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Fractures System Characterization for the Low-Temperature Laugaland Geothermal Field

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ABSTRACT

The Laugaland geothermal field is located on the southern flank of the South Iceland Seismic Zone, a tectonically active strike-slip area connecting the East and West Volcanic regions of Iceland. The field is operated by Veitur Utilities and provides hot water for the district heating systems in Hella, Hvolsvöllur and the neighboring rural area. Shortly after production started from the field, reservoir pressure declined dramatically with limited production. This occurred in spite of the feed zones encountered in the production wells being highly yielding. Ever since the district heating system started operation, its operators have been struggling with declining reservoir pressure and rising demand. Traditional methods for locating more resources in the area have proven unsuccessful, repeatedly. Drilling is by far the highest capital cost for developing these resources further. After two failed drilling attempts, it was time to step back and start again with a detailed tectonic study of the area. This field has proven to be successful for extracting and injecting water from feed zones with a favorable local and regional stress (NS and NE fractures) from which the best wells have been located closer to before. This, summed to the previous conceptualization where a high influence from fractures is present, are the main motivation for this work, where previous lineament mappings were analyzed, filtered, and re-traced as possible surface faults to be then classified and correlated with subsurface observations from borehole televiewer logs' interpretations, allowing to start generating intensity-based correlations according to fault-related fracturing mechanisms. Additionally, fractures' geometrical parameters such as orientation and dimensions along with their distribution through depth have been quick-looked, all of which could be further added to the current well planning strategies.

1. INTRODUCTION

The Laugaland low-temperature field is located in the active transform zone of South Iceland Seismic Zone (SISZ) in southwest Iceland, providing district-heating for the Hella, Hvolsvöllur and the neighboring rural areas. The geothermal field has three production wells, GA-01, LL-04 and LL-06, with permeable feedzones that allow for good flow rates, but show that pressure in the geothermal system rapidly declines with production. As a consequence, only one of the wells can be used at a time as a producer for the district heating system, which is struggling with growing demand. The main motivation of this study is to further understand the geological controls on the wells' interconnectivity in the Laugaland area.

Feedzones are high-permeability, high-yield natural fractures, not necessarily connected to convective geothermal systems but to the wells. The typical strong convective character of geothermal systems appear different in the temperature profiles than the permeable productive feedzones and, as stated by Hanano (2000), in liquid-dominated geothermal systems, there are two different roles that natural fractures play:

a. To act as flow paths connecting wells.
b. Allowing for natural convection and up-flow, and thus, the geothermal system to exist,

with fractures playing one role not necessarily being the same ones as the ones playing the other, due the flow velocities required for the natural convection being of the order of 10^{-9} m/s, much lower than the 10^{-1} to 10^{1} m/s ranges required for a feedzone to discharge in a well.

Fractures characterization can be subdivided into two major types: Primary and secondary. The primary refers to the individual characteristics such as orientation and length, while the secondary describes the main topological trends such as intensity and density.

Currently, in the Laugaland field, the production wells are located in a relatively small area and uncertainty exists on how to best expand the production. Additional thermal gradient wells were recently drilled to the NE from the producing area giving disappointing results, while a well south of the current production polygon (HR-24) showed more promising temperature profiles (Ingimarsson, 2020).

Recently, surface lineament mappings were made by Khodayar (2020) over a frame of 7 x 6.5 km (45.5 km^2) around the production region for adding better insight into the tectonic setting within the field and its surroundings, integrating aerial photographs and outcrop observations. Khodayar classified her observations into two groups: older, longer segments, appearing sharper in the topography, and younger, shorter segments that appear as subtle local breaks along longer older ones. This study provided a geodatabase that was used for a surface fracture trace mapping employed in further analyses, in terms of structural hierarchy, primary and secondary characterization. The geodatabase and the location of the study area are shown on Figure 1 with Khodayar's (2020) results and the wellhead locations. The interpretations were compared to a geological map, finding them to be representative of the subsurface lithology, predominantly basaltic flows and hyaloclastites, alternating with tillite and sedimentary horizons.

The wells whose name starts by HR-, are the shallow gradient wells (50-200m) only used to measure temperature profiles and were not the focus of this study.

