Assessment of Morphotectonics along Western Phayao Fault Zone in Northern Thailand

Pichawut Manopkawee[1,*], Jiratchaya Khamkaew[2]

[1] Department of Geological Sciences, Faculty of Science, Chiang Mai University, Thailand
[2] School of Earth and Environment, University of Leeds, UK
Email: ee22jk@leeds.ac.uk (J.K.)
*Correspondence: pichawut.m@cmu.ac.th (P.M.)

***Abstract*—Phayao Fault Zone (PFZ) is one of the active fault zones in Northern Thailand that has triggered low-magnitude earthquakes in Lampang, Phayao, and vicinities. Despite an active fault zone, the amount of deformation on the landscape affected by tectonic processes is largely unknown. In the study, we used morphotectonic analysis from geomorphic indices to evaluate tectonic activity across Khuang Kom and Ban Kho faults, the two main active faults along the west of the PEZ. These faults are bounded by high terrains in the west and by Mueang Pan sub-basin in the east. A high-resolution digital elevation model was used to extract topographic and hydrologic characteristics across the study site. We primarily analyzed two geomorphic indices of mountain front sinuosity (Smf) and stream length-gradient (SL). The combination of these indices potentially indicates the degree of fault activities and the implication of deformation and tectonic processes. The morphotectonic analysis revealed that the lineament patterns of Khuang Kom and Ban Kho faults mainly trend in the N-S direction. Most drainage patterns are parallel and rectangular drainage patterns, indicating numerous joints and minor faults. Analysis of geomorphic indices from these faults shows that the value of Smf varies from 1.02-2.04, and 89% of the study site is considered an active mountainous area. The value of SL mostly ranges from moderate to high gradient meters near the base of the mountain. Our finding suggests that the location of two abutting faults experiences the highest level of rock uplift and/or deformation from oblique-slip fault movement due to the effects of lithologic contact and intersecting fault networks. Our study optimally provides an insight into the advantage of using topographic analysis and geomorphic indices as a tool to estimate tectonic activity and evaluate the potential deformation in the region.**

***Keywords*—phayao fault zone, khuang kom fault, ban kho fault, morphotectonic analysis, geomorphic indices, tectonics**

I. Introduction

Landscape topography in tectonically active mountain ranges reflects an interplay between tectonics and climatically-driven surficial processes. Tectonics acts to create topography and relief, whereas erosion tends to wear them down. Spatio-temporal changes in the landscape are defined by patterns of deformation on geomorphic markers. Without the geomorphic markers, however, an investigation of levels of deformation relies on the topographic analysis from drainage patterns, channel profiles, topographic gradient and relief, and the field of tectonic geomorphology.

Channel networks and hillslopes are sensitive to tectonic and climatic perturbations. Channel defines the relief structure of the landscape [1], transmits a signal of changes from perturbations throughout a landscape via knickpoint migration [2], and sets a new boundary condition for hillslope [3, 4]. So, channel networks can be qualitatively and quantitatively used to investigate the impact of tectonics and climate on landscape [5, 6]. Geomorphic indices are used as a measure of deformation on the landscape. They can estimate the level of tectonic activity, evaluate the influence of geo-environmental factors in landscape development, and imply the relative deformation and tectonic evolution [7, 8].

Northern Thailand is susceptible to the tectonic perturbation because it is bounded by numerous active faults. Most active faults have generated at least 4-magnitude earthquakes across the region [9]. The northern and eastern segments of the Phayao Fault Zone (PFZ) are detected about 6-8^{o}C thermal anomalies during pre- and post-earthquake events with magnitude 6.1 or greater [10]. Despite severe earthquakes found in northern and eastern segments, it does not mean that the western segment of PFZ is less active. Our study focuses on Khuang Kom and Ban Kho faults, the two main faults along the western Mueang Pan sub-basin, that have generated fewer earthquakes in records. The use of morphotectonic analysis with field investigations along these faults can spot tectonic anomalies and estimate the degree of tectonic activity and deformation.

