PS Fractured Basement Reservoirs Characterization in Central Sumatera Basin, Kotopanjang Area, Riau, Western Indonesia: An Outcrop Analog Study*

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Abstract

Fractured basement reservoirs in Central Sumatera Basin would be a future Indonesian oil and gas development. An analog outcrop model needs to be conducted as a first step toward predicting subsurface fracture system attributes. The Kotopanjang Area was chosen for this study because of good quality outcrops of pre-Tertiary basement of the Central Sumatera Basin. The Central Sumatra Basin is one of the most hydrocarbon prolific Indonesian Tertiary back-arc basins today. It was formed as a pull-apart basin related to NW-SE trending dextral strike-slip faulting. It experienced three tectonic deformation phases: Mesozoic compressional, Eocene-Oligocene extensional, and Pliocene-Pleistocene compressional tectonics. The objective of this study was to conduct fracture characterization on basement outcrops and to obtain empirical and functional relationships between the fracture attributes.

The methods used in this study included geological field mapping and scanline sampling, data sorting, data calculation, statistical analysis, and interpretation. Scanline sampling was conducted on pebbly mudstone (Carbon-Early Permian). Data calculation results were plotted in graphical form, analyzed statistically, and interpreted geologically. The results would be useful in predicting: (i) fracture zone width, (ii) geometry of fracture zone, and (iii) fracture porosity and permeability.

The study area is dominated by NW-SE and NE-SW trending basement structures. The fractures observed in study area include fault-related fracture systems. Two damage zones can be observed in scanline sampling: Damage Zone #1 and Damage Zone #2. Damage Zone #1 shows that the fractures are related to dextral strike-slip faulting. Damage Zone #2 shows that the fractures are related to normal faulting. Both of damage zones indicate several high strain zones with average intensity of three to five fractures per meter. Rose diagrams illustrated three main fracture orientations: NE-SW, NNE-SSW, and WNW-ESE trending fractures. The NE-SW trend consists of two average strike orientations N 215° E and N 235° E represented by conjugate fractures systems. The NNE-SSW trend with an average strike of N 185° E is represented by joints and veins. Veins trend WNW-ESE. We summarize that the main stress controlling all the fractures was in the NNE-SSW direction. Fracture spacing, length, and thickness cumulative distribution plots demonstrated that all fractures follow Power-Law distribution with fractal dimension (D) 1.0 to 2.

American Association of Petroleum Geologists
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FRACTURED BASEMENT RESERVOIRS CHARACTERIZATION IN CENTRAL SUMATERA BASIN, KOTOPANJANG AREA, RIAU, WESTERN INDONESIA: AN OUTCROP ANALOG STUDY

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ABSTRACT

Fractured basement reservoirs in Central Sumatera Basin would be a future Indonesian oil and gas development. An analog outcrop model need to be conducted as a first step toward predicting subsurface fracture system attributes. Kotopanjang area was chosen for this study because of good quality outcrops of pre-Tertiary basement of Central Sumatera Basin. The Central Sumatra Basin is one of the most hydrocarbon prolific Indonesian Tertiary back-arc basins today. It was formed as pull-apart basin related to NW-SE trending dextral strike-slip faults. It experienced three tectonic deformation phases: Mesozoic compressional, Eocene-Oligocene extensional, and Pliocene-Pleistocene compressional tectonic. The objective of this study was to conduct fractures characterization on basement outcrops and to obtain empirical and functional relationships between the fracture attibutes.

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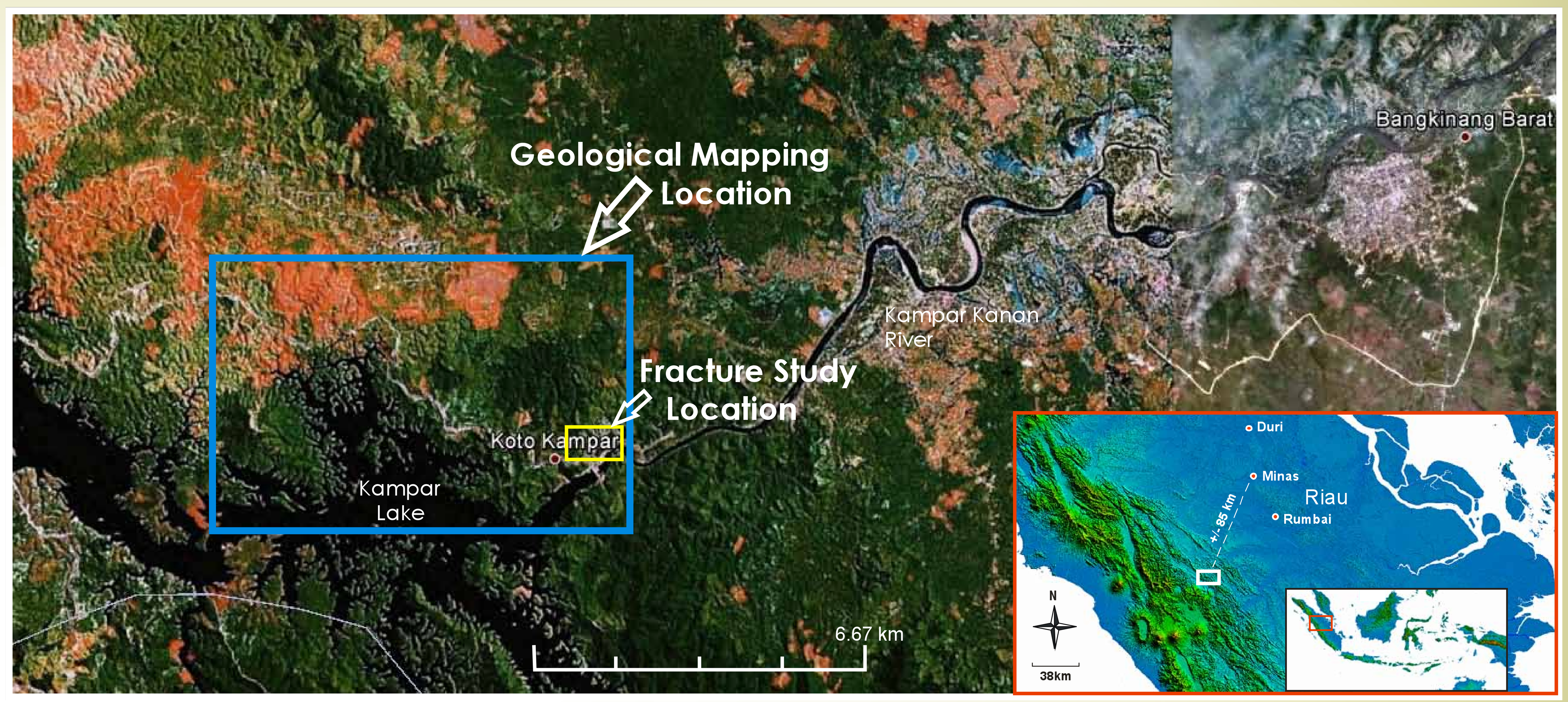

Figure-1. Map showing the location of geological mapping in Kotopanjang area, Kampar Regency, Riau, Central Sumatera, Indonesia. Research area lies at mountain front of Barisan Hill, western part of Central Sumatera Basin. The southern part of the research area is Kampar Lake. Kampar Lake at several years ago was Kampar Kanan River, but today it is dammed for power generation. The research area is located about 85 km from Minas giant field area to southwest. The fracture characterization study was conducted in southeastern geological mapping area.

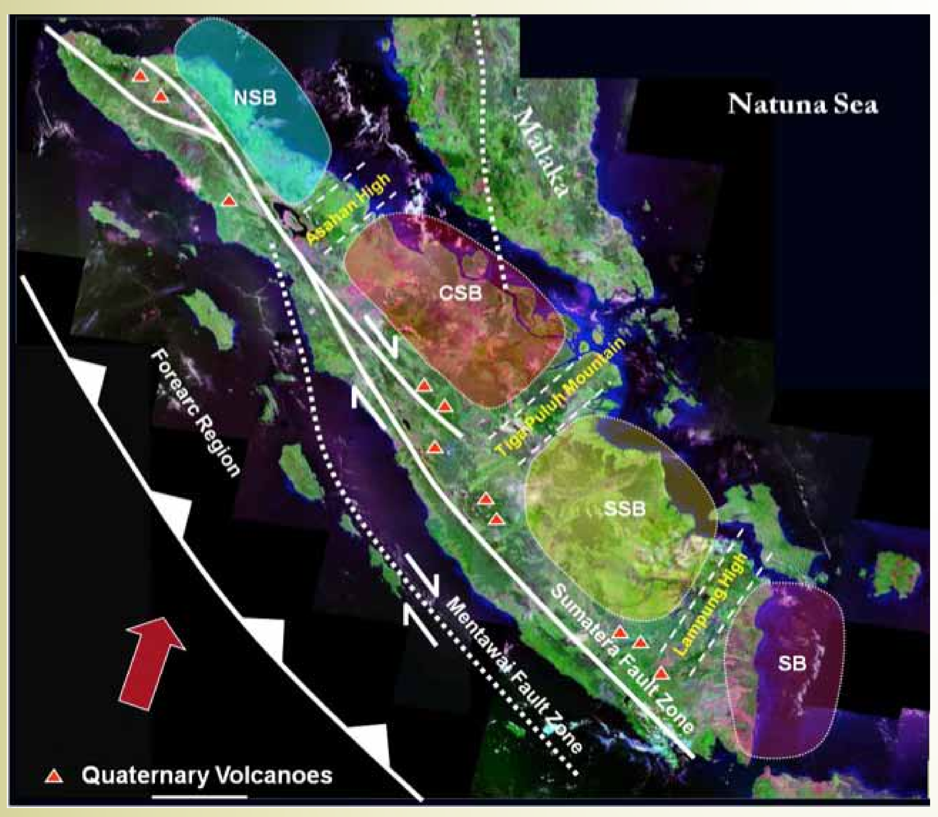

Figure-3. Regional Tectonic Setting of Central Sumatera Basin (CSB)

