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Geothermal Systems Constrained by the Sumatran Fault and Its Pull-Apart Basins in Sumatra, Western Indonesia

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ABSTRACT

Two types of geothermal systems occur in Sumatra, western Indonesia; one is situated on the slope of volcanic edifices and the other is situated in pull-apart basins along the Sumatran fault. The latter type is formed as thirteen pull-apart basins by the special tectonic setting where the major strike-slip Sumatran fault and volcanic zone coexist in Sumatra. The latter type gives extra reservoir frameworks in Sumatra, duplicating geothermal resources in this Island. All the thirteen pull-apart basins along the Sumatran fault are distributed near clustered volcanoes, but rarely inside of the areas. Fault segments are often warped from the general trend of the Sumatran fault with their closing to the volcanic clusters. Fault segments penetrating the volcanic clusters often exhibit "z"-shaped drags. The genesis of pull-apart basins is explained by the depth distribution of the brittle-plastic transition along the Sumatran fault. With the increasing obliquity of the subduction, segments of the strike-slip faults commence nucleation in non-volcanic areas where the brittle layer is thick. These segments are growing toward the volcanic clusters where the brittle layer is very thin and initially inhibits fault segment expansion. The tips of the fault segments are warping near the volcanic cluster where clockwise rotation deformation occurs by the thin brittle crust layer and underlying dehydration front of the brittle-plastic transition. Finally, new segments penetrate the volcanic clusters and form pull-apart basins together with the pre-existing warped tips of the fault segments. When the length of thirteen pull-apart basins is plotted against the latitude along the Sumatran fault, the length tends to be larger to the northwest and smaller to the southeast. This tendency is broadly consistent with known slip rates of the Sumatran fault. Boundary normal faults of pull-apart basins play an important role as major discharge zones for geothermal fluid, because the extensional stress is concentrated in the boundary normal faults. The vapor-dominated type geothermal resources may be common on the volcanic edifices and the water-dominated type geothermal resources with the neutral chloride type or bicarbonate type thermal water may be common in the pull-apart basins.

1. INTRODUCTION

Numerous studies have been done on the geneses of pull-apart basins along major strike-slip faults throughout the world since the 1960s (Burchfiel et al., 1966). However, a process to localize a pull-apart basin along major strike-slip faults is still a difficult problem. The subject of this paper is to elucidate how a major strike-slip fault is segmented and stepped over each other in the generation process of pull-apart basins.

The Sumatran fault, Indonesia, is one of the major strike-slip faults and many papers have been published on its slip-rate (McCaffrey, 1991; Bellier and Sébrier, 1995; McCaffrey et al., 2000; Genrich et al., 2000; Prawirodirdjo et al., 2000), whereas little has been published on the pull-apart basins along the Sumatran fault. An exception was the comprehensive mapping on the Sumatran fault (Sieh and Natawidjaja, 2000), where valleys along the Sumatran fault, virtually synonymous to pull-apart basins, were described, and a generation process of one of them, Singkarak, was described in detail. Another exception was the satellite image analyses (Bellier and Sébrier, 1994), which emphasized that some calderas had been evolved from pull-apart basins. It is economically important that huge potentials of high-temperature geothermal resources in Sumatra are associated with the Sumatran fault (Hochstein and Sudarman, 1993), and many of these geothermal fields are situated in the pull-apart basins as documented in the Sarulla basin (Hickman et al., 2004). All these previous authors, however, used the term "graben" for the pull-apart basins that might make their geneses obscure. A notable geological feature of the Sumatran fault is that its trend almost coincides with the Sumatran volcanic zone and often crosses over its clustered volcanoes. The previous studies on the Sumatran fault have paid little attention to the role of the shallow level of the brittle-plastic transition induced by the high-level magma systems of the volcanic zone.

This paper describes pull-apart basins along the Sumatran fault with special attention to their spatial relationship to the clustered volcanoes and proposes a generation model on the pull-apart basins that are localized by the role of the magma-induced plastic crust.

2. DISTRIBUTION OF PULL-APART BASINS ALONG THE SUMATRAN FAULT

The Sumatran fault is one of the major trench-parallel strike-slip faults that bounds the fore-arc sliver and back-arc plates of Sundaland as shown in Figure 1.