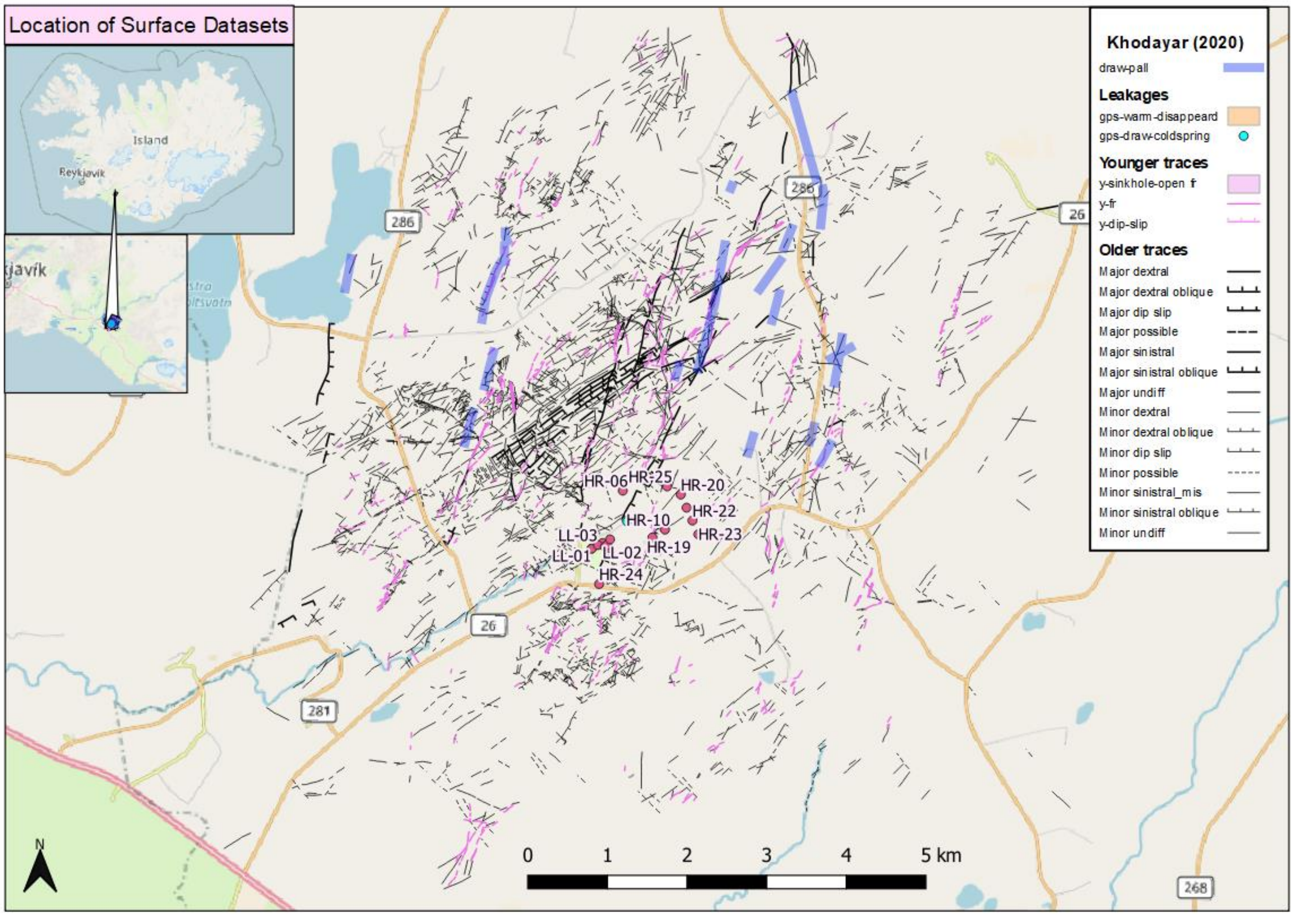

Figure 1. Laugaland surface mapping and wellbores' location. Adapted from Khodayar results geodatabase (2020).

In 2016 Iceland GeoSurvey (ÍSOR) ran borehole televiewer (BHTV) logs in four wells in the area, providing additional local fracture primary characteristics at depth and adding to the two-dimensional surface observations. This is essential as developing into the three-dimensional knowledge of the natural fracturing of reservoir rocks may improve the wells future planning and targeting.

Fault-related fractured reservoirs

"Tectonic naturally fractured reservoirs are those whose origin can, on the basis of orientation distribution and morphology, be attributed to or associated with a local tectonic event" (Nelson, 2001). One of their types is the fault-related fractured systems, such as the ones present in Laugarland, responding mainly to major shear forces in the nearby transform zones and their discontinuities or other mechanisms. The fault-related reservoirs are often conceptualized in terms of their systematic fracturing patterns around the faults, with most of the fractures being of shear origin and oriented parallel to the fault, conjugate shear fractures to the fault or extension fractures bisecting the acute angle between these two directions.

More to these local patterns of fracture orientation, there is the concept of fault-damage zone, which includes the overall 3D architecture concept. Williams et al (2016) mention two types of conceptual models for fault damage zones illustrating, on Figure 2 , two endpoints of complexity of a single damage zone, from simple to more realistic. This helps visualizing the possible overlapping systems in the Laugaland area and how they can control permeability, when only focusing on fault zones.

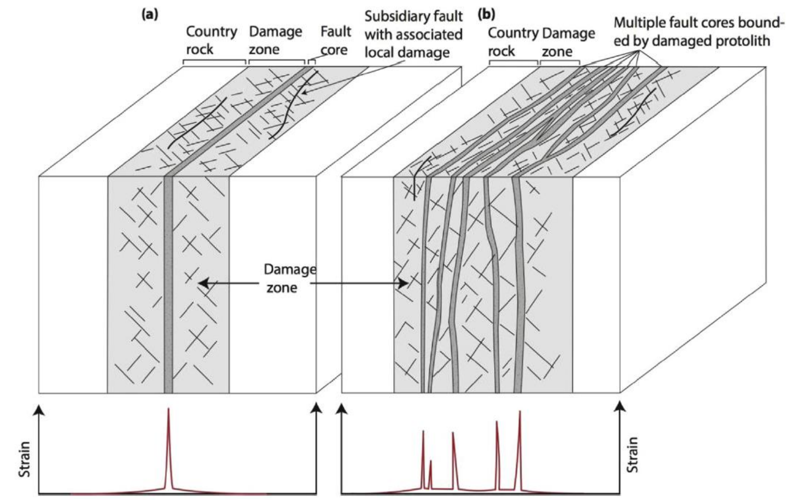

Figure 2. Examples of conceptual fault zone architectures including the core, the damage zone and subsidiary faults. a) single fault core, and b) multiple anastomosing fault cores bounded by lenses of damage rock. Source: Williams et al (2016)

This study aims to, based on the current information availability and review-status, perform a quick-look analysis that serves as a stepping zone towards advancing the conceptualization of permeability relative to the energy and hydrological resources in the subsurface.

