Research Journal of Applied Sciences 8 (2): 125-130, 2013
ISSN: 1815-932X

Fracture Density Analysis in the Sai Yok Fault, Western Thailand and its Implications for Hydrological Exploration

Che-Azlan Chemong and Piyaphong Chenrai
Department of Geology, Faculty of Science, Chulalongkorn University,
254 Phayathai Road, Pathumwan, 10330 Bangkok, Thailand

Abstract: Fracture and Drainage Density (FD and DD), defined as the total length of fractures and drainages per unit area, respectively are a fundamental property of natural terrain that influences the hydrological reservoir units. Hence, the accurate measurement of the FD and DD is useful for hydrological applications. These measurements were evaluated for the Kanchanaburi area along the Sai Yok Fault, Western Thailand which is dominated by an active fault zone using the Digital Elevation Model (DEM) derived data. Damage zones or highly fractured areas were typically found on the Southwest side of the Sai Yok Fault within which Permian limestone is considered to be highest fractured area compared to the adjacent units. Analysis of the FD and DD provide a simple and more general way to locate hydrological reservoir units in a highly faulting area and allows the examination of a large area at a very reasonable cost. However, the FD analysis from the DEM can only allow the identification of the FD in the two surface dimensions and does not address any FD in the depth dimension. Nevertheless, the changes in the FD and DD of an individual geological unit are generally more useful at a local scale to determine the location of highly fractured structures containing a water reservoir along a fault zone whereas FD and DD changes in an individual fault side influences the fracture connectivity for a water reservoir at a regional scale.

Key words: Fracture density, drainage density, Digital Elevation Model, damage zone, connectivity

INTRODUCTION

In many ground water reservoir areas, there is a strong correlation between a high Fracture Density (FD) and the presence of water. An increase in fractures and faults often marks subsurface features that influence the reservoir units and the post-depositional tectonic fracture enhancement of reservoirs. Analysis of the FD is a simple technique that can be applied in hydrological exploration to locate highly fractured areas. These areas are assumed to be associated with underground water reservoirsand FD analysis has already been found to be useful in the location of ground water sources (Wechsler *et al.*, 2009). Hence, this technique could be important to the investigation of potential ground water sources in areas of water shortage.

Fractures may be formed by rock deformation during tectonic activity such as folding and faulting. Generally, strike-slip faults accommodating horizontal displacements are found as normal structures in response to plate movements in the Earth's crust (Sylvester, 1988). Strike-slip faults reflect the fracture damage zone due to horizontal slip. Theoretically, a damage zone or highly fractured area is expected to accumulate on the stiffer side which sequentially experiences a tensile stress field during plate movement (Ben-Zion and Shi, 2005). In addition, the FD may have different patterns and a special signature for each rock type due to their different lithology. The FD technique used in this study utilized the Digital Elevation Model (DEM) data and the shaded relief tool which is available in some mapping or GIS Software such as Global Mapper, Surfer and ArcGIS. DEM data provide valuable information in many ways, one of which derives from the stereoscopic study of straightand/or arcuate lineation, caused by breaks in the rocks showing at the surface of the earth. Additionally, the Drainage Density (DD) technique is also used in this study in order to better locate a damage area that could potentially contain a water reservoir.

In this study, two neighboring terrains of the Three Pagoda Fault Zone (TPFZ) in Western Thailand were used in this as the study site. Quantification of the FD and DD relating to the rock damage area were used to determine the location of any highly fractured zone. Hence, the premise that the study of FD and DD may provide another tool to be used in pinpointing hydrological exploration targets.

