Pull-Apart Basins of Sumatran Fault: Previous Works and Current Perspectives

Conference Paper · October 2016

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PULL-APART BASINS OF SUMATRAN FAULT: PREVIOUS WORKS AND CURRENT PERSPECTIVES

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ABSTRACT

The Sumatran Fault has been subjected of scientific researches for decades. Katili (1967) is regarded as the earliest work for defining The Sumatran Fault having transcurrent deformation in the light of plate tectonics. Following the work of Katili (1967), Bellier and Sebrier (1994) proposed structural interpretation of Sumatran Fault pull-apart basins using SPOT images. In 2000, Sieh and Natawidjaja published their work concerning neotectonics of Sumatran Fault. Previous works emphasizes on intensive segmentation of Sumatran Fault as distinctive feature. To address the segmentation of Sumatran Fault, concerns should be paid to tectonic evolution of the area. Sumatra was built based upon continental collisions from Late Paleozoic to Late Mesozoic. The collisions generated NW-SE trending basement structure (Barber et al., 2005). Counterclockwise rotation of Sundaland on Middle Miocene triggered the activation of Sumatran Fault in right-handed kinematics. Pre-existing basement structure facilitated the deformation. Sumatran Fault has right-stepping geometry, so that several pull-apart basins develop along the fault. This paper concerns with current interpretation of fault configuration based on SRTM data. Interpretation runs from Aceh, Kutacane Graben, Toba Caldera, Tarutung-Sarulla Basins, Barumun-Angkola Segments, Lake Singkarak, Muaralabuh-Sungai Penuh Basins, Musi-Manna Segment, Lake Ranau, Suoh Valley, and Sunda Strait. Fault interpretation aims to classify Sumatran Fault pull-apart basins in terms of structural mechanism and kinematic models. Structural mechanism comprises fault-bend and oversteps basins. Meanwhile, kinematic models emphasizes on fault configuration. New division of Sumatran Fault is proposed, applying structural mechanism as the basis. Sumatran Fault can be packaged in three repetitions of fault-bend mechanism followed by overstep one. Northern, central, and southern structural packages are elaborated in the paper.

Kata kunci : *Sumatran Fault, Basement Structures, Fault-bend Basin, Overstep Basin, Structural Mechanism, Kinematic Model.*

I. INTRODUCTION

Sumatran Fault is a transcurrent fault extending 1900 km in NW-SE along the western part of the island. The fault has been inviting scientific interest, provided many researches produced in the area. Katili (1967) is regarded as early work defining The Sumatran Fault in the light of plate tectonics. Decades later, Bellier and Sebrier (1994) provided structural interpretation of the fault based on SPOT images. In the beginning of 21st century, Sieh and Natawidjaja (2000) characterized Sumatran Fault through 1:50.000 - scale topographic maps and 1:100.000 - scale aerial photographs. Previous works emphasize intensive segmentation as distinctive feature of Sumatran Fault.

With the aid of Shuttle Radar Topography Mission (SRTM) data, more detailed interpretation could be achieved in this paper. The aim of this paper is to characterize the structural mechanism and kinematic models applied along Sumatran Fault. Characterization of Sumatran Fault is critical in terms of seismicity and resources. Active tectonic setting enables Sumatran Fault to slip at any time. On the other hand, considerable geothermal resources lie beneath Sumatran Fault.

II. DATA AND METHOD

Detailed geomorphic expression of SRTM data provides reliable basis for interpretation. Interpretation of SRTM data will be tied to structural mechanism and kinematic models of pull-apart basin provided by Allen and Allen (2005). Structural mechanism comprises overstep basin and fault-bend basin (Figure 1). Meanwhile, kinematic models include overlap of side-stepping faults, slip on divergent fault segments, and coalescence of scale-dependent basins. Mechanisms and models proposed by Allen and Allen (2005) are end-members. Further consideration should be put in place when applying the concepts in Sumatran Fault.

III. TECTONIC EVOLUTION AND REGIONAL SETTING

Propagation of transcurrent fault along Barisan Mountains of Sumatra strongly relates to the tectonic evolution of the area. Sumatra is the result of continental collisions since Late Paleozoic until Late Mesozoic. Tectonic collisions in Sumatra provide pre-existing structure for Sumatran Fault to move along.

Barber and Crow (2009) in Figure 2 concluded that the collision of Indochina Block and Sibumasu Block occurred in Late Permian. The collision is not marked by suture, but a wide accretionary zone recognized as Bentong-Raub Accretionary Complex. West Sumatra Block drifted from SE Indochina Block along right-lateral transcurrent fault (Barber et al., 2005), later regarded as Medial Sumatra Tectonic Zone (MSTZ). Spreading of Meso-Tethys provided tectonic mechanism for MSTZ to propagate in Early Triassic. Obduction of Woyla Nappe over West Sumatra Block in Late Cretaceous marked the end of amalgamation of Sumatra.

The collisions of tectonic blocks generate NW-SE trending basement structure. In Middle Miocene, counterclockwise Sundaland rotation became tectonic mechanism for the activation of the Sumatran Fault with right-lateral kinematics (Hall, 1996). Based on Figure 1, Sumatran Fault is concentrated in the western part of the island. Distribution of tectonic blocks is suggested as the constraining factor for the position and distribution of Sumatran Fault. With changing spatial distribution of tectonic blocks, deformation generated along the fault also differs. In addition, oblique subduction becomes physical mechanism to partition subduction into dip-slip along the trench and strike-slip movement on the overriding plate (McCaffrey, 2009), enabling recent seismicity. Sequence of geologic events generating Sumatran Fault is summarized in Figure 3.

IV. FAULT CONFIGURATION OF PULL-APART BASIN ALONG SUMATRAN FAULT

Sieh and Natawidjaja (2000) has contributed substantial insight in the segmentation of Sumatran Fault. The Sumatran Fault can be recognized in 19 segments from Aceh to Sunda Strait with predominantly dilational stepover. These geometric characteristics enable the formation of several pull-apart basins. Structural interpretation starts from Aceh to Kutacane Graben, then running along west of Toba Caldera, moving to Tarutung-Sarulla Basins and jumping to Barumun-Angkola Segments. The trip continues to Lake Singkarak, Muaralabuh-Sungai Penuh Basins, Musi-Manna Segments, Lake Ranau, Suoh Valley, and eventually Sunda Strait. Characterizing Sumatran Fault in terms of structural mechanism and kinematic models will part of the following discussions.

Aceh-Simeuleum-Tripa Segments

Aceh and Simeuleum Segments have synthetic fault splaying. The Sumatran Fault from NW offshore area enters the onshore by a releasing bend (Figure 4). Distinctive depression of spindle-shape can be recognized in the SRTM data. Moving southeast, Aceh and Simeuleum Segments merge to form Tripa Segment. Tripa Segment has left-bending geometry, giving rise to the uplift along the bending. Restraining bend becomes structural mechanism of the segment.

Kutacane Graben

Kutacane Graben has distinctive geomorphic feature as spindle-shaped depression with uplifted area surrounding it. Structural features of Kutacane Graben are result of Sumatran Fault releasing bend mechanism. Barber et al. (2005) marked two bounding faults namely Toru Fault in the north and Lawe Alas Fault in the south.

Kutacane Graben is best at depicting anastomosing fault pattern. SRTM interpretation marks three strike-slip faults responsible for deformation in Kutacane Graben and the surrounding area. KcF1 Fault in the north (Figure 5) bends in releasing manner to form Kutacane Graben. In the meantime, KcF2 Fault propagates along the western part of the graben. To ensure the deformation to proceed efficiently, KcF3 Fault facilitates the deformation as connecting fault. As a result, anastomosing fault geometry achieved.

Toba Caldera

Toba Caldera has been recognized as tectono-volcanic feature of Sumatra with phenomenal eruption 73.000 years ago. With NW-SE trending elongate geometry, Sumatran Fault influence on the formation of caldera was proposed by Bellier and Sebrier (1994). Bellier and Sebrier (1994) built a structural evolution of Toba Caldera (Figure 6). Wide dilational stepover (100 x 30 km) formed initially. The faults ran along the NE and SW margins of Toba Caldera and controlled the collapse mechanism of the caldera and uplift of Samosir Island. NW-SE trending normal faults in Samosir Island were regarded as the influence of en echelon strike-slip fault. Currently, bounding faults forming Toba Caldera is interpreted to be inactive (Bellier and Sebrier, 1994) and continues to Tarutung - Sarulla basins.

Interpretation of SRTM data provides another perspective regarding Toba Caldera in Figure 7. The caldera has extensive geometry, requiring wide bounding faults to form the structures. Toba Caldera has incomparable dimension than other pull-apart basins along Sumatran Fault. To create such an extensive stepover, tectonic blocks should provide pre-existing structures for the fault to move along. The challenge is that Toba Caldera standing on Sibumasu Block and being in a distance with tectonic contact. Current Sumatran Fault runs along west of Toba Caldera and makes use the contact between Sibumasu Block and West Sumatra Block.

Deformation in Samosir Island is an interesting subject in Figure 8. Since Sumatran Fault hardly forms the structure for Toba Caldera, deformation in Samosir Island should not be in relation to the regional strike-slip faulting. Samosir Island exists as horst within the caldera, being the result of collapse. SRTM interpretation provides two particular structural trends in Samosir Island. Sms1 Fault formed initially in curvilinear geometry in response to collapse with NW-SE. Then, southern part of Samosir Island achieved equilibrium with collapse in N-S trend. Cross-cutting relationship between the two fault trends can be observed in the southern part of the island.

Tarutung-Sarulla Basins

Tarutung-Sarulla Basins lies in the southeast of Toba Caldera with prospective geothermal resources, as related to volcanism. Tarutung-Sarulla Basins are two distinct pull-apart basins formed by releasing bend of Sumatran Fault. Interpretation of SRTM data provides that the basins have elongate, narrow geometry. Southern bounding fault of Tarutung Basin connects with the northern bounding fault of Sarulla Basin. The structural correlation of the two basins give rise to the understanding that only one fault extending in the area. Therefore, fault-bend mechanism is applied to Tarutung - Sarulla Basins. Fault configuration in Tarutung - Sarulla Basins is comparable to slip on divergent fault segments (Figure 9).