2. REGIONAL STRUCTURAL CONTEXT OF THE LAUGALAND FIELD

From Khodayar's observations and a general literature review (Einarsson et al, 2008 and Tibaldi et al, 2018), it can be inferred that the most important fracturing mechanisms typical of Laugaland's surrounding region are:

i) The compressional features, such as Riedel shears, that currently dominate the tectonic and seismicity behavior appearing as strike-slip faults oriented mainly NS, NNE (N160°E to N20°E) and NE (N40°E to N50°E). EW and ENE sparse sinistral- and WNW and NW/NNW dextral-motion structures, seem to be linked to the strike slip faults.

ii) The rifting processes parallel to the current plate boundary orientation and related to the transform zone in the SISZ which express as NNE (N20°E to N40°E) to regional extensional fractures derived from normal faulting of significant throw, without coherent *en échelon* arrangements, and E-W faults, respectively. As the NNE faults are derived from current or recent rifting events, they are likely to have the largest apertures and volumes available for flow and potential significance for natural convection.

iii) The extensional features derived from nearby extinct volcanism, mentioned by Khodayar (2020) as potentially important from the Stóra-Laxá central volcano, about 15 km NNE of the area.

iv) The tensile fracturing due to cooling of the lava fields, of unknown orientation or significance in the observations of the present study.

In the interpretations performed, it is important to note that the temperature data was not considered, and the focus was solely on the permeability.

2.1 General stratigraphy of the area

Khodayar (2020) study states that the bedrock in Laugaland is part of the Hreppar formation, consisting of basaltic flows and hyaloclastites, alternating with tillite and sedimentary horizons. Other authors have described the deeper bedrock in Laugaland as composed of basaltic lavas, sometimes separated with thin sedimentary layers. Vertical basaltic dyke intrusions cut through these older formations orienting parallel to the current rift activity (NE). The estimated age of these formations is 2,5 to 3 million years (Vilmundardóttir et al, 1999). Close to the surface, younger basaltic lavas are still the most common formation regionally, but sediments and hyaloclastites are present forming horizontal layers that are sometimes tens of meters in thickness. The local geothermal resource in Laugarland has been attributed in the past to a fissure swarm of the extinct Stóra-Laxá volcano, but with permeability along a NS and ENE structures (Björnsson, 1993).

2.2 Regional Stress Regime of the South Iceland Seismic Zone (SISZ)

The stress tensor magnitudes and orientations can be reduced to three principal perpendicular directions and according to their inclination, they can be classified into the maximum horizontal, S_{Hmax}, the minimum horizontal, S_{hmin}, and the vertical stress, S_v.

Ziegler et al (2016) used different stress indicators studies and compiled them to map the stress pattern of Iceland, mainly wells breakouts and drilling-induced tensile fractures of the SISZ are significant for this study, which were analyzed from tens to thousands of meters ranges. Other stress indicators in Icelandic-like settings such as dated vent alignments, eruptive fissures and dykes were also included in their study. The maximum horizontal stress was mapped as NE striking in the area of study, about 38° ± 29°, as seen on Figure 3.

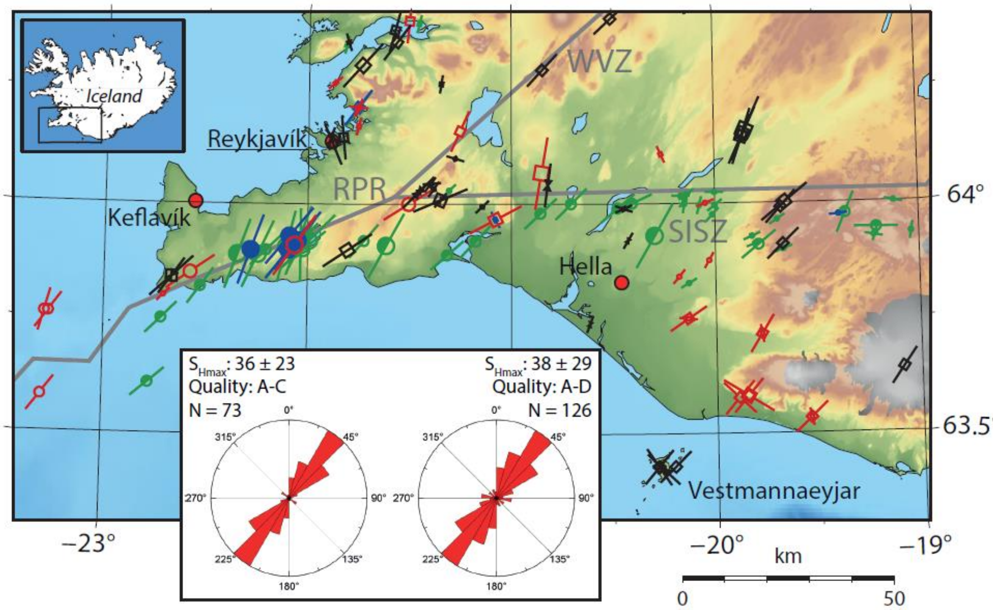

Figure 3. Maximum horizontal stress orientation mapped regionally in SW Iceland. After Ziegler et al (2016)

2.3. Local stress state indicators available in the Laugaland field

In order to constrain the orientations of the tensor, indirect rock failure indicators in boreholes are typically used. Such indicators can be of two types and their accuracy will depend, among other factors, on the lithology response, the image log quality and the interpreter's experience:

1. Borehole breakouts, as cavings occurring from shear failure at the points of maximum stress concentration, causing ovalization of the wellbores as they are spaced 180° always occurring in pairs, and thus aligned with S_{hmin}.
2. Induced tensile fractures, occurring also in pairs every 180° of wellbore circumference, generally vertical, occurring as points of maximum stress reduction, thus, aligned with the S_{Hmax}.

