorphologic measurements in the field (Phan Trong Trinh et al., 2007). The Phong Tho-Nam Pia slip fault-right lateral trust stretches from Phong Tho in the west, to Phu Yen in the northwest. This fault zone is divided into many fault segments with different activity levels. In the Son La hydropower dam area, the fault segment Muong La 1 stretches 10 km, and the fault segment Muong La 2 stretches 30 km. The shortest distance from section Muong La 1 to Pa Vinh dam is 4.4 km, and to the Ta Bu dam is 4.2 km. The fault dip is determined as 75° thanks to observations of schistosity surfaces related to the fault. The fault depth cannot be determined correctly. To calculate a maximum credible earthquake magnitude, the fault depth can be estimated in 2 ways. The first is based on seismic characteristics in the area and along the fault zone. In general, the focal depths in the area vary between 10 and 20 km. The second is based on the change in mechanical characteristics of the Earth's crust with depth. Normally, the focal depth does not exceed 2/3 of the length of the fault on the surface. Therefore, it is assumed that the maximum depth of a possible earthquake for section Muong La 1 is 10 km. The segment Muong La 2, belonging to the Phong Tho-Nam Pia fault, is of 30 km in length, the depth is estimated to be 15 km, and its dip is 75° to the southwest. The shortest distance from this fault segment to Pa Vinh is 17 km, and to Ta Bu 10 km. Because the fault segment Muong La 1 is very close to the Pa Vinh and Ta Bu dams, the exact determination of its size is very important in forecasting expected earthquake intensities. Therefore, a series of

Table 5
Input data and maximum earthquake for active fault segments along the Red River and Chay River.

Fault name	Length (km)	Width (km)	Dip angle	Maximum displacement (m)	Sense of slip	Maximum magnitude
RR 1	10.17	10	90	0.15	Strike-slip	6.2
RR 2	11.94	10	90	0.18	Strike-slip	6.3
CR1	17.74	12	90	0.33	Strike-slip	6.5
CR2	51.36	15	90	1.27	Strike-slip	7.0

Table 6
MCE at the Hoa Binh dam estimated by fault segments Hoa Binh 1, Hoa Binh 2.

Fault segment	Length (km)	Depth (km)	Dip	Character	Magnitude (MCE)
HB1	4.0	6.0	75°	Normal	5.6
HB2	8.4	6.0	70°	Normal	6.1

specialized measurements involving seismology, electricity and nuclear trace detectors have been carried out near the end of the fault segment. This should be helpful to determine the exact extent of the fault segment Muong La 1. The location of the cross-section for this investigation is decided on the basis of SPOT image analysis. Fault length, fault dip and nature of displacement are the main parameters used for the estimation of the maximum earthquake magnitude. Table 6 presents the maximum earthquake estimated for the Son La hydropower dam region.

In the Hoa Binh hydropower dam area, three N–S-trending segments next to HB dam root which generates a nearly vertical-flank graben. In some sites, the graben is 2.5 km wide filled with alluvial–proluvial deposits up to 70 m thick. The fault segment at the east flank is 8.4 km long and the another segment is 4 km long at the west. Distance between the latter and the dam is only 0.3–2.5 km. Diverging movement of the segments can be clearly observed on SPOT, Landsat image, DEM and in the field. This movement is characterized by triangular facets. We identified fault systems which are potential to generate earthquake and could cause direct damages to the Hoa Binh dam. That is sub-meridian fault system which is broadly developed. They also consist of segments focusing on the central part of the east and west flanks of Hoa Binh-Bat Bat graben, on Kim Boi dome and on Tu Ly arc-uplifting massif. Except the faults controlling Hoa Binh-Bat Bat, which are more than 10 km in length, other faults are less than 10 km long. On each flank of Hoa Binh-Bat Bat graben, the normal fault surfaces are nearly vertical, dipped to the graben center and each fault coincides with some landforms and controls distribution of river terraces and alluvial flat. In general, all of the regions belonging to the SW part of the RRFZ and Quaternary graben and tectonic breccia zones develop next to the RRF with acute angle that exhibits right lateral movement. The sub-meridian fault system is distributed along two flanks and controls the structure of Hoa Binh graben. The western branch is more than 4 km long. Its fault surface dips to the east (Fig. 6). Along this segment, we can recognize some normal active shear zone which could cause surface crack in this area. The eastern fault branch consists of an 8.4 km long segment, along which there are strongly developed triangular facets. The fault controls flow of river and stream system according to different base levels. They are represented clearly on satellite images, actual topography through scrap and facets. Remarkably, along some segments at