Nukman and Moeck (2013) provides interesting insights about Tarutung Basin. Strike-slip faults develop from E-W to NW-SE trends, while normal faults trending in WNW-ESE to NE-SE. Strike-slip faults acted as the basin margin. Correlation of the structures to principal displacement zone (PDZ) trend gives that rotation has been involved in normal faults for 90 – 120o. Reverse faults existed outside the basin margin with WNW-ESE trend with no rotation observed. Left-lateral strike-slip fault also observed as antithetic association to the PDZ in ENE-WSW outside the basin margin (Figure 10).

Barumun-Angkola Segments

Sieh and Natawidjaja (2000) regarded Barumun-Angkola Segments as equatorial bifurcation. Complex geology is observed in the area. Sieh and Natawidjaja (2000) stated that Toru Segment branches to Barumun Segment with dilational stepover. Angkola Segment also makes no distinctive contact to Toru and Sumpur Segments. Dilational stepover also observed between Barumun and Sumpur Segments.

SRTM interpretation in Figure 11 provides that Barumun-Angkola Segments involve transtensional duplex mechanism. Double fault bending is responsible to create rhomboid basin geometry. Sumatran Fault trends in NW-SE then bends to NNW-SSE in Barumun Segment as the northern bounding fault. Meanwhile, Angkola Segment bends from NNW-SSE trend to NW-SE trend. Double fault bending causes the uplift along the outer margin of the faults. Area inside the bounding faults experienced extension. Uplifted area inside the bounding faults acts as horst, being a response to flexural effect to tectonic unloading.

Complex structural geometry in Barumun-Angkola Segments cannot be approached with structural mechanism and kinematic models. Constraining factor in the formation of complex structure in Barumun-Angkola Segments is basement configuration. Referring to tectonic blocks map of Barber and Crow (2009), Barumun-Angkola Segments lies above narrow contacts between Sibumasu Block, MSTZ, West Sumatra Block, and Woyla Nappe. Intricate pre-existing structures of the basement provide the basis for complex deformation. Going to southeast, West Sumatra Block widens and narrow contacts between tectonic blocks are not observed.

Lake Singkarak

Lake Singkarak is a distinct form of overstep basin with slip on divergent fault segments model. Sieh and Natawidjaja (2000) stated that Lake Singkarak formed due to the stepover of Sianok and Suliti Segments. Lake Singkarak has length of 23 km and width of 7 km. Bellier and Sebrier (1994) proposed a structural evolution of Lake Singkarak in three phases (Figure 12). The first two phases are development of stepover to form pull-apart basin. The last phase is the end of Lake Singkarak extension since a new strike-slip fault moved within the lake and terminated extension. The early formed fault came to extinction.

Singkarak, Diatas, and Dibawah Lakes have distinctive fault configuration. Two bounding faults exist in the north, namely SgF1 and SgF2 Faults, and another exist in the south as SgF3 Fault. SgF1 Fault has left-bending geometry with possible contractional structures. SgF1 and SgF2 Faults are arranged in left-stepping geometry, enabling formation of contractional structures in between. SgF3 Fault propagates as one fault from Lake Singkarak to Lake Diatas-Dibawah (Figure 13).

Singkarak, Diatas, and Dibawah Lakes are proposed to form as a pull-apart basin. Interpretation is based on the termination of SgF1 Fault and existence of Mount Talang. SgF1 Fault doesn’t terminate by merging with SgF3 Fault, but forming a gap in between. SgF2 Fault which lies in the left side of SgF1 Fault extends southeastward to merge with SgF3 Fault. On the other hand, Mount Talang stands inside the pull-apart basin. Volcanism of the mountain obscures structural features of Diatas-Dibawah Lakes. By observing structural lineament and removing volcanism, structural correlation between Lake Singkarak and Diatas-Dibawah Lakes can be built.

Muaralabuh-Sungai Penuh Basins

Muaralabuh-Sungai Penuh Basins are cases of fault splaying. Muaralabuh-Sungai Penuh Basins are formed by fault-bend mechanism with different dimension. Muaralabuh Basin has smaller dimension due to gentle fault splaying. Southern bounding fault of Muaralabuh Basin connects with northern bounding fault of Sungai Penuh Basin. Sungai Penuh Basin widens to the southeast, as the faults running subparallel. Kinematic observation from this case is that Sungai Penuh Basin has greater angle of oblique medial fault as the connecting fault within the basin (Figure 14).

Musi-Manna Segments

Musi-Manna Segments have confusing relation due to volcanism of Mount Patah. Musi Segment forms pull-apart basin narrowing to the southeast. Fault-bend mechanism of the basin is proposed due to narrow geometry and bounding faults configuration. Subparallel faults indicate slip on divergent fault segments model. Extending to southeast, relationship between Musi-Manna Segments is interpreted to be dilational stepover. The interpretation is based on assumption that volcanism makes use of pre-existing structure for its emplacement (Figure 15).

Lake Ranau

Lake Ranau has rectangle geometry with 12 x 16.5 km dimension. Bellier and Sebrier (1994) stated that Sumatran Fault pull-apart basin in this area correlates to the formation of Pleistocene volcanism (Figure 16). Such volcanism existed in the southwestern margin of stepover. Caldera eruption caused the collapse and integration of volcanic and tectonic depressions into a lake. The final phase is a new strike-slip fault intersecting the inner basin to join with Suoh Valley in the southeast. Extension in Lake Ranau was terminated since the last phase.

Lake Ranau forms with overstep mechanism and overlap of side-stepping fault model. SRTM interpretation in Lake Ranau carries out another perspective in Figure 17. Pull-apart basin and Pleistocene volcanism is not related spatially. Caldera eruption was initially outside pull-apart basin. The interpretation begins with challenge in terminating the movement of a fault segment. The southern bounding fault of Lake Ranau by Bellier and Sebrier (1994) must have been active since it formed. The challenge in deactivating a fault segment is by rapid, thick sediment burial and no operating tectonic forces. Tectonic setting as in Sumatra cannot enable deactivation of tectonic forces, since oblique subduction still operating. Although a fault segment can terminate by horse-tailing, the fault may not increase in horizontal dimension, but it becomes uplifted or depressed. Caldera eruption of the volcano which made tectonic and volcanic depressions merged to be Lake Ranau.

Suoh Valley

Suoh Valley is best at depicting overstep basin mechanism with overlap of side-stepping fault model in Sumatran Fault. Suoh Valley expresses interesting structure since two basins develop in different time (Figure 18). Suoh Valley (C1) was initially formed by the overlap of SuF1 and SuF2 Faults. As time progressed, the basin deepened and created steep slope. Another fault segment then developed in between SuF1 and SuF1 Faults as SuF3 Fault. SuF3 Fault along with SuF1 Fault formed another pull-apart basin (C2). C2 is interpreted to form later based on shallower basin depth than C1.

Sunda Strait

Barber et al. (2005) defined Sunda Strait opening as the interaction of Sumatran Fault and Ujungkulon Fault. Sumatran Fault and Ujungkulon Fault are arranged in right-stepping geometry (Figure 19). Therefore, pull-apart basin with N-S trending structure and 1800 meters depth develop. The opening of Sunda Strait by strike-slip faulting also provides the reason why distance between Sumatra and Java is further in the south then in the north. Structural mechanism forming Sunda Strait is overstep basin with overlap of side-stepping fault.

V. RELATION OF SUMATRAN FAULT PULL-APART BASINS WITH VOLCANIC CLUSTERS

Muraoka et al. (2010) provides great insights in understanding the relation between Sumatran Fault pull-apart basins with the volcanic clusters. Muraoka et al. (2010) elaborated three important ideas: roles of volcanic clusters in pull-apart basins formation, geometry of fault tips against volcanic clusters, and clockwise rotation within Sumatran Fault.

Volcanic clusters can act as generators and inhibitors of pull-apart basins (Muraoka et al., 2010). In northwest Sumatra, volcanic clusters develop in the back-arc side of the island, away from Sumatran Fault. This observation is regarded as volcanic cluster fostering pull-apart basin formation. In the other case, pull-apart basin is missing in volcanic cluster zone. For instance, pull-apart basin is absent west of Toba Caldera. Tightly-spaced volcanic clusters also contribute to the absence of pull-apart basins, as observed in Talamau-Marapi volcanic clusters and Dempo-Pesagi volcanic clusters.

Muraoka et al. (2010) emphasizes the control of volcanic clusters over fault geometry. Muaralabuh and Sungai Penuh Basins are taken as examples. Both basins become wider in southward direction, as facing to Kerinci volcanic clusters for Muaralabuh Basin and to Masurai volcanic clusters for Sungai Penuh Basin. Eastward warping of northern fault segment forming the basins is considered as spatial compensation to volcanic clusters. In other words, formation of Muaralabuh and Sungai Penuh Basins are composite effects of tectonic and volcanic aspects.

The challenges to the idea proposed by Muraoka et al. (2010) are the warping mechanism and geologic time-frame. As discussed in previous section, formation of Muaralabuh and Sungai Penuh Basins are triggered by fault splaying with fault-bend mechanism. Rather than arranged in parallel manner, faults are configured at an angle, giving rise to southward-widening basin geometry.

Warping mechanism begins with the formation of pull-apart basins in Middle-Miocene by overstep mechanism, given three faults arranged in en echelon manner. In Quarternary, Kerinci and Masurai volcanic clusters built up, disturbing the pre-existing spatial arrangement of the geology. The northern fault segments of both basins warp to the east, widening the basin to the south. In order to warp the fault segment, accommodating structures must have proceeded (Figure 20). North – south to NNE – SSW left-lateral faults must have been observed north of the basin to enable eastward warping. Meanwhile, faults with similar orientation and with right-lateral kinematics must have accommodated deformation in the south of southern bounding fault.

However, geomorphic expression near the northern fault segments is consistent with NW-SE structural lineaments. Therefore, structural mechanism forming Muaralabuh and Sungai Penuh Basins is fault splaying. Emergence of volcanic clusters has no significant impact on the re-arrangement of pre-existing geology.