INTRODUCTION

The pre-Tertiary basement rocks floored the Tertiary sediments in the Central Sumatra Basins. The Central Sumatra Basin is one of the most hydrocarbon prolific Indonesian Tertiary back-arc basins today. Tertiary play remains primary target proven and produced in the Central Sumatra Basin, while the pre-Tertiary fractured basement play is still secondary target and need to be explored further. Eocene-Oligocene graben Pematang rich in hydrocarbons lied directly on pre-Tertiary basement rock is source rock for petroleum system in Central Sumatra Basin. Understanding to fault / fracture systems and flow behavior of pre-Tertiary basement rock will make possible to generate prospect of fractured basement reservoirs in Central Sumatra. The objective of this study was to conduct fractures characterization on basement outcrops and to obtain empirical and functional relationships between the fracture attibutes. The result need to bridge the relationship between seismic and well data so that fractured basement reservoirs model generated in subsurface will be validated. Research area location map and panorama view is presented on **Figure-1** and **Figure-2**.

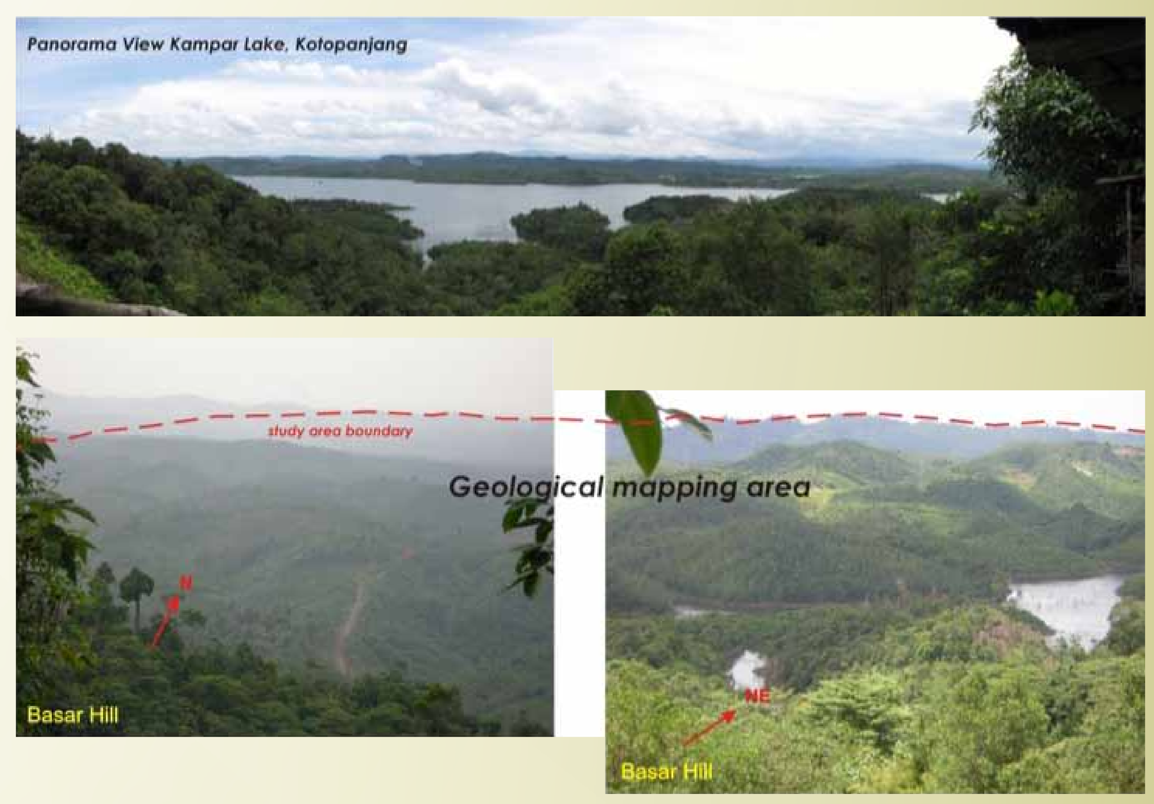

Figure-2. Panorama View photos of geological mapping area situation. (A) Panorama View Kampar Lake, Kotopanjang, taken from geological mapping area to the south. (B) & (C) Panorama View of northern and northeastern geological mapping area taken from Basar Hill. Geographically, the situation of the research area is relatively jungle and consists of undulating hills. Several wild animals, such as bears, still can be found in area of research. Research areas are also part of the rubber forests, plantations and human settlement.

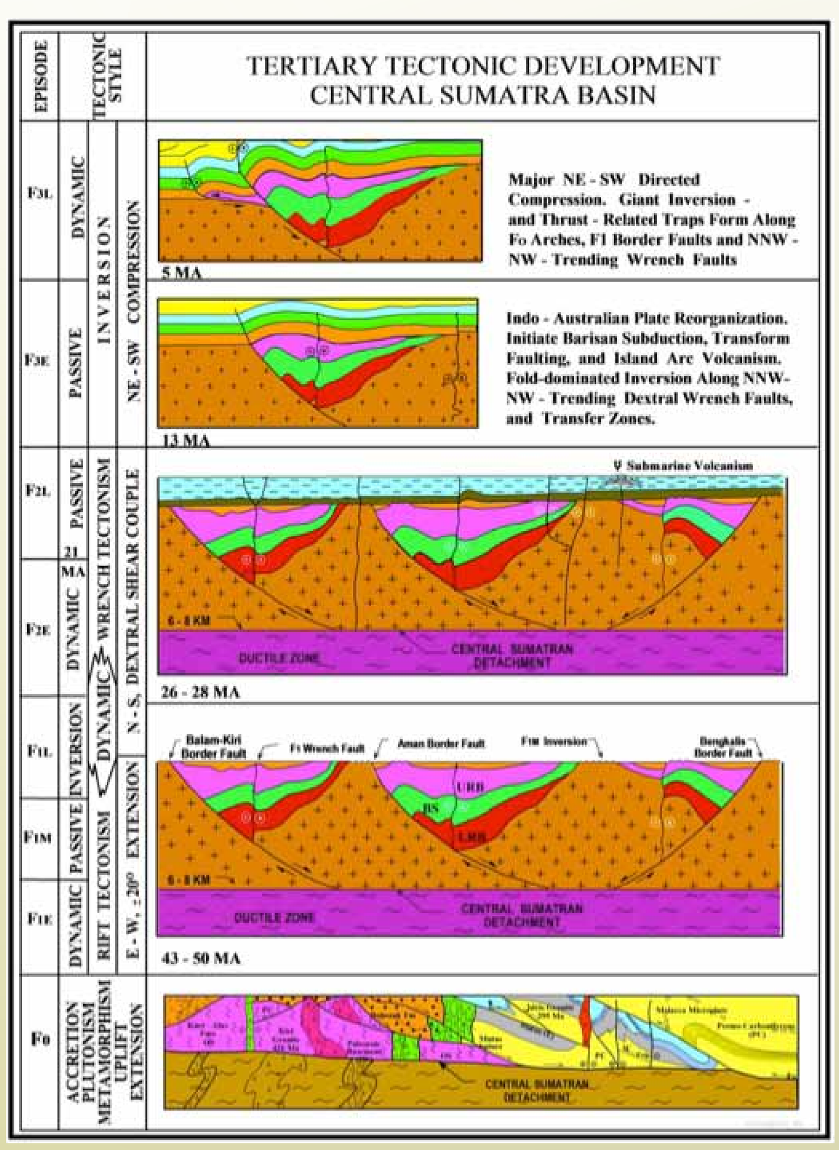

Figure-4. Tectonic development of the Central Sumatra Basin showing four major sequence of deformation (F0, F1, F2, F3) (Heidrick and Aulia, 1996)