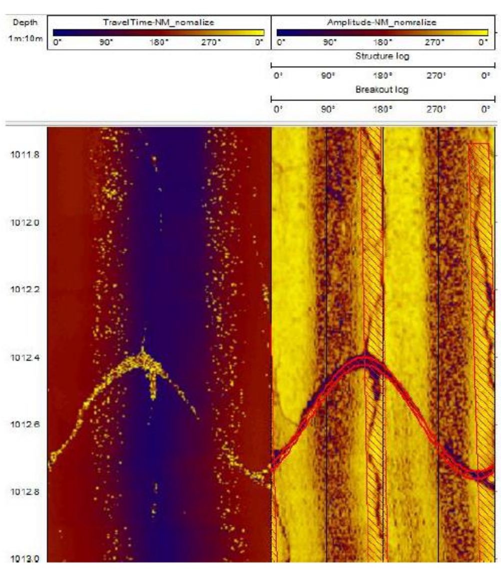

Figure 4. Laugaland's wellbore showing induced fractures on red dashed rectangles and breakouts signaled on black straight vertical lines on the right track of the figure, both crossing an open natural sinusoidal fracture (starting at around 1012.4 m depth) in acoustic borehole televiewer log (source: ÍSOR reports for Orkuveita Reykjavíkur).

The magnitudes of the horizontal stresses can be constrained from formation integrity tests during drilling, such as extended leak-off tests (XLOT) or leak-off tests (LOT), which have not been performed yet in the area, nor accounted from other previous studies if they have happened. For the vertical stress magnitude, a density log is generally integrated through depth, but these are rarely run in this area, hence only the maximum and minimum horizontal stresses directions could be considered at the time of the study.

3. METHODS

3.1 Previous lineament mapping re-interpretation as fractures

Khodayar (2020) mapped 2,927 older traces which were predominantly NE oriented, significant in length and pervasiveness over space, as seen on Figure 1. Only these older features were used to re-trace the lineaments as faults. The resultant surface faults are shown on Figure 5 overlapping the previous study, differentiated by color according to their orientation.

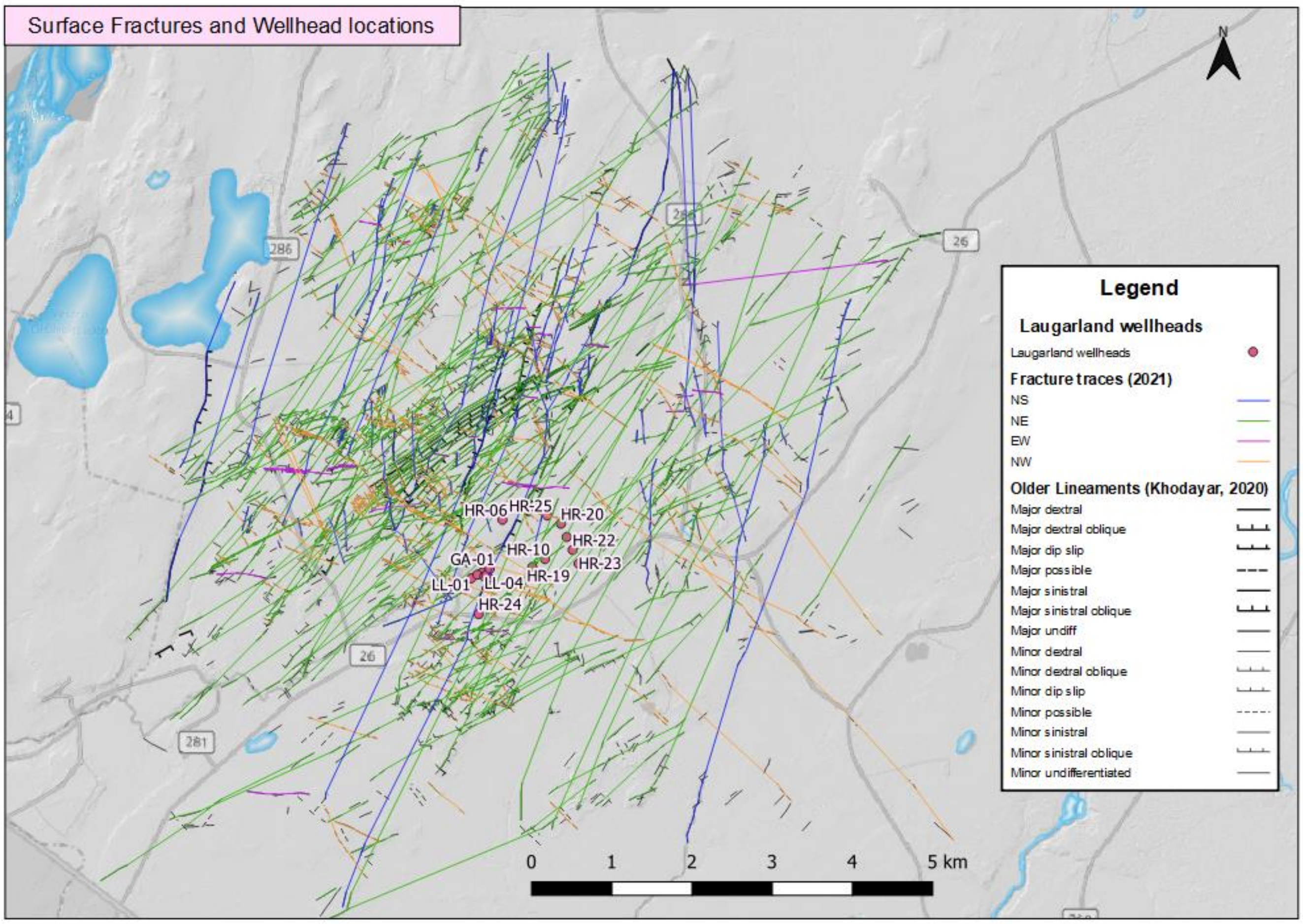

Figure 5. Fractures traces to be used during the analysis after re-tracing surface fractures

After the fractures were mapped over the whole area, they were filtered by those likely to be influencing the current production area, which mainly are those surrounding the LL-# and GA-01 wells. This subsampled fracture network was called the Production fracture network and is shown on Figure 6. It was later analyzed in terms of primary and secondary fractures characteristics by using the FracPaQ package in Matlab® (Healy, 2017).