MATERIALS AND METHODS

The study area (Fig. 1) is based upon the Sai Yok Fault (SYF) within the TPFZ and consists of a Northwest-

Corresponding Author: Piyaphong Chenrai, Department of Geology, Faculty of Science, Chulalongkorn University, 254 Phayathai Road, 10330 Bangkok, Thailand

striking 50 km wide zone of deformation located in the Western part of Thailand that is documented to be associated with earthquake activity (Charusiri *et al*., 1998; Hinthong, 1995; Pananont *et al*., 2011). The TPFZ lies South of and parallel to the Mae Ping Fault and extends Northwest into Myanmar (Rhodes *et al*., 2005) and shows significant features related to its geological structure on the DEM data. The surface ruptures around this area are interpreted as having occurred between 4500-5000 years ago as determined by TL-age results (Songmuang *et al*., 2007). Geological structures can be recognized on the DEM data as either linear or curvilinear features. The DEM dataset with a 90 m pixel resolution, covers an area of approximately 15,000 km^2 and was derived from SRTM (shuttle Radar Topography Mission) data obtained from the CGIAR-CSI SRTM website (http://srtm.csi.cgiar.org). With the DEM dataset, the geological map of Kanchanaburi, obtained from Department of Mineral Resources, Thailand is used to locate and identify the geological units and their description of lithology.

The database of the TPFZ, sourced from the active fault map in Thailand (Department of Mineral Resources, 2006; Pananont *et al*., 2011) was used to delinate the Sai Yok Fault (SYF) in the study area into each fault or fault segment. This fault zone is believed to be controlled by the interaction of the Australian-India, Burma and SE Asian plates (Rhodes *et al*., 2005; Charusiri *et al*., 2003). The TPFZ has been attributed to either right or left-lateral movement. However, the lastest phase of activity was a right-lateral strike-slip movement during the Pliocene to Holocene period (Rhodes *et al*., 2005).

There are various geological units within this region and those located along the SYF within this study area are shown in Table 1. Although, several geological units

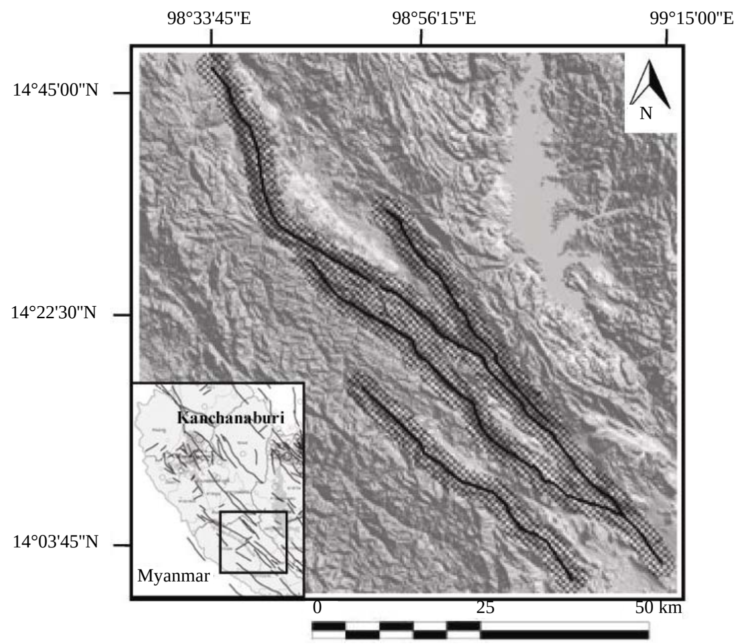

Fig. 1: Regional setting of the study area. Inset: location map of Western Thailand showing (rectangle) the location of the study area shown in the main map. Main map: shaded relief derived from the SRTM data showing the topography. Sai Yok Fault (SYF) segments are marked with black lines and are derived from the active fault map of Thailand (Department of Mineral Resources, 2006; Pananont *et al*., 2011)

Table 1: Geological units, their description and formation age (geological period) in the SYF study area

Name	Description	Age
Kgr	Hornblended-biotite granite, medium to fine-grained muscovite granite and porphyritic granodiorite	Cretaceous
Qc	Alluvial deposit: gravel, sand, silt and clay, unconsolidated to semi-consolidated	Quaternary
Tmm	Claystone and siltstone	Tertiary
Ju	Mudstone, siltstone, sandstone and limestone	Jurassic
Trl	Conglomerate and shale, interbedded with siltstone and sandstone	Triassic
Pr	Limestone, dolomitic limestone with chert nodules	Permian
CPk-1	Shale, dark grey to black, sandstone and pebbly mudstone	Permian-Carboniferous
DCtn	Greywacke, siltstone, shale and pebbly mudstone	Carboniferous-Silurian
D	Chert and shale	Devonian
O	Limestone with argillaceous band, dolomitic limestone and marble	Ordovician

appeared only on one side of the faultand so can not be used to compare the degree of damage between both sides, they are nevertheless useful for comparison of the degree of damage among different geological units and on a regional scale between the opposite sides of the fault.