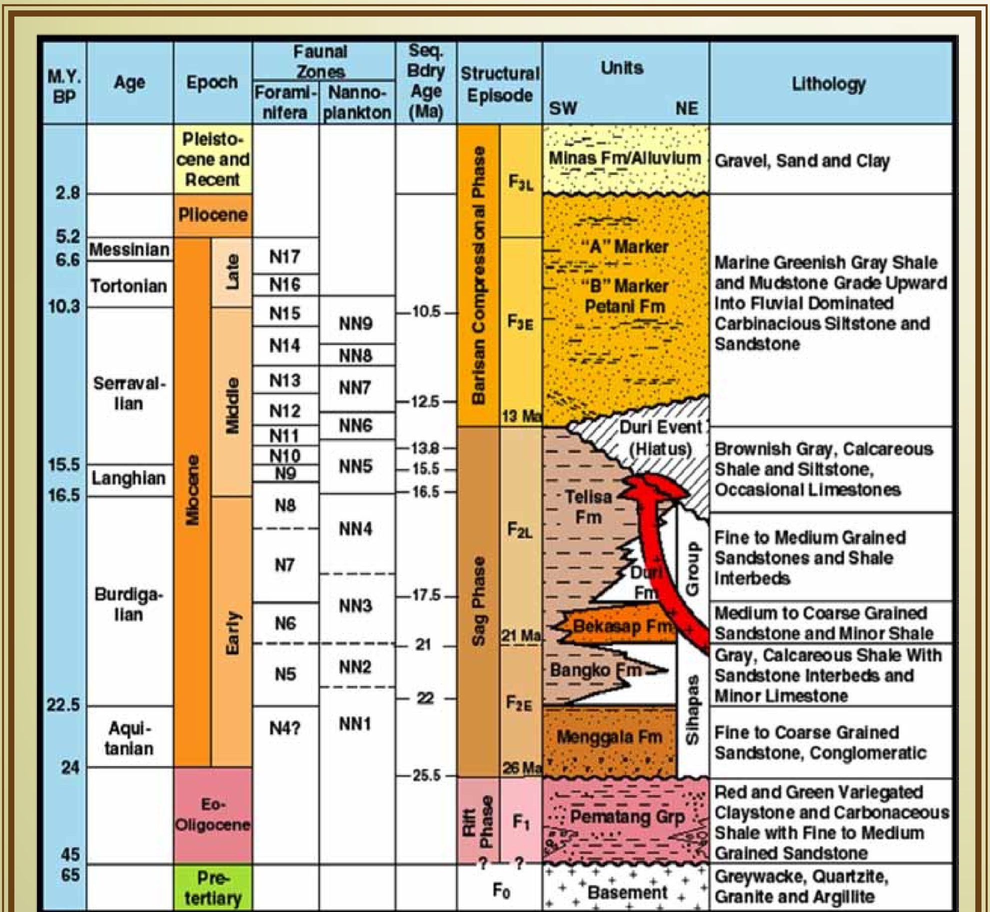

Figure-5. Stratigraphic nomenclatures of the Central Sumatera Basin (Heidrick and Aulia, 1996).

REGIONAL GEOLOGY

Figure-3 shows regional tectonic setting of Central Sumatera Basin (CSB). The Central Sumatra basin is bound to the southwest by Barisan Mountain's geanticlinal uplift and volcanic arc, to the north by the Asahan arch, to the southwest by the Tigapuluh high and to the east by the Sunda Craton. Structuring in the Central Sumatra Basin is related to the first order NW -SE trending right lateral strike-slip fault (The Sumatra Fault System), in response to an oblique northward low angle subduction of the Indian Ocean Plate beneath the Asian Plate which gave rise to a traspressional stress system.

De Coster (1974) explains that the structural features present in the Central Sumatera Basin are the result of orogenic activity that occurred in at least three separate episodes, the mid-Mesozoic orogeny, the Late Cretaceous-Early Tertiary tectonism and Plio-Pleistocene orogeny. The earliest of major episodes was the mid- Mesozoic orogeny when the Paleozoic and Mesozoic strata were metamorphosed, faulted, and folded into large structural blocks or belts of metamorphic rock and intruded by granite batholiths. The second significant tectonic event probably occured in the Late Cretaceous and early Tertiary time, when the major tensional structures that include grabens and fault blocks were formed in the basins of Sumatra.

Figure-4 presented tectonic development of the Central Sumatra Basin showing four major sequence of deformation (F0, F1, F2, F3) (Heidrick and Aulia, 1996). F0 deformation is related to basement structures in which faults and fold-fault zones belonging to this family of structures are old having formed in Late Triassic-Early Jurassic time (Pulunggono and Cameron, 1984). F0 is classified as pre-rift structures in report based on tectonostratigraphic division. F1 deformation is dominated by extension along NS trending structures forming ES rifting. The sedimentary unit related to this event is classified as syn-rift deposit. F2 deformation is related to dextral strike-slip faulting particularly along N-S trending fractures system. The youngest deformation event, F3, is a compression causing inversion on previous structures particularly N-NW trending dextral strike-slip fault system. F3 deformation is directly linked to the development of Sumatran transform margin commencing at 13-15 Ma.

Figure 5. Stratigraphic nomenclatures of the Central Sumatera Basin (Heidrick and Aulia, 1996). It shows syndepositional formations, respective episodes of deformation and brief lithologic descriptions of cotectonic formations. The Paleogene of Pematang sediments are syn-orogenic in character having been deposited in deep grabens formed during a phase of regional Eocene-Oligocene extension (syn-rift deposit). The Pematang is often separated from the overlying Sihapas Group by a distinct regional unconformity. The trangressive phase of the Neogene is represented by the Sihapas group and overlying diachronous Telisa Formation. Top Neogene is characterized by pronounced erosional unconformity overlain by a thin layer of Holocene alluvial sandstone and gravel as a result of basin uplift during Pliocene time.

