INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Tectonic Activity Phases of Cenozoic Period in Xuat Hoa Area, Bac Kan Province, Northeast Region, Vietnam

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Manuscript received: February, 28, 2019; revised: August, 28, 2019;
approved: September, 27, 2019; available online: December, 9, 2019

Abstract - This paper presents the analytical results of a hundred and three striations from twenty-five survey locations along 3B highway in Xuat Hoa area, Bac Kan Province, Vietnam. The analytical results have determined four main phases of tectonic activity: NW−SE, E−W, NE−SW, and N−S. The first phase, the compressive stress state in the direction of NW−SE, caused the right lateral strike-slip motion of faults in the direction of E−W and the left lateral strike-slip motion of faults in the direction of N−S. The second phase, the compressive stress state in the direction of E−W, caused the left lateral strike-slip motion of faults in the direction of NW−SE and the right lateral strike-slip motion of faults in the direction of NE−SW. The third phase, the compressive stress state in the direction of NE−SW, caused the left lateral strike-slip motion of faults in the direction of E−W and the right lateral strike-slip motion of faults in the direction of N−S. The final phase, the compressive stress state in the direction of N−S, caused the left lateral strike-slip motion of faults in the direction of NE−SW and the right lateral strike-slip motion of faults in the direction of NW−SE. In addition, these stress states also created thrust faults in the directions of NE−SW, N−S, NW−SE, and E−W. Based on the analytical results, field investigation, and previous studies, this study proposes the order of the main compressive stress states in the directions of 1) NW−SW, 2) E−W, 3) NE−SW, and 4) N−S.

Keywords: stress state, strike-slip, right lateral, left lateral, thrust fault

How to cite this article:
Thanh, P.T., 2019. Tectonic Activity Phases of Cenozoic Period in Xuat Hoa Area, Bac Kan Province, Northeast Region, Vietnam. *Indonesian Journal on Geoscience*, 6 (3), p.311-325. DOI: 10.17014/ijog.6.3.311-325

Introduction

The Xuat Hoa area, Bac Kan Province, is located in the northeast region of Vietnam, between two major fault zones in the direction of NW−SE: the Red River fault zone and Cao Bang - Tien Yen fault zone (Figure 1). The rocks are mainly sedimentary rocks of Devon age. Their components include polymictic conglomerate, gritstone, limestone bearing, clayish siltstone, and marlaceous shale. Similar to the other parts of the northeast region, this area is also influenced by the movement of the India-Australian Plate to the north and the Pacific Plate to the west, forming the compressed and extended area (Phung *et al*., 1996). During the Cenozoic period, the northeast region of Vietnam as well as the Xuat Hoa area, Bac Kan Province, has suggested that it must be influenced by two main tectonic activity phases. The first is compressive phase (early phase) occurring in the direction of E−W, from the Eocene to the Late Miocene, and the second compressive phase (late phase) was in the direction of N−S, from the Pliocene to the present.

Currently, there are still some different opinions about these tectonic activity phases. In order

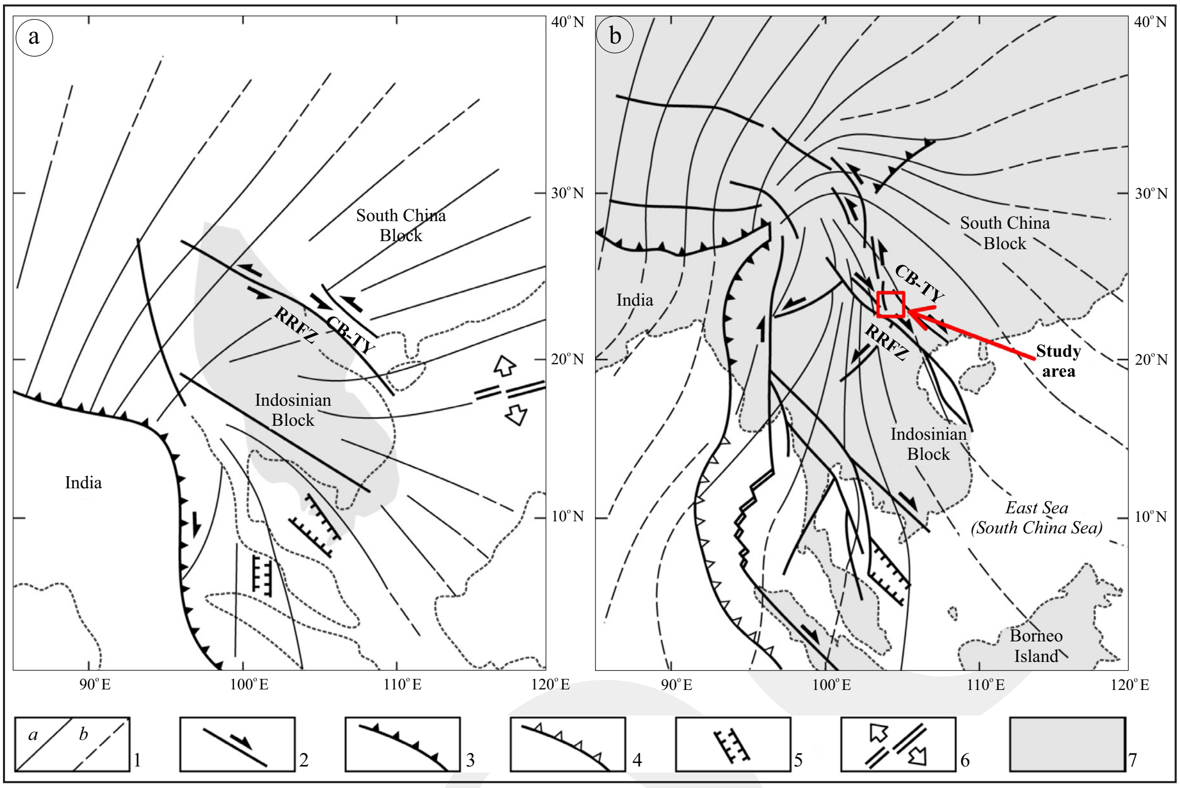

Figure 1. Trajectories of the maximum compressive stress within the Indochina Peninsula during (a) the Oligocene and (b) at the present time (Kasatkin *et al.,* 2014; modified from Huchon, 1994). The legend on the map in Figure 1 is described as follows: (1) trajectories of the maximum compressive stress are directly related to the Indo-Eurasian plate collision (a) and its far-field effects (b); (2) faults and directions of displacement (arrows); (3) zone of continental collision; (4) subduction zone; (5) extension structures; (6) spreading zones; (7) current position of the land; Red River Fault System (RRFS); Cao Bang - Tien Yen fault (CB - TY)

to make the tectonic activity phases in the region clear, this paper presents the analytical results of determining the tectonic activity phases in detail based on the striation data of faults which were collected from twenty-five survey locations in the Xuat Hoa area, Bac Kan Province, Vietnam (Figure 2).

