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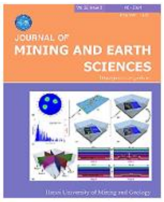

Identification of Deep Tectonic Structures of the Pho Lu area, Northwestern Vietnam Using Digital Elevation Model and Earth Focal Mechanism

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ABSTRACT

The digital elevation model and the earthquake focal mechanism are utilized to define the geological structure of the Pho Lu area, northwestern Vietnam. The results allow the identification of lineaments and recognition of the correlation between the lineaments and geological structures directed in the study area. The digital elevation model (DEM) was used in the methodology of interpretation trends of lineaments derived from various enhancing techniques to show that the most lineament trend in the NW– SE direction. Further more, the interpreted lineament map demonstrates the NW–SE system is correlated with the Red River fault zone, which is interpreted as a positive flower structure combined with the focal mechanism of earthquake. The results also demonstrate the capacity to used the digital elevation model and focal mechanism of the earthquake to identify deep geological structures.

1. Introduction

Digital elevation models (DEM) have been applied in increasingly geomorphological and geological researches in recent years. The methods have successfully been used in to recognize of tectonic lineaments on the earth's surface and become more visuals and significant progress in the digital data processing. Discontinuous structures of rocks and topographic highlights identified with tectonic action frequently brings about morphological lineaments as fault scarps, joints, and fold axis (Ramsay and Huber, 1987). The linear valleys and linear ridge lines present these lineaments (Jordan et al., 2005). Therefore, many specific landforms are related to faults, identifying the fault type (Burbank and Anderson, 2001; Hung, 2016; Keller and Pinter, 1996). The fault scarp is the most obvious fault feature (Ollier, 1981) and a steep slope with the same aspect parallel as the fault trace. The size of fault scarps varies from a few meters to hundreds of kilometers in length

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(Burbank and Anderson, 2001) and from a fraction of a meter to hundreds of meters in height.

High-dip faults of natural, reverse, and strike-slip type have the most visible linear fracture traces, whereas thrust faults have more erratic topography (Burbank and Anderson, 2001; Ollier, 1981).

The Red River shear zone (RRSZ) is considered the main structure in northwestern Vietnam. It has recorded and undergone many periods of tectonic evolutions in Asia (Leloup et al., 1995; Cuong, 2007). In recent decades, many researches about the RRSZ have controversial remains on timing activation and tectonic structures of this fault zone. The Pho Lu area locates within the RRSZ, where bearing many fault traces of the RRSZ. Therefore, the DEM and earthquake focal mechanism test application of can identify geological structures in the Pho Lu area and is necessary.

The collision between India and Eurasia plates is the most typical example of active mountain construction, plateau development, and continental-scale strike-slip faults on the earth. These processes made northwestern Vietnam a mountainous region dominated by several high elevation ranges - e.g. Hoang Lien Son, Phi Si Lung, and Phu Den Dinh. This montage region contains a relatively large area of uplands above 2,000 m, with broad valleys interposed as the Song Hong, Song Da, Chan Nua valleys, etc. The study area also comprises plateaus, basins, and including those at the Pho Lu area with elevation up to 1,500 m above sea level.

The purpose of this study is based on the construction of the DEM and combining the earthquake focal mechanism, which is occurred in the RRSZ to determine tectonic lineaments and geological structures in the area.

2. Geological setting

Most lithologies of the Pho Lu area are Proterozoic-Paleozoic sedimentary sequences, including carbonates and terrigenous sedimentary rocks (Xuyen, 1988). Proterozoic and Paleozoic rocks consisting of metamorphic, carbonates sedimentary rocks, schists, and Quaternary sediments also occur therein. Generally, the Proterozoic and Paleozoic lithologies were intruded by the Proterozoic, Paleozoic, and Cenozoic intrusive bodies (Figure 1).

Magmatic rocks consist of intrusive rocks, occupying a large part of the Pho Lu area and