In the study, we evaluate a relative tectonic activity based on an integration of a remote sensing approach, GIS, and geomorphic indices. We make an implication of the relative degree of deformation that is influenced by the tectonic process and evolution. Overall, our study highlights the use of morphotectonic analysis as an efficient tool to describe tectonic evolution and dynamic deformation over space and time.

Manuscript received January 12, 2023; revised March 23, 2023; accepted May 20, 2023.

doi: 10.18178/ijges.9.1.11-15

II. Material and Methods

A. Study Site

Khuang Kom and Ban Kho faults lie along the western side of Mueang Pan sub-basin with a total length of 75 km. Seventy percent of the study site is underlain by the high mountain in the west with 33 headwater channels draining to the east. Another thirty percent is categorized as a lower basin in the east. Lithology underneath the study site is Silurian-Devonian metamorphosed sandstone to quartzite, phyllite, schist, and Triassic granitic rock. The sub-basin is mantled by Tertiary and Quaternary alluvial terraces [11], Fig. 1. In terms of geologic structure, the study site is considered a half-graben that orients in the N-S direction with the east dip-direction. The average annual accumulated rainfall from 1991 to 2020 across the study site is 1200 mm [12], indicating that topography is not likely to experience strong differences in climatic conditions. Moreover, the study site presents evidence of geomorphic features such as fault scarps, triangular facets, offset streams, and hot springs that are observed on satellite images, and field observations.

B. Channel Network Characterization

We extracted 33 channel networks from the 12.5 m. digital elevation model (DEM) obtained from ALOS satellite PALSAR, Alaska Satellite Facility (ASF), and DEM obtained from SRTM 1 Arc-Second Global. We relied on a hydrologic toolset installed in ArcGIS Pro for channel extraction, characterization of patterns of channel networks by comparing with some examples of known drainage patterns in fault zone [13] and determining the distribution of different patterns of drainage systems.

C. Geomorphic Indices

Despite various geomorphic indices to assess tectonic activity, we relied on mountain front sinuosity (Smf) and stream-length gradient (SL) indices as a primary adjustment for channel-hillslope coupling [14].

Smf represents the relationship between stream erosion and slope processes that tends to produce a sinuous mountain front. However, the vertical tectonic process attempts to produce a straight mountain front [15]. Smf is computed as

$$\mathrm{Smf} = \frac{\mathrm{Lmf}}{\mathrm{Ls}} \tag{1}$$

where Lmf is the length of the mountain front along the foot of the mountain, and Ls is the true length of a straight line of the mountain front (Fig. 2). We determined a sinuous line along the mountain front with the contour interval at 10 m. Then, we calculated the Smf value at Ls ≈ 2 km each.

Strem-length gradient (SL) is a method to detect anomalies in channel profiles to interpret tectonic activity. SL shows the relationship between channel slope and distance from topographic divides that potentially implies influences of rock resistance, the presence of a fault, and climate variation [16, 17]. SL is calculated as

$$\mathrm{SL} = \frac{\Delta \mathrm{H}}{\Delta \mathrm{L}} \mathrm{x}\ \mathrm{L} \tag{2}$$

where ΔH is a change in elevation of channel reach, ΔL is the length of channel reach, and L is the length from the topographic divide to the midpoint of the reach [Fig. 3]. The calculation of SL has fixed a constant ΔL at 50 m, and ΔH was calculated via SLiX Toolbox installed in ArcGIS Pro [18]. Then, we calculated SL throughout the channel length.