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METHODS OF STUDY

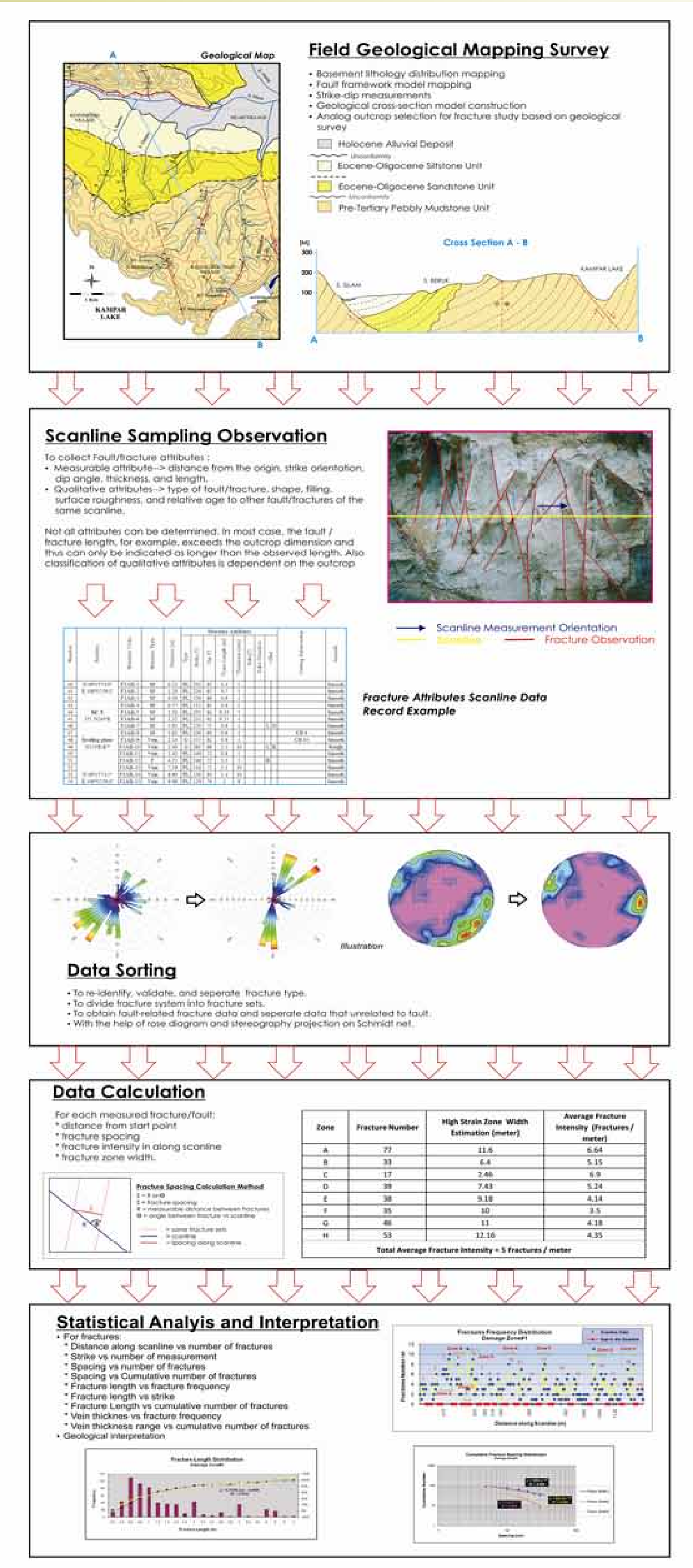


Figure-6. Methods that are used in this study

FIELD GEOLOGICAL MAPPING SURVEY

Field geological mapping area was conducted covering 83.4 km2 (11.5 km x 7.25 km) in Kotopanjang area . The objective of geological mapping is to map the basement rock and conduct fracture characterization on basement outcrop. Geological map, cross section, and stratigraphy can be observed in **Figure-7.** Based on the result, structural setting model of research area is a half-graben. The pre-rift is pebbly mudstone unit (Carbon-Early Permian), schist-quartzite unit (Carbon-Early Permian), and granite intrusion unit (Middle Permian-Early Jurassic) as pre-Tertiary basement. The syn-rift deposition is filled by Pematang Formation (Eocene-Late Oligocene) consisting sandstone and siltstone unit. Sihapas Formation, Telisa Formation, and Petani Formation can not be observed in the reserac area. It can be caused by two probabilities, no deposition or eroded. Alluvial deposit Holocene covered area of Silam River. Structural elements that can be observed in the research area consisted of faulting, folding, and fractures. Faulting is represented by NE-SW dextral strike-slip fault, NW-SE sinistral strike-slip fault, and NNE-SSW normal fault. It can be interpreted that the main stress controlling structural elements in the research are is NNE-SSW. Based on geological map result, fracture characterization was conducted on pebbly mudstone of Bohorok Formation in Southeastern of research area (see **Figure-7**). The fracture study area is located in paleohigh basement, part of flexural margin. It covered Beranakan dextral strike-slip fault and Angsa Normal Fault.

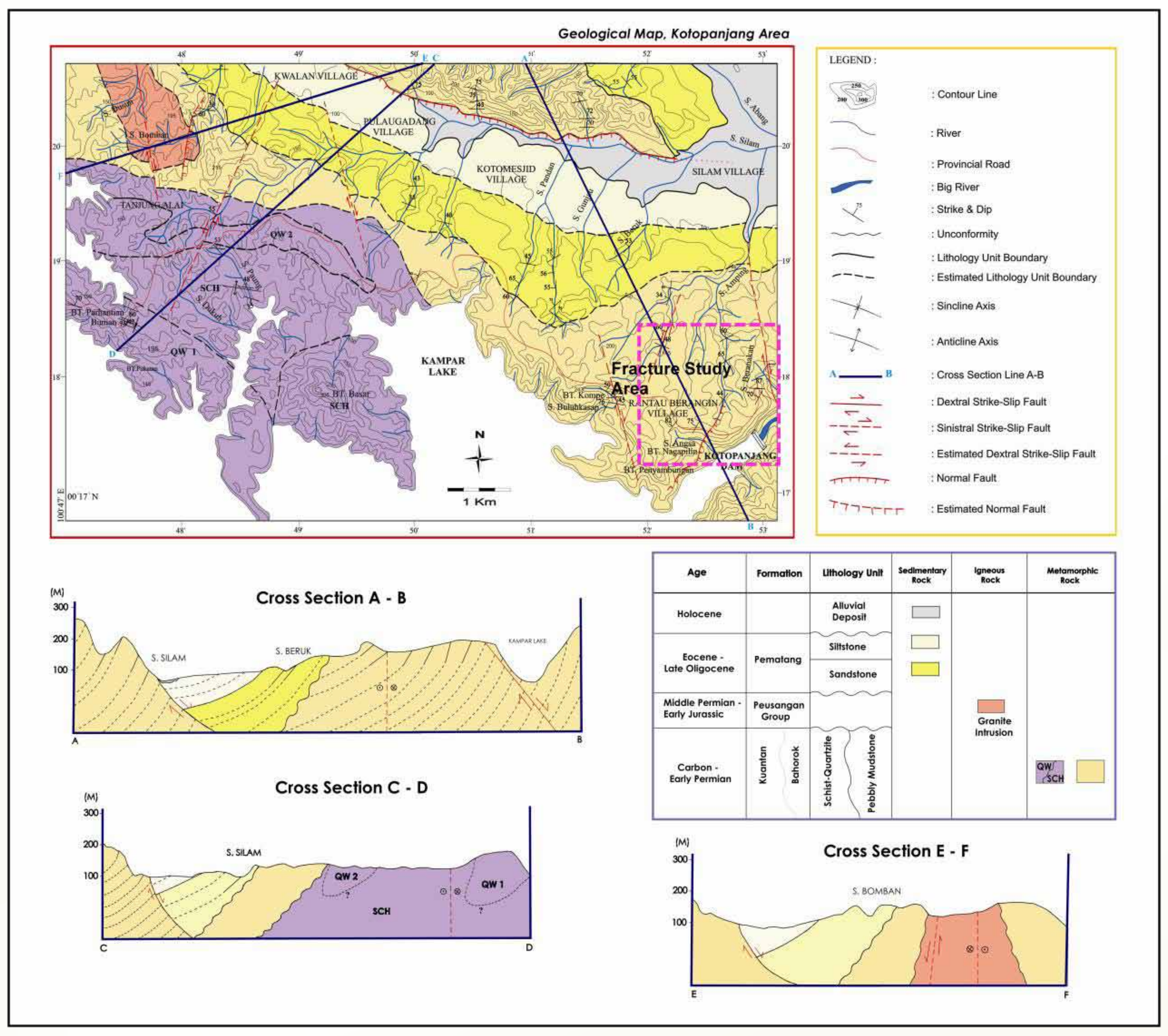


Figure-7. Field Geological Map of Kotopanjang Area.