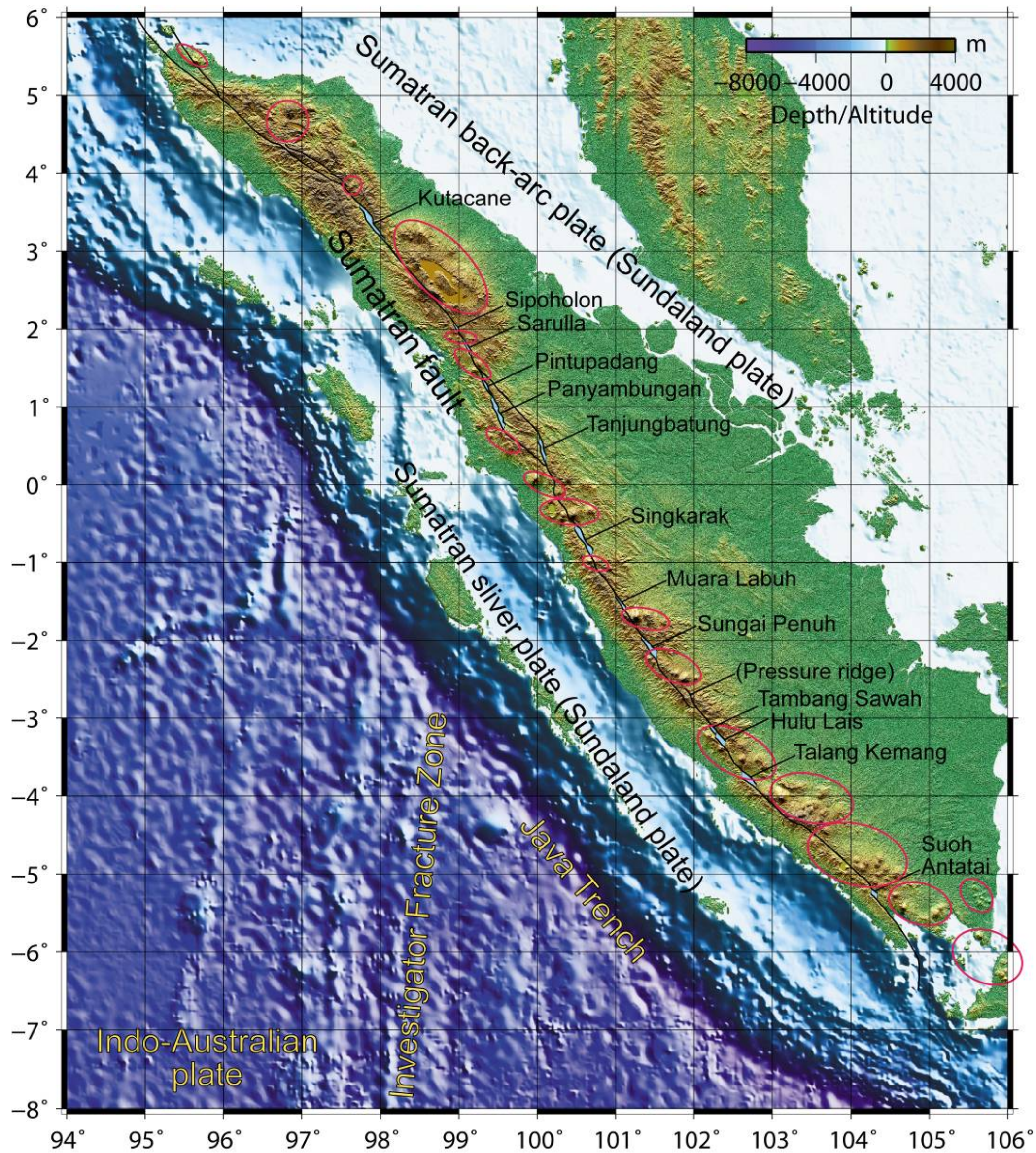

Figure 1: Regional map of topography, fault segments, pull-apart basins, a pressure ridge and clustered volcanoes along the Sumatran fault. Names of pull-apart basins are shown on the map. Topography and bathymetry were made by the SRTM 3 second data released from the U.S. Geological Survey and the global topographic data released from the University of Alaska, respectively.

This is the right lateral strike-slip fault that is traced about 1660 km on Sumatra. A variety of observations such as geologic unit offset, stream offset, and geodetic measurement including the Global Positioning System (GPS) indicate that the slip rate is large in northwestern Sumatra by 24 mm/yr and small in southeastern Sumatra by 6 mm/yr (McCaffrey, 1991; Bellier and Sébrier, 1995; Genrich et al., 2000; McCaffrey et al., 2000; Prawirodirdjo et al., 2000). This slip rate regime inevitably gives rise to the along-arc stretching of the fore-arc sliver plate. It should be noted that the major volcanic zone of Sumatra often crosses over the Sumatran fault, but the majority of the zone lies in the back-arc side parallel to this fault. The Quaternary volcanoes tend to form en echelon shaped elliptical clusters common in the oblique subduction or sheared subduction zones (Muraoka et al., 2002; Muraoka and Nasution, 2004; Figure 1).

Thirteen pull-apart basins and one pressure ridge are recognized along the Sumatran fault not only by the observation of topographic maps and satellite images but also by our field surveys (Figure 1). Almost all the pull-apart basins along the Sumatran fault occur near the clustered volcanoes, but rarely inside of the areas (Figure 1). This observation indicates two contradictory roles of the volcanic clusters in the formation of pull-apart basins: one is that the volcanic clusters macroscopically play a role of generators to pull-apart basins along the Sumatran fault and the other is that the areas of the volcanic clusters themselves are inhibitors to pull-apart basins. The former role is typically observed in northwestern Sumatra. The Sumatran volcanic zone from 3.7ºN to the northwest is away from the Sumatran fault on the back-arc side where pull-apart basins are not present (Figure 1). The latter role is observed in the large volcanic cluster areas. A typical example is found in the fore-arc side of the largest Toba caldera volcanic cluster where pull-apart basins are missing for 150 km along the Sumatran fault from 2.1ºN to 3.2ºN. Likewise, pull-apart basins are absent in the tightly spaced two volcanic clusters along the Sumatran fault such as the Talamau and Marapi volcanic clusters from 0.2ºN to 0.5ºS and the Dempo and Pesagi volcanic clusters from 4.0ºS to 5.2ºS (Figure 1).