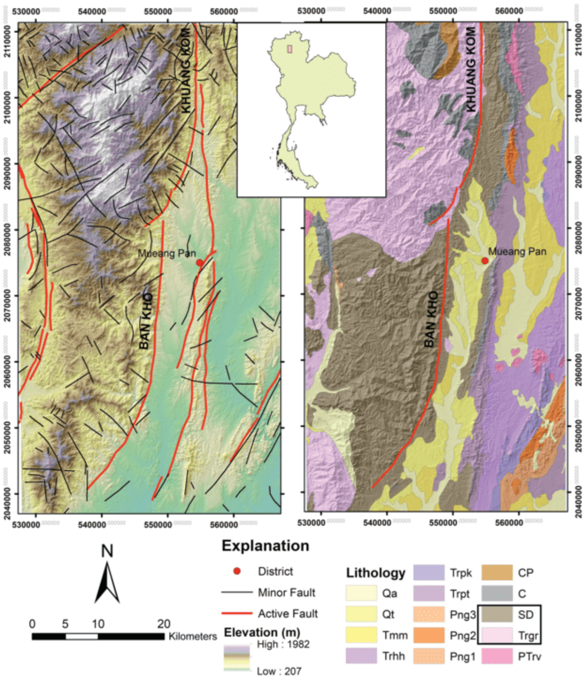

Figure 1. Left: geographic map of the study site shows location with Khuang Kom and Ban Kho faults (red lines) in Thailand (inset); Right: geologic map shows the distribution of lithology. Black rectangle represents the major lithology across the study site.

III. Result

A. Channel Network Characterization

Most channels flow from west to east. The flow corresponds to the topography of the area which is bounded by the high mountain in the west and the lower sub-basin in the east. We found that half of the channels are narrow and straight within v-shaped valleys. As a result of the characterization of 33 channel networks, we found the three main patterns of drainage networks: 1) a dendritic drainage pattern as channel flows along the slope of the terrain and the confluence is less than 90°, 2) a rectangular drainage pattern as the confluence is at the right-angle bends, and 3) a parallel drainage pattern as channels run parallel to each other along a sloped terrain (Fig. 4).

B. Geomorphic Indices

Smf demonstrates the adjustment of both vertical and horizontal channel erosion compared to the tectonic process of uplift and/or subsidence. We determined 19 lineaments in different parts along Khuang Kom fault and found that the Smf value varies between 1.02 and 2.04 (Fig. 5). The low Smf values are in the northern and southern parts, while the high Smf values are in the center of the range. Along Ban Kho fault where 21 lineaments were determined, we found that the lower Smf values distribute in the northern and central parts, whereas the Smf values higher than 1.6 are in the southern section. The categories of activeness derived from Smf are based on the range of active tectonics [15, 17].

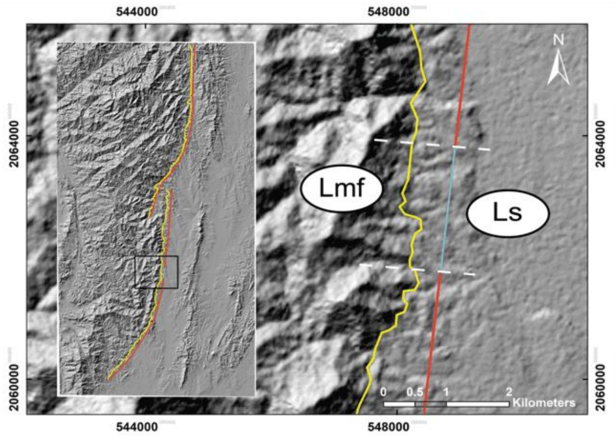

Figure 2. Smf analysis using the ratio between Lmf (yellow) and Ls (red). The blue section represents a location to calculate specific Smf.

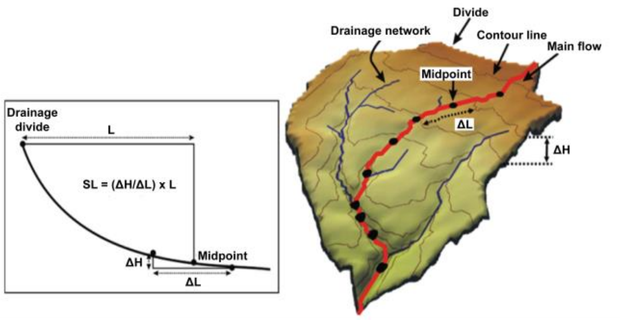

Figure 3. Left: an example of SL analysis using the ratio between ΔH and ΔL, and L from drainage divide; Right: watershed objects required for SL calculation ([19] after [16]).