Tectonic Setting

The movement of the India-Australian Plate toward the north, extruding Eurasian Plate, has changed the tectonic framework of Asia (Tapponnier *et al*, 1990). In the Cenozoic period, the tectonic activity has caused not only left lateral strike-slip movement of the Red River fault zone, but also a series of faults in the same direction of NW−SE (Tapponnier *et al*, 1990; Schoenbohm *et al.*, 2004). Some other study results have suggested that the Cenozoic period having two major phases of tectonic activity occurred in the northeast region of Vietnam, including the 3B highway in Xuat Hoa area, Bac Kan Province (Nguyen, 1991; Phung *et al.*, 1996). The early phase was determined to occur from the Eocene to the Late Miocene period, whilst the late phase was interpreted to occur during the Pliocene−Quaternary period (Vu, 2002; Pubellier *et al.*, 2003). The first tectonic activity phase caused the left lateral strike-slip motion of the fault system in the direction of NW−SE, and the late phase caused the right lateral strike-slip motion of this fault system.

The left lateral strike-slip motion of the Red River fault zone is the result of the India-Eurasia plate collision (Tapponnier *et al.*, 1986), and it took place from 30 to 5.5 Ma, corresponding to the Oligocene-Miocene period, based on the analytical results of the seismic data (Rangin *et*

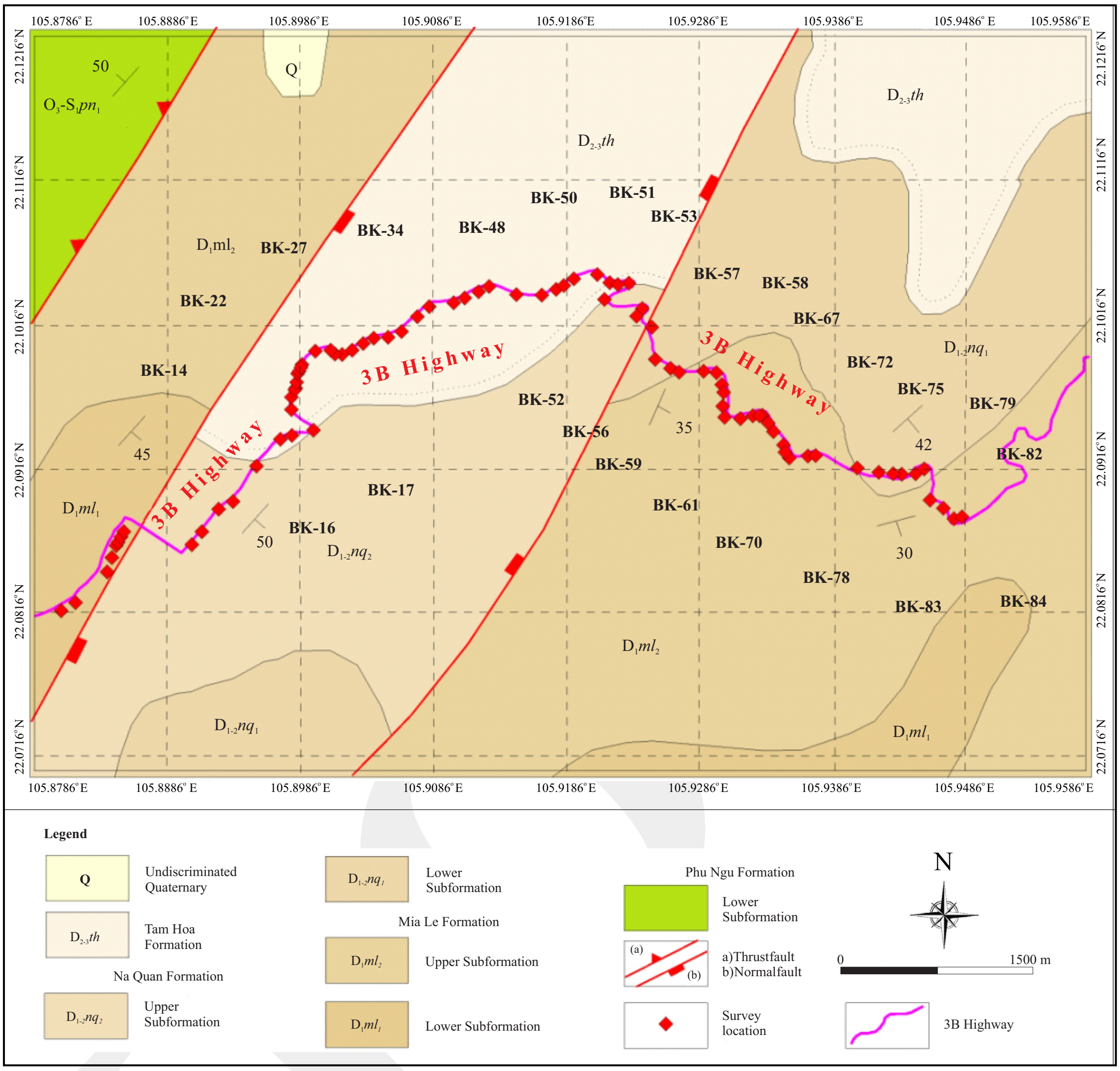

Figure 2. Geological map, minimized from scale 1: 200.000, and survey locations (Nguyen *et al*., 2000).

al., 1995). Another analytical result of seismic profiles in the north area of the Red River sedimentary basin also identified one phase of the left lateral strike-slip motion which occurred before 21 Ma between the Lo River and Chay River fault zones, belonging to the Red River fault zone (Nguyen and Zuchiewicz, 2001). Besides, the study has also indicated that one different tectonic activity phase with the compressive direction of NE−SW caused the tectonic inversion of fault system in the direction of NW−SE during 10.5 - 5.5 k.y.

Recently, the analysis of tributaries of the Red River fault zone from Quaternary alluvial fans, river valley on Landsat and SPOT satellite images, detailed topographical maps, and a field survey determined that right lateral offsets of stream channels ranged between 150 and 700m (Phan *et al*., 2012). This is the result of the N−S compressive stress state and E−W extensive stress state which caused the right lateral strike-slip motion along the Red River fault zone, and probably began in the Pliocene time. The tectonic phase was also clearly visible in the Red River fault zone and the Dien Bien fault from the analytical results of Landsat and SPOT satellite images (Lacassin *et al*., 1994; Phan *et al*., 2012).

Another analysis also recognized that Cao Bang - Tien Yen fault zone, which is located in the NE region of the Red River fault zone, showed the right lateral strike-slip motion, resulting from the compressive direction of N−S using Landsat and SPOT satellite images, aerophotographs, and 1:50,000 topographic maps (Phan *et al*., 2012). The relation to dextral strike-slip motion of the Red River fault zone in the episode of Pliocene−Quaternary was also confirmed in the study of Witold *et al*. (2013). The result of tectonic-geomorphic studies indicates that the amount of Quaternary dextral offset of the Red River fault zone in Vietnam was calculated from the offset and the deflection of the tributary valleys between 400 m and 5.3 km. Similarly, another study also indicates that the predominant sinistral strike-slip motion of the Red River fault zone formed as a result of ENE regional compression (80°) during the Oligocene−Miocene period, and dextral strike-slip motion of the Red River fault zone formed as a result of NNW regional compression (330-350°) during the Pliocene−Quaternary period (Kasatkin *et al*., 2014).

Materials And Methods

Materials

The geological investigation was carried out at eighty-four survey locations in Xuat Hoa area, Bac Kan Province, Vietnam (Figure 2). The striation data were collected at twenty-five survey locations using a compass at each survey location in detail. The data and survey locations in the studied area are recorded in Table 1 and Figure 2.