This production surface fracture network is the basis for defining the local controlling flow paths likely related to convection in the area.

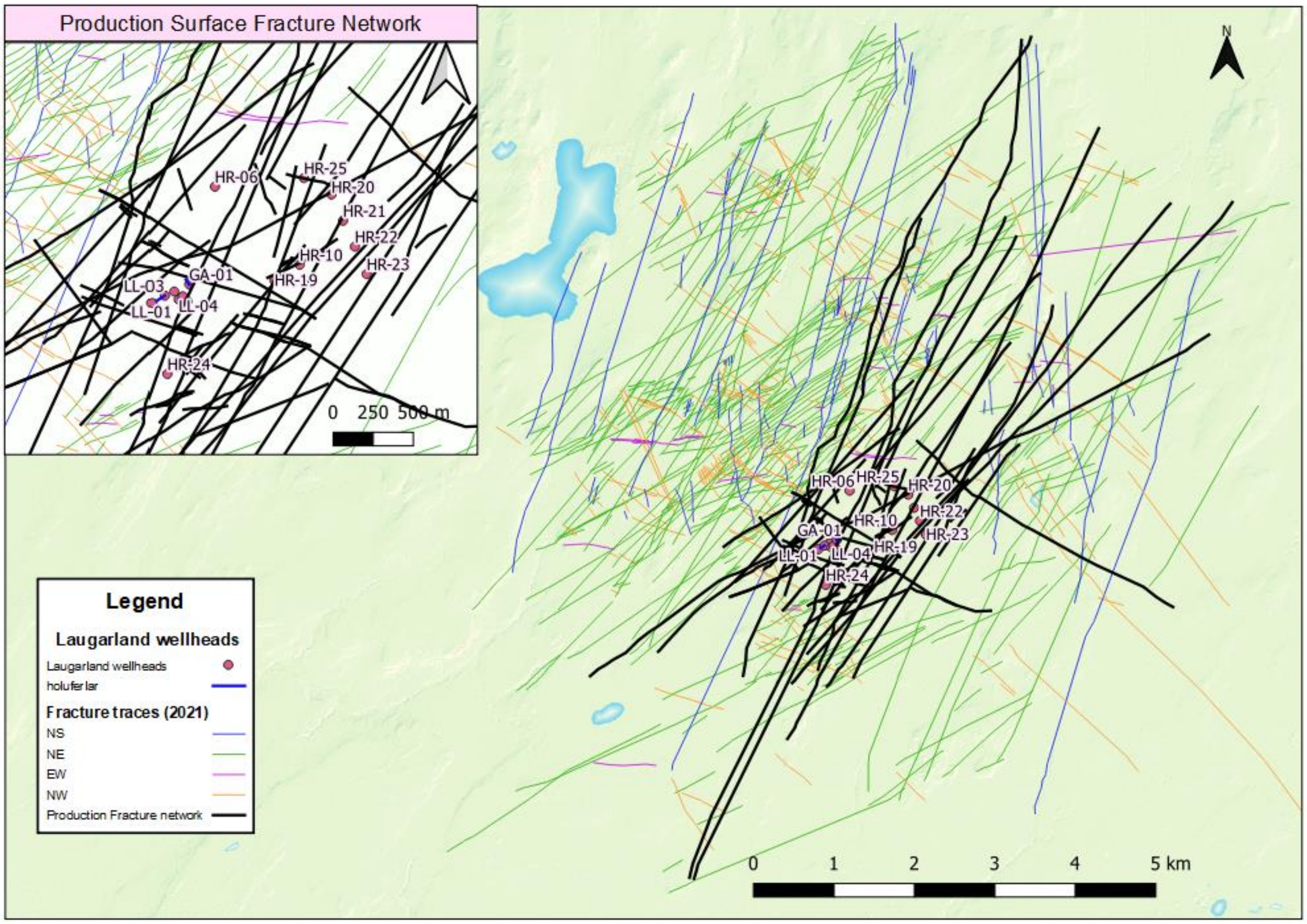

Figure 6. Production Fracture network subsample embedded on the overall fracture network in Laugaland. A zoom in into the wells shows purple lines indicating the directional well paths (holuferlar). HR- wells are usable only for temperature gradient mapping as they are low in diameter and depth.

3.2 Natural fractures characteristics from borehole televiewers

Four deep wells in the area have borehole televiewer interpretations, all of them almost vertical with maximum deviation angle of approximately 10°:

- LL-02: Drilled in 1963
- LL-03: Drilled in 1977
- GA-01: Drilled in 1984
- LL-06: Drilled in 2017

Using Stereonet (Allmendinger, 2012 and 2013), pole fracture data were calculated from borehole televiewers and by means of contouring their distributions, different subsets were identified in the different main directions, as observed in Figure 7. In general, by gathering all the borehole televiewer fracture picks one can have a coarse idea of what can be found in the subsurface of the area, as the wellbores are closely spaced, and the surface tie will be essential once proven it agrees with the subsurface.

Overall, fractures are not completely vertical for all directions, NS (0 - 22° and 160 - 180° strikes) fractures sets predominate, followed by NE strike sets, and last EW with two different dipping groups. A very limited number of NW strike sets appear in the BHTV logs.