SL is computed along 23 mainstreams that mainly flow to the fault (Fig. 6). For 10 channels that flow to Khuang Kom fault, SL ranges between 0.01 and 3191.58 ∇m. The lower values are along channels in the center, while the higher values are along channels in the northern and southern sections of the fault. For 13 channels that flow to Ban Kho fault, SL ranges between 0.01 and 2801.37 ∇m. The lower values distribute along channels in the center. The higher values are found in channels toward the north and the south. In addition, we observe numerous knickpoints throughout all channels. They are localized in the range of elevation at 400-500 m. with a range of moderate to high SL values (Fig. 7). The presence of knickpoint may indicate the temporal channel adjustment to the recent tectonic activity.

C. Field Observations

Field surveys were conducted to collect the geomorphic features along Khuang Kom and Ban Kho faults. We observed numerous fault scarps and triangular facets along the mountain front. Some channels such as Mae Pai, Mae Mon, and Mae Sui show offset streams on the digital elevation model, and at the location of fault trace. The direction of the stream is offset toward the northeast, and then, they turn back to the southeast. Moreover, we found the presence of the Chae Son hot spring that is located at the trace of the fault (Fig. 8).

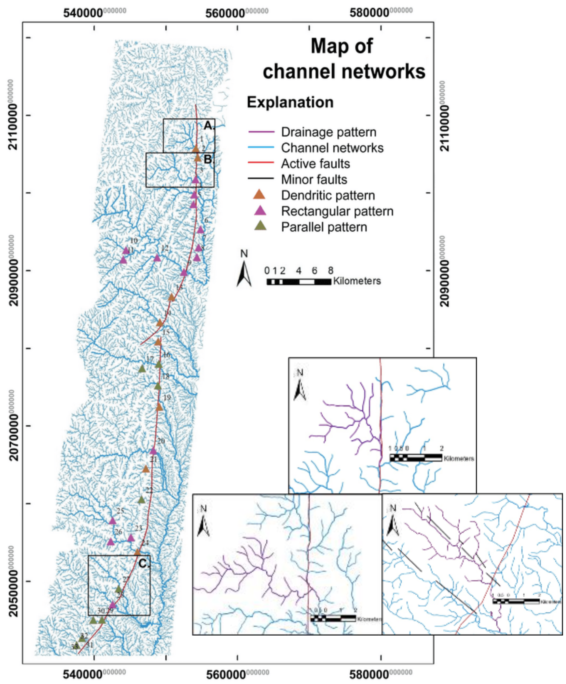

Figure 4. Map of drainage patterns across the study site. A. an example of a dendritic drainage pattern in Pa Kha stream; B. an example of a rectangular drainage pattern in Mae Tom stream; C. an example of a parallel drainage pattern in Mae Sui stream.

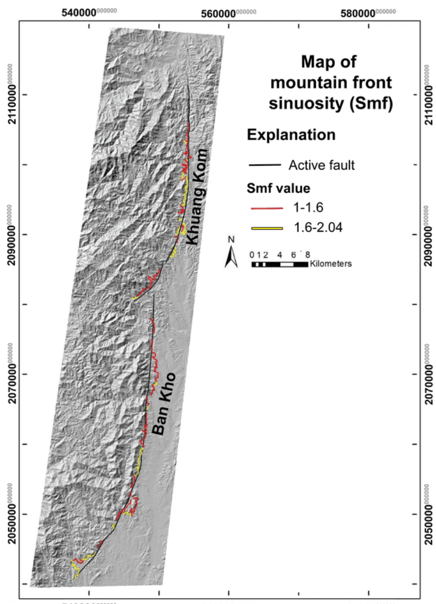

Figure 5. Map of mountain front sinuosity (Smf) across the study site.