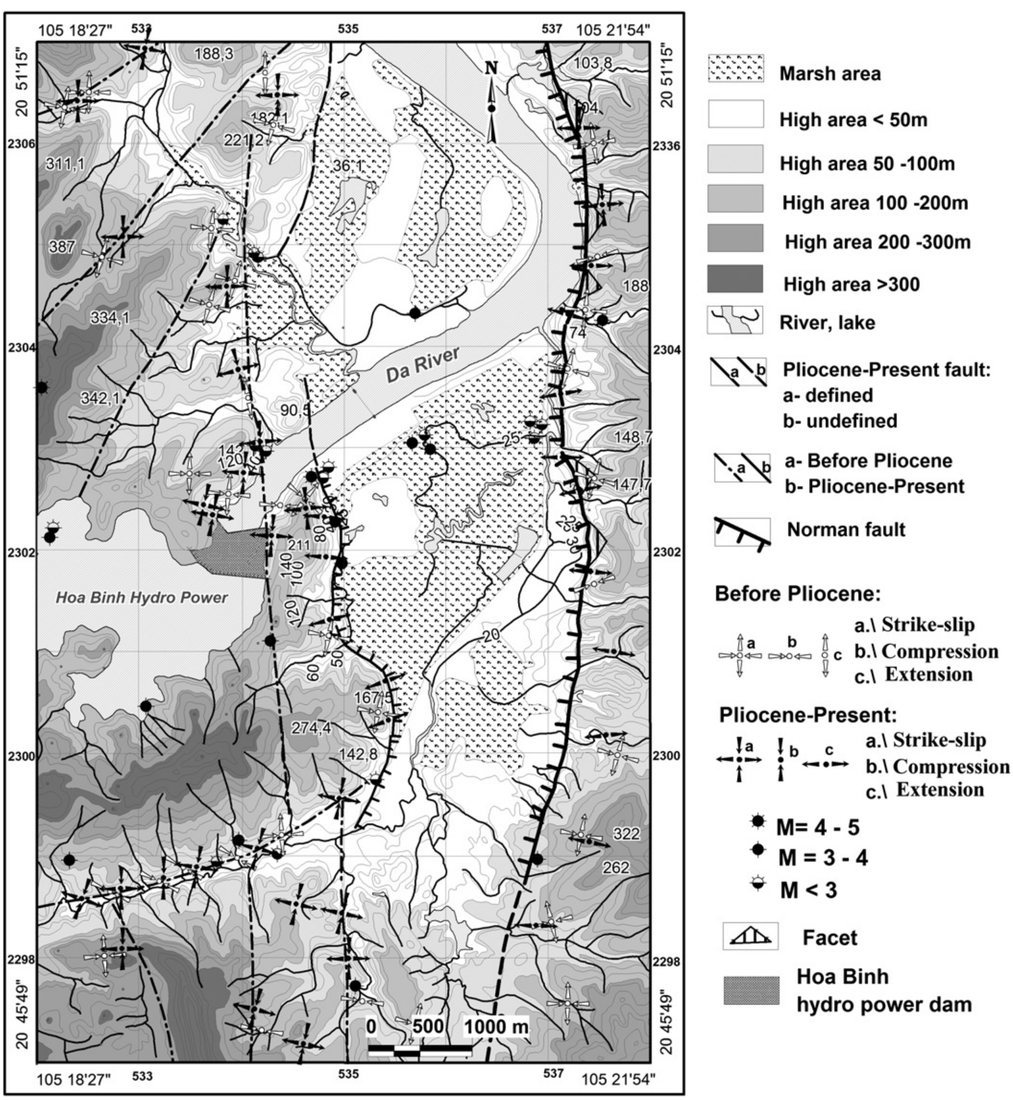

Fig. 6. Seismotectonic map of the Hoa Binh hydropower dam area.

the eastern Hoa Binh depression, we identify a series of triangular facets in the Lang Ngoi and Lang Su areas. These facets have a height of 70–120 m and a foot-side wide of more than 500 m. Hoa Binh graben is filled up with formations of alluvial–colluvial pebble, gravel, sand and a little of marsh facies at the south of Hoa Binh. Thickness of this sedimentary layer varies according to each location, reaching 50–60 m in the Hoa Binh area. In order to assess seismic hazard for Hoa Binh hydropower dam area, we focus on the fault systems with significant size. Sub-meridian fault system is distributed along two flanks. The western fault branch is more than 4 km long. Its nearly vertical fault surface dips to the east. The shortest distance from section HB1 to Hoa Binh dam is of 0.3 km, the fault dip is determined to be 75°. The eastern fault branch is one segment with 8.4 km length. The shortest distance from section HB 2 to Hoa Binh dam is of 2.5 km, the fault dip is determined to be 70°.

For seismic assessment, from MCE and distance from the fault to the dam, one can estimate the peak ground acceleration (PGA).

5. Conclusion

In North Vietnam, two main zones, the Red River fault zone and Dien Bien Phu fault, seem to move fast. Assuming that the major phase of incision is visible in this area, close to the Red River delta due to the onset of Riss glaciation, we estimate the slip rate to be 1.7 ± 1.5 mm/yr for the Red River right branch, 4.0 ± 1.8 mm/yr for the Red River left branch and 2.5 ± 1.5 mm/yr for the Song Chay branch. Using the average length of offset channels and a minimum rate of 100 mm/yr for river propagation, slip rates are estimated to be 2.1 ± 1.5 mm/yr for the Red River right branch, 2.3 ± 1.5 mm/yr for the Red River right branch, 2.9 ± 1.7 mm/yr for the Song Chay branch. Vertical slip rate of Phong Tho-Nam Pia fault is estimated to be 0.2–0.4 mm/y for the Pliocene-present, 0.5–3 mm/y for the Quaternary-present and 0.6–1.7 for the present time. Maximum credible earthquakes are estimated from a combination of various methods: fault segment, fault surface, seismic moment and seismic moment rate. The application of earthquake assessment is used for many hydropower sites in Vietnam such as: Hoa Binh and Son La and along the Red River. Maximum credible earthquakes are 5.6–6.1 in Hoa Binh area, 6.2–7.0 along the Red River fault and Chay River fault and 5.2–6.1 in Son La hydropower dam area.

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