As transcurrent faulting related to block rotation, both Kerinci and Masurai volcanic clusters display clockwise drag within deformation zone (Muraoka et al., 2010). Weak drags are observed as an indication of overprinting of recent fault movements over Quarternary volcanoes. Interesting tectonic mechanism observed in Sumatra is the clockwise rotation within Sumatran Fault, triggered within counterclockwise Sundaland rotation.

VI. STRUCTURAL SYNTHESIS OF SUMATRAN FAULT

Structural synthesis of Sumatran Fault aims to emphasize the possible correlation between structural mechanism, basement structures, and regional setting. Considerations put in the synthesis set out from the work of Sieh and Natawidjaja (2000) which divides Sumatra into three zones based on structural features: northern, central, and southern domains. Northern domain extends from Aceh-Simeuleum Segments until southeastern tip of Kutacane Graben, while central domain ends at the southeastern tip of Barumun-Angkola Segments. Southern domain extends until the Sunda Strait. The synthesis attempts to develop this division, by providing structural pattern and basement structures consideration.

Sumatran Fault displays fault-bend mechanism and overstep mechanism interchangeably, with the latter being in the southeastern part. Turning into the structural pattern, Sumatran Fault has three repetitions along from Aceh-Simeulem Segments until Sunda Strait. The northern structural package starts from Aceh-Simeuleum Segments until Renun Segment. The transition takes place in Kutacane Graben. The central structural package extends from Tarutung-Sarulla Basins to Lake Singkarak. This package has distinctive Barumun-Angkola Segments as connection between fault-bend mechanism with the overstep one. The southern structural package bears the longest distance, extending from Muaralabuh-Sungai Penuh Basins until Sunda Strait. Overstep mechanism tends to dominate the southern package quantitatively.

The implication of structural packaging is to capture the correlation of structural mechanism and the basement structures. The northern structural package has relatively wide and long fault-bend mechanism zone, before changing into straight Renun Segment. The cause of wide, long fault-bend mechanism of northern structural package is intricate basement structures, as depicted by Barber and Crow (2009) in Figure 1. In contrast, Renun Segment sits on a straight fault contact between Sibumasu Block and West Sumatra Block, being in the absence of MSTZ.

Basement structures after Renun Segment display right-bending geometry before being in contact with MSTZ. The fault bending later on becomes deformation zone for Tarutung-Sarulla Basins. Structural mechanism becomes more complex in Barumun-Angkola Segments since Sibumasu Block, MSTZ, and West Sumatra Block are arranged in narrow zone, enabling intricate basement structures. The complexity of basement structures in the area is represented by transtensional duplex mechanism. Going to Lake Singkarak, overstep mechanism develops since the continental contacts have been wider.

The southern structural package possesses fault-bend mechanism in Muaralabuh-Sungai Penuh Basins and Musi-Manna Basins due possibly to stratigraphic heterogeneities of West Sumatra Block which come into contact with Woyla Nappe. Combination of thrust-related structures and pre-existing strike-slip faulting give rise to intricate basement structures in the area. Entering Lake Ranau until Sunda Strait, tectonic block tends to be as homogenous as Woyla Nappe.

The correlation between structural mechanism and basement structures is that intricate pre-existing structures trigger fault-bend mechanism, as depicted in complex tectonic contacts. On the other hand, overstep mechanism develops in area of straight tectonic contact or lying in relatively homogenous basement stratigraphy.

VII. RECOMMENDATION FOR FUTURE WORKS ON SUMATRAN FAULT

Works on Sumatran Fault have come through various perspectives. Previous works emphasized in this paper focus on fault configuration and deformation characteristics. Recommendations for future works on Sumatran Fault come in two domains: research and resources. In terms of research, we have to address ideas on the correlation between Sumatran, Ujung Kulon, Cimandiri, and Lembang Faults. Correlation should be worked on in order to build a framework regarding Sundaland Transcurrent System. The primary reason for this correlation is that Sumatran Fault creates overstep basin with Ujung Kulon Fault. Rather than terminating in Sunda Strait, Sumatran Fault builds a system with other transcurrent faults.

Two challenges must be overcome in order to define Sundaland Transcurrent System: basement geology and subduction mechanism. To integrate Sumatran, Ujung Kulon, Cimandiri, and Lembang Faults, they must have existed possibly in the same basement stratigraphy. Extension of Sibumasu Block, West Sumatra Block, and Woyla Nappe in West Java is in question.

Oblique subduction in Sumatra has long been regarded as important mechanism in transcurrent faulting. Obliquity of subduction changes to be gentler in West Java. This change may affect the transcurrent system developing in the area. Subduction obliquity is also critical to link Sumatran, Ujung Kulon, Cimandiri, and Lembang Faults.

Resources, the second domain, deal with subsurface structures of Sumatran Fault. Structures beneath the SRTM interpretation always attract attention since we have complex deformation in surface geology. Integrated geophysical surveys combined with seismicity may generate desirable conclusion of subsurface Sumatran Fault.

VIII. CONCLUSIONS

Study of previous works and interpretation of SRTM data provide a chance of redefining Sumatran Fault. Sumatran Fault develops as transcurrent fault due to pre-existing basement structure and counterclockwise Sundaland rotation as tectonic mechanism. Oblique subduction is recent physical mechanism of how transcurrent fault develops. With right-stepping geometry and right-lateral kinematics, several pull-apart basins develop along Sumatran Fault. Based on structural mechanism categorization, overstep basin can be observed in Lake Singkarak, Musi-Manna Segments, Lake Ranau, Suoh Valley and Sunda Strait. Meanwhile, fault-bend basin is expressed in Kutacane Graben, Tarutung-Sarulla Basins, and Muaralabuh-Sungai Penuh Segments. Barumun-Angkola Segments belong to transtensional duplex mechanism since double fault bending characterizes the area. Kinematic model of overlap of side-stepping fault is observed in Lake Ranau, Suoh Valley, and Sunda Strait. Slip on divergent fault segments can be observed in Aceh-Simeuleum Segments, Kutacane Graben, Tarutung-Sarulla Basins, Lake Singkarak, Muaralabuh-Sungai Penuh Basins, and Musi Segment Basin.

Structural mechanism of Sumatran Fault can be classified into northern, central, and southern structural package. Northern structural package extends from Aceh-Simeuleum Segment until Renun Segment, central package from Tarutung-Sarulla Basins until Lake Singkarak, and southern package from Muaralabuh-Sungai Penuh Basins until Sunda Strait. Fault-bend mechanism and overstep one exist interchangeably along Sumatran Fault within three repetitions, as related to structural packaging. The primary reason of interchanging structural mechanisms is the arrangement of basement structures and stratigraphy.

Geologic flow diagram (Figure 21) can be drawn to explain the occurrence of Sumatran Fault. Basement structures and stratigraphy began to set up in Late Mesozoic, marked by obduction of Woyla Nappe. Paleogene volcanism and stratigraphy of Barisan provided rock units to be involved in Sumatran Fault deformation. Sundaland counterclockwise rotation in Middle Miocene became tectonic mechanism enabling right-lateral strike-slip faulting in Sumatra. Paleogene rock units were uplifted to form Barisan Mountains. The tectonic mechanism also continues ever since, manifested in recent seismicity. Sumatran Fault deformation is arranged into interchanging repetition of fault-bend mechanism and overstep one, given that the latter always being in the southeastern part.

REFERENCES

Allen, P. A., dan Allen, J. R., 2005, *Basin Analysis: Principles and Applications: Second Edition*: Malden, Blackwell Publishing company, 549 p.

Barber, A. J., Crow, M. J., dan Milsom, J. S., 2005, *Sumatra: Geology, Resources, and Tectonic Evolution*: London, Geological Society, 290 p.

Barber, A. J., dan Crow, M. J., 2009, *Structure of Sumatra and Its Implication for the Tectonic Assembly of Southeast Asia and the Destruction of Paleotethys: Island Arc*, John Wiley & Sons Australia.

Bellier, O., dan Sebrier, M., 1994, *Relationship Between Tectonism and Volcanism Along the Great Sumatran Fault Zone Deduced by SPOT Image Analyses*: Tectonophysics Volume 233, Elsevier, Amsterdam.

Hall, R., dan Blundell, D., (eds), 1996, *Tectonic Evolution of Southeast Asia*: Geological Society Special Publication No. 106, London.

Katili, J. A., and Hehuwat, F., 1967, On the Occurrence of Large Transcurrent Fault in Sumatra, Indonesia: *Journal of Geosciences Volume 10*, Osaka City University, Osaka.

McCaffrey, R., 2009, The Tectonic Framework of the Sumatran Subduction Zone: *The Annual Review of Earth and Planetary Sciences* 37:345-66, Annual Reviews, Palo Alto.

Muraoka, H., Takahashi, M., Sundhoro, H., Dwipa, S., Soeda, Y., Momita, M., and Shimada, K., 2010, Geothermal Systems Constrained by the Sumatran Fault and Its Pull-Apart Basins in Sumatra, Western Indonesia: *Proceedings World Geothermal Congress*, Bali, Indonesia.

Nukman, M., dan Moeck, I., 2013, Structural Controls on a Geothermal System in the Tarutung Basin, North Central Sumatra: *Journal of Asian Earth Sciences* Volume 74, Elsevier, Amsterdam.

Sieh, K., dan Natawidjaja, D., 2000, Neotectonics of Sumatran Fault, Indonesia: *Journal of Geophysical Research* Volume 105, American Geophysical Union, Washington D. C.