IV. Discussion

Tectonic evolution across Southeast Asia during Cenozoic Era was a result of the collision between the NW-SE oriented Indian-Australian plate and the Eurasian plate. The collision caused a clockwise rotation of the Eurasian plate that introduced the formation of a magmatic arc and the change in fault orientations across Northern Thailand [20]. Simultaneously, various undeveloped triangular facets. It suggests the recent vertical movement of the fault that interprets the moderate to the high degree of tectonic and fault activity.

Cenozoic basins were pulled apart by E-W transtensional forces [21] that caused the oblique-slip Khuang Kom and Ban Kho faults in the PFZ and the formation of Mueang Pan half-graben. Khuang Kom and Ban Kho faults depict the relationship between drainage patterns and geomorphic features in the aerial photo and field surveys. Straight channels within v-shaped rectangular and parallel drainage patterns correspond to the presence of undeveloped triangular facets. It suggests the recent vertical movement of the fault that interprets the moderate to the high degree of tectonic and fault activity.

To imply the degree of tectonic activity, the presence of a straight mountain front with steep channels along the southern section of Khuang Kom and the northern section of Ban Kho faults suggests a higher degree of tectonic activity. However, a more sinuous mountain front and gentler channels near the mountain toe in the central zone of both faults implies to a lower degree of tectonic activity. The results reveal that 89% of the total study area reasonably falls in an active mountain front, while the remaining 11% is less active.

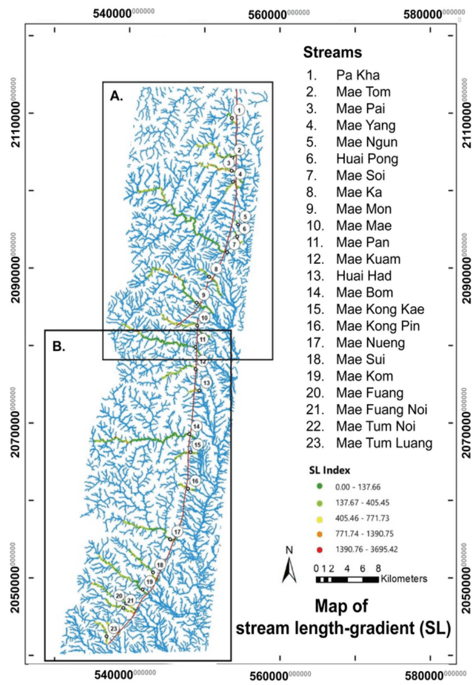

Figure 6. Map of stream length-gradient (SL) across the study site. A. SL in 10 mainstreams (#1-#10) along Khuang Kom fault; B. SL in 13 mainstreams (#11-#23) along Ban Kho fault.

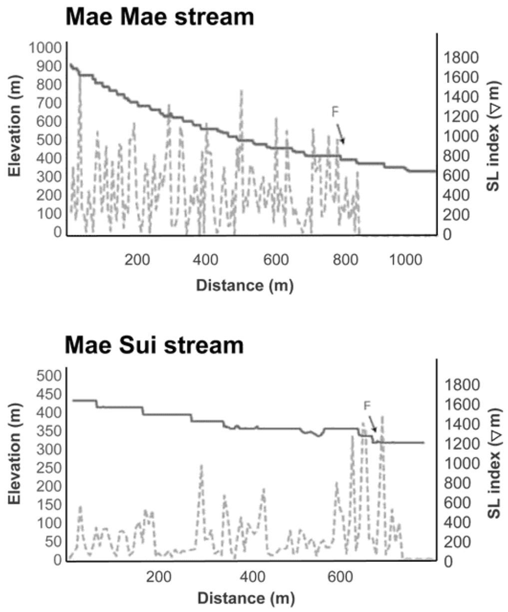

Figure 7. The relationship between longitudinal profile (dark gray) and SL (gray dashed line). Top: an example of Mae Mae stream along Khuang Kom fault; Bottom: an example of Mae Sui stream along Ban Kho fault; F illustrates the location of the fault trace.