Table 1. Survey Locations, Coordinates, Geological Age, and Statistical Striation Number

No	Survey location index	Longitude (Degree)	Latitude (Degree)	Geological age	Striation number
01	BK-14	105.897278°	22.093611°	$D_{2\text{-}3}th$	2
02	BK-16	105.898432°	22.093914°	$D_{2\text{-}3}th$	2
03	BK-17	105.899778°	22.094222°	$D_{2\text{-}3}th$	3
04	BK-22	105.898528°	22.097583°	$D_{2\text{-}3}th$	4
05	BK-27	105.899944°	22.099750°	$D_{2\text{-}3}th$	10
06	BK-34	105.905417°	22.100694°	$D_{2\text{-}3}th$	3
07	BK-48	105.921667°	22.103250°	$D_{2\text{-}3}th$	9
08	BK-50	105.922694°	22.104278°	$D_{2\text{-}3}th$	10
09	BK-51	105.923500°	22.104361°	$D_{2\text{-}3}th$	2
10	BK-52	105.924500°	22.102583°	$D_{1\text{-}2}nq_2$	3
11	BK-53	105.925222°	22.101278°	$D_{1\text{-}2}nq_1$	9
12	BK-56	105.927250°	22.098139°	D_1ml_2	8
13	BK-57	105.929083°	22.098167°	D_1ml_2	1
14	BK-58	105.930028°	22.098083°	D_1ml_2	8
15	BK-59	105.930444°	22.097250°	D_1ml_2	3
16	BK-61	105.930500°	22.095722°	D_1ml_2	3
17	BK-67	105.933917°	22.094528°	D_1ml_2	1
18	BK-70	105.935090°	22.092770°	D_1ml_2	1
19	BK-72	105.935472°	22.092083°	D_1ml_2	4
20	BK-75	105.940556°	22.091333°	$D_{1\text{-}2}nq_1$	2
21	BK-78	105.943917°	22.090889°	$D_{1\text{-}2}nq_1$	1
22	BK-79	105.944944°	22.090917°	$D_{1\text{-}2}nq_1$	3
23	BK-82	105.947000°	22.088500°	D_1ml_2	4
24	BK-83	105.947806°	22.087750°	D_1ml_2	3
25	BK-84	105.948417°	22.087889°	D_1ml_2	4

Where:

$D_{2\text{-}3}$*th*: Tam Hoa Formation: polymictic conglomerate, gritstone, clayey shale, and limestone;

D_1*ml*$_{2:}$ Mia Le Formation: clayey siltstone, marly shale;

$D_{1\text{-}2}$*nq*$_1$: Na Quan Formation: marly shale;

$D_{1\text{-}2}$*nq*$_2$: Na Quan Formation: Shale interbedded with limestone.

Methods

To determine the overall sense of slip along the fault, a fault-slip dataset was collected from numerous discrete fault surfaces that occurred on the fault zones in the Xuat Hoa area, Bac Kan Province, Vietnam. A population of fault-slip data was collected by measuring the orientation of fault plane and striations. To interpret the population of fault-slip data and test for multiple overprinting deformations along the fault zone, the FaultKin 7 software was used (http://www.geo.cornell.edu/geology/faculty/RWA/programs/faultkin.html) with input data that included strike and dip angle of fault plane together with the rake angle (pitch angle) which were the angle of striation, measured on the fault plane. To present it, Kinematic Axes - Linked Bingham; Fault Plane Solution - From Linked Bingham has been chosen in the FaultKin 7 software, and the GIS method was used to draw the map of stress states which caused the fault slip motion in the Cenozoic period in the Xuat Hoa area, Bac Kan Province, Vietnam. The use of graphical methods of Merrett and Allmendinger (1990) and the Faultkin software for analyzing deformations along the fault zone have been conducted in many studies (Paul and Robert, 2014; Benyamin, 2016). The analyses of the striation of the fault at each survey location were conducted as shown in Figures 3 - 5.

RESULTS

The analytical results of a hundred and three striations from twenty-five survey locations in the studied area have been determined 04 mainly compressive stress states in the directions of NW−SE, E−W, NE−SW, and N−S which caused the right and left lateral strike-slip motion of the fault systems in the directions of NE−SW, NW−SE, E−W, N−S and tectonic inversion of these faults.

Compressive Stress State in the Direction of NW−SE of Strike-slip Faults

Similarly, the statistical data have also indicated that 09 survey locations have compressive stress state in the direction of NW−SE caused the right lateral strike-slip motion of faults in the direction

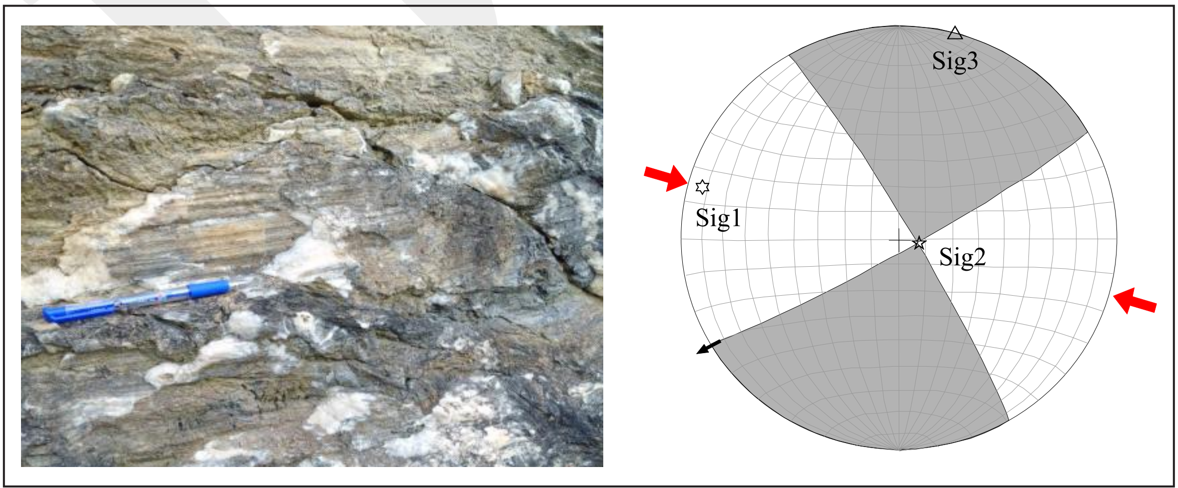

Figure 3. The right lateral strike-slip motion of fault orientation of $150^0/85^0$ (dip direction/dip angle) and striation pitch angle 03^0 at the survey location of BK-52. The analytical result determined the stress state: Sigma 1 = $285^o/07^o$; Sigma 2 = $101^o/83^o$; Sigma 3 = $015^o/0.5^o$.