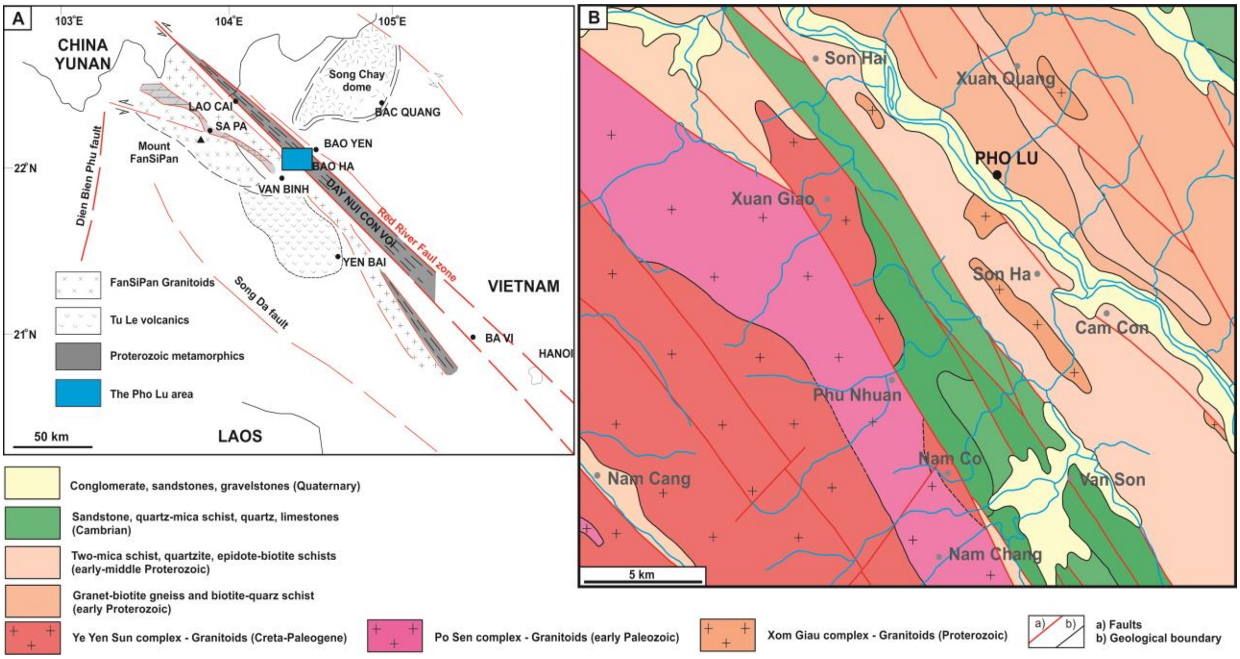


Figure 1. A-Tectonic sketch map of the RRSZ (adapted from Tri et al., 1979); B-Simplified geological map of the Pho Lu area, northwestern Vietnam (adapted from Xuyen, 1988).

forming bodies of various sizes (Tri et al., 1979; Xuyen, 1988). Main magmatic activities took place during Proterozoic, early Paleozoic, and Cenozoic, resulting in various types of granites, namely Xom Giau, Po Sen, and Ye Yen Sun granitoid complexes. They are distributed mainly in the southwestern studied area.

Based on the geologic map of Bac Quang-Ma Quang (1988) and field observations, two faults are identified. The Red River and Chay River faults runs NW–SE across the Pho Lu area and displaces a syncline filled with Lower Miocene sediments in a right-lateral sense by 15÷20 km (Cuong, 2007). Moreover, faults of the Pho Lu area play an important role in the present structural plan. The major fault system represents the main dividing boundaries of tectonic regions, zones, and structural complexes, and most faults are of northwest-southeast direction.

3. Methods and data

3.1. Digital elevation model from topographic maps

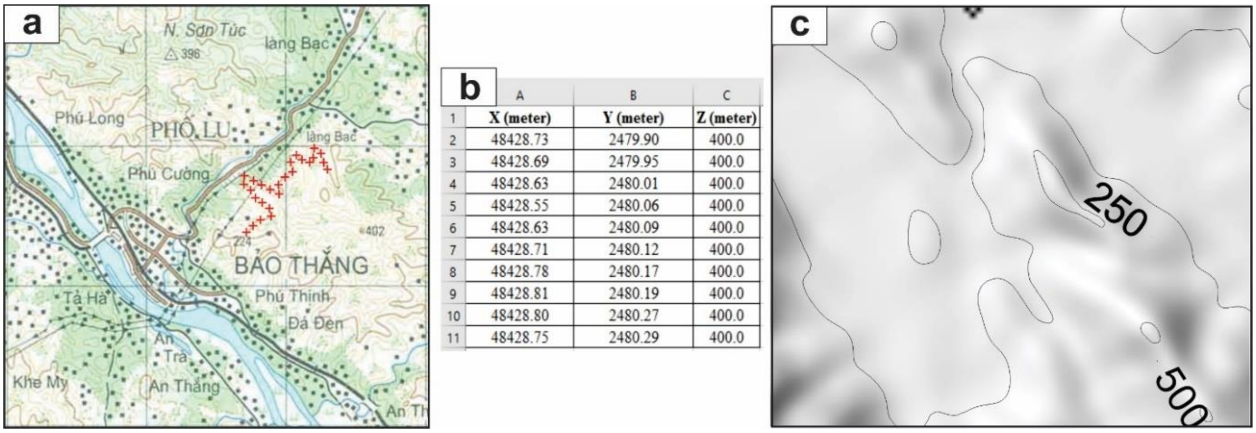
The DEM formation process starts with the scanned topographic map at a scale of 1:100,000. After that, extract contour lines, point elevations, coastlines, and rivers/streams from the raster image, convert them to digital vectors and give the elevation values (Figure 2).

Extraction of the contour lines into X, Y, Z data can be done using the Surfer software through screen digitization (Robertson, 2008). Surfer software procedures include loading the map file with the contours as the basic map, selecting the map, and then making a selection in the Map/Digitize menu. Then, click them on the screen to store these coordinates in the editing window. The Z value will not be automatically stored, but we can have X, Y, and Z data after adding Z values in the Surfer worksheet. In this way, we can interpolate a grid file from the X, Y, and Z data, and save the result from Surfer in its Grid format (GRD). Moreover, the method is presented in more detail in Hung (2016).

3.2. Focal mechanism of earthquakes

Fault activities are often associated with earthquakes. Determination of the seismic waves from earthquakes recorded at the seismograph station can be used to define the properties of the faults to infer the direction of the fault plane. The result of this analysis is called focal mechanism solution (FMS) or fault plane solution. This technique represents a powerful method for analyzing fault motion. However, most earthquakes with magnitude 5.5 and higher can provide reasonable mechanism solutions. Therefore, we can use seismic data from the studied area or a neighboring area, which may not be a direct study to determine fault plane solution.