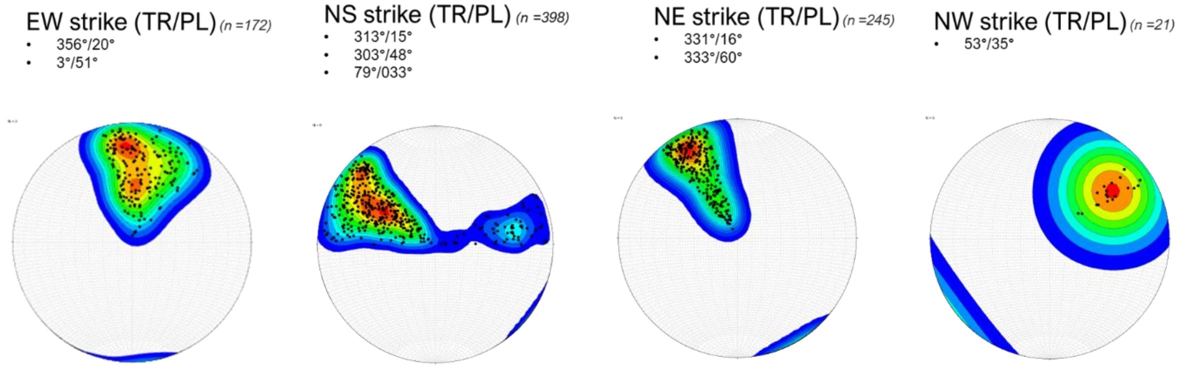

Figure 7. All subsurface fractures poles (trend and plunge) identified in borehole-televiewers run in the Laugaland field's deep wells. Higher fracture density (P10) is represented by warmer colors. Upper hemisphere.

From the groups or clusters observed on Figure 7, the plunges are suggesting dip angles between 74 and 40°, which does not necessarily agree with the typical assumption of completely vertical fractures. Therefore, expanding the fracture orientation data usage at depth becomes important.

3.3 Local stress orientations observed in the field

Drilling-induced tensile fractures have been interpreted by the contractor ÍSOR from three wells: LL-02, LL-03, GA-01. The maximum horizontal stress direction is on average 55° ± 42° if all the induced fractures strikes are considered, but this is caused by the anomalous rotated orientations found on LL-03 well, which is not productive. According to the examination of the regional stress, these values in LL-03 are possible, but based on the high spread metric of the data , it is more likely to find values agreeing with the current strike-slip faults direction, closer to NS or 20° strikes such as those in LL-02 and GA-01 added to them having more weight in terms of number of measurements than those in LL-03. A summary of the induced fractures orientations is shown on Table 1.

Table 1. Average strike of Induced fractures per well and altogether in the Laugaland field

Well	**Strike (°)**		**Number of values**
	Mean	**Standard Deviation**	
GA-01	31	35	18
LL-02	26	8	35
LL-03	71	40	3
All	**55**	**42**	**56**

4. RESULTS

4.1 Local Structural Hierarchy

The overall Laugaland fracture network was filtered by trace length (>5000 m) to roughly identify possible fault-damage zones. As seen on Figure 8, a NNE major fault trend was identified at this scale summed to a tendency of fracture trace length decreasing sideways from a central fault right next to the current production polygon. This production area-associated fault might be strongly related to the major faulting structures and permeability controls in the area.

From Figure 8, it can also be observed that the large fractures have also conjugates at this scale, which causes the spread at 3000 and 5000 m measured over the scanline .

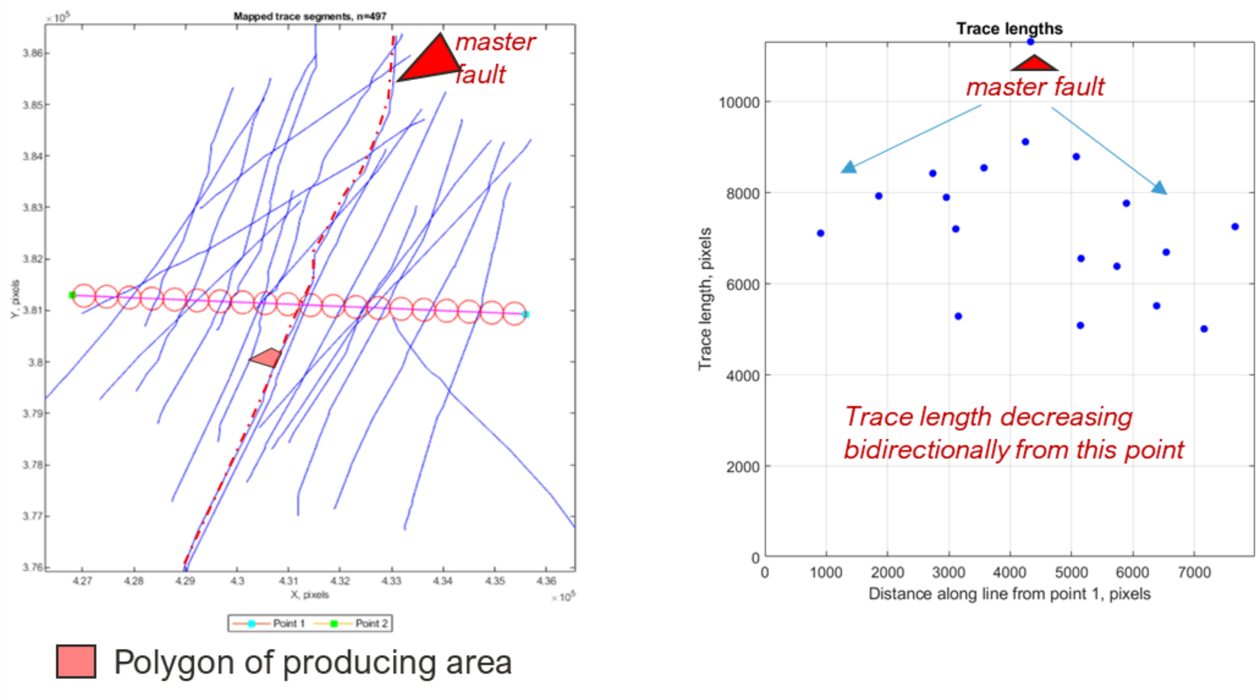

Figure 8. Surface fractures of length higher than 5 km to identify the main large-scale structural trends and circular scanline trace length trends observed. Each pixel is equivalent to 1 meter.