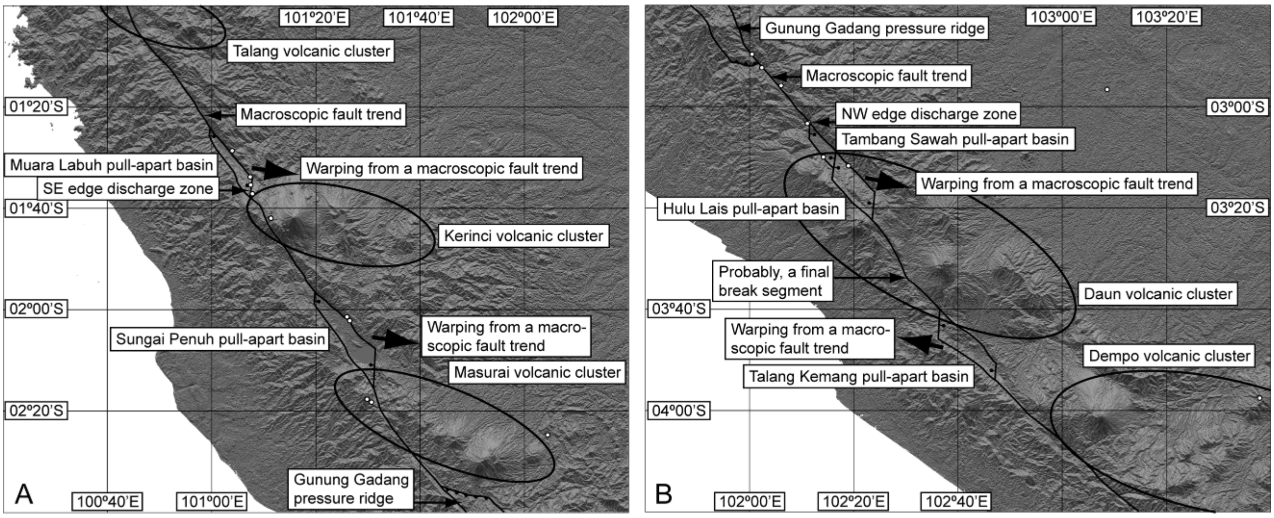

Figure 2: Geometrical relation of the tips of fault segment and clustered volcanoes. Open circle shows natural hot springs. (A) Fault tips against Kerinci and Masurai volcanic clusters. (B) Fault tips against Daun volcanic cluster.

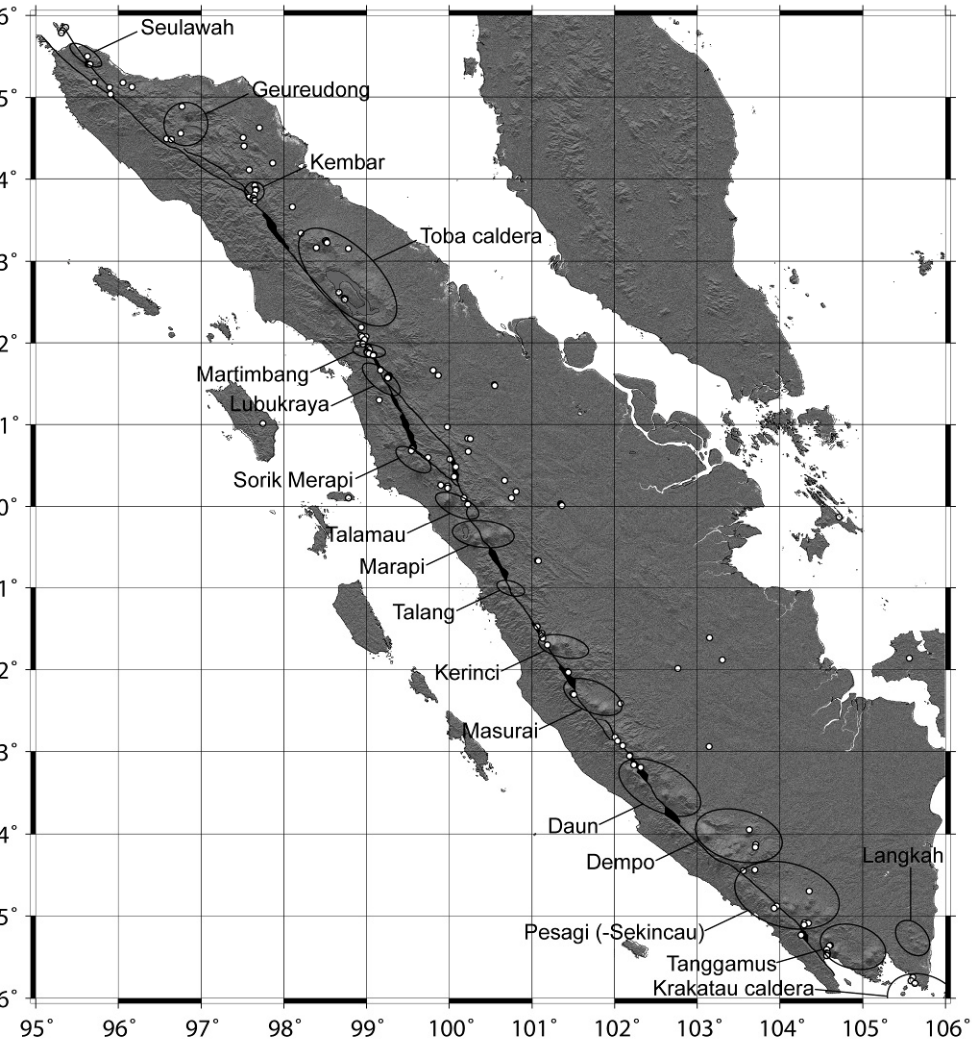

Figure 3: Regional map of hot spring discharges on Sumatra Island. Open circle shows natural hot springs. These data are based on our survey and those from 1:250000 geological maps (Bennett et al., 1981; Cameron et al., 1981, 1982a, 1982b, 1983; Aspden et al., 1982; Clarke et al., 1982; Aldiss et al., 1983; Rock et al., 1983; Gafoer et al., 1986, 1992, 1993; Kusnama et al., 1992; Suwarna et al., 1992; Amin et al., 1993; Mangga et al., 1993; Djamal et al., 1994; Mangga and Djamal, 1994; Simandjuntak et al., 1994; Nas and Supandjono, 1995; Silitonga and Kastowo, 1995; Sutisna et al., 1994; Rosidi et al., 1996). Names of volcanic clusters are shown on the map. Topography was made by the SRTM 3 second data released from the U.S. Geological Survey.