The FMS is presented as the “ball beach plot” symbol (Figures 3, 4), depicting the stress orientation. This work requires delivery of the values of tension, pressure axis, and slip data, and then we put all the data into the software, which is contributed by Scherbaum, Kuehn, and



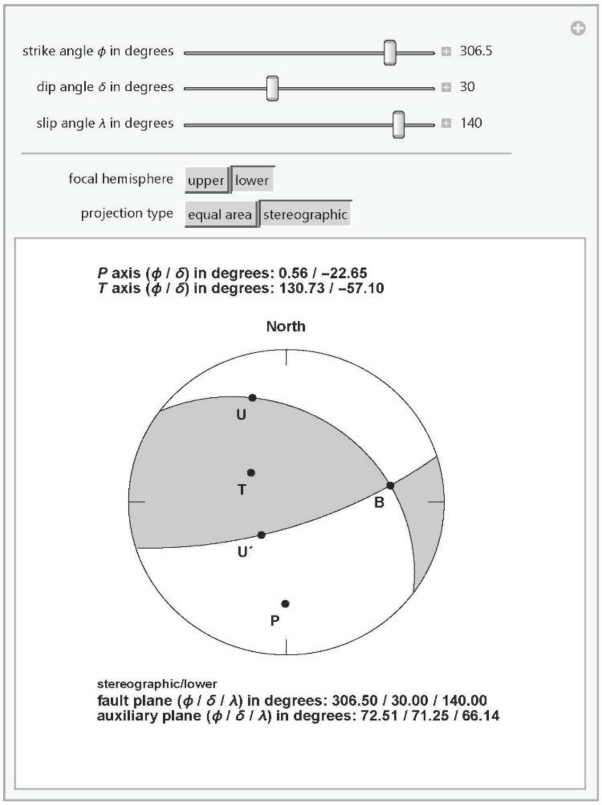
	A	B	C
1	X (meter)	Y (meter)	Z (meter)
2	48428.73	2479.90	400.0
3	48428.69	2479.95	400.0
4	48428.63	2480.01	400.0
5	48428.55	2480.06	400.0
6	48428.63	2480.09	400.0
7	48428.71	2480.12	400.0
8	48428.78	2480.17	400.0
9	48428.81	2480.19	400.0
10	48428.80	2480.27	400.0
11	48428.75	2480.29	400.0

Figure 2. The converted process of the topographic map to create DEMs model: a) Topographic map consists of the digital points (red plus sign); b) Table composite of X, Y, Z point system; c) Generated DEM model.

Zimmermann (2009). The focal sphere surrounding the earthquake source is represented by the beachball symbol (Figure 4a). The stress field's direction at the time of dislocation interferes with the sliding direction on the fault plane. It also depicts the movement of stress on the beachball. In the schematic cartoon (Figure 3), the grey quadrants of the beachball maintain the tensile axis (T), which reflects the direction of the most minor compressive stress, and the white quadrants of the beachball hold the pressure axis (P), which reflects the principle of maximum compressive stress. The focal mechanisms calculated in the software only display the P and T-axes and do not use shadows (USGS, 2009).

For a mechanism that only uses the first motion direction of the seismic waves to calculate, these incorrect first motion observation results may significantly influence the calculated focal mechanism parameters. According to the distribution and quality of first motion data, more than one FMS may be equally suitable for the data. Generally, the mechanism calculated from the direction of first motion and some methods of modeling the waveform are ambiguous in identifying the fault plane, where the slip occurs from the mathematically equivalent orthogonal auxiliary plane. Figure 4b has presented the four examples of this ambiguity. In most cases, the two possible types of fault motion are often excited in the block diagrams adjacent to each focal mechanism can represent. By comparing the directions of the two fault planes with the arrangement directions of small earthquakes and aftershocks, the ambiguity of this problem can be resolved. The first three examples describe fault motion, namely strike-slip or normal/reverse mechanisms. The last one is the oblique-reverse mechanism, which shows that slipping may also have horizontal and vertical components.

In many cases, considering the local geology of the earthquake area and comparison with the FMS can resolve the ambiguity of the fault plane solution.



strike angle ϕ in degrees 306.5

dip angle δ in degrees 30

slip angle λ in degrees 140

focal hemisphere lower

projection type stereographic

P axis (ϕ / δ) in degrees: 0.56 / −22.65

T axis (ϕ / δ) in degrees: 130.73 / −57.10

stereographic/lower

fault plane (ϕ / δ / λ) in degrees: 306.50 / 30.00 / 140.00

auxiliary plane (ϕ / δ / λ) in degrees: 72.51 / 71.25 / 66.14

Figure 3. Earthquake focal mechanism.

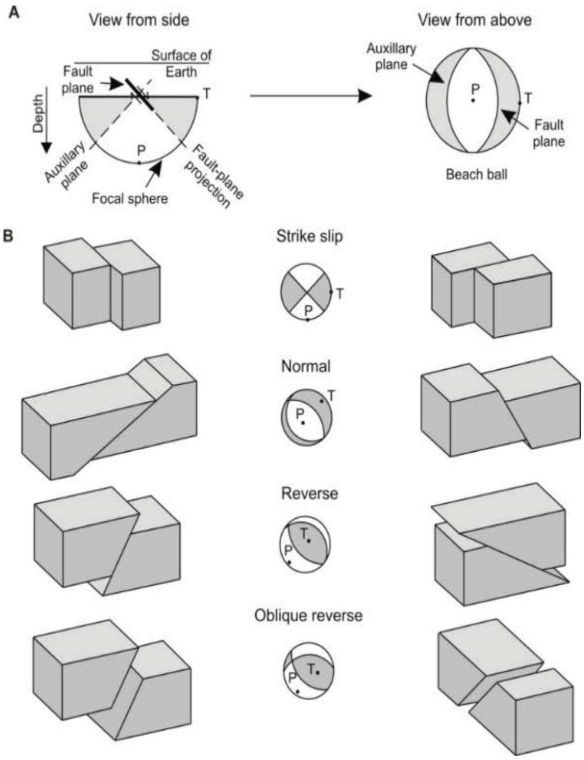


Figure 4. General diagram of an FMS (after USGS, 2009).