FIGURES

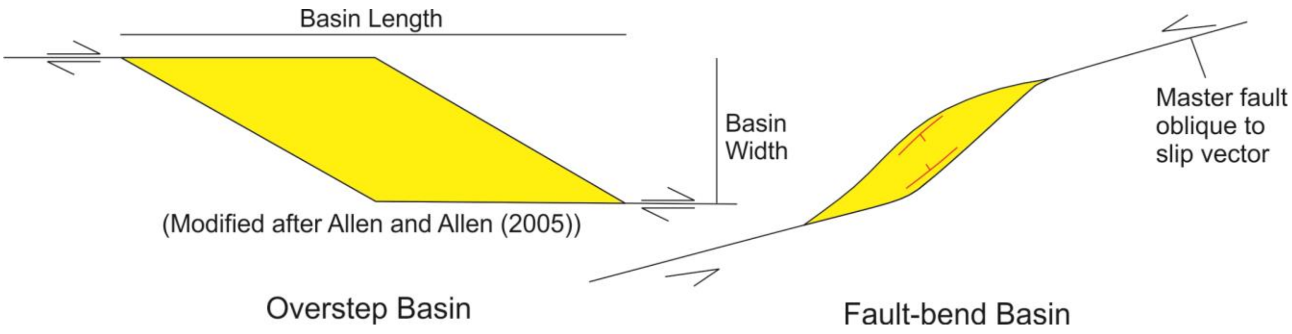

Figure 1. Geometry of Overstep and Fault-bend Basins (modified after Allen and Allen (2005))

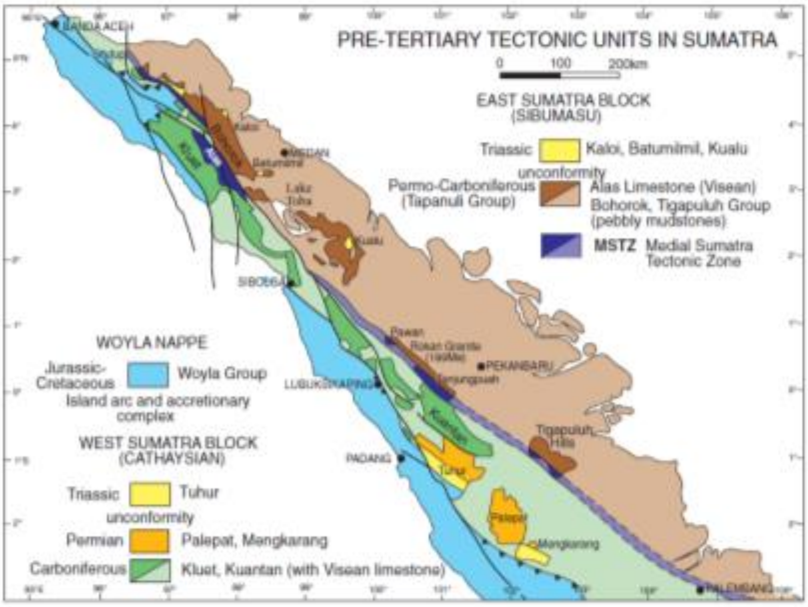

Figure 2. Tectonic Blocks of Sumatra (Barber and Crow, 2009)

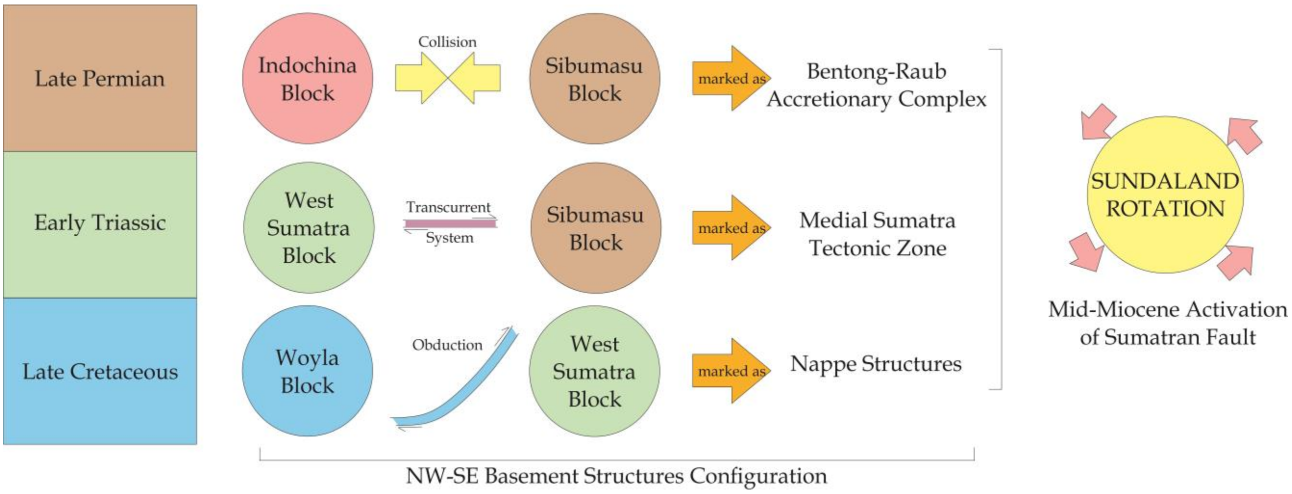

Figure 3. Sumatran Fault Activation Diagram

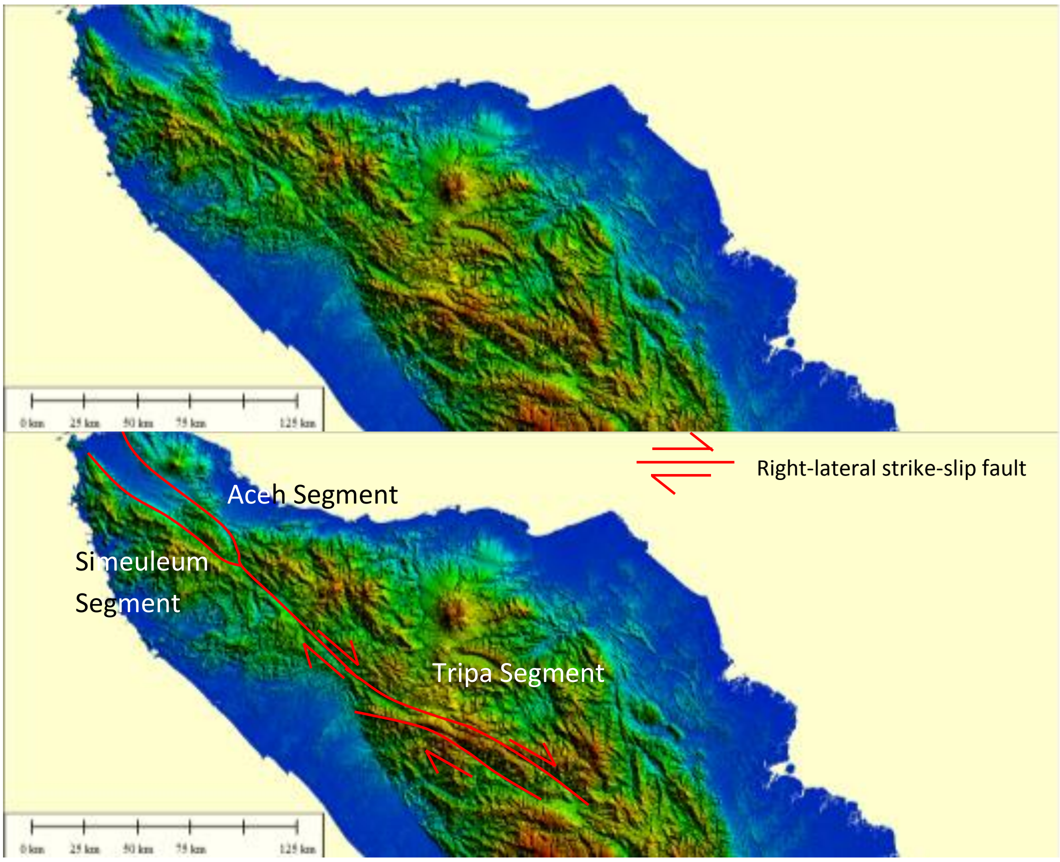

Figure 4. Structural Interpretation of SRTM Data in Aceh, Simeuleum, and Tripa Segments