The DEM datasets were analyzed using the Global Mapper 11 Software. For each DEM dataset, the study area was delineated by using a 2.5 km buffer around the main SYF which therefore results in a 5 km wide zone. An example of the analytical process is shown in Fig. 2. The study area was then divided into the five apparent fault segments (Fig. 3). Each side of the fault that is the Northeast (NE) and Southwestern (SW) sides was observed separately and compared to the opposite side for every segment. For each type of geological unit and for each side of the fault, fractures and drainages that are completely or almost completely contained within the fault

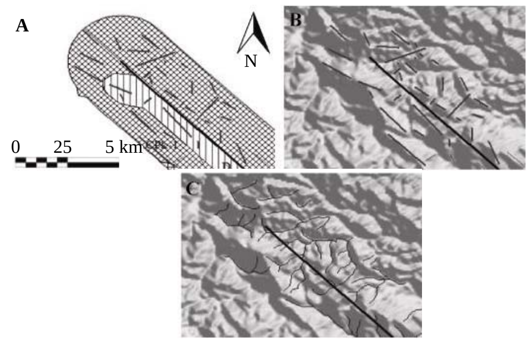

Fig. 2: An example of the results of fracture and drainage delineation along the SYF using the DEM dataset, showing the: A) buffered zone of interest area, B) the fracture delineation and C) the drainage network