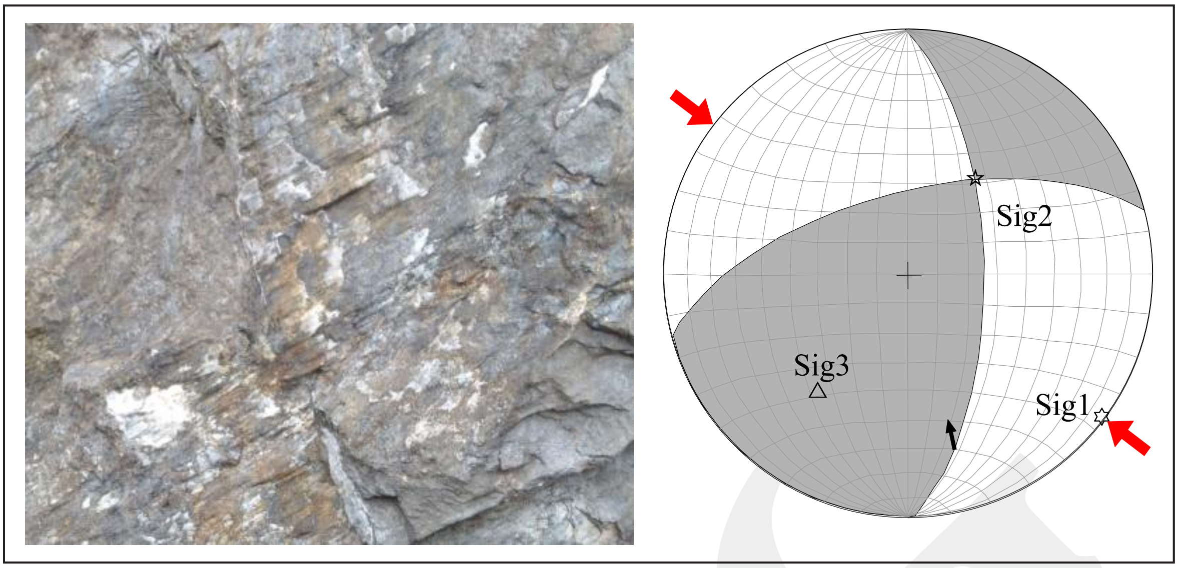

Figure 4. The left-lateral/reverse motion of fault orientation of 090/65 (dip direction/dip angle) and striation pitch angle 30° at the survey location of BK-50. The analytical result determined the stress state: Sigma 1 = 127°/02°; Sigma 2 = 035°/51°; Sigma 3 = 218°/38°.

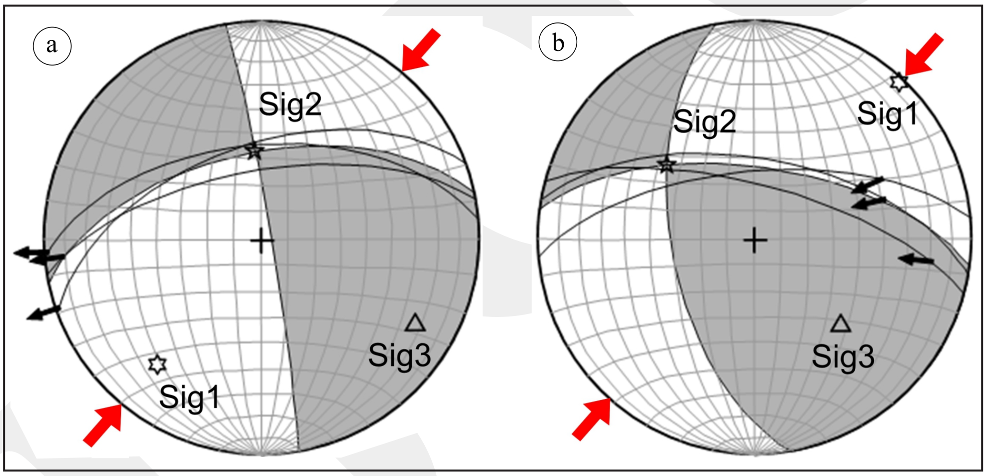

Figure 5. The analytical result of striation on the fault surface at the survey locations: BK-50 (a) and BK-48 (b). The stress states determined: Sigma 1 = 219°/24°; Sigma 2 = 356°/58°; Sigma 3 = 120°/20° for survey location of BK-50 and Sigma 1 = 043°/03°; Sigma 2 = 310°/46°; Sigma 3 = 135°/44° for survey location BK-48.

of E–W at the survey locations of BK-27, BK-50, BK-53, BK-56, BK-61 and the left lateral strike-slip motion of faults in the direction of N–S at the survey locations of BK-51, BK-52, BK-59, and BK-72 (Table 2; Figure 6).

Compressive Stress State in the Direction of E–W of Strike-slip Faults

The statistical data have indicated that 09 survey locations have a compressive stress state in the direction of E–W which caused the left lateral strike-slip motion of faults in the direction of NW–SE at the survey locations of BK-56, BK-82 and the right lateral strike-slip motion of faults in the direction of NE–SW at the survey locations of BK-14, BK-17, BK-48, BK-50, BK-51, BK-52, and BK-84 (Table 3; Figure 7).

Compressive Stress State in the Direction of NE–SW of Strike-slip Faults

The statistical data have indicated that twelve survey locations have a compressive stress state

Table 2. Compressive Stress State in the Direction of NW–SE Caused the Right Lateral Strike-slip Motion of Faults in the Direction of E–W and the Left Lateral Strike-slip Motion of Faults in the Direction of N–S

No	Survey location index	Dip direction/ dip angle of fault surface	Fault description	Sigma1	Sigma2	Sigma3
1	BK-27	350°/85°	Right lateral strike-slip	125°/05°	340°/85°	215°/03°
2	BK-50	165°/85°	Right lateral strike-slip	300°/04°	155°/85°	030°/03°
3	BK-51	085°/85°	Left-lateral/normal, pitch angle=20°	309°/17°	162°/69°	042°/10°
4	BK-52	075°/60°	Left-lateral/normal, pitch angle=5°	295°/24°	075°/59°	197°/17°
5	BK-53	343°/82°	Right lateral strike-slip	117°/07°	335°/82°	208°/05°
6	BK-56	335°/60°	Right lateral strike-slip	115°/22°	343°/59°	214°/19°
7	BK-59	087°/69°	Left lateral strike-slip	314°/15°	092°/69°	220°/14°
8	BK-61	180°/55°	Right-lateral/normal, pitch angle=30°	301°/44°	135°/46°	038°/07°
9	BK-72	080°/84°	Left lateral strike-slip	305°/04°	090°/84°	215°/03°