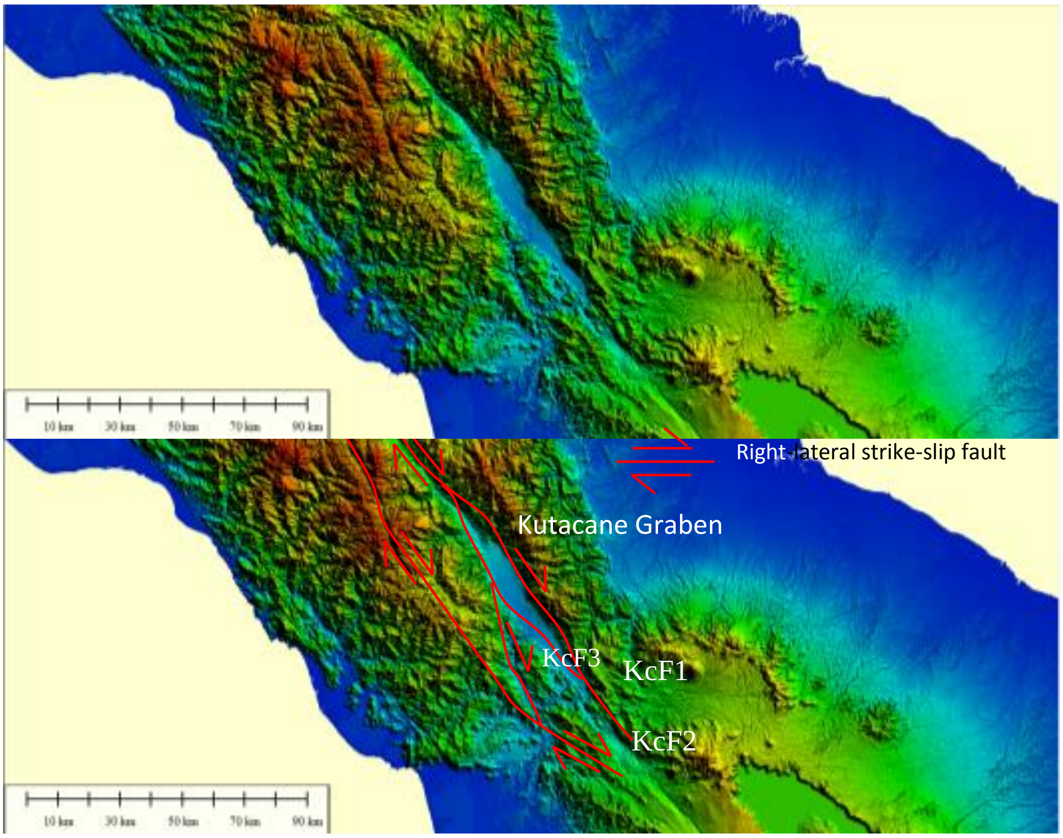

Figure 5. Structural Interpretation of SRTM Data in Kutacane Graben

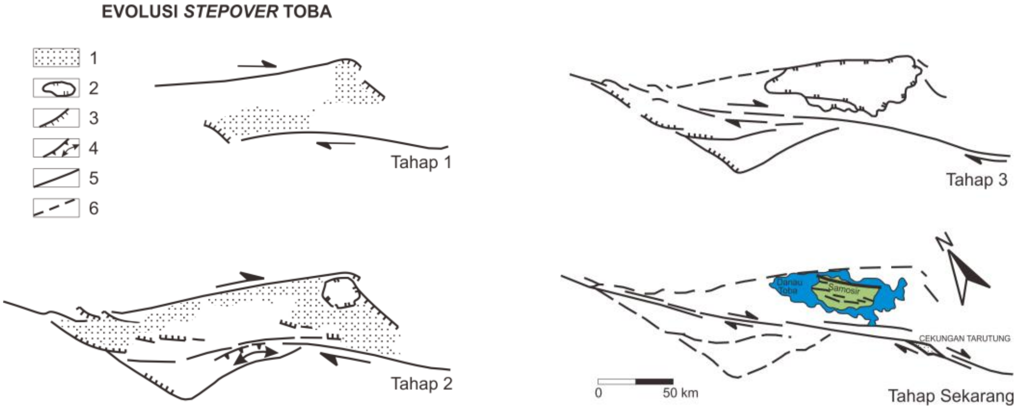

Figure 6. Structural Evolution of Toba Caldera: 1 = subsided zone; 2: caldera margin; 3: active fault with normal-dominated kinematics; 4: active restraining zone; 5: trace of major fault; 6 = inactive fault trace. (Bellier and Sebrier, 1994)