Figure 8. Examples of geomorphic features along Khuang Kom and Ban Kho faults. Left: triangular facets (white lines) behind Ban Kho fault (red dashed line). Right: Chae Son hot spring located at the fault trace

Rock uplift and deformation are possible to be a role of tectonic activity where Ban Kho fault abuts Khuang Kom fault. The footwall of normal-faulted terrain is uplifted with a reduction of overburden loads. Highly active mountain front at lithologic contact may relate to an abrupt change of rock resistance for stress accumulation and release on the faults. To better evaluate tectonic activity across the region, various geomorphic indices such as valley floor width-height ratio, drainage asymmetry, basin shape index, and hypsometrical integral are additionally required to classify the whole relative indices of active tectonic (RIAT). Future studies of structural geology, seismology, and geodynamics will be coupled with the geomorphic indices for a stronger evaluation of a tectonic activity.

V. Conclusion

Khuang Kom and Ban Kho faults are the two main active faults along the western Phayao Fault Zone. They orient in the north-south direction and dip eastward to the Mueang Pan lower basin. Geomorphic features observed along the faults are fault scarps, triangular facets, offset streams, and hot springs. Most channels are narrow and straight within v-shaped valleys. The patterns of channel networks are rectangular and parallel that indicate the presence of joints and minor faults.

Geomorphic indices are used as morphotectonic analysis to determine the level of tectonic activity. Our result from lower mountain front sinuosity with steep channel gradient at the base of the mountain front reveals that 89% of the whole study site is active mountain front. Particularly, a site where two abutting oblique-slip faults and lithologic contact potentially experiences higher uplift of rock and deformation. The remaining 11% falls into higher mountain front sinuosity with a lower channel gradient that implies less activity. Although the combination of more geomorphic indices can help us evaluate tectonic activity more accurately, our study, at least, provides a valuable tool and method for estimating tectonic activity and a potential deformation in the region.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The authors confirm contribution to the paper as follow: Pichawut Manopkawee (PM) stated research problem and research design; Jiratchaya Khamkaew (JK) collected data; PM and JK analyzed the data; PM and JK interpreted the data; PM wrote the paper; all authors had approved the final version of the paper.

Acknowledgement

The authors would like to express thanks to experienced researchers and lecturers, and senior students in the Department of Geological Sciences, Faculty of Science, Chiang Mai University who gave a big collaboration to conduct the research. This work was supported in part by a grant from the 50th Anniversary Geology Fund, Chiang Mai University.

References

[1] K. X. Whipple and G. E. Tucker, "Dynamic of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs," *J. Geophys. Res.,* vol. 104, pp. 17661–17674, Aug 1999.

[2] E. Kirby and K.X. Whipple, "Expression of active tectonics in erosional landscapes," *J. Struct. Geol.,* vol. 44, pp. 54–75, Aug 2012.

[3] R. A. DiBiase, A. M. Heimsath, and K. X. Whipple, "Hillslope response to tectonic forcing in threshold landscapes," *Earth Surf. Process. Landf*., vol. 37, no. 8, pp. 855–865, Jan 2012.

[4] M.D. Hurst, S.M. Mudd, M. Attal, and G. Hilley, "Hillslopes record the growth and decay of landscapes," *Science,* vol. 341, pp. 868-871, Aug 2013.

[5] N. P. Snyder, K. X. Whipple, G. E. Tucker, and D. J. Merritts, "Landscape response to tectonic forcing: Digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California," *Geol. Soc. Am. Bull.*, vol. 112, pp. 1250–1263, Aug 2000.