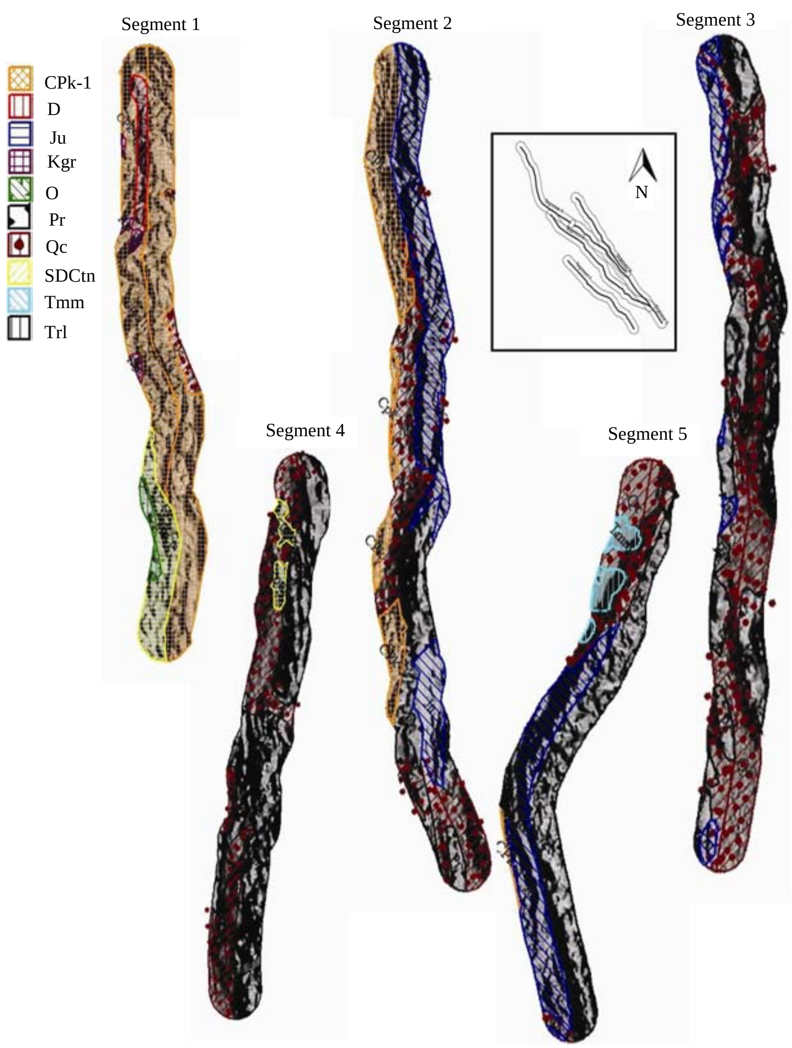

Fig. 3: The study area was divided into five distinct fault segments, numbered 1-5. The geological details are as described in Table 1. Inset: proximal location map for the five fault segments of the SYF, Western Thailand

buffer zone or one side of the fault (does not cross the fault) were selected for the FD and DD calculations. The FD is the ratio between the total fracture lengths and the geological unit areaand is expected to be higher in the damaged area. Similarly, the DD is the ratio between the total stream length and the geological unit areaand is related to the rate of erosion, so that the DD is higher where the erosion rate is stronger.

RESULTS AND DISCUSSION

The selected fractures and drainages were all contained within various geological units and buffer zones for the comparison between both sides for each parameter as shown in Fig. 4. The comparative results are summarized in Table 2 where the FD and DD values are compared across all five of the fault segments for each

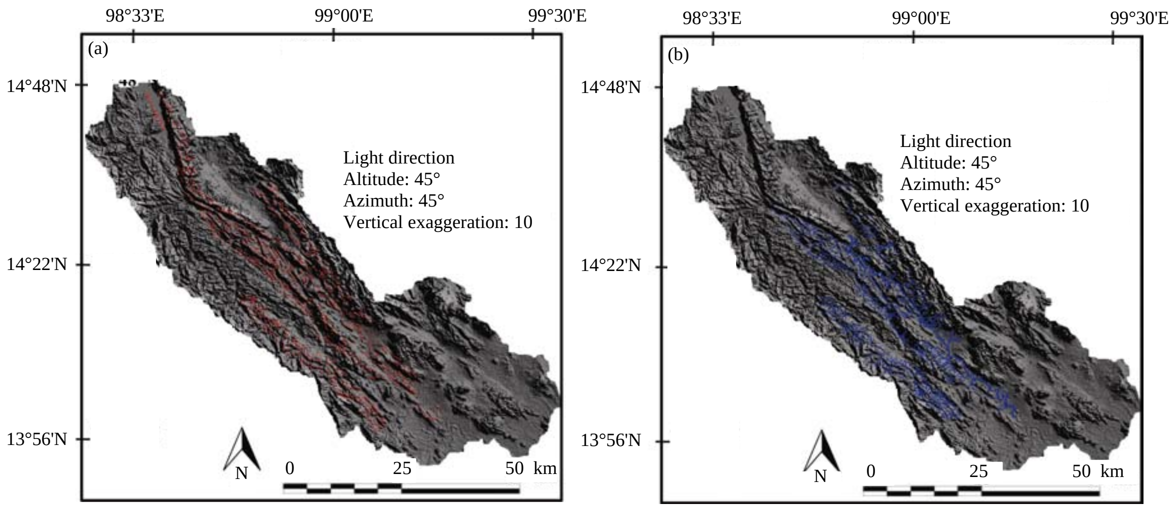

Fig. 4: Shaded relief image of the Digital Elevation Model (DEM) of the SYF study area with enhanced parameters for the fracture and drainage delineation used in this study along the SYF showing; a) the fracture delineation and b) the drainage network

Table 2: Comparative analysis of the Fracture (FD) and Drainage (DD) densities delineated from the Digital Elevation Model (DEM) dataset