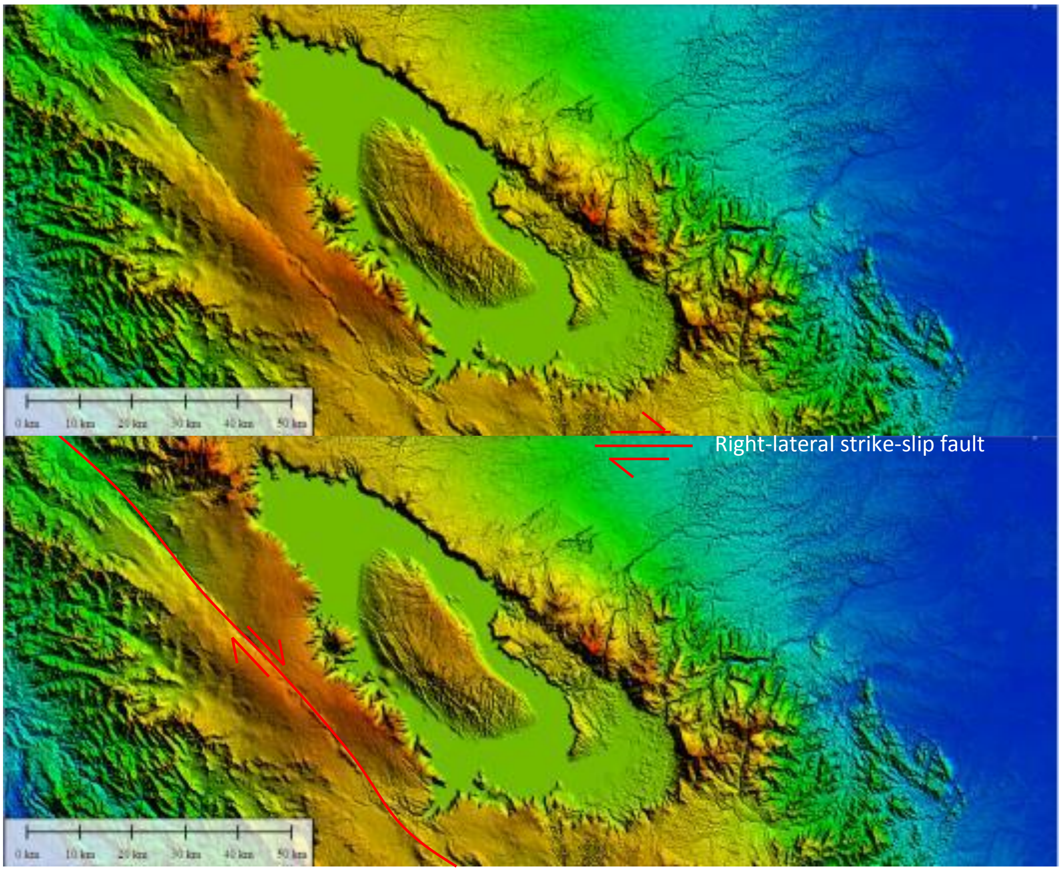

Figure 7. Structural Interpretation of SRTM Data in Toba Caldera

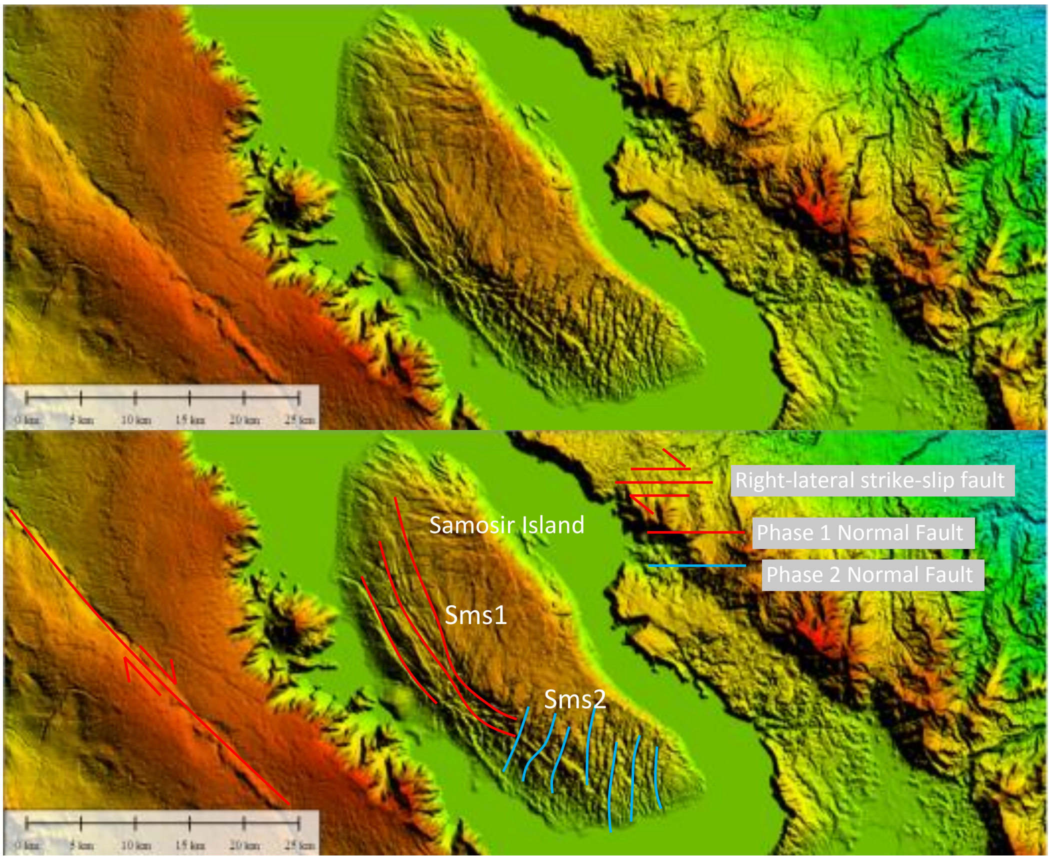

Figure 8. Structural Interpretation of SRTM Data in Samosir Island

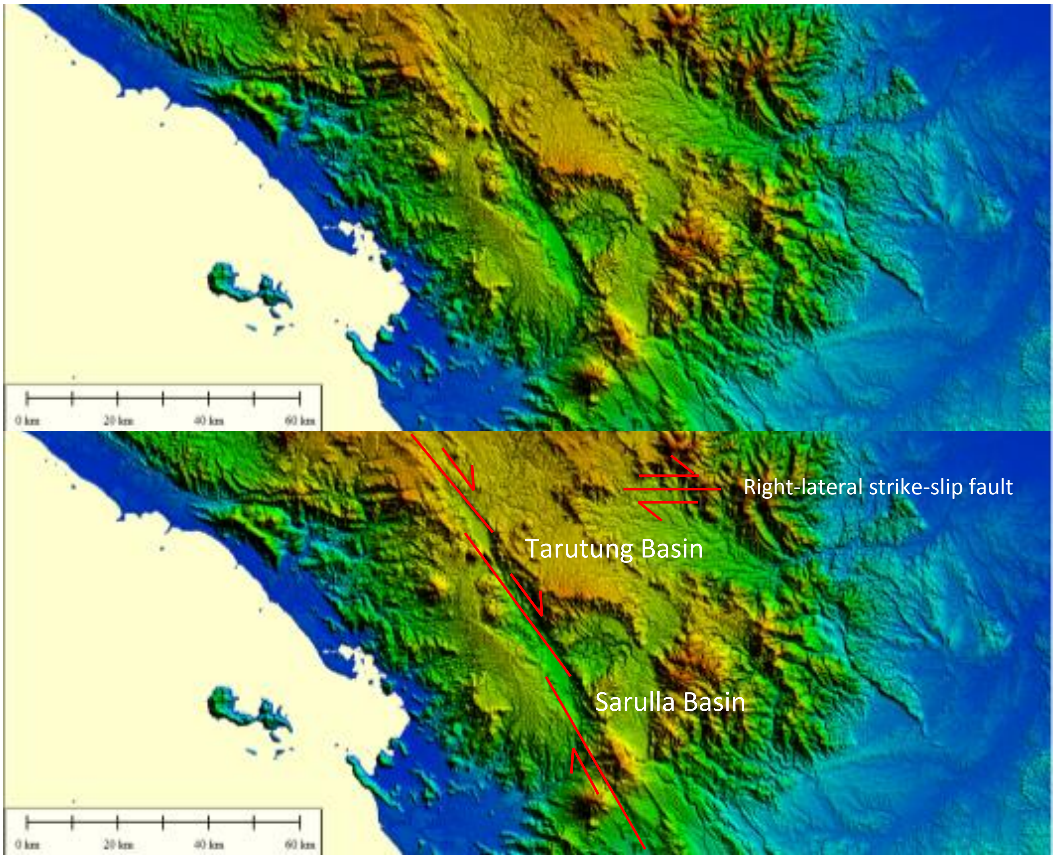

Figure 9. Structural Interpretation of SRTM Data in Tarutung-Sarulla Basins

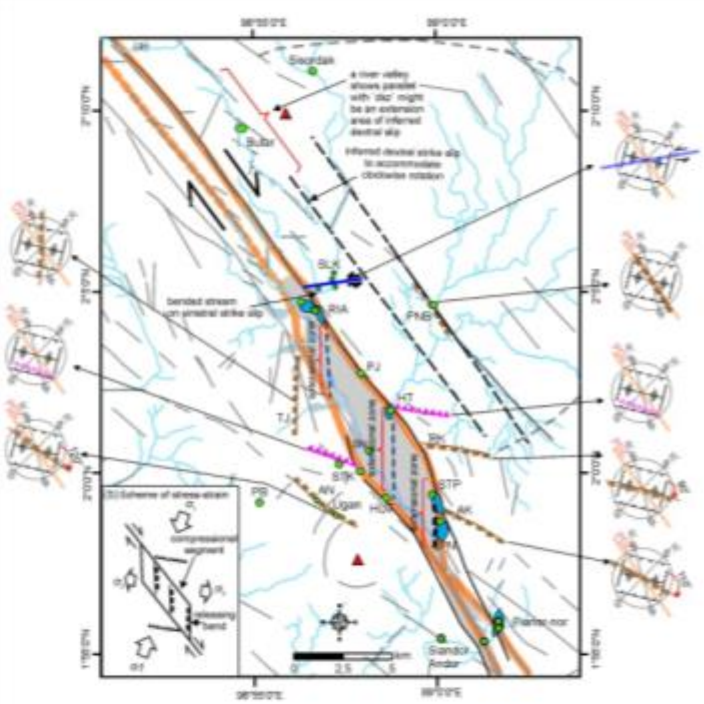

Figure 10. Structural Map of Tarutung Basin (Nukman and Moeck, 2013)

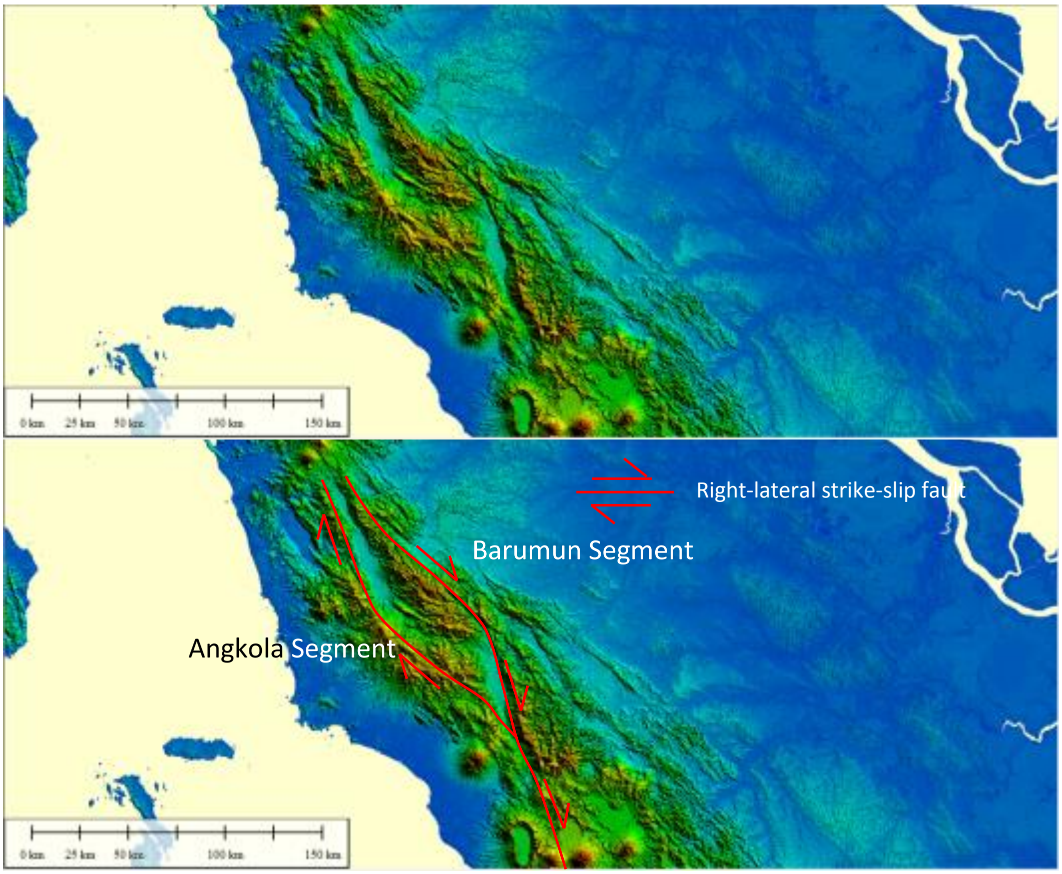

Figure 11. Structural Interpretation of SRTM Data in Barumun-Angkola Segments

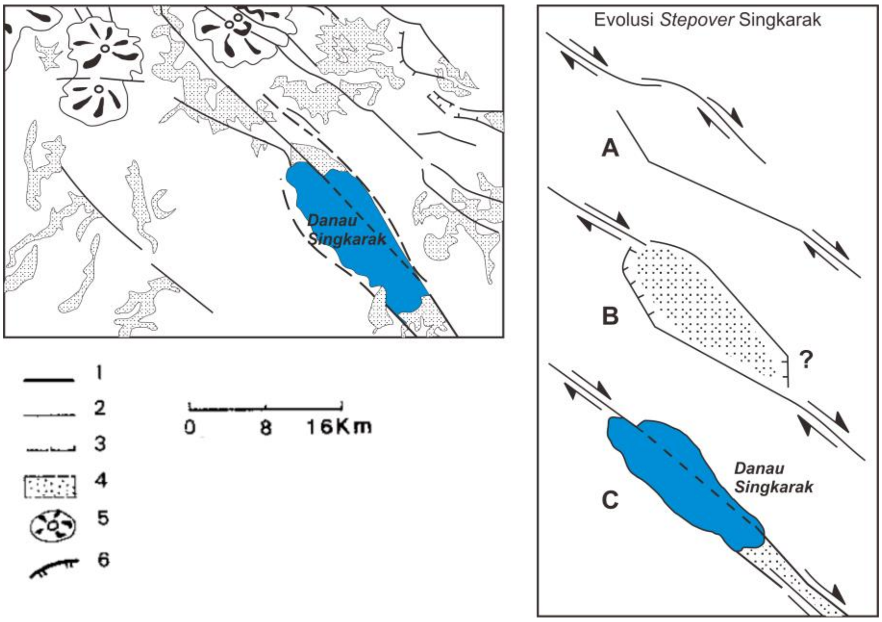

Figure 12. Structural Evolution of Lake Singkarak (Bellier and Sebrier, 1994)

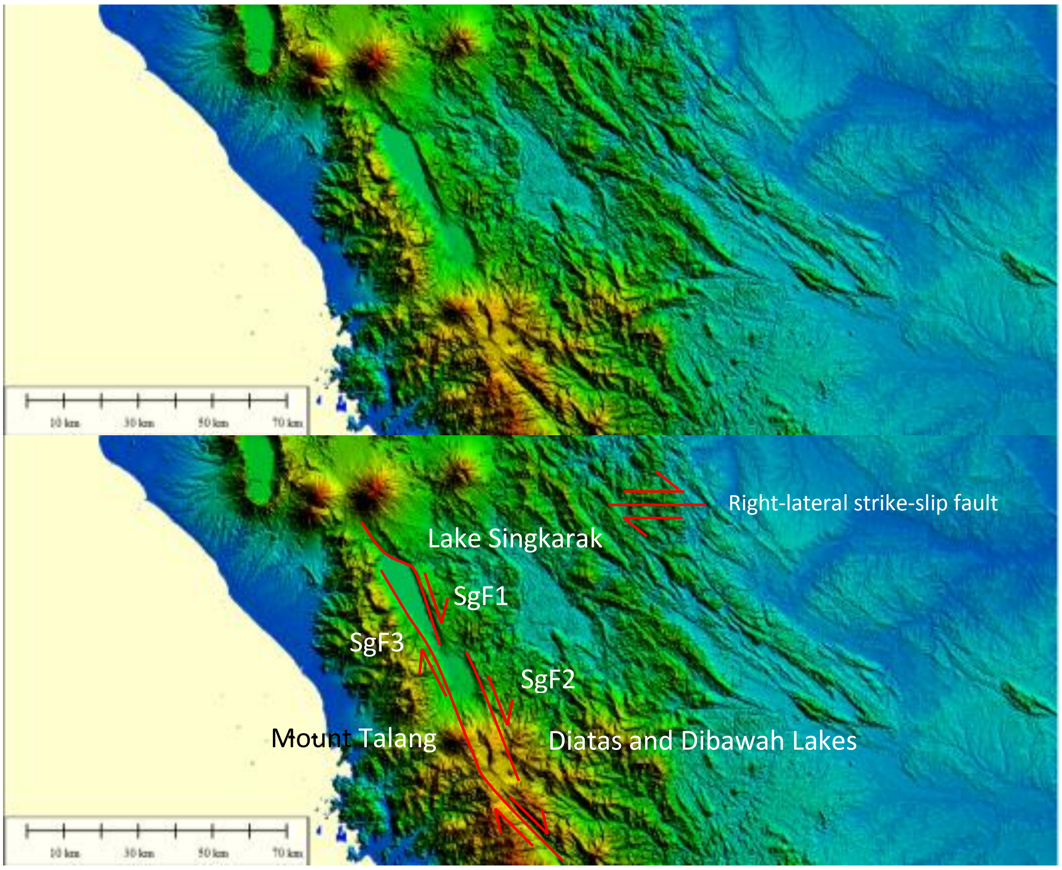

Figure 13. Structural Interpretation of SRTM Data in Singkarak, Diatas, and Dibawah Lakes