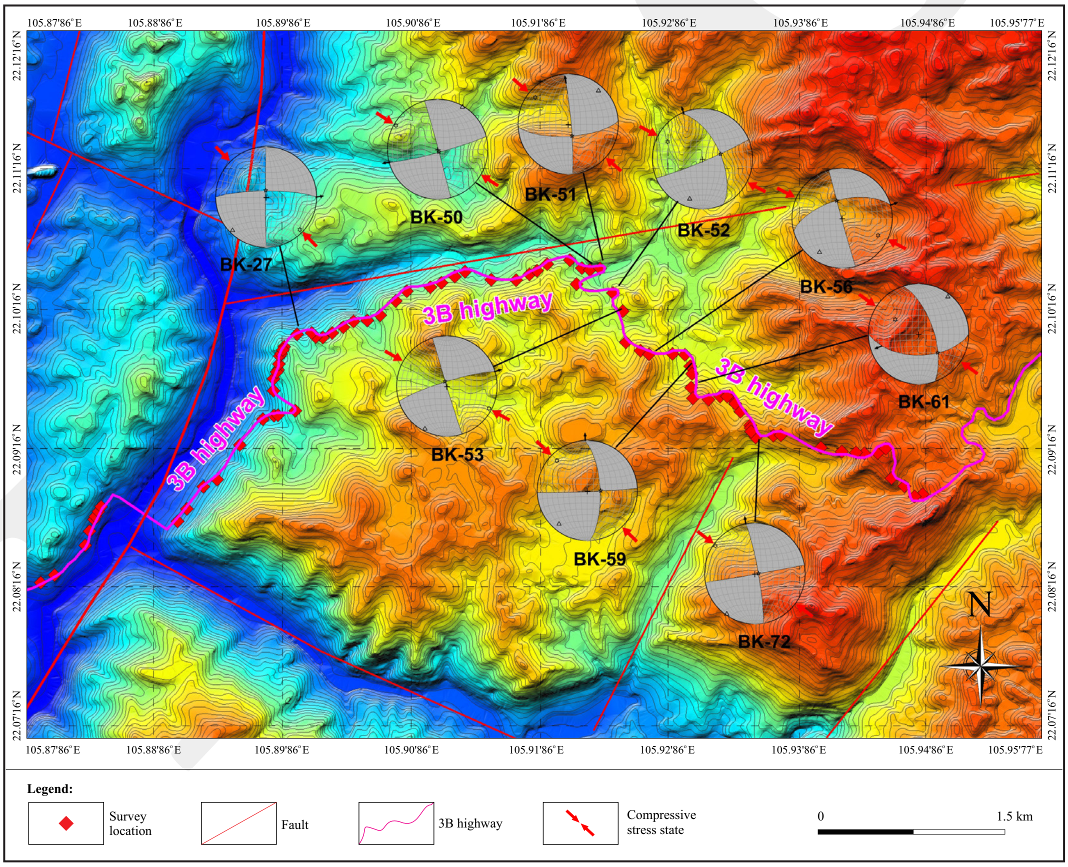

Figure 6. Map of compressive stress state in the direction of NW–SE of survey locations in Xuat Hoa area, Bac Kan Province, Vietnam.

in the direction of NE–SW which caused the left lateral strike-slip motion of faults in the direction of E–W at the survey locations of BK-27, BK-50, BK-53, BK-58, BK-75, BK-79 and the right lateral strike-slip motion of faults in the direction of N–S at the survey locations of BK-34, BK-48, BK-58, BK-59, BK-61, and BK-72 (Table 4; Figure 8).

Table 3. Compressive Stress State in the Direction of E–W Caused the Left Lateral Strike-slip Motion of Faults in the Direction of NW–SE and the Right Lateral Strike-slip Motion of Faults in the Direction of NE–SW

No	Survey location index	Dip direction/ dip angle of fault surface	Fault description	Sigma1	Sigma2	Sigma3
1	BK-14	310°/85°	Right lateral strike-slip	085°/04°	298°/85°	175°/03°
2	BK-17	330°/65°	Right-lateral/normal, pitch angle=30°	098°/39°	277°/52°	008°/01°
3	BK-48	120°/85°	Right lateral strike-slip	259°/08°	119°/80°	350°/07°
4	BK-50	330°/55°	Right-lateral/normal, pitch angle=10°	096°/31°	313°/54°	197°/18°
5	BK-51	140°/70°	Right-lateral/normal, pitch angle=40°	273°/42°	072°/46°	174°/11°
6	BK-52	150°/85°	Right-lateral/normal, pitch angle=50°	285°/07°	103°/83°	015°/01°
7	BK-56	050°/88°	Left lateral strike-slip	275°/02°	069°/88°	185°/01°
8	BK-82	043°/81°	Left lateral strike-slip	269°/07°	050°/81°	178°/06°
9	BK-84	132°/83°	Right lateral strike-slip	267°/05°	123°/84°	357°/04°

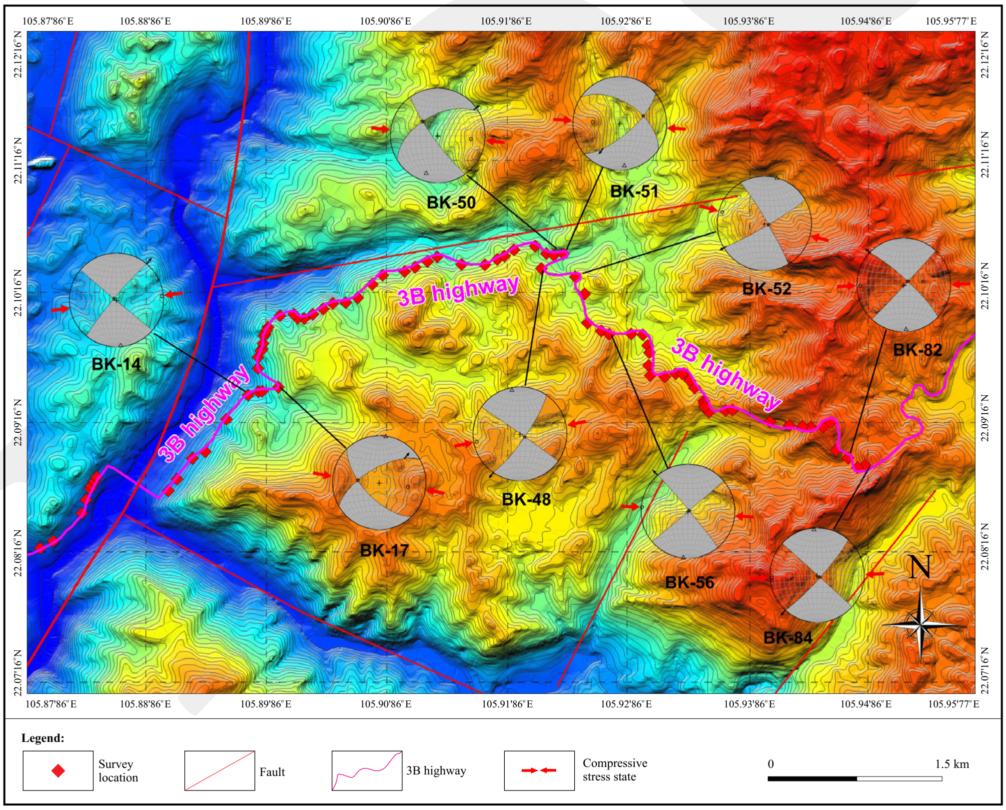

Figure 7. Map of compressive stress state in the direction of E–W of survey locations in Xuat Hoa area, Bac Kan Province, Vietnam.

Compressive Stress State in the Direction of N–S of Strike-slip Faults

The statistical data have indicated that 08 survey locations have a compressive stress state with the N–S direction which caused the left lateral strike-slip motion of faults in the direction of NE–SW at the survey locations of BK-53, BK-56, BK-58, BK-84, and caused the

Table 4. Compressive Stress State in the Direction of NE−SW Caused the Left Lateral Strike-slip Motion of Faults in the Direction of E−W and the Right Lateral Strike-slip Motion of Faults in the Direction of N−S

No	Survey location index	Dip direction/ dip angle of fault surface	Fault description	Sigma1	Sigma2	Sigma3
1	BK-27	020°/87°	Left lateral strike-slip	245°/03°	035°/87°	155°/02°
2	BK-34	166°/76°	Right-lateral/normal, pitch angle=13°	033°/18°	210°/71°	302°/01°
3	BK-48	110°/78°	Right lateral strike-slip	244°/09°	105°/78°	335°/08°
4	BK-50	350°/65°	Left-lateral/normal, pitch angle=10°	220°/24°	012°/64°	125°/11°
5	BK-53	000°/80°	Left lateral strike-slip	226°/08°	003°/80°	135°/07°
6	BK-57	285°/35°	Right lateral strike-slip	044°/36°	284°/35°	164°/35°
7	BK-58	095°/75°	Right-lateral/normal, pitch angle=15°	228°/21°	049°/69°	318°/01°
8	BK-59	097°/83°	Right lateral strike-slip	232°/06°	077°/83°	322°/03°
9	BK-61	077°/86°	Right lateral strike-slip	212°/04°	045°/85°	302°/01°
10	BK-72	080°/84°	Right-lateral/normal, pitch angle=40°	220°/32°	357°/50°	116°/23°
11	BK-75	190°/80°	Left lateral strike-slip	056°/59°	201°/80°	325°/06°
12	BK-79	005°/83°	Left-lateral/normal, pitch angle=5°	050°/08°	221°/81°	320°/02°