SCANLINE SAMPLING

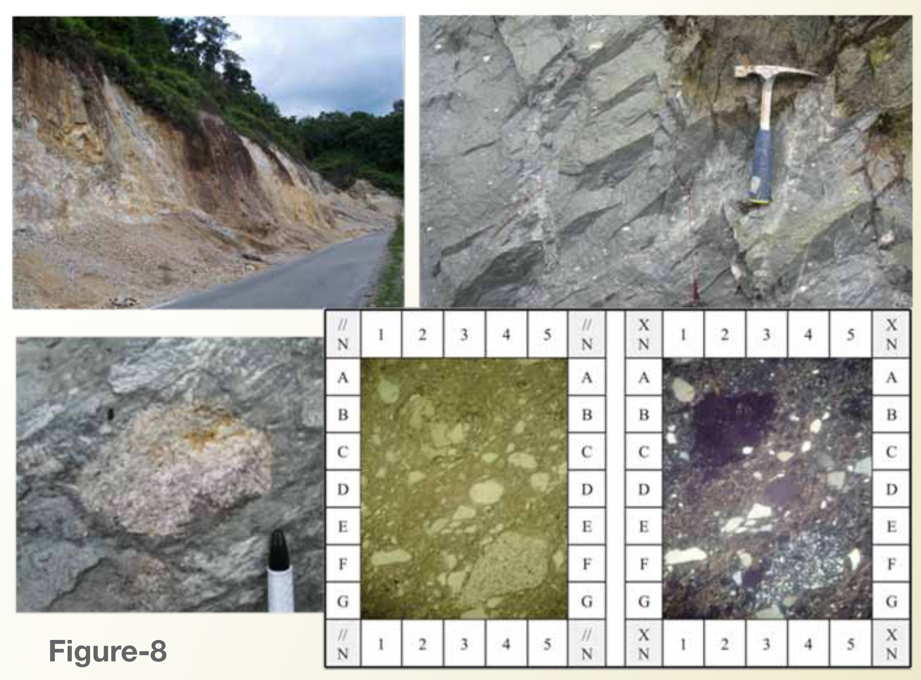
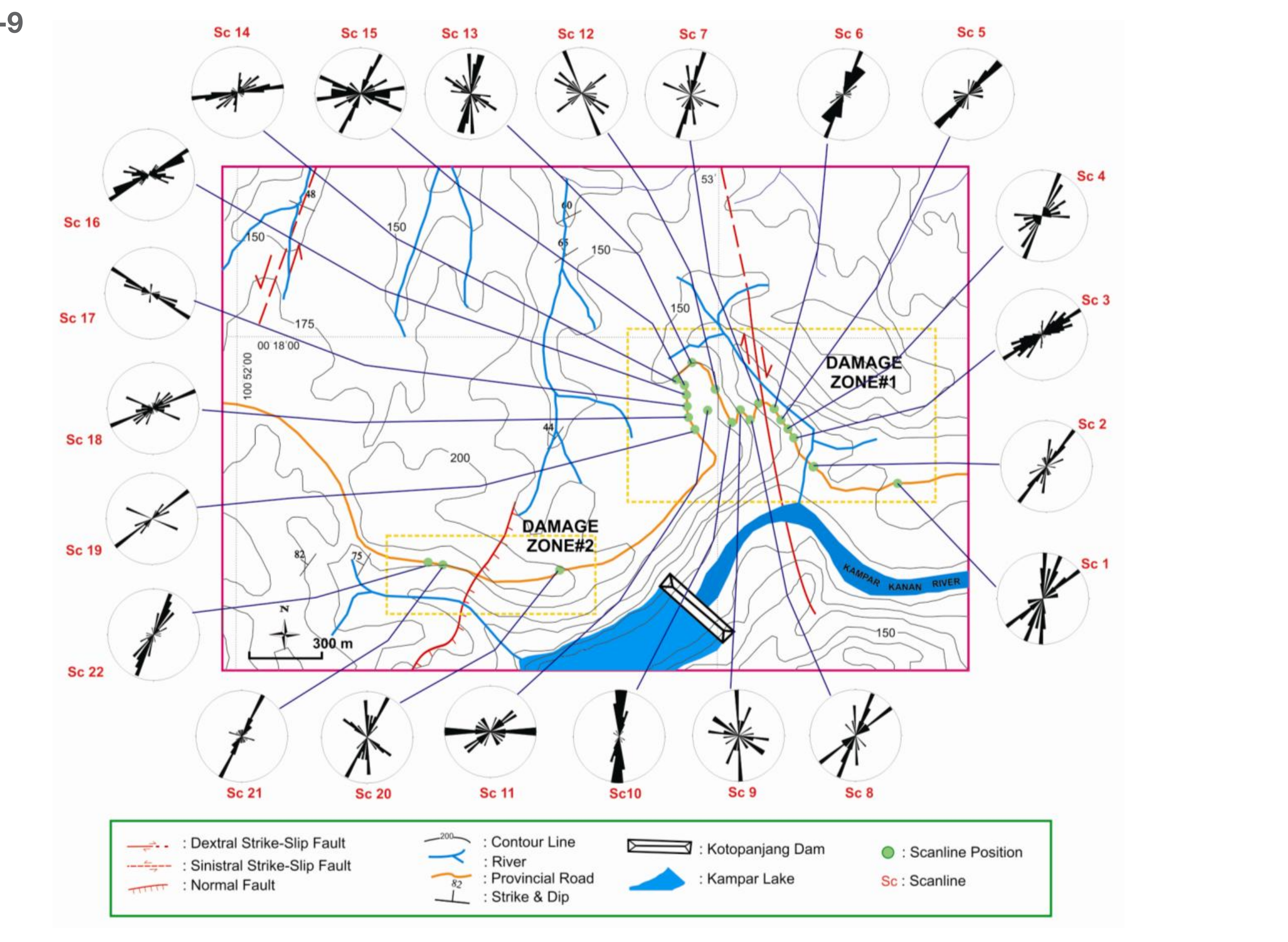


Figure-8

Scanline sampling is conducted on Pebbly Mudstone, Bohorok Formation ,Carbon-Early Permian. **Figure-8** shows pebbly mudstone outcrop photos and thin section. **Figure-9** shows scanline sampling map where fracture study is conducted. Total length of the scanline measurements for the fracture characterization on pebbly mudstone outcrops amounted to ± 208 m. The total number of fractures which can be observed by scanline during this study amounted to 719 fractures. There are 22 numbers of scanline successfully conducted during the study. Based on fracture distribution proximity main faults, it can be divided into two damage zones, Damage Zone#1 and Damage Zone#2. Damage Zone#1 is associated with Beranakan Dextral Strike-Slip Fault, whereas Damage Zone#2 is associated with Angsa Normal Fault.

Figure-9



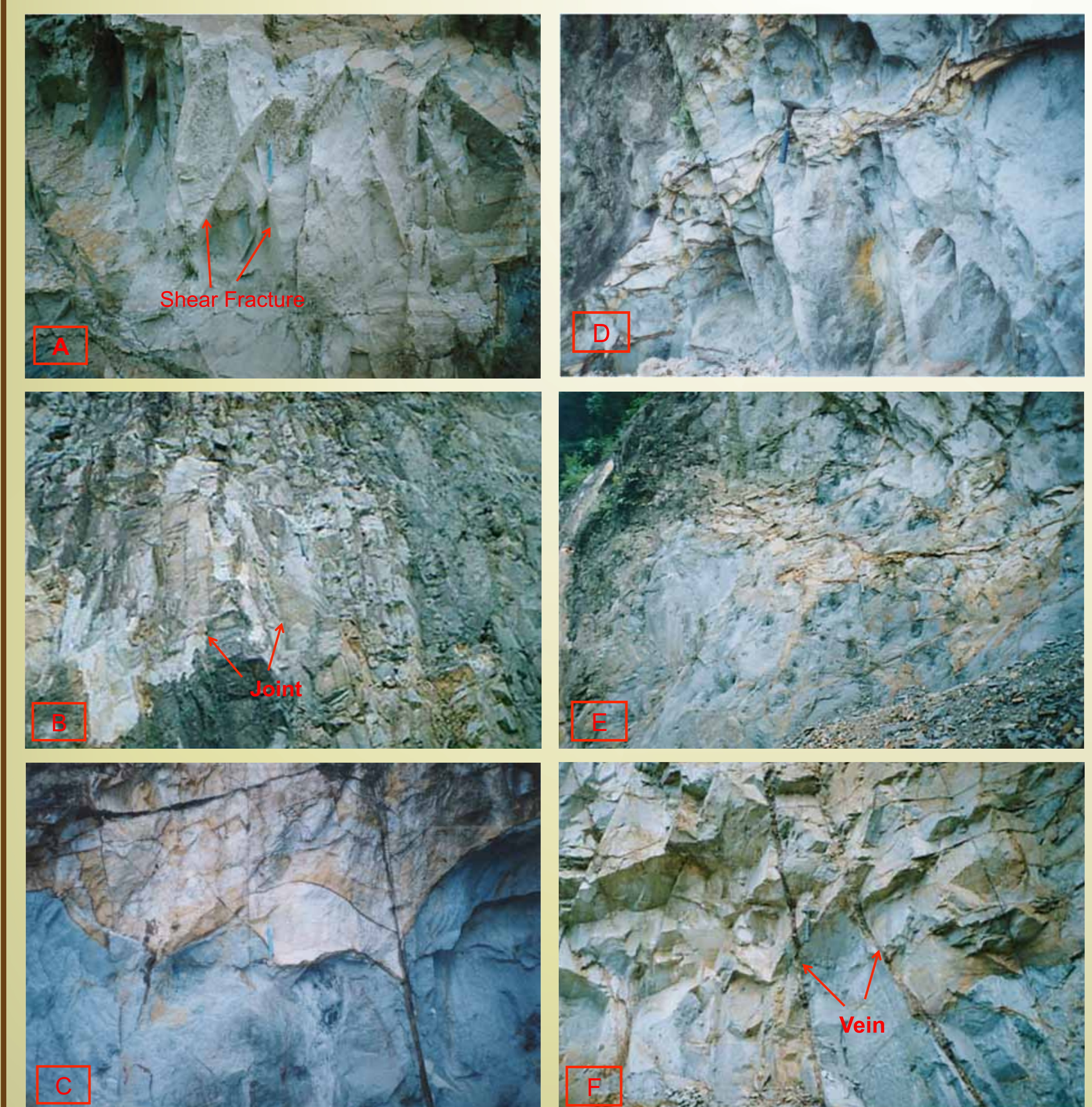


Figure-10 E-F. Fracture characteristic of pebbly mudstone outcrops observed in study area.