[6] R. A. DiBiase, K. X. Whipple, A. M. Heimsath, and W. B. Ouimet, "Landscape form and millennial erosion rates in the San Gabriel Mountains, CA," *Earth Surf. Process. Landf*., vol. 289, pp. 134–144, Nov 2009.

[7] E. Kirby, C. B. Johnson, K. P. Furlong, and A. M. Heimsath, "Transient channel incision along Bolinas Ridge, California: Evidence for differential rock uplift adjacent to the San Andreas Fault," *J. Geophys. Res.,* vol. 112, 2007.

[8] C. B. Johnson, K. P. Furlong, and E. Kirby, "Integrated geomorphic and geodynamic modelling of a potential blind thrust in the San Francisco area, California," *Tectonphysics,* vol. 471, pp. 319–328, June 2009.

[9] P. Charusiri, S, Pailoplee, S. Kosuwan, I. Takashima, and B. Rhodes, "Active fault and seismic zonation in Thailand: An empirical compilation," *Bull. Earth Sci of Thailand,* vol. 14, no. 1, pp. 11–34, Feb 2022.

[10] P. Wongpornchai, and C. Suwanprasit, "Feasibility study of thermal anomaly detection for earthquake: A case study from 2014 Mae Lao earthquake, Thailand," in *Proc. IOP Conf. Ser.: Earth Environ. Sci.,* vol. 538, 2020.

[11] Department of Mineral Resources, Thailand, Geological Survey Division. *Geologic map of Changwat Lampang Quadrangle scale 1:250000*. [Online], Available: https://oer.learn.in.th/search_detail/result/14921#/MLA

[12] Lamphun Meteorological Department. *Average annual accumulated rainfall within a period of 30 years (1991-2020)* [Online]. Available: http://www.cmmet.tmd.go.th/station/lpn/

[13] A. I. Mejia and J. D. Niemann, "Identification and characterization of dendritic, parallel, pinnate, rectangular, and trellis networks based on deviations from planform self-similarity," *J. Geophys. Res.,* vol. 113, 2008.

[14] M. Church, "Pattern Instability in a wandering gravel bed channel," *International Association of Sedimentologists*, Special Publication 6, Oxford, 1983, pp. 169–180.

[15] W. B. Bull and L. D. Fadden, "Tectonic geomorphology north and south of the Garlock Fault, California," in *Proc. 8th Annual Geomorphology Symposium on Geomorphology in Arid Regions,* State University of New York, Binghamton, 1997, pp. 115–138.

[16] J. T. Hack, "Stream-profile analysis and stream-gradient index," *J. Res. US Geol Surv*., vol. 1, no. 4, pp. 421–429, Aug 1973.

[17] E.A. Keller and N. Pinter, "Active tectonics: Earthquake, uplift and landscape," 2nd ed. Upper Saddle River, N.J.: Prince Hall, 2022, pp. 126–133.

[18] D. Piacentini, F. Troiani, T. Servizi, O. Nesci, and F. Veneri, "SLiX: A GIS toolbox to support along-stream knickzones detection through the computation and mapping of the stream length-gradient (SL) Index," *ISPRS Int. J. Geoinfo*., vol. 9, no. 69, pp. 1–14, Jan 2020.

[19] M. Font, D. Amorese, and J. L. Lagarde, "DEM and GIS analysis of the stream gradient index to evaluate effects of tectonics: the Normandy intraplate area (NW France)," *Geomorphology,* vol. 119, pp. 172–180, July 2010.

[20] G. Peltzer, and P. Tapponnier, "Formation and evolution of strike-slip fault, rift, and basin during the India-Asia collision: An experimental approach," *J. Geophys. Res.,* vol. 93, pp. 15085–15117, Dec 1988.

[21] W. Uttamo, C. Elders, and G. Nichols, "Relationships between Cenozoic strike-slip faulting and basin opening in northern Thailand," *Geol. Soc. Spec. Publ*., vol. 210, pp. 89–108, Jan 2003.