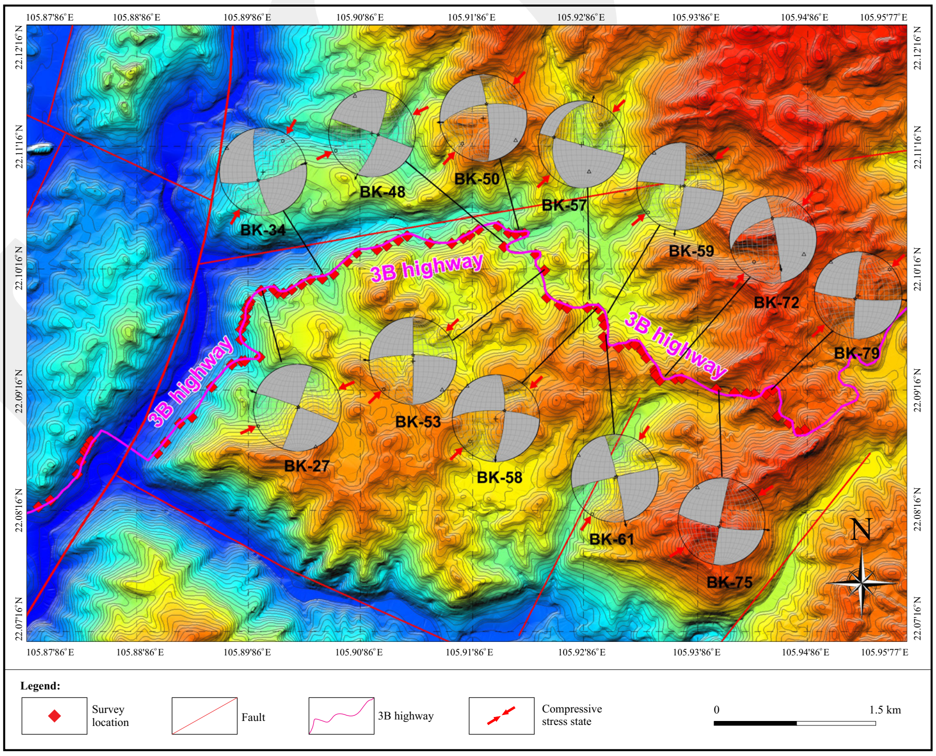

Figure 8. Map of compressive stress state in the direction of NE−SW of survey locations in Xuat Hoa area, Bac Kan Province, Vietnam.

right lateral strike-slip motion of faults in the direction of NW−SE at the survey locations of BK-22, BK-34, BK-58, and BK-79 (Table 5; Figure 9).

Table 5. Compressive Stress State in the Direction of N−S Caused the Left Lateral Strike-slip Motion of Faults in the Direction of NE−SW and the Right Lateral Strike-slip Motion of Faults in the Direction NW−SE

No	Survey location index	Dip direction/ dip angle of fault surface	Fault description	Sigma1	Sigma2	Sigma3
1	BK-22	234°/88°	Right lateral strike-slip	009°/02°	214°/88°	099°/02°
2	BK-27	050°/80°	Right lateral strike-slip	185°/08°	044°/80°	275°/06°
3	BK-34	240°/85°	Right lateral/normal, pitch angle=10°	015°/11°	179°/79°	284°/03°
4	BK-53	120°/80°	Left lateral strike-slip	346°/07°	126°/80°	255°/06°
5	BK-56	325°/75°	Left lateral/normal, pitch angle=30°	191°/12°	330°/75°	099°/10°
6	BK-58	125°/60°	Left lateral strike-slip	354°/21°	128°/60°	256°/20°
7	BK-79	030°/59°	Right lateral strike-slip	161°/23°	027°/59°	259°/21°
8	BK-84	295°/84°	Left lateral strike-slip	160°/05°	304°/84°	070°/04°

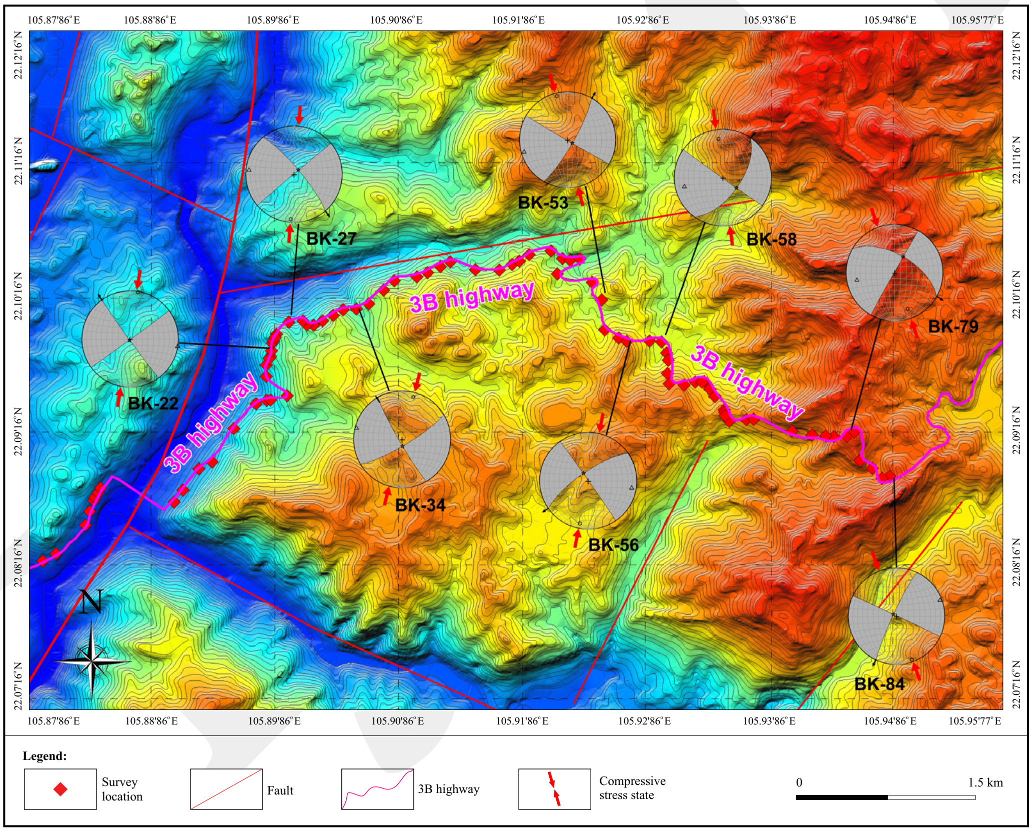

Figure 9. Map of compressive stress state in the direction of N−S of survey locations in Xuat Hoa area, Bac Kan Province, Vietnam.