3.3. Structural analysis

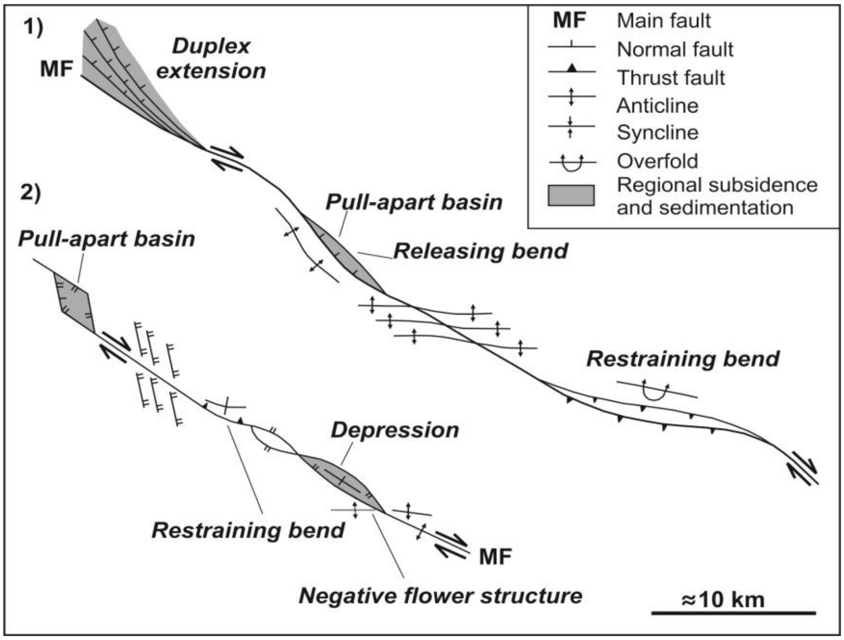


Figure 5. Geological structures of the combined fault systems (after Hung, 2016).

The combination of the faults can form typical structures, as presented in Figure 5. Constructive or constrained bending and offsets are local areas of convergence where materials are pushed together by the spread fault motion. The link between adjacent fault segments is usually achieved by forming P-shear splay faults. When the volume of the depressed area is constant, local shortening will produce vertical elongation, which will cause the surface uplift or depression. This push-up/pull-apart area will be eroded or the site for sedimentation. Therefore, the bending and deflection of the structure and extension can alternate along a single but complex strike-slip zone.

If the vertical component is normal, the fault tends to be a listric fault of fracture and forms a positive or negative flower structure, thereby forming a depressed area. In the map view, the subsidence (often an informal area) usually has a wedge - or rhomb - shape. It creates a sag pond, a rhomb graven, or a larger pull-apart basin. Strike-slip faults and depositions: the sedimentary basins formed in a strike-slip environment are usually rhomb-shaped. The pull-apart depressions at the fault boundary are formed in the extension zone.

4. Results and discussion

4.1. Digital elevation model and remote sensing image of the Pho Lu area

The obtained model of DEM construction covers an area of 611.5 km^2 and 54 m to 2458 m above sea level. Extracted lineament is based on a change in the angle of illumination shaded relief map, a contour map is an interval of every 40 m (Figure 6), and the spatial model (3D surface) (Table 1).

Table 1. Parameters of digitized values and DEM interpolation.

Parameters	Pho Lu (Cam Duong)
Number of digitized parameters	120270
Z Minimum	54.36
Z Maximum	2458.34
Z Mean	463.56
Z Median	316.64
Z Standard Deviation	405.8
Interpolated type	Kriging point
Drift	linear
Grid Size	100/97