This confirmed that the selection of the production fracture network presented earlier is accurate with respect to the inclusion of the major structures in the full fracture network trend. The central fault has a strike of 22° or NNE, showing multiple parallel structures at both of its sides.

4.2 Production fracture network characteristics

With the major structures established as included in the production network, the primary characteristics of the fractures observed at the surface are examined such as length and orientation. The secondary characteristics are also assessed.

<u>Fracture trace length</u>

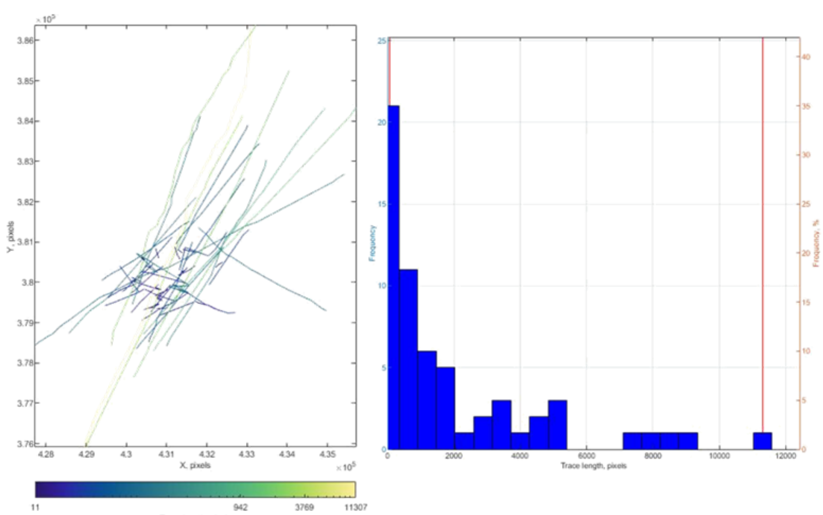

Figure 9. Trace length distributions in space (left) and number (right) for the production surface fracture network. Each pixel is equivalent to 1 meter.

As seen on Figure 9, fracture trace lengths vary between 11 m to more than 11 km, meaning that the surface fractures spread over various orders of magnitude in space, being concentrated mostly over the 11 to 2000 m lengths. Smaller fractures are mostly oriented EW, ENE and NW.

Fracture orientation

As seen on the rose diagram on Figure 10, most fractures are oriented in the NNE and NE directions. There is also the WNW fracture trend followed by a pure NS, NNW, and NW fractures sets in importance. The total number of segments is 526 which make the 60 fracture traces connected to the current production area.

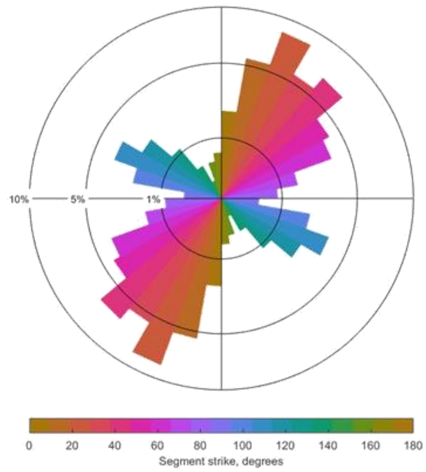

Figure 10. Trace length segment orientations of the production fracture network

Fracture density and intensity

Two measurements of areal fracture abundance are used in this study: P21, as the number of meters of fractures length and P20, as the number of fracture segments, both normalized to the same sampling area, as seen on Figure 11 (see appendix for Pxy notation explanation). This figure shows the location of the current production polygon in green, located over the relative fracture abundancy maps. These maps indicate higher fracturing trending SW and the current production polygon location in an intermediate-to-high region in both maps. Of special importance is the higher fracture intensity towards the south of the current production area, appearing in both maps.

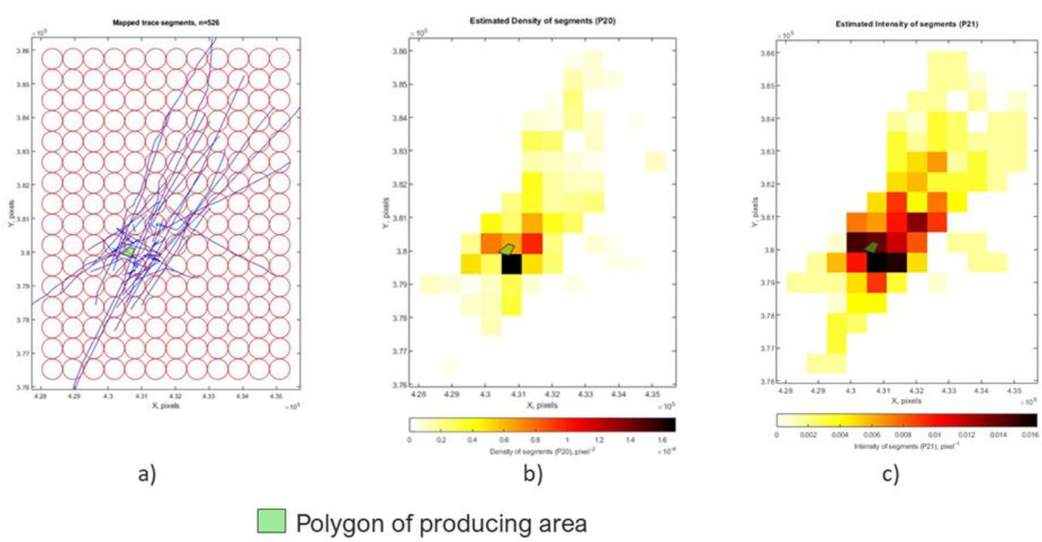

Figure 11. a) Circular window sampling scheme for production network. b) Density of segments (#segments/circular window area) c) Fracture trace intensity (#length of fractures/area of circular window). One pixel is equivalent to one meter.