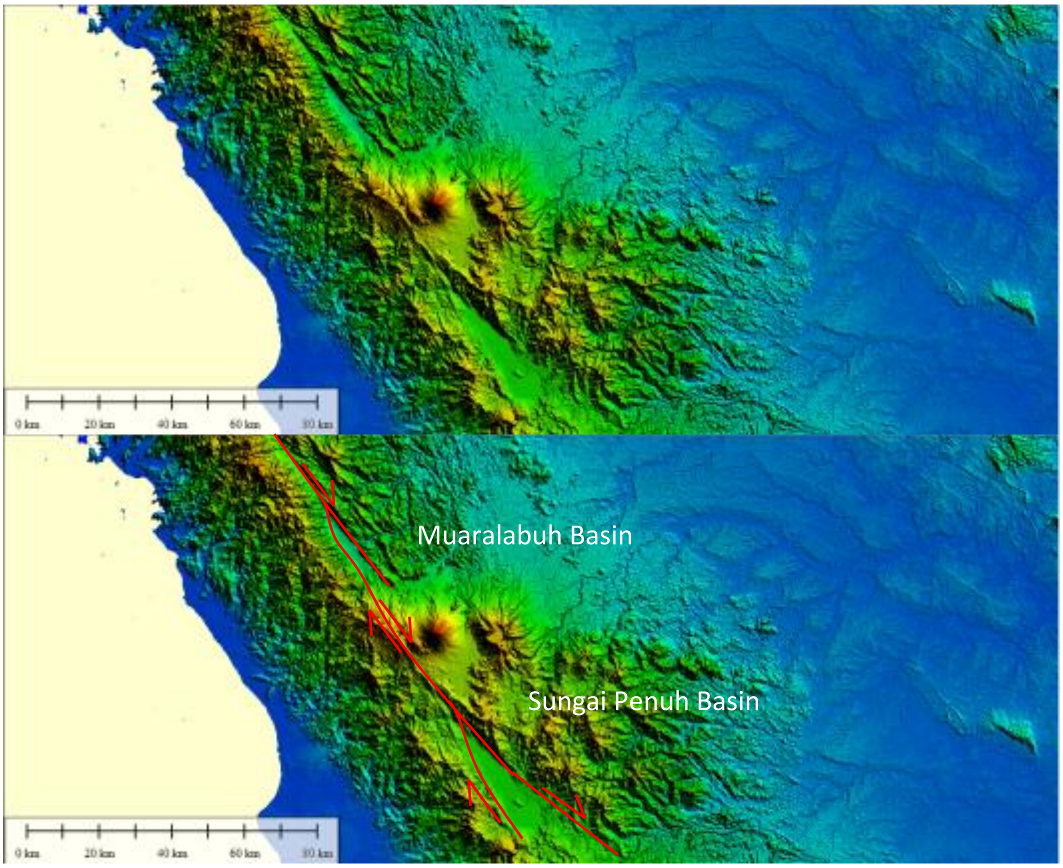

Figure 14. Structural Interpretation of SRTM Data in Muaralabuh-Sungai Penuh Basins

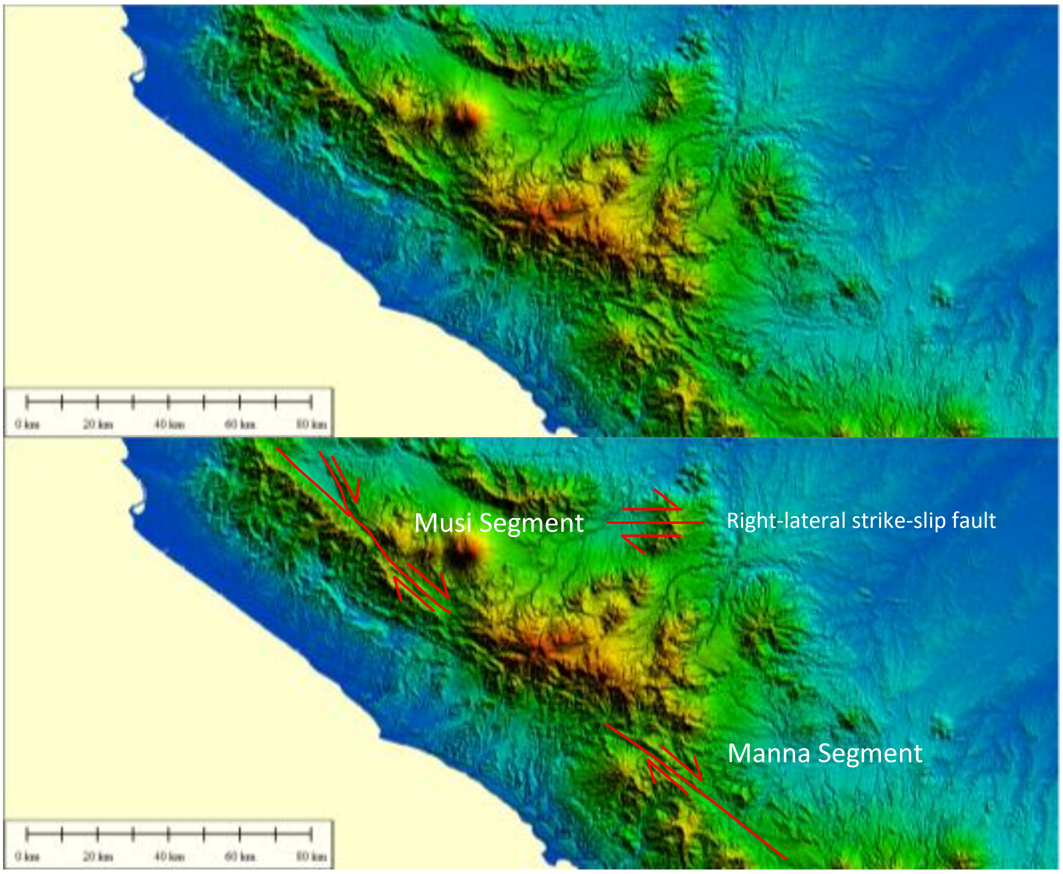

Figure 15. Structural Interpretation of SRTM Data in Musi-Manna Segments

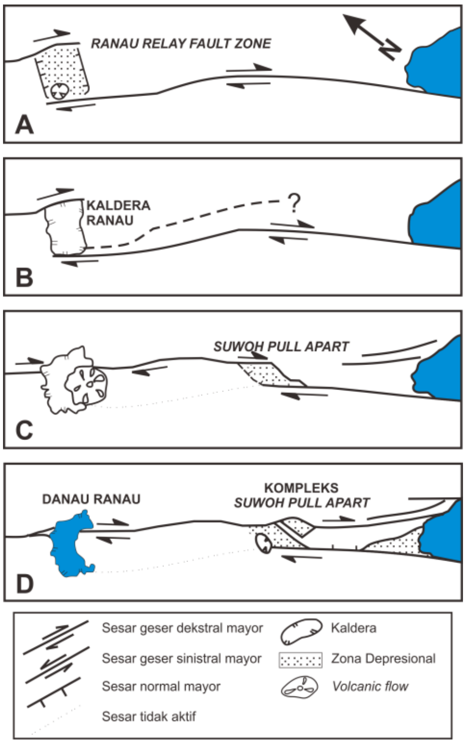

Figure 16. Structural Evolution of Lake Ranau and Suoh Valley (Bellier and Sebrier, 1994)