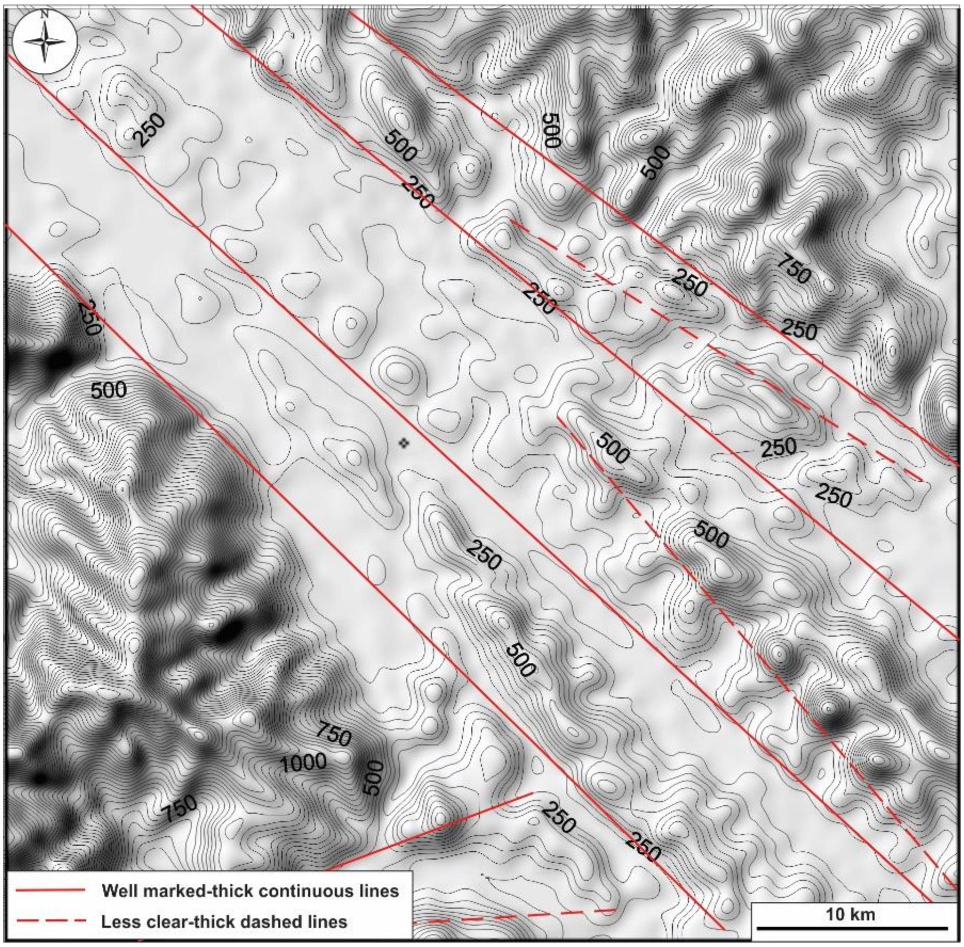


Figure 6. Shaded relief map combined with contour lines intervals of every 40m for the Pho Lu area, light position angles horizontal 138°, vertical 65°.

Contour lines represent terrain height and morphological information. Contour density in the contour map is considered and concentrated in contour lines when dealing with linear structures. The method has been used by Hung (2016) for the Dien Bien area to determine the zones of discontinuity. The group of lineaments trending in the SE-NW direction dominates in the Pho Lu area, showing also arrangement in faults (Figure 6). Some of these lineaments arranged in the Red River valleys, along slopes of the Con Voi mountain range, indicate a part of the RRSZ.

4.2. Focal mechanism of earthquakes in the Pho Lu area

In the northern Vietnam segment, the earthquake's focal mechanism was determined very rarely or not published. Therefore, earthquake parameter data from Global CMT and China Earthquakes catalogs were used. The earthquake coded as event No.042495B in the Global CMT catalog occurred on 24th April 1995 in the RRSZ in Yunnan province, near the Chinese-Vietnamese boundary. It is also listed in Zhu (et al., 2004) but mentions of the earthquake characteristics. The parameters of the earthquake were:

latitude j = 22.88°,
longitude l = 103.16°,
depth 33.0 km,
body-wave magnitude Mb = 4.9.

The source was connected with the southern part of the AS-RRSZ with the epicenter near the Vietnam segment.

The focal mechanism of this event determined right-lateral strike-slip with direction

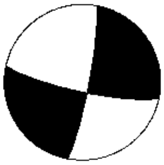


Figure 7. Focal mechanism of the event – No. 042495B (after Zhu et al., 2004).

and slipped at 102° and -173°, respectively (Figure 7). There fore, the strike-slip mechanism is as follows:

- NW-SE strike nodal plane (A) tilts 80° to SSW (azimuth angle 192°), oblique sinistral lateral slip (strike-slip: -173°);
- NE–SW strike plane (B) tilts 83° to NW (281° in azimuth), oblique dextral lateral slip (strike-slip: -10°).

– Compression axis (T) dips 2° towards EN (azimuth: 57°).

- Dilatation axis (P) dips 12° towards NW (azimuth: 326°).

4.2. Align morphological features and domain analysis of geological field data

Along the RRSZ, several narrow Quaternary valleys were observed. Based on the basin sizes, dextral offsets of the RRSZ have been calculated to be 0.07-17 km (Tuc and Yem, 2001), 200–1,200 m (Trinh et al., 1993), 0.3–2 km (Lacassin et al., 1998) or 2 km (Cuong and Zuchiewicz, 2001). Therefore, the corresponding Quaternary right-lateral slip range is from 1 to 9 mm/yr (Allen et al., 1984) or between 1 and 4 mm/yr (Weldon et al., 1994).