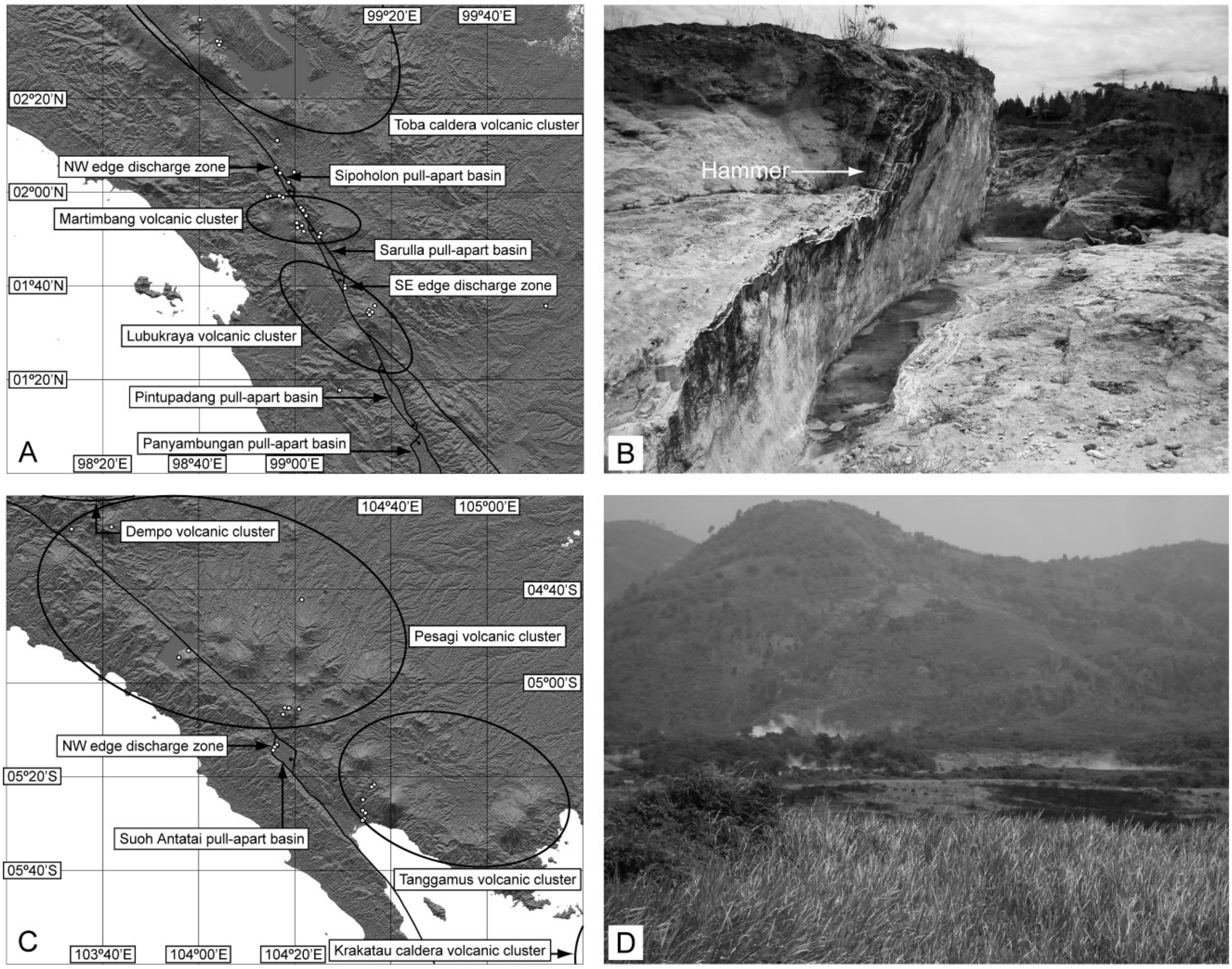

Figure 4: Hot spring discharges from pull-apart basins. Open circle shows natural hot springs. (A) Hot spring discharges from the northwestern boundary normal fault in the Sipoholon pull-apart basin. (B) Photograph of the hot spring discharges from the northwestern boundary normal fault in the Sipoholon pull-apart basin. (C) Hot spring and steam discharges from the northwestern boundary normal fault in the Suoh Antatai pull-apart basin. (D) Photograph of the hot spring and steam discharges from the northwestern boundary normal fault in the Suoh Antatai pull-apart basin.