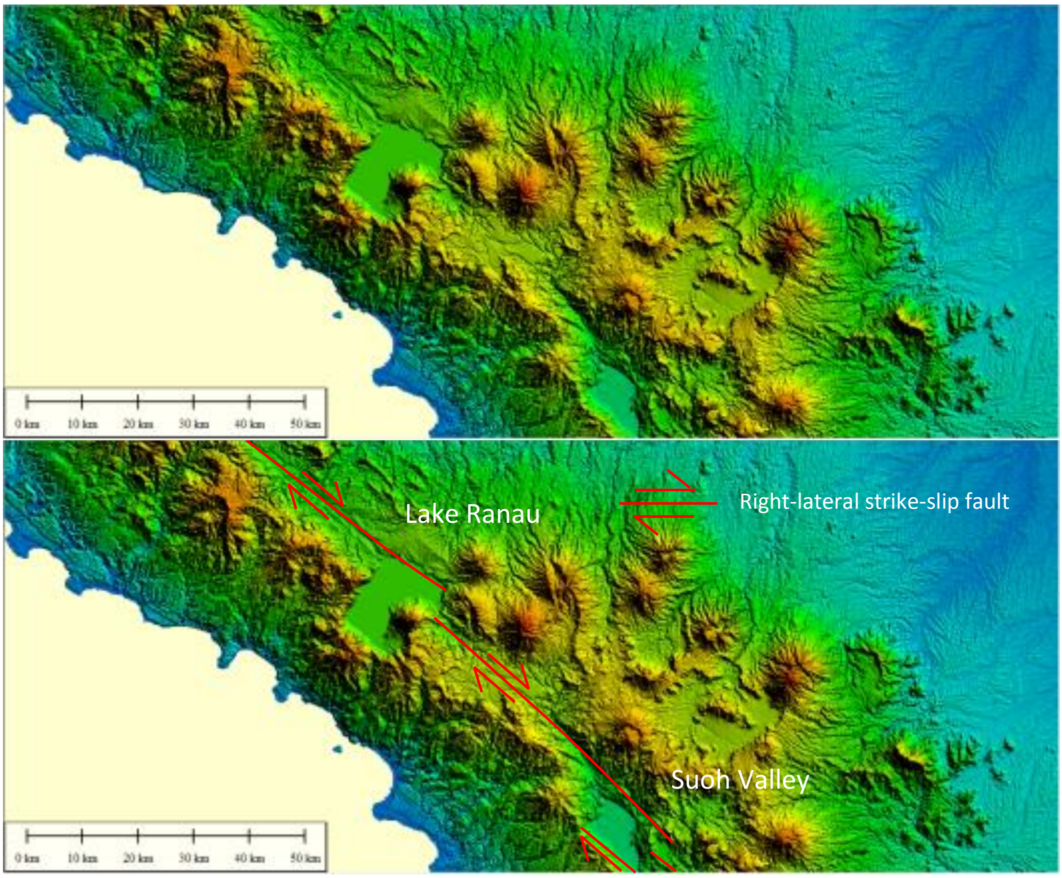

Figure 17. Structural Interpretation of SRTM Data in Lake Ranau and Suoh Valley

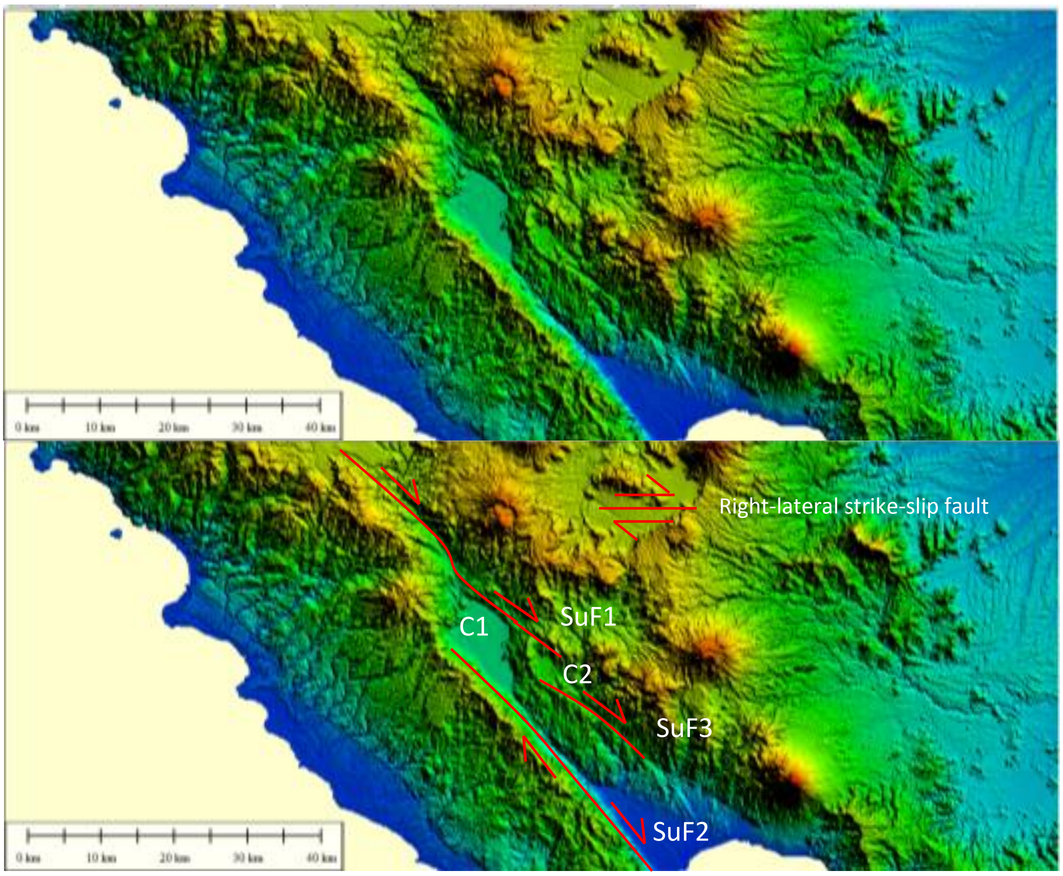

Figure 18. Structural Interpretation of SRTM Data in Suoh Valley

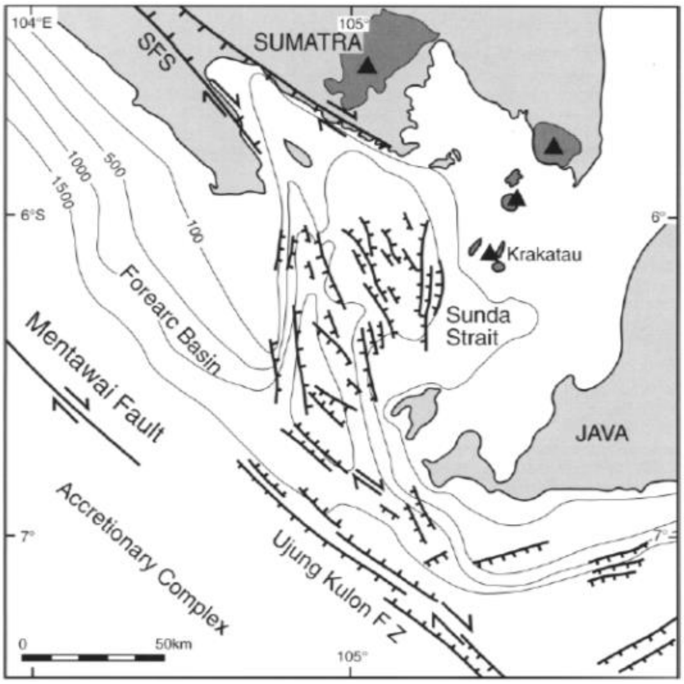

Figure 19. The Opening of Sunda Strait (Barber et al., 2005)

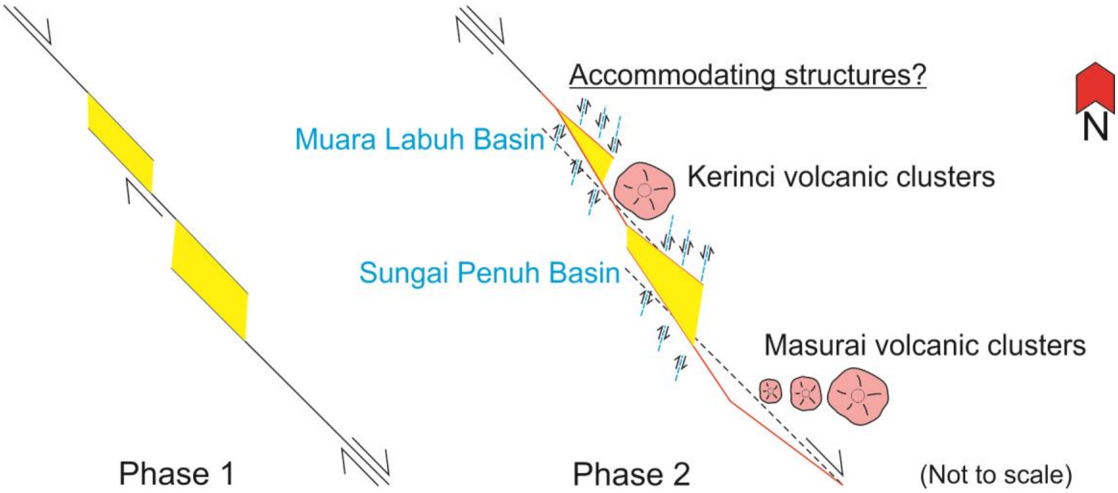

Figure 20. Schematic Diagram of Possible Structural Evolution and Spatial Re-arrangement of Fault Configuration in Muaralabuh-Sungai Penuh Basins after Volcanic Emplacement

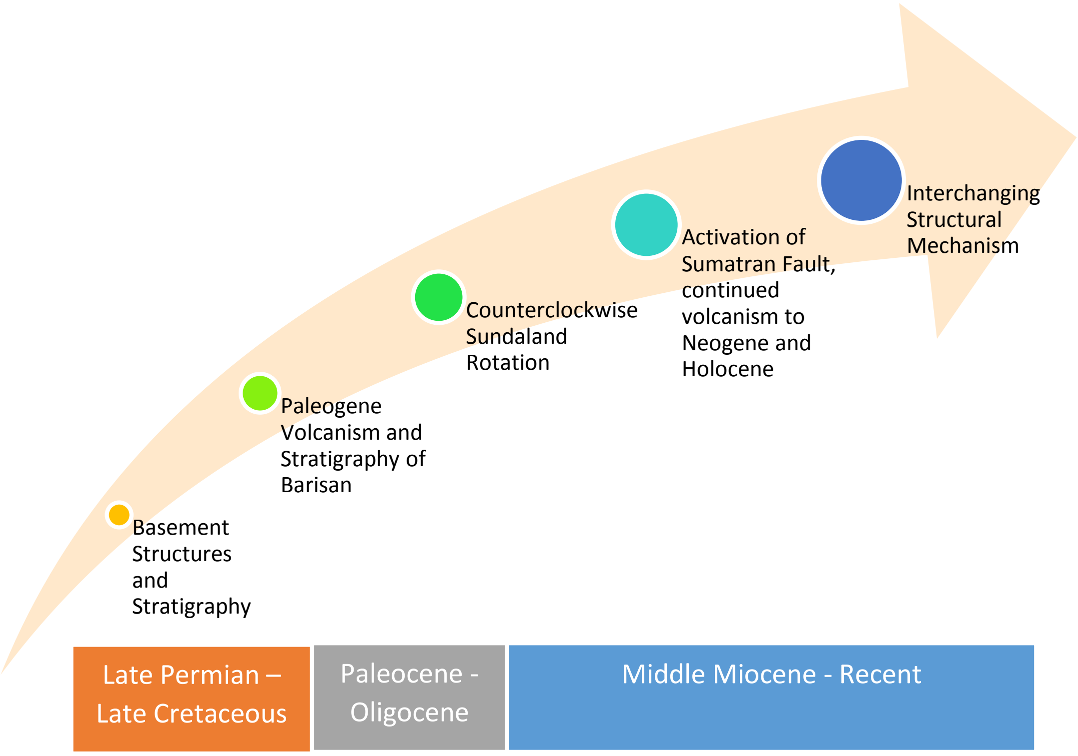

Figure 21. Geologic Flow Diagram of Sumatran Fault