Segments	Geological unit	Location relative to fault	Enclosed area (sq mi)	Total fracture length (miles)	Total drainage length (miles)	FD ($mile^{-1}$)	DD ($mile^{-1}$)
1	Qc	NE	2.74	2.49	10.11	0.91	3.71
	CPk-1	NE	49.12	48.81	117.72	0.99	2.39
		SW	28.08	19.58	60.36	0.70	2.15
	Kgr	SW	1.94	1.57	6.51	0.81	3.35
	D	SW	5.62	4.05	13.74	0.72	2.44
	SDCtn	SW	13.92	17.16	26.50	1.23	1.90
	O	SW	2.48	2.80	4.09	1.13	1.65
2	Qc	NE	10.87	5.41	12.52	0.49	1.15
		SW	29.01	23.67	70.21	0.82	2.42
	CPk-1	SW	30.12	23.80	26.19	0.79	0.87
	Ju	NE	48.21	36.88	87.37	0.77	1.81
	Pr	NE	13.84	13.30	12.65	0.96	0.91
		SW	13.73	10.93	27.56	0.80	1.78
3	Qc	NE	36.88	11.50	54.48	0.31	1.48
		SW	33.55	16.63	67.70	0.49	2.12
	Pr	NE	33.55	22.65	20.40	0.67	0.61
		SW	24.63	29.82	36.17	1.21	1.47
	Ju	SW	11.04	6.37	26.20	0.58	2.37
4	Qc	NE	2.12	1.30	4.37	0.61	2.06
		SW	31.85	12.20	51.37	0.38	1.61
	Pr	NE	46.53	41.63	38.53	0.89	0.83
		SW	13.10	14.81	18.81	1.13	144.00
	SDCtn	SW	3.24	4.00	1.92	1.24	0.59
5	Qc	NE	8.69	6.71	0.00	0.77	0.00
		SW	11.78	7.51	1.57	0.64	0.13
	Pr	NE	41.50	34.67	2.07	0.84	0.05
	CPk-1	SW	1.13	0.85	2.44	0.75	2.16
	Ju	SW	29.50	22.60	28.48	0.77	0.97
	Tmm	SW	5.59	2.34	0.58	0.42	0.10
	Trl	SW	2.85	2.67	0.00	0.95	0.00