3. GEOMETRY OF THE FAULT TIPS AGAINST CLUSTERED VOLCANOES

Geometry of the fault tips against clustered volcanoes is here described on two areas along the Sumatran fault. Figure 2A shows the shape of the fault tips against the Kerinci and Masurai volcanic clusters. The Muara Labuh pull-apart basin is situated north of the Kerinci volcanic cluster. This basin becomes wider southward the nearest Kerinci volcanic cluster. In the similar manner, the Sungai Penuh pull-apart basin is situated north of the Masurai volcanic cluster. This basin also becomes wider southward the nearest Masurai volcanic cluster. In general, formation of a pull-apart basin needs stepping over of two fault segments. The stepping over of the fault segments in these pull-apart basins are performed by the eastward warping of the northwestern fault segment to the macroscopic fault trend closer to the clustered volcanoes. It is also noted that "z"-shaped clockwise drags of the fault segment are observed in the inner areas of both the Kerinci and Masurai volcanic clusters, although the drags are weak.

Figure 2B shows the geometry of the fault tips against the Daun volcanic cluster. The Hulu Lais and Tambang Sawah pull-apart basins are situated north of the Daun volcanic cluster. The Talang Kemang pull-apart basin is situated south of the Daun volcanic cluster. They become wider toward the nearest Daun volcanic cluster. They are formed by the eastward warping of the northwestern fault segment and westward warping of the southeastern fault segment to the macroscopic fault trend closer to the clustered volcanoes. A weak "z"-shaped clockwise drag of the fault segment is again observed in the inner area of the Daun volcanic cluster.

4. GEOTHERMAL FLUID DISCHARGES IN PULL-APART BASINS

A close spatial relationship between pull-apart basins and geothermal fluid discharges is observed along the Sumatran fault. Figure 3 shows the distribution of natural hot springs in Sumatra that are based on our own field surveys and those quoted from 23 sheets of 1:250,000 scale quadrangle geological maps describing hot springs (Bennett et al., 1981; Cameron et al., 1981, 1982a, 1982b, 1983; Aspden et al., 1982; Clarke et al., 1982; Aldiss et al., 1983; Rock et al., 1983; Gafoer et al., 1986, 1992, 1993; Kusnama et al., 1992; Suwarna et al., 1992; Amin et al., 1993; Mangga et al., 1993; Djamal et al., 1994; Mangga and Djamal, 1994; Simandjuntak et al., 1994; Nas and Supandjono, 1995; Silitonga and Kastowo, 1995; Sutisna et al., 1994; Rosidi et al., 1996). Our GIS-base database on the geothermal fluid discharge points has not been completed, but it seems clear that about a half of the high-temperature geothermal systems is associated with volcanic edifices in volcanic clusters, and another half is associated with pull-apart basins. Even if no hot springs are described in some pull-apart basins, there still remains a high possibility of finding hot springs in future field surveys.

A pull-apart basin is generally sided by major strike-slip faults along its long-axis and bounded by normal faults along its short-axis. When we observe the faults responsible for the discharges of geothermal fluids in pull-apart basins, the normal faults often play the most important role in major discharges of geothermal fluids. Figure 4A shows the Sipoholon and Sarulla pull-apart basins where the major fluid discharges are observed along the NW boundary normal fault in the Sipoholon pull-apart basin and SE boundary normal fault in the Sarulla pull-apart basin. Figure 4B shows the NW boundary normal fault of the Sipoholon pull-apart basin at Ria-Ria-Sipoholon, which is situated at the top of a travertine terrace with a 35 m height, 500 m width in the ESE-WNW direction and 1000 m length in the NNW-SSE direction. The vertical fault and 1m-thick vertical travertine vein have a N5ºE strike and 75ºW dip. They cut the horizontal travertine terrace deposits where the thermal water is at a temperature of 64.9 ºC and discharging at a rate of 6,000 liters/minute (a total of many discharge points near the fault). Figure 4C shows continuous thermal water and steam discharges along the NW boundary normal fault of the Suoh Antatai pull-apart basin. These discharges are roughly aligned along the N5ºE azimuth (Figure 4D). The boundary normal faults' effect on the geothermal fluid discharges may be closely related to the spreading process of the pull-apart basin.

5. DISCUSSION

5.1 The Localization Process of Pull-Apart Basins along the Sumatran Fault

In spite of numerous studies on pull-apart basins, the localization process of pull-apart basins has not been elucidated. The cause of the segmentation and stepping over should not necessarily be the single mechanism. The Sumatran fault exhibits one of the typical localization processes of pull-apart basins. Faults usually reduce the displacement or slip rate toward their tips (Muraoka and Kamata, 1983), but a segment of the strike-slip fault in pull-apart basins is a special case. They do not reduce the displacement or slip rate at their tips because the excess displacement or slip rate accommodated at the tips is an essential driving force for the spreading of pull-apart basins (Figure 5). This process requires the formation of a deep hole in the crust, but it is not realistic to consider such a deep hole because of the large energy required for the spreading against the increasing stress of the crust with depth. It is more realistic that pull-apart basins are formed as a shallow hole in the crust that is underlain by a horizontally decoupled plane at a relatively shallow depth.

Along the Sumatran fault, pull-apart basins usually occur near the volcanic clusters. The depth of the brittle-plastic transition in these areas is expected at a shallow depth because of the high-temperature thermal fields formed by the shallow-depth magma chambers (Figure 6A). The depth of the brittle-plastic transition is known to be as shallow as 3.1 km at a temperature of 380 ºC in the Kakkonda geothermal field of the Hachimantai volcanic cluster, Northeast Japan, which was penetrated by a high-temperature well exceeding 500 ºC (Muraoka et al., 1998). Even if this is the shallowest case, the depth of the brittle-plastic transition in the volcanic clusters along the Sumatran fault may be in the order of several kilometers. On the other hand, the depth of the brittle-plastic transition at a non-volcanic area along the Sumatran fault may be much deeper (Figure 6A). The plastic layer does not yield any fractures and pores. The dehydration front will be physically formed in the brittle layer just above the brittle-plastic transition. The contact metamorphic dehydration reactions such as the cordierite-forming reaction will also chemically contribute to the formation of the dehydration front (Muraoka et al., 1998; Muraoka and Otani, 2000). The dehydration front will yield a high pore pressure, resulting in numerous horizontal fractures (Muraoka et al., 1998; Muraoka and Otani, 2000) and will provide the horizontally decoupled plane as a bottom of the pull-apart basins at a relatively shallow depth.

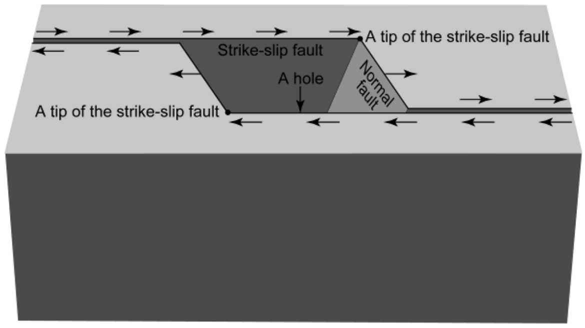

Figure 5: Basic geometry of a pull-apart basin.

When we consider the development process of a major strike-slip fault, it should be initiated by the incipience of oblique subduction (Figure 6B). A paleomagnetic study actually demonstrated that a clockwise rotation of Sumatra Island relative to Java Island is ongoing at least for the last 2.1 Ma at the rate of 5 or 10 º/m.y. (Nishimura et al., 1986). The nucleation of the fault segments needs a stress concentrator that should be expected in the area of the thick brittle layer (Muraoka and Kamata, 1983). The nucleated fault segments in the thick brittle layer will gradually expand their fault tips toward the volcanic cluster (Figure 6A). However, the inside of the volcanic cluster is composed of a thin brittle layer that is free from the underlying plastic layer by the intervention of the dehydration front (Figure 6A). This thin brittle layer is easily deformed and inhibits the expansion of the fault segment at the earlier stage. This gives the first step for the formation of pull-apart basins along the Sumatran fault, particularly for the segmentation of the fault.

Before the fault segment will penetrate the volcanic cluster, clockwise rotation deformation will occur in response to the dextral moment (Figure 6B). A "z"-shaped clockwise drag of the fault segment is observed in these volcanic clusters even after the fault segment appeared (Figure 2). This dextral deformation causes lateral warping of the fault tips of the northwestern and southeastern segments to the macroscopic fault trend, providing across-fault space between the tips (Figure 6B). Most pull-apart basins tend to be wider toward the nearest volcanic clusters (Figure 2), demonstrating that the warping of the fault tips actually occurred. This gives the second step for the formation of pull-apart basins, particularly for the across-fault space between the tips of the fault segments.

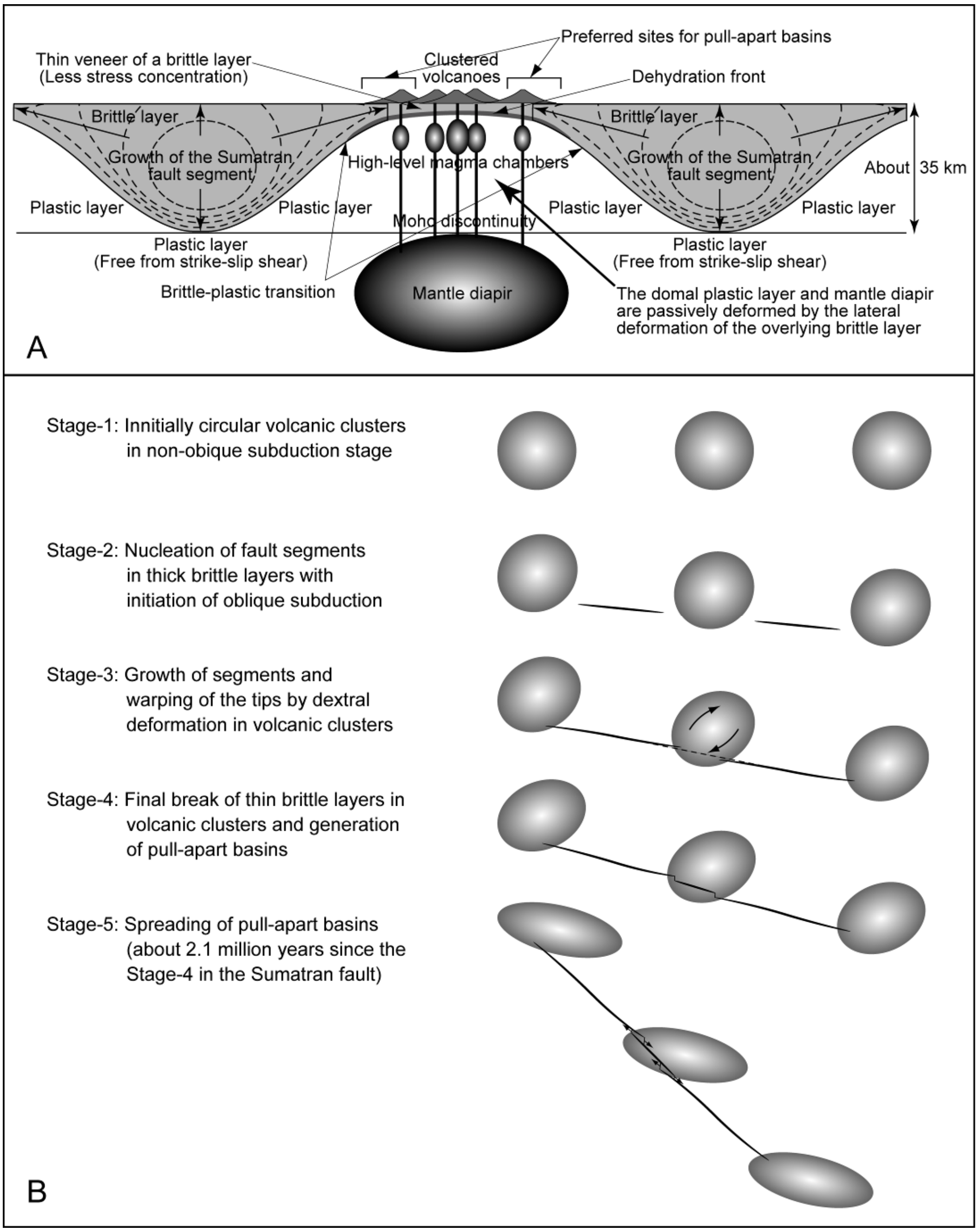

Figure 6: A model for localization of pull-apart basins along the Sumatran fault. (A) Schematic cross section model along the Sumatran fault showing the depth distribution of the brittle-plastic transition. (B) Schematic plan view model of the segmentation and step-over processes of the Sumatran fault with increasing obliquity of subduction.

When we consider the essential role of the major strike-slip fault decoupling on both sides of the plates, a slip rate should be partitioned over the entire fault system. This is necessary for the macroscopic motions of both sides of the relatively rigid plates. Penetration of a fault segment is, therefore, necessary even in the place of the volcanic clusters at the final stage (Figure 6B). A new segment finally penetrates the volcanic cluster along the macroscopic fault trend. This precedes the final step for the completion of pull-apart basins. Spreading of pull-apart basins follows this process. Idealistically, two pull-apart basins are formed on the opposite sides of the volcanic cluster (Figure 2B), but only one basin occasionally appears on one side of the volcanic cluster (Figure 2A). This model, thus, explains a variety of the observed features on the pull-apart basins along the Sumatran fault and represents a typical generation process of the pull-apart basins.

5.2 Estimate of Slip-Rate Partitioning by the Pull-Apart Basins

If the excess displacement or slip rate accommodated at the fault tips is an essential driving force for spreading the pull-apart basins (Figure 5), the length of pull-apart basins would provide the total displacement by the slips throughout the oblique subduction period (Aydin and Nur, 1982). When the length of thirteen pull-apart basins is plotted against the latitude along the Sumatran fault (Figure 7A), the length tends to be larger to the northwest and smaller to the southeast. This tendency is broadly consistent with the estimates of slip rates from other methods in the previous papers (McCaffrey, 1991; Bellier and Sébrier, 1995; Genrich et al., 2000; McCaffrey et al., 2000; Prawirodirdjo et al., 2000), but some pull-apart basins are obviously shorter than the general trend. Because the Hulu

Lais and Tambang Sawah pull-apart basins are exactly continued (Figure 2B), if their lengths are summed up, their length comes to be close to the general trend. The Sarulla and Sipoholon pull-apart basins are not continued in a strict sense because of the very narrow width of both the pull-apart basins (Figure 4A), but there still remains a possibility that they are continued. If they were assumed to be continued, their total length comes close to the general trend.

The estimate becomes complex when looking at the part of the double fault zone from 0.3ºN to 1.5 ºN along the Sumatran fault where the total length of two pull-apart basins in the frontal branch is obviously longer than the general trend. However, in the back-arc branch is shorter than this length. It should be noted that their long axes of the pull-apart basins are obviously oblique to the general trend of the Sumatran fault. This means that their spreading does not directly contribute to the displacement along the Sumatran fault. If these pull-apart basins are further spreading, the width between the double faults inevitably becomes larger, particularly to the frontal side (Figure 7B). The double fault zone probably plays a role of compensator to the along-arc stretching of the sliver plate by this swelling process. The cause of a stretch absorber existing in this place is not necessarily clear but a possible interpretation is that it may be related to the northern extension of the Investigator Fracture Zone (Figure 1). Whatever the cause of the double fault zone, the length of pull-apart basins in this zone would be better excluded for the estimate of the integrated displacement.

We obtain a relatively reliable data set on the length of pull-apart basins along the Sumatran fault. The period of the oblique subduction of Sumatra relative to Java is given to be the last 2.1 million years (Nishimura et al., 1986). When we subdivide the integrated displacement by this period, we obtain a slip rate partitioning along the Sumatran fault as shown in Figure 7C. This would provide a simple method to estimate the slip rate over the almost entire Sumatran fault and is well consistent with the previous estimates from other methods (McCaffrey, 1991; Bellier and Sébrier, 1995; Genrich et al., 2000; McCaffrey et al., 2000; Prawirodirdjo et al., 2000).

5.3 Tectonic Significance to Geothermal Systems in Sumatra

The database on geothermal fluid discharges is not completed, but it is evident that there is a tight spatial relationship between the pull-apart basins and geothermal fluid discharges in Sumatra (Figure 3). As discussed above, pull-apart basins along the Sumatran fault that are formed near the volcanic clusters provide promising geothermal heat sources. In addition, the extensional nature of pull-apart basins provides an adequate reservoir structure at a shallow depth including the formation of extensional fractures and sedimentation of permeable basin fills. For these reasons, pull-apart basins along the Sumatran fault typically form high-temperature geothermal fields in Sumatra (Hochstein and Sudarman, 1993; Hickman et al., 2004).

Boundary normal faults of pull-apart basins play an important role as major discharge or up-flow zones for geothermal aquifer (Figure 4). The extensional driving force by the excess displacement or slip rate should be always concentrated at the fault tips in the growing process of pull-apart basins. As a result, the concentration of the extensional stress is expected in the boundary normal faults

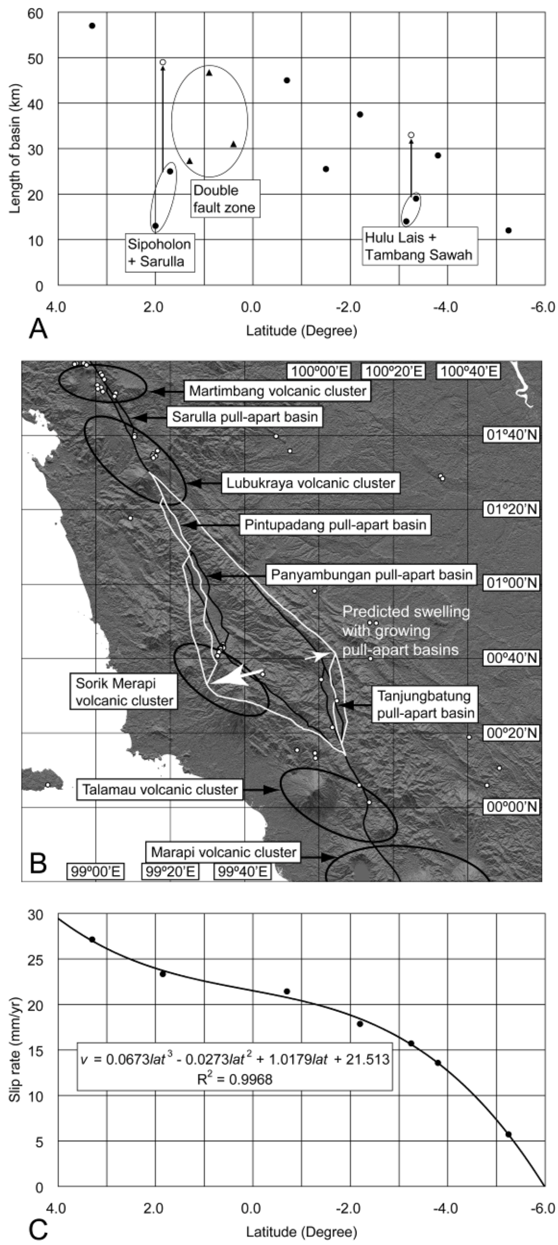

Figure 7: Estimate of slip-rate partitioning along the Sumatran fault. (A) Length of pull-apart basins along the Sumatran fault. (B) The double fault zone of the Sumatran fault from 0.3ºN to 1.5 ºN as a stretch absorber. (C) Estimate of slip-rate partitioning along the Sumatran fault.

and their vicinities as demonstrated by the finite-element simulations (Bertoluzza and Perotti, 1997). The major geothermal fluid discharges from the NW boundary normal faults in the Sipoholon and Suoh Antatai pull-apart basins actually confirm the roles of extensional stress concentration. Their strikes show about N5ºE azimuth that would coincide with the horizontal maximum principal stress axis as well as the subduction azimuth between the Indian-Australian versus Sundaland (Southeast Asian) plates (McCaffrey, 1991). About a half of geothermal resources in Sumatra is expected on the slope of volcanic edifices in the volcanic clusters, and the other half is expected in the pull-part basins. The vapor-dominated type geothermal resources may be common in the former and the water-dominated type geothermal resources with the neutral chloride type or bicarbonate type thermal water may be common in the latter. Huge geothermal potentials in Sumatra could thus be attained by the spatial coincidence of the volcanic clusters and the Sumatran fault, particularly by the formation of pull-apart basins.

6. CONCLUSIONS

We propose a generation process of pull-apart basins along the strike-slip fault with a special reference to the Sumatran fault, Indonesia. All the pull-apart basins along the Sumatran fault are situated near the volcanic clusters, but rarely inside of the areas. This contradictory relation is basically explained by the depth variation of the brittle-plastic transition induced by the high-level magma systems of the volcanic zone along the Sumatra fault with the following process. Increasing the obliquity of the subduction, nucleation of segments of the strike-slip faults is initiated in non-volcanic areas where the brittle layer is thick. These segments are growing toward the volcanic clusters where the brittle layer is very thin and initially inhibits fault segment expansion. The tips of these fault segments are warping near the area of the volcanic cluster where clockwise rotation deformation occurs by the dextral moment with response to the thin brittle crust and underlying dehydration front of the brittle-plastic transition. Finally, a new segment penetrates the volcanic clusters and forms pull-apart basins together with the pre-existing warped tips of the faults.

The slip-rate partitioning along the Sumatran fault is estimated from the length of pull-apart basins and is consistent to the previous estimates from other methods. We also show that the pull-apart basins serve for the formation of geothermal reservoirs in Sumatra and their boundary normal faults particularly serve for the major discharges of thermal water by their dynamic extension.

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