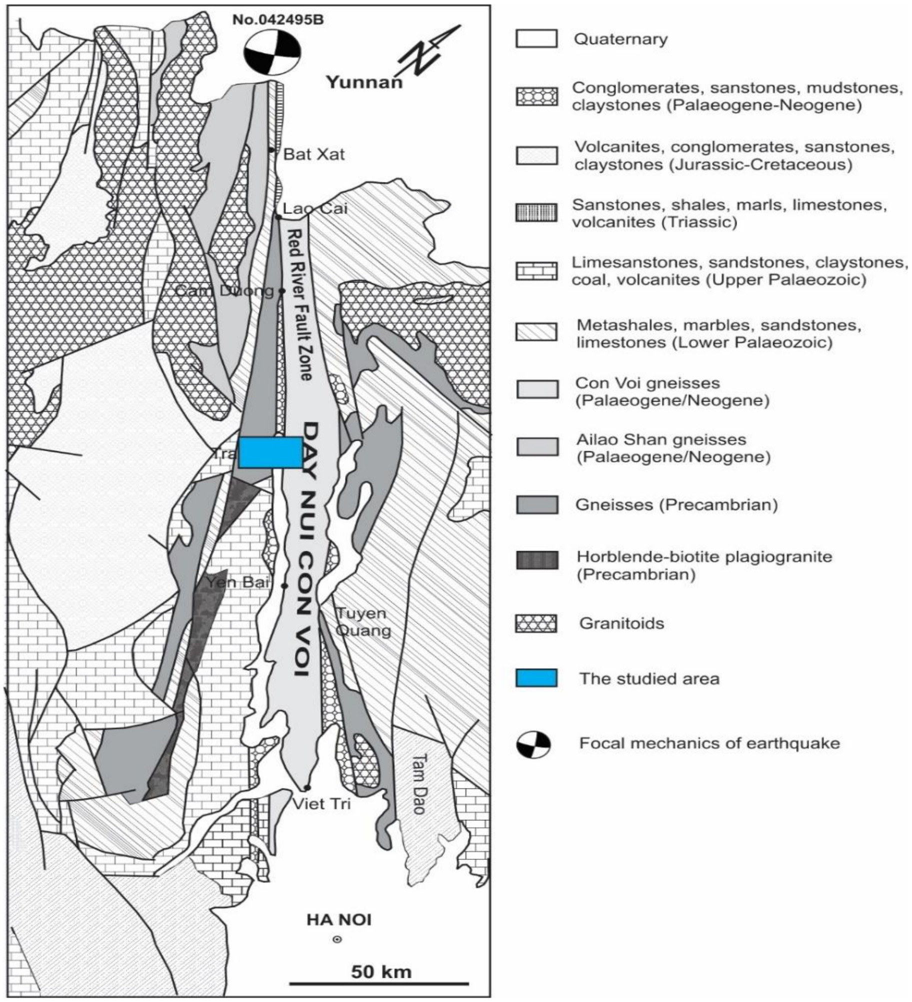


Figure 8. Analysis and results of fault kinematics are represented by the focal mechanism solution of the earthquake "beachballs" for the RRSZ (adapted from Allen et al., 1984).

Significantly, the author's result on calculating the Red River's drainage network between Cam Duong and Chau Que Thuong areas indicate that the dextral offset is between 941-966m and 1 238–2 866m. The cumulative impact of several deformation events has resulted in a tortuous Red River of nearly 8.969 km-long dextral offsets.

The dextral offset derived from the deflected drainage pattern has been shown in the Pho Lu area (Figure 8). Particularly, Cuong and Zuchiewicz (2001) pointed out that right-lateral slips, including drainage deflection, ranges between 941 m and 2.866 m. A lot of morphological features display fault traces as beheaded streams, shutter ridges, and fault-line scarps, so on. The relief does not exceed 30÷50 m.

In the Bao Ha area, examples of rectilinear river valleys and drainage offset and deflection are provided by Red River faults. The displacement of alluvial fans and associated terraces is apparent, and near Cam Duong (Figure 9), where well-developed shutter ridges can be found.

At the feet of mountain fronts, the morphological and structural features of the normal slip in the southeastern parts of the RRSZ consist of the triangular facets, the appearance of the ubiquitous hanging wineglass valleys, and rectilinear fault scarps, they usually accompanied by related half-grabbers and minor horsts or pressure-ridges (Cuong and Zuchiewicz, 2001). In the northwestern section of the RRSZ, the heights of the triangular and trapezoid are relatively small, as Trai Hut, near Cam Duong (Figure 10).

Furthermore, the evidence of the Song Hong strike-slip fault is also derived from geological features. Based on the results of the fieldwork investigation, many localities are presented along the Song Hong fault, where relatively young gravels can be seen to be cut by the fault. In addition, clasts in Neocene conglomerates are commonly fractured; one of them is situated in the Tertiary strata of the Lao Cai basin (Figure 11).

According to the relief surface feature at the Pho Lu area,, the Pho Lu relief is quite complete; it is interposed between the Con Voi and Pung Luong high mountain ranges with dense river networks. So, we can call it a valley, a segment of the RRSZ that forms a typical structure of the positive flower type, which reflects the transpression regime. Positive flower structure is produced by convergence in strike-slip motion or a combination of reverse faults (Twiss and