FRACTURE CHARACTERIZATION

A. Damage Zone#1 – Dextral Strike-Slip Fault Setting
B. Damage Zone#2 – Normal Fault Setting

Fracture System of Study Area → *Fault-Related Fracture System*

(Nelson, 1985)

Damage Zone#1 Fracture System

Fracture Set #1 > *joint & vein, main strike* orientation N 185°E

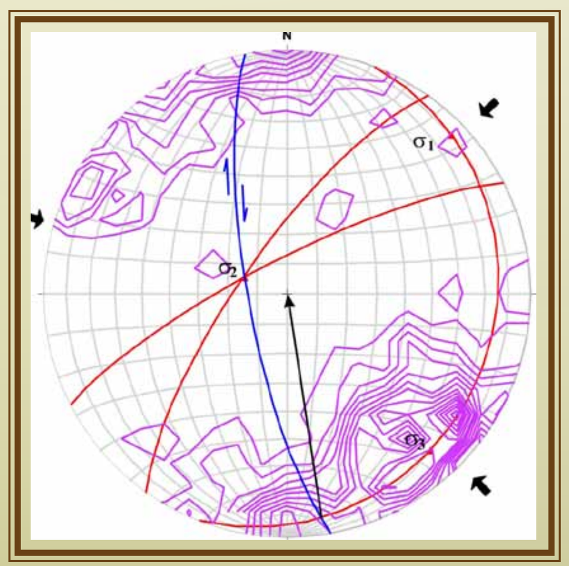
Fracture Set #2 & #3 > *shear fracture*, main strike orientation N 215°E and N 235°E

Damage Zone#2 Fracture System

Fracture Set #1 > *shear fracture, main strike* orientation N 30°E

Fracture Set #2 > *shear fracture*, main strike orientation N 210°E

A. DAMAGE ZONE#1



#Structural Setting

σ1 : 6.8°, N 46°E
σ2 : 74.7°, N 291.1°E
σ3 : 13.9°, N 137.6°E

Figure-11. Beranakan Dextral Strike Slip Fault Kinematic Analyisis. Damage Zone#1 is associated with this fault.

#Fracture Frequency Distribution

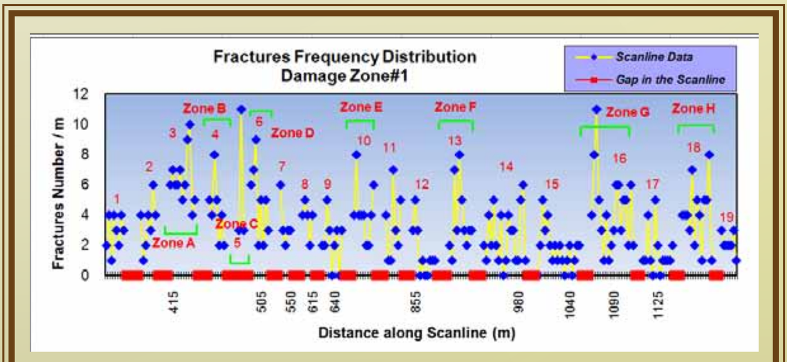


Figure-12. Fracture Frequency Distribution Plot in Damage Zone#1

Zone	Fracture Number	High Strain Zone Width Estimation (meter)	Average Fracture Intensity (Fractures / meter)
A	77	11.6	6.64
B	33	6.4	5.15
C	17	2.46	6.9
D	39	7.43	5.24
E	38	9.18	4.14
F	35	10	3.5
G	46	11	4.18
H	53	12.16	4.35
Total Average Fracture Intensity = 5 Fractures / meter			

Table-1. Statistical Data of High Strain Zone in Damage Zone #1

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#Fracture Strike Distribution

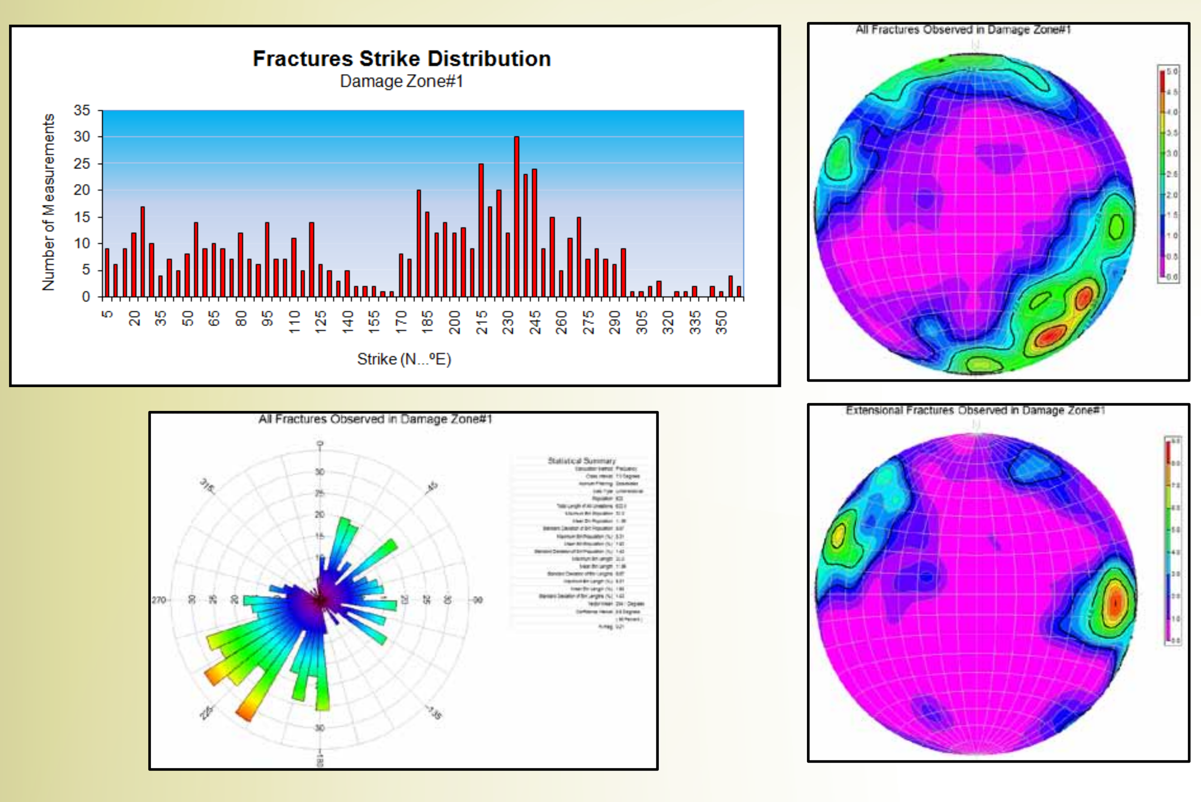


Figure-13. Histogram, rose diagram and equal area stereographic plots showing fracture orientation distribution in Damage Zone#1.

#Fracture Spacing Distribution

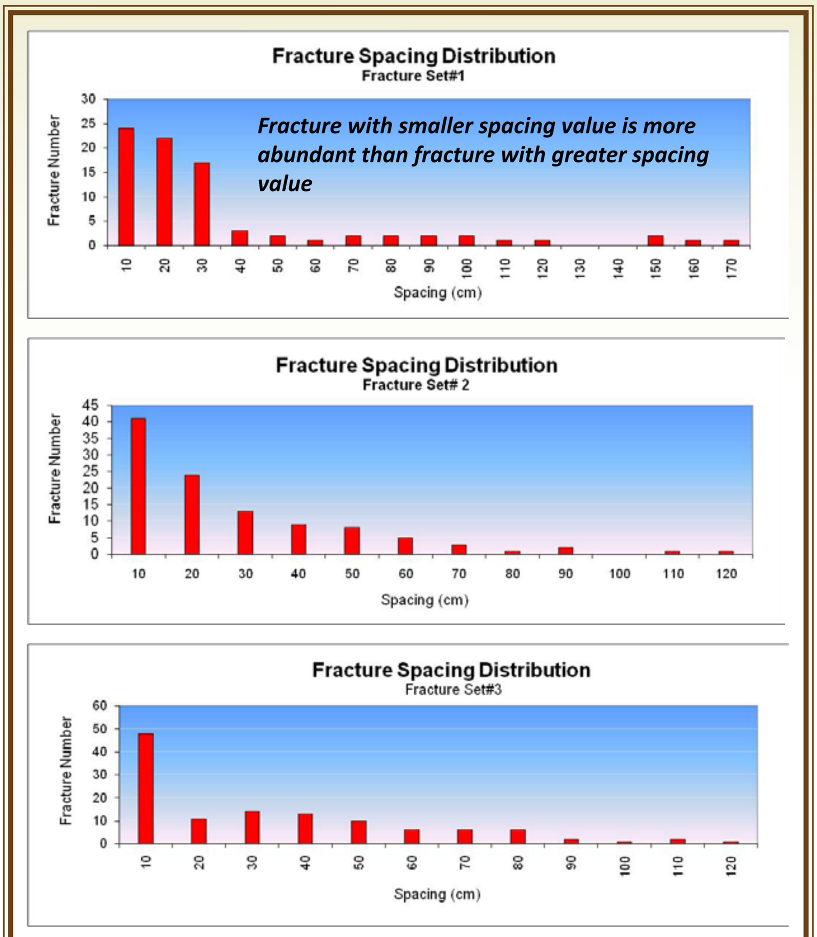


Figure-14

Based on distribution of fracture spacing plots, fracture with smaller spacing value is more abundant than fracture with greater spacing value. Fracture number increasing exponentially from greater spacing value to the smaller shows that the fracture pattern follows a fractal distribution (Power-Law Distribution). Fractal distributions are formulated:

$N (r_n) = (1 / r_n)^D = r_n^{-D}$

D is defined as the fractal dimension of fractal object, whereas the distribution of $N (r_n)$ is an exponential distribution (Maldelbrot, 1982). Cumulative fracture spacing distribution of the three fracture sets are presented together in **Figure-15**. This distribution is logarithmic and shows the fractal relationship between fractures. The fractal distribution is represented by straight line on that log-log plot, indicating the fractal dimension defined by its slope. Straight line equation shows fractal dimension (D) values of fracture sets, those are 1.46 (fracture set#1), 1.21 (fracture set#2), and 1.09 (fracture set#3). Based on this log-log plot, it appears that straight line slope of fracture set#2 and fracture set#3 are relatively close. This explains that two fracture sets are formed in the same phase of deformation. Conversely, straight line slope of fracture set#1 relatively is much different compared to straight line slope of fracture set#2 and fracture set#3. It means that fracture set#3 occurs genetically in different phases of deformation to fracture set#2 and fracture set#3. Fracture set#2 and fracture set#3 are represented by conjugated fracture, whereas fracture set#1 is represented by joint and vein.

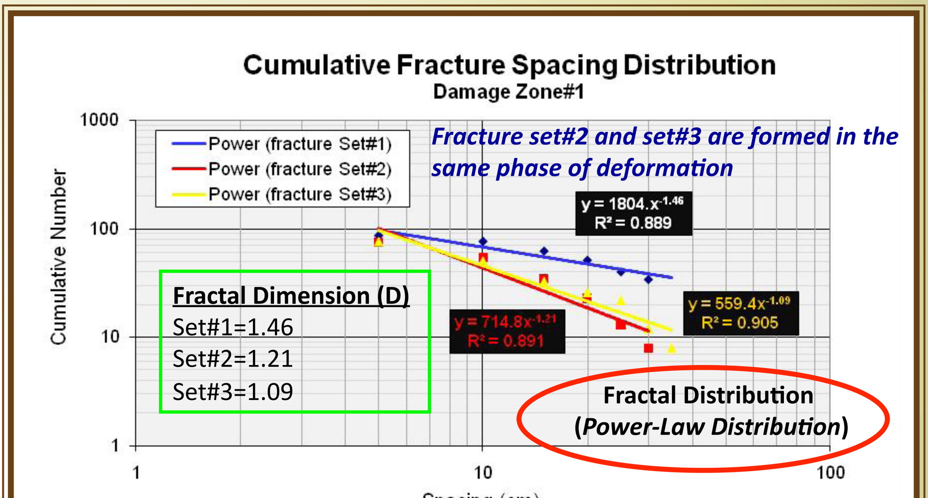


Figure-15

#Fracture Length Distribution

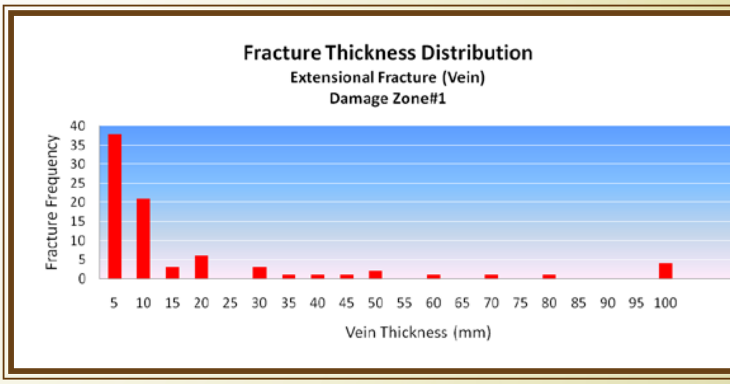


Figure-19

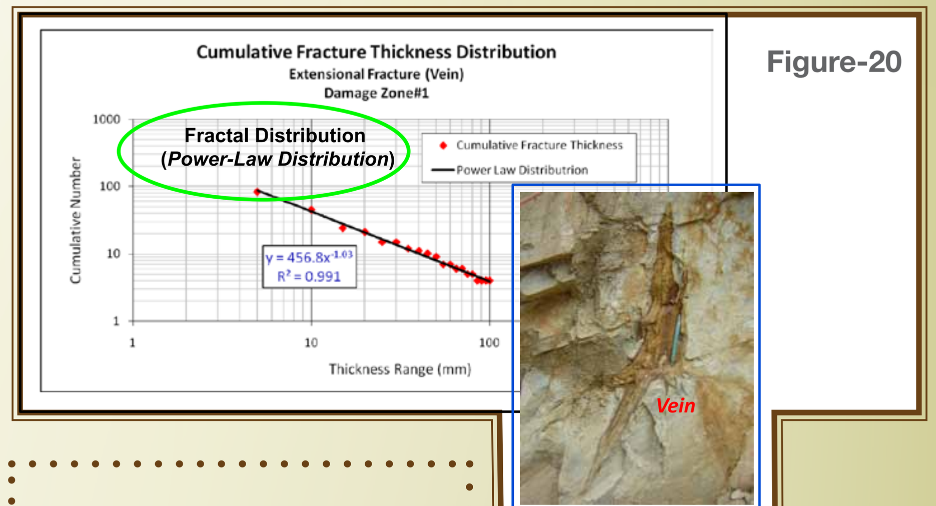
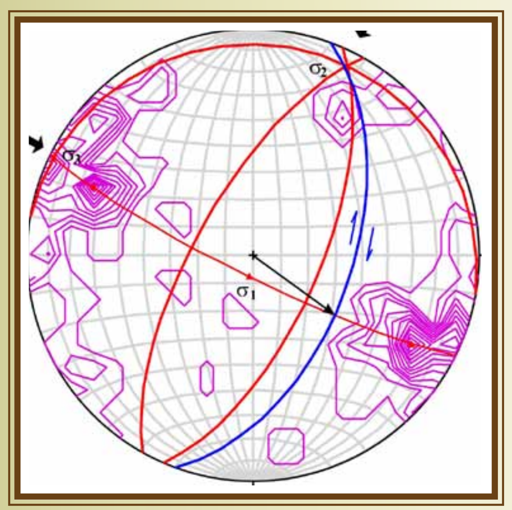


Figure-20

B. DAMAGE ZONE#2



#Structural Setting

σ_1 : 82.4°, N 189.9°E
σ_2 : 7.5°, N 26.8°E
σ_3 : 2.2°, N 296.7°E

Figure-21.
Angsa Normal Fault Kinematic Analyisis. Damage Zone#2 is associated with this fault.

#Fracture Frequency Distribution

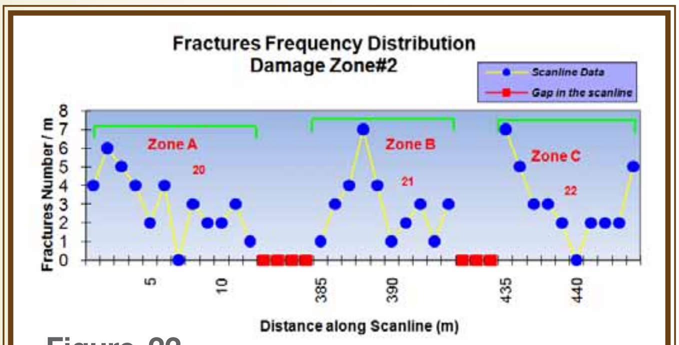


Figure-22

Zone	Fracture Number	High Strain Zone Width Estimation (meter)	Average Fracture Intensity (Fractures / meter)
A	36	11.35	3.17
B	30	9.36	3.2
C	20	5	4
Total Average Fracture Intensity = 3.45 Fractures / meter			