4.3 Subsurface orientations and basic Fracture stratigraphy

The fracture stratigraphy aims to understand the spatial distribution of fractures in stratified rocks to make them more predictable (Laubach, 2009). With the fracture logs derived from the borehole televiewer interpretations of the four wells, a classification based on strike and a fracture density (P10) calculation was performed in 100 m-measured depth windows and compared at depth, as seen on Figure 12, with each color indicating one specific well.

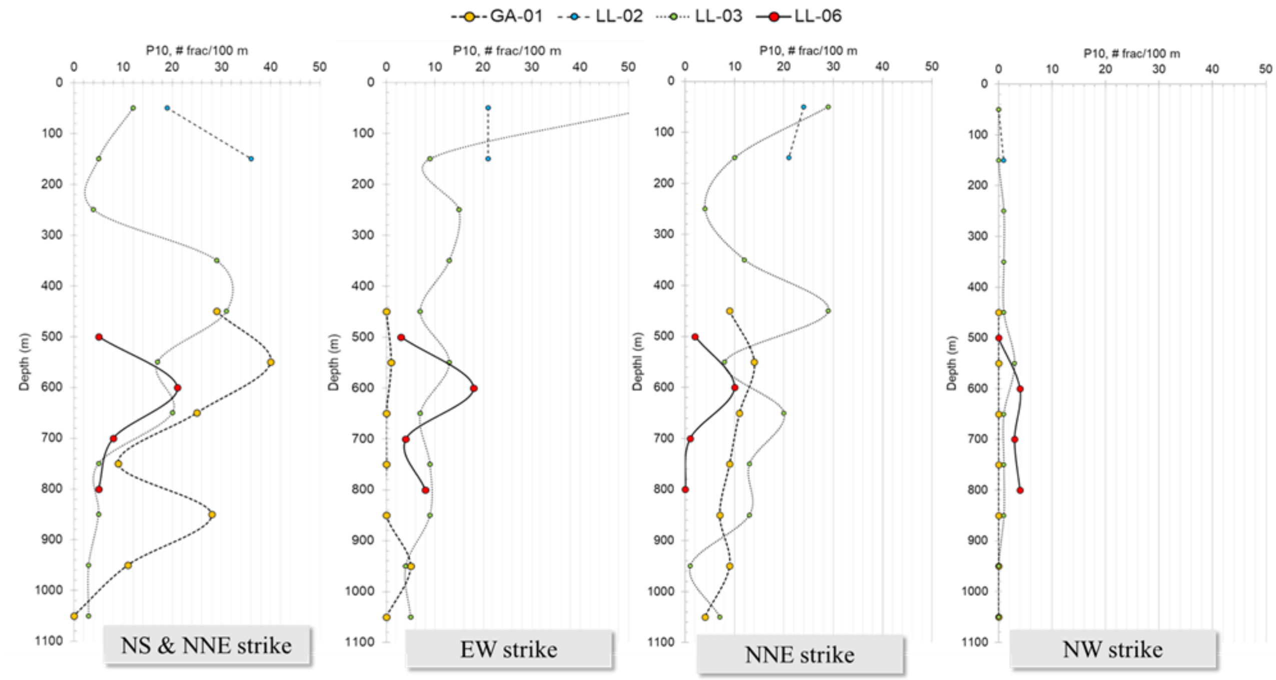

Figure 12. Orientation depth trends for all the wells with borehole televiewers in the Laugaland production area

From Figure 12, the NS and NNE fractures have the highest density and are common to all the wells in high frequency at intervals between 300 and 900 meters, with a generalized decrease in frequency between 700 and 800 meters where ENE fractures become more prominent. On the other hand, the only well showing a high frequency of ENE fractures is LL-03, which is close to the NE surface fracture. Additionally, NW fractures are very scarce, which agrees with surface observations as the closest surface NW feature is about 1 kilometer away from GA-01.

4.4 Possible fault damage zone dimensioning approach around master fault

As fault damage zones are complex structures commonly observable at both the field and geophysical surveys, where the main feature used to delimitate, its spatial distribution is the decrease on fracture abundance away from the core in a systematic manner, it is assumed here that the datasets are sufficient to perform a prediction on its dimension from surface faults. It was observed that the average fracture density maxima at depth followed a linear tendency against the shortest distance from the well to the nearest corresponding direction fault.

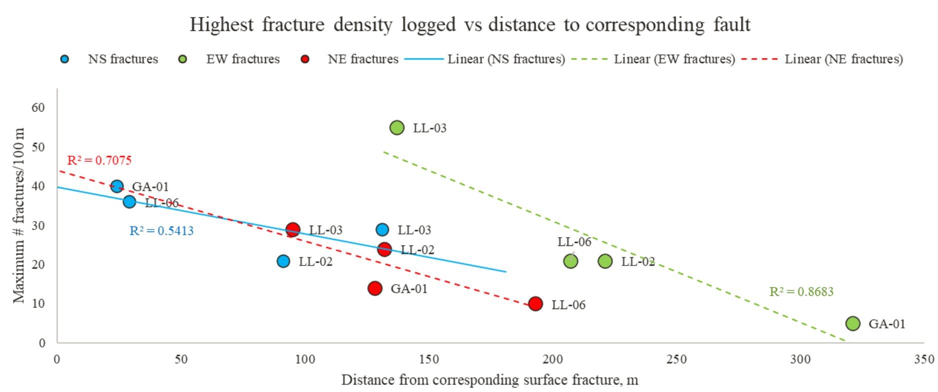

Figure 13. Maximum fracture density (P10