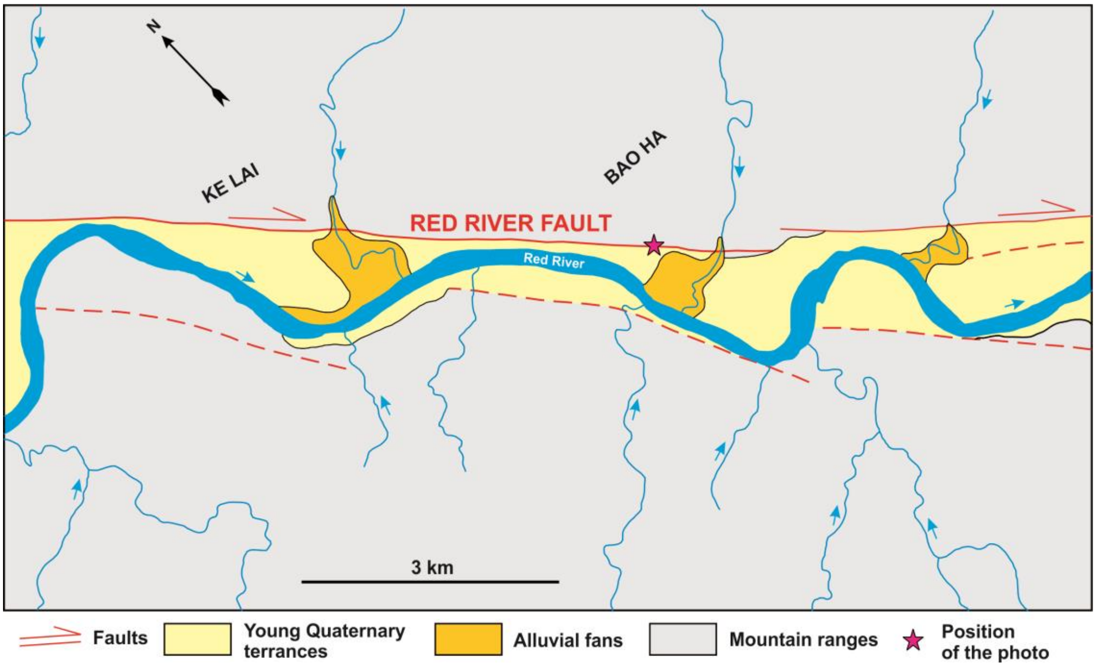


Figure 9. Cartoon showing dextral displacement along with a fragment of the RRSZ close to Bao Ha (after Cuong, 2007).

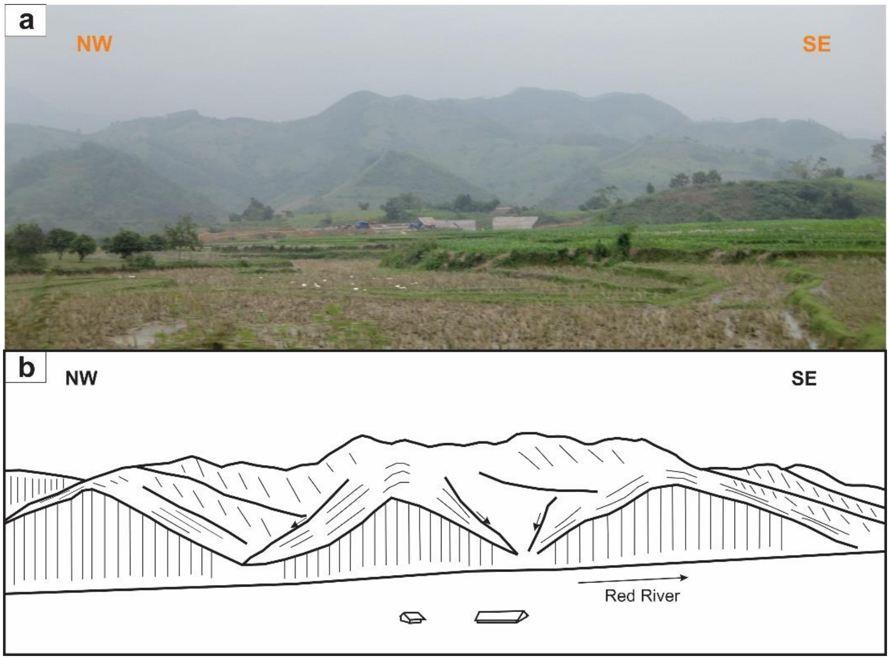


Figure 10. A photograph is captured at the star point (in Figure 9) in the Pho Lu area indicated: (a) Right-lateral drainage deflection along the Red River, (b) Drawing from the picture showing minor triangular facets are accompanying the RRSZ.

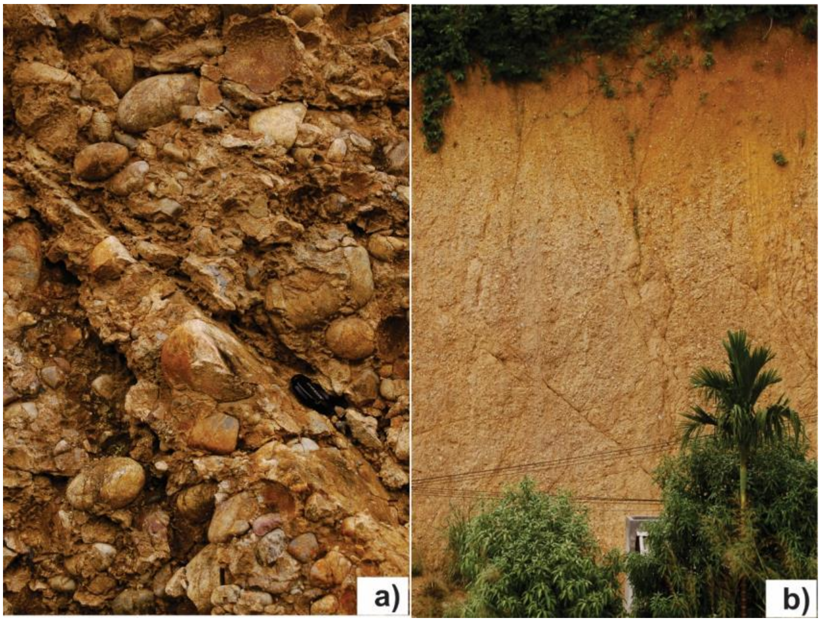


Figure 11. The small-scale structural characteristics of the Tertiary layer in the Lao Cai valley; a,b - Clast-scale joints (arrows) arranged in linear zone of RRSZ, the faufel tree is in between 3 to 3.5 m in height.

Moores, 1992). The development of the observed structural type was probably connected with the SE-NW transpression. The tectonic structure of the Con Voi mountain range is parallel to the Phan Si Pan range (Figure 12). Thus, a valley is located between two uplifts. The flower structures were also confirmed by the geological survey and seismic profiles in the Song Hong Basin in the East

Sea (Rangin et al., 1995). Subsidence in this basin was caused by a trans - tension regime, forming a negative flower structure. The tectonic lineament system in Figure 12 showing the valley between uplift corresponds to the model in Figure 13.