Table-2. Statistical Data of High Strain Zones in Damage Zone #2

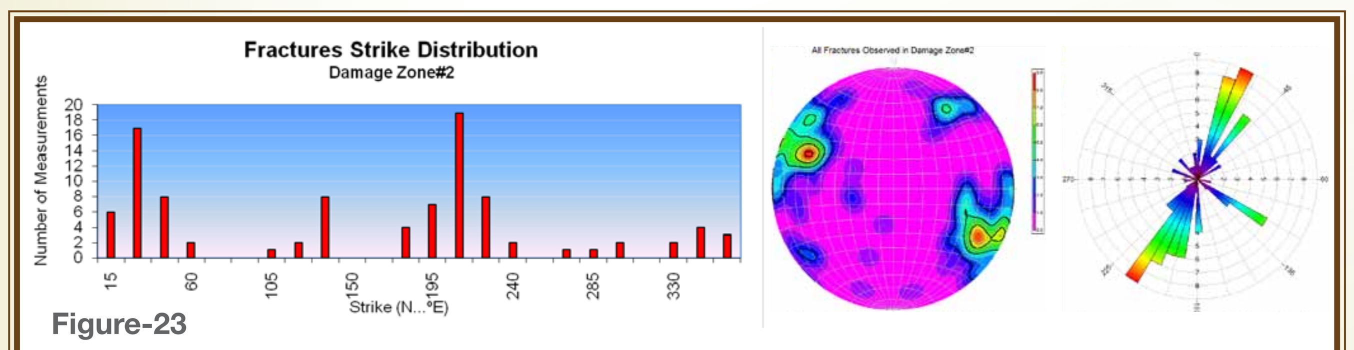


Figure-23

#Fracture Strike Distribution

#Fracture Length Distribution

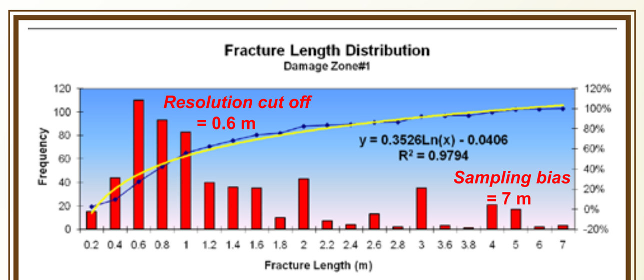


Figure-16

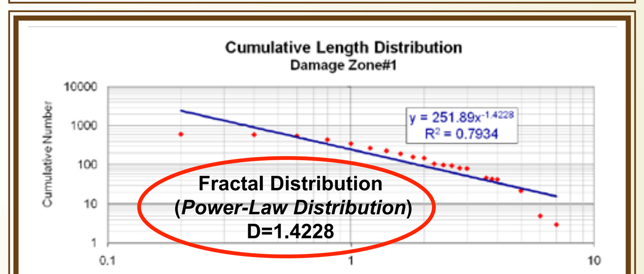


Figure-17

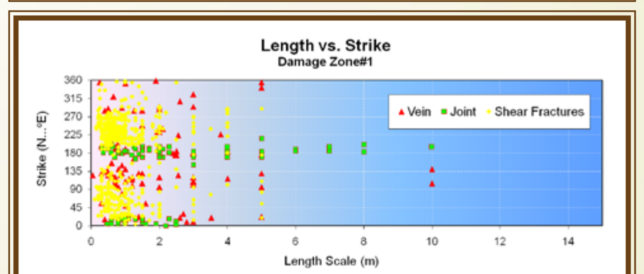


Figure-18

#Fracture Spacing Distribution

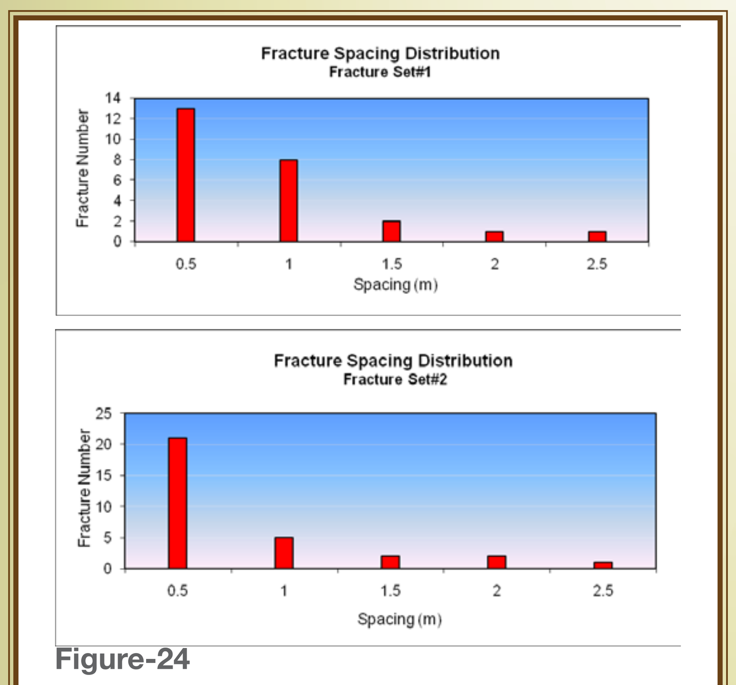


Figure-24

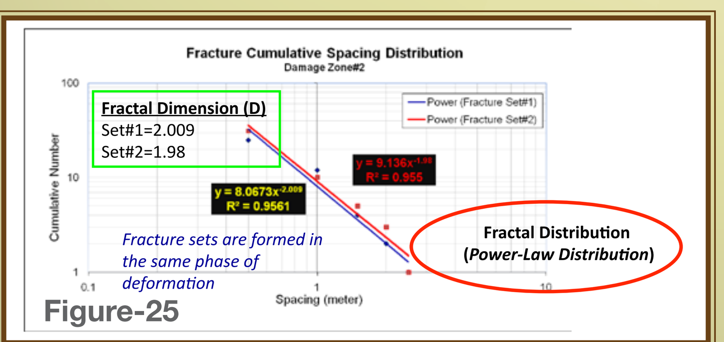


Figure-25

#Fracture Length Distribution

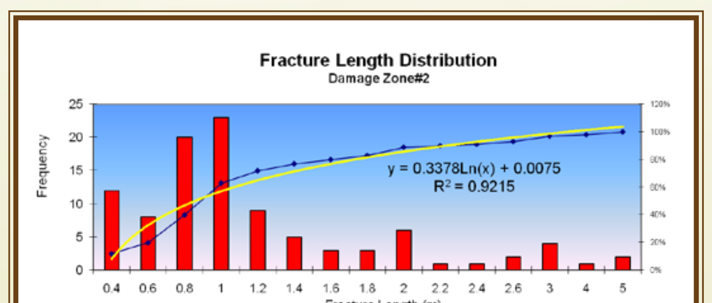


Figure-26

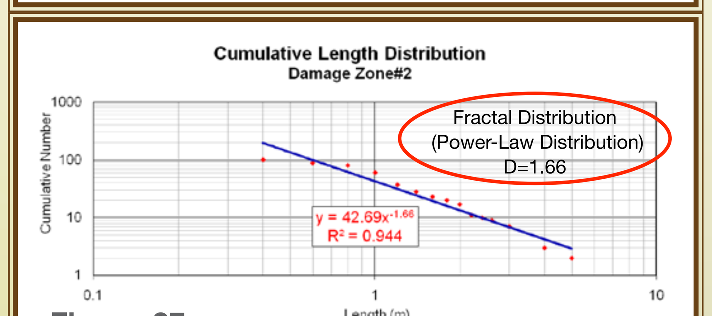


Figure-27

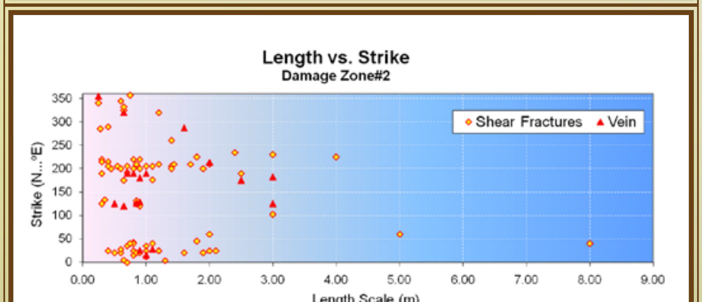


Figure-28

Conclusion

- The study area is dominated by NW-SE and NE-SW trending basement structures.
- The fractures observed in study area include fault-related fracture system. Two damage zones can be observed in scanline sampling: Damage Zone#1 and Damage Zone#2.
- Damage Zone#1 shows that the fractures are related to dextral strike-slip fault. Damage Zone#2 shows that the fractures are related to normal fault. Both of damage zones indicate several high strain zones with average intensity 3 to 5 fractures per meter.
- Rose diagram demonstrated three main fractures orientation: NE-SW, NNE-SSW, and WNW-ESE trending fractures. NE-SW trend consists of two average strike orientations N 215 °E and N 235 °E represented by conjugate fractures system. NNE-SSW trend with average strike N 185 °E is represented by joints and veins. WNW-ESE trend is represented by veins. It can be summarized that main stress controlling all the fractures is NNE-SSW direction.
- Fractures in dextral strike-slip damage zone setting shows smaller spacing value between same fracture sets than fractures in normal fault damage zone setting.
- Fracture spacing, length, and thickness cumulative distribution plot demonstrated that all of fractures follows Power-Law distribution with fractal dimension (D) 1.0 to 2.
- This study can be used as additional data in interpreting well data, such as image logs. Further more, it will help in subsurface fracture property distribution modeling.

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