Compressive Stress State in the Directions of E−W and NE−SW of Thrust Faults

The statistical data have indicated that ten survey locations have a compressive stress state in the direction of E−W that created thrust faults in the directions of N−S and NW−SE at the survey locations of BK-22, BK-34, BK-53, BK-58, BK-78, BK-84, and have a compressive stress state in the direction of NE−SW that created thrust faults in the directions of E−W, N−S, and NW−SE at the survey locations of BK-48, BK-50, BK-59, BK-83 (Table 6; Figure 10).

Table 6. Compressive Stress State in the Directions of E−W And NE−SW Created Thrust Faults in the Directions of N−S, NW−SE, and E−W

No	Survey location index	Dip direction/ dip angle of fault surface	Fault description	Sigma1	Sigma2	Sigma3
1	BK-22	234°/88°	Left-lateral/reverse, pitch angle=45°	269°/28°	146°/46°	018°/31°
2	BK-34	035°/55°	Left-lateral/reverse, pitch angle=30°	253°/07°	350°/45°	156°/44°
3	BK-48	355°/65°	Left-lateral/reverse, pitch angle=40°	028°/06°	292°/44°	125°/46°
4	BK-50	090°/65°	Right-lateral/reverse, pitch angle=30°	052°/02°	144°/52°	321°/38°
5	BK-53	055°/70°	Left-lateral/reverse, pitch angle=30°	093°/05°	356°/54°	187°/35°
6	BK-58	285°/70°	Right-lateral/reverse, pitch angle=45°	254°/13°	356°/42°	151°/45°
7	BK-59	180°/72°	Left-lateral/reverse, pitch angle=45°	211°/15°	107°/42	316°/43°
8	BK-78	220°/87°	Left-lateral/reverse, pitch angle=30°	260°/18°	135°/60°	358°/23°
9	BK-83	260°/40°	Left-lateral/reverse, pitch angle=65°	062°/07°	330°/15°	177°/73°
10	BK-84	308°/56°	Right-lateral/reverse, pitch angle=40°	095°/02°	004°/39°	187°/51°

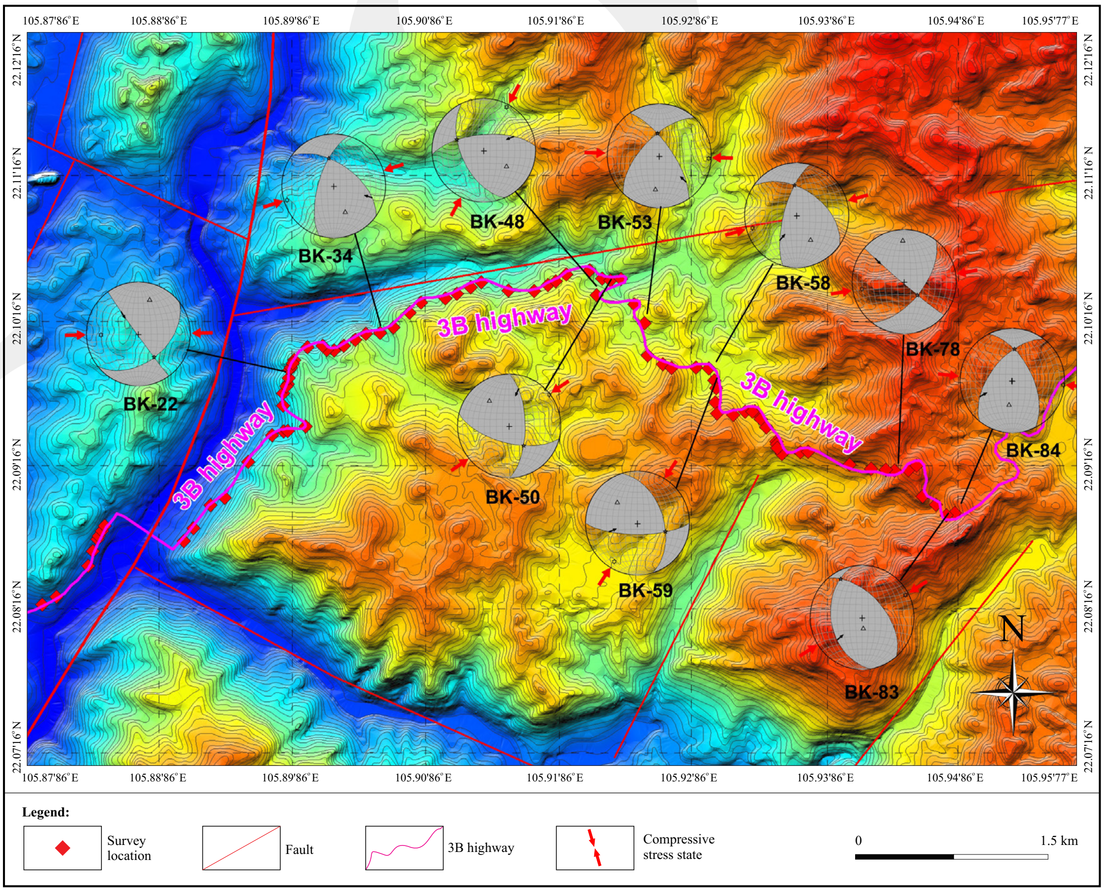

Figure 10. Map of compressive stress state in the directions of E−W and NE−SW of survey locations in Xuat Hoa area, Bac Kan Province, Vietnam

Compressive Stress State in the Directions of N-S and NW-SE of Thrust Faults

The statistical data have indicated that twelve survey locations have a compressive stress state in the direction of N−S that created thrust faults in the directions of E−W and NW−SE at the survey locations of BK-16, BK-70, BK-83, and have the compressive stress states in the direction of NW−SE that created thrust faults in the directions of E−W and NW−SE at the survey locations of BK-27, BK-48, BK-50, BK-56, BK-58, BK-67, BK-79, and BK-82 (Table 7; Figure 11).

The statistical results in Table 9 show that the compressive stress states which caused the strike-slip motion of fault systems in the directions of NE−SW, NW−SE, N−S, and E−W are 37. While the compressive stress states which created thrust faults in the directions of N−S, NW−SE, NE−SW and in the direction of E−W are 22. The compressive stress state in the direction of NW−SE caused nine strike-slip faults and seven thrust faults; the compressive stress state in the direction of E−W caused nine strike-slip faults and six thrust faults; the compressive stress state in the direction of NE−SW caused twelve strike-slip faults and four thrust faults; the compressive stress state in the direction of N−S caused eight strike-slip faults and five thrust faults. In addition, the analytical results in this table also indicated that within the studied area, survey locations from BK-27 to BK-59, the striation number of survey locations is determined to be higher than 03. It is easy to identify that these survey locations belong to the fault zones in the directions of NE−SW, NW−SE, and E−W.