In this study, we first presented a new RRSZ segment model using DEM and the earthquake focal mechanism methods for identifying geological structures in the Pho Lu area. The results show that the strike-slip motion of the Red River fault, it probably associated NE-SW tectonic lineament system, they indicated that the RRSZ presents a positive flower structure and dominated younger faults on the surface at the study area.

5. Conclusions

In this study, the DEM and focal mechanism of the earthquake are used to identify geological structures of the Pho Lu area, northwestern Vietnam. The results obtained from this study indicate that:

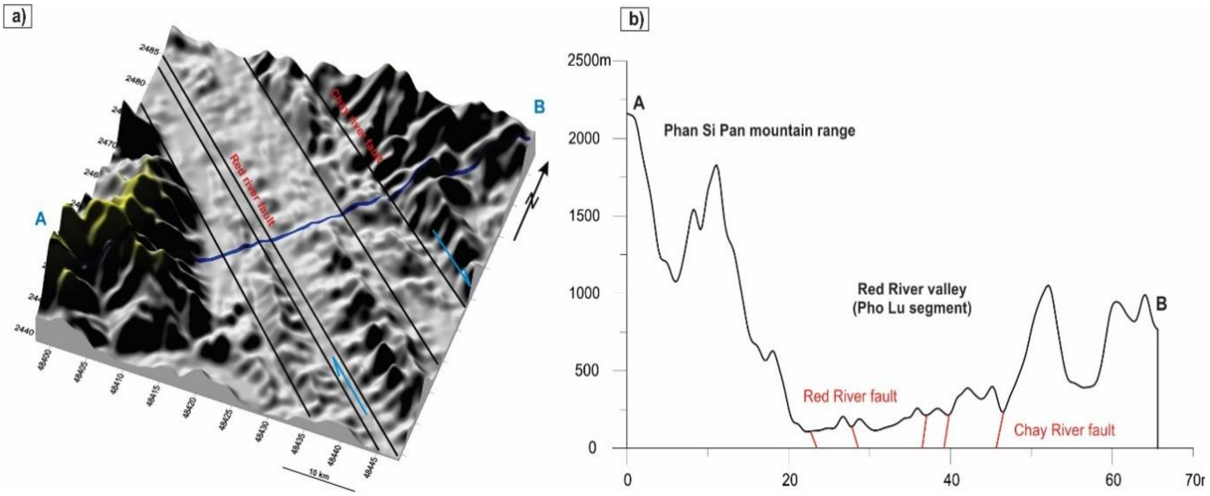


Figure 12. a) Model landslides of the Song Hong valley (Pho Lu segment) and location of the AB cross-section line in the Pho Lu area; b) the A-B topographic profile (Pho Lu segment).

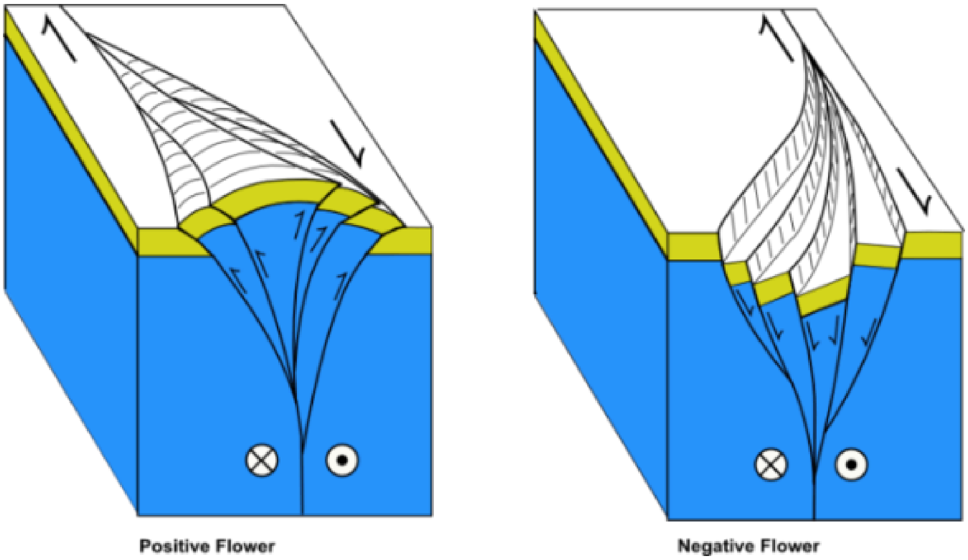


Figure 13. Flower structure models modified from Nielsen and Sylvester (1995) appropriate for the designated structures in the Pho Lu segment of the RRSZ - a positive flower structure reflects the transpression regime in particular.

(1) The results have obtained particular successes as the good results generated DEM from a topographic map at a scale of 1:100 000. The DEM analysis has allowed linear elements recorded on the topographic surface and directly correlated to the RRSZ. Using a focal mechanism combined with the geological investigation in the field enables identifying the movement mechanism of the fault. The combination of fault factors led to speculate a positive flower structure existing in the RRSZ.

(2) Combination of the DEM analysis and earthquake focal mechanism illustrated and interpreted as fault traces based on the morphological features are beneficial for geological applications.

(3) The DEM and its analysis play an essential role in the geological survey. The DEM can be used for further geological investigation to meet the mineralized criteria, which is the first step in mineral and mining.

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Author contributions

Hung The Khuong study conception and design draft of the manuscript, acquisition of DEM data, and analysis and interpretation of data, the author has done all critical revisions.

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