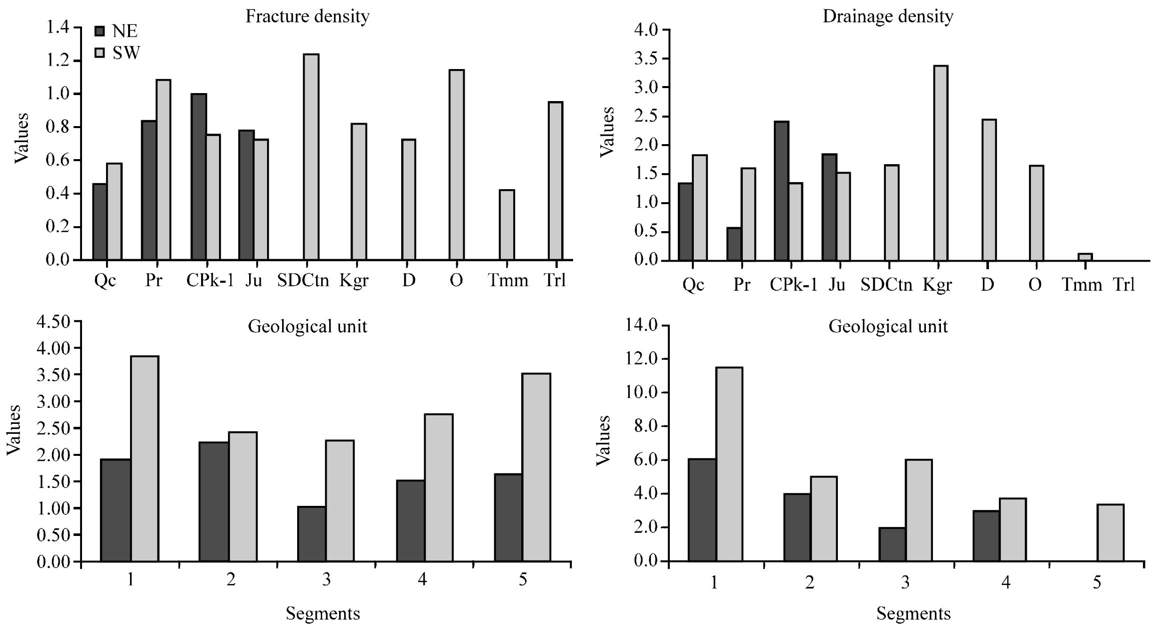

Fig. 5: The Fracture (FD) and Drainage (DD) Densities in different geological units and different fault segments of the SYF. The corresponding data is presented in Table 2. On the top is the results of each geological unit (abbreviations in Table 1) for both sides of SYF whereas on the bottom is the results of the entire study area for both sides of SYF (segments in Fig. 3)

geological unit. Regionally, the FD and DD values are higher on the SW side of the fault than on the NE side for each segment.

A comparison of the FD and DD values of varying geological units along the fault is not consistent between the two sides of the fault (Fig. 5). In the Qc and Pr geological units, the FD and DD values are higher on the SW side of the fault whereas they are higher on the NE side of the fault for the CPk-1 and Ju geological units. Thus, the differences in the observed FD and DD values are also dependent on the lithology differences. However, the FD value in each geological unit and on each side of the fault is usually higher where the DD value is high or the erosion is more intense. From the comparison of the values on the opposite side of the fault, the FD and DD values are consistently higher on the SW side of the fault. Thus, an asymmetric distribution of the damaged area across the fault occurs so that the SW side of the SYF is more damaged.

Fracture observations revealed that highly fractured areas are mostly located in the SW side of the SYF. In addition, the FD and DD values are considered to be high on the damaged side. There is some lack of congruency between the different geological units between the SW and NE side of the fault in terms of supporting that the SW is more damaged where the CPk-1 and Ju indicated more damage on the NE side. It may be that the 5 km wide scale of the DEM dataset which is using a large buffer is too wide and may capture the effects of the activity of the other minor faults in the NE part of the study area.

When the lithologic boundaries are unknown, there may be some difficulty in differentiating between the FD increases caused by anomalous tectonic action within a homogeneous lithologic unit or by simply changes in the rock type. In the first case, additional fracturing may be of interest while in the second instance, a non-water reservoir rock body may exhibit more bedding, schistosity and joints without enhancement of the reservoir properties, permeability and fluid-flow. Although, high FD anomalies could be assumed to always indicate zones of interest to the exploratory hydrologist, it must be considered that a damage area width of approximately 1 km is best reflected in the hydrology (Wechsler *et al*., 2009).

This study, based upon the quantification of the FD and DD determinants has effectively outlined those areas that exhibit a high damage or a highly fractured area. It allows the examination of a large area at a very reasonable cost. The FD analysis presented here is limited to the identification of FD in the two surface dimensions (i.e., on a geological map) and does not address the FD in the depth dimension. Changes in the FD and DD of individual geological units are generally more useful at a local scale to determine the location of the highly fractured areas that may contain water reservoirs along a fault zone whereas the changes in the FD and DD in the individual fault side influences the fracture connectivity for the water reservoir at a regional scale.

CONCLUSION

Structure is one of the principal controls of a hydrological reservoir and the formation of high FD zones within faults and shear zones may provide pathways of enhanced permeability and fluid-flow during deformation. In the Kanchanaburi region, Western Thailand which is dominated by a major fault zone, the analysis of the FD and DD is one method of quantifying the density of fracturing of a region. The FD and DD analysis proved to be potentially useful for hydrological exploration and can be applied to terrains where the existence of hydrological reservoirs has a demonstrated relationship between high FD and water reservoir development.

High FD and DD values were typically located on the SW side of the SYF which may be associated with fractures caused by tectonic deformation and could become recharged areas. Permian limestone is considered to be more easily damaged and fractured compared to the surrounding geological units. High water saturate units are considered to be located in the damaged zones, characterized by a high FD.

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