Discussions

The occurrence of tectonic activity phases in the region causes the left and right lateral strike-slip motion of the fault system in the direction

Table 7. Compressive Stress State in the Directions of N−S And NW−SE Created Thrust Faults in the Directions of E−W, NW−SE, E−W, and NW−SE

No	Survey location index	Dip direction/ dip angle of fault surface	Fault description	Sigma1	Sigma2	Sigma3
1	BK-16	145°/75°	Left-lateral/reverse, pitch angle=10°	009°/03°	111°/73°	278°/17°
2	BK-27	010°/75°	Right-lateral/reverse, pitch angle=10°	136°/04°	033°/72°	227°/18°
3	BK-48	350°/45°	Right-lateral/reverse, pitch angle=55°	146°/05°	054°/24°	248°/65°
4	BK-50	005°/55°	Right-lateral/reverse, pitch angle=50°	328°/02°	059°/32°	235°/58°
5	BK-56	020°/40°	Right-lateral/reverse, pitch angle=40°	166°/14°	067°/29°	279°/56°
6	BK-58	262°/81°	Left-lateral/reverse, pitch angle=35°	299°/16°	185°/54°	039°/31°
7	BK-67	107°/76°	Left-lateral/reverse, pitch angle=40°	141°/16°	032°/48°	244°/38°
8	BK-70	043°/83°	Right-lateral/reverse, pitch angle=15°	359°/05°	109°/74°	268°/15°
9	BK-79	265°/78°	Left-lateral/reverse, pitch angle=10°	129°/02°	225°/75°	039°/15°
10	BK-82	083°/72°	Left-lateral/reverse, pitch angle=20°	125°/02°	034°/63°	215°/27°
11	BK-83	056°/75°	Right-lateral/reverse, pitch angle=10°	192°/03°	090°/72°	283°/17°

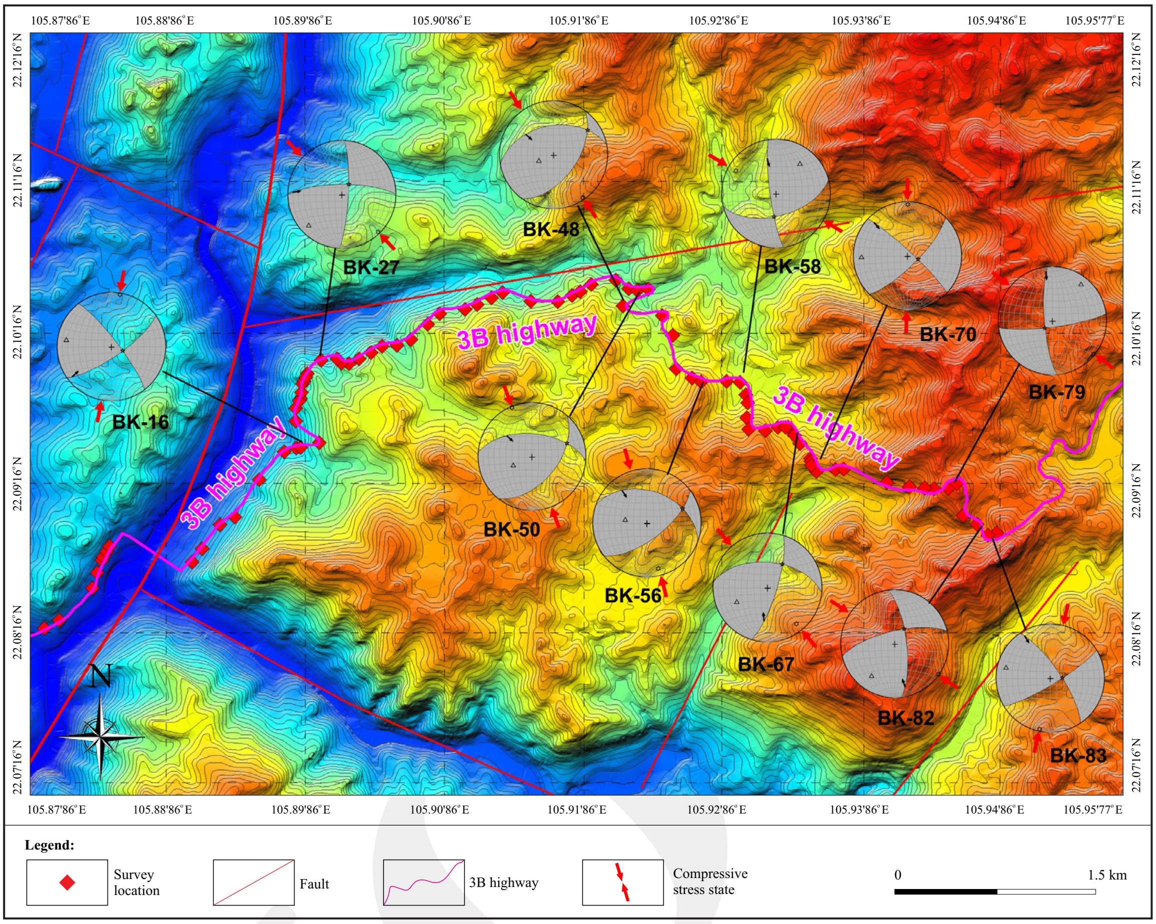

Figure 11. Map of compressive stress state in the directions of N−S and NW−SE of survey locations in Xuat Hoa area, Bac Kan Province, Vietnam.

of NW−SE in the Cenozoic period, especially in the Red River fault zone and the Cao Bang - Tien Yen fault zone. These faults are determined to be the left lateral strike-slip motion from the Eocene to Late Miocene due to the effect of the compressive stress state in the direction of E−W (Rangin *et al*., 1995; Vu, 2002; Kasatkin *et al*., 2014). These faults are also determined to be the right lateral strike-slip motion from the Pliocene to the present due to the impact of the compressive stress state in the N−S direction (Lacassin *et al*., 1994; Vu, 2002; Phan *et al*. 2012; Witold *et al*., 2013; Kasatkin *et al*., 2014; Michael and Phung, 2015). Kasatkin *et al*. (2014) has also indicated that predominantly sinistral strike slip of the Red River fault zone formed as a result of the ENE regional compression (80°) during the Oligocene−Miocene period, and dextral strike slip of the Red River fault system formed as a result of NNW regional compression (330−350°) during the Pliocene−Quaternary time. This result is also similar to the recent study based on analyzing striation data on the Co To - Thanh Lan Islands of Phi *et al*. (2018), which has determined four main compressive phases in the directions of NW−SE, E−W, NE−SW, N−S, and two extensive phases in the NE−SW and NW−SE directions.

Conclusions

The analytical results from a hundred and three striations on the fault planes at twenty-five survey locations along 3B highway in Xuat Hoa area, Bac Kan Province, Vietnam, have identified four main tectonic activity phases NW−SE, E−W, NE−SW, and N−S directions. The first phase, the compressive stress state in the direction of NW−

SE, caused the right lateral strike-slip motion of faults in the direction of E−W and the left lateral strike-slip motion of faults in the direction of N−S. The second phase, the compressive stress state in the direction of E−W, caused the left lateral strike-slip motion of faults in the direction of NW−SE and the right lateral strike-slip motion of faults in the direction of NE−SW. The third phase, the compressive stress state in the direction of NE−SW, caused the left lateral strike-slip motion of faults in the direction of E−W and the right lateral strike-slip motion of faults in the direction of N−S. The final phase, the compressive stress state in the direction of N−S, caused the left lateral strike-slip motion of faults in the direction of NE−SW and the right lateral strike-slip motion of faults in the direction of NW-SE. Besides, the stress states in these directions also caused the tectonic inversion of fault systems in the directions of N−S, NW−SE, NE−SW, and E−W. The order of the main compressive stress states is in the directions of 1) NW−SW, 2) E−W, 3) NE−SW, and 4) N−S.

Acknowledgements

This research is supported by the Project of "Research on the application of Block Theory to assess the risk of slope failure along the highway. The case study is from km 0 to km 80 on the 3B highway", with code: TNMT.2018.03.18 of Ministry of Natural Resources and Environment, within the time 2018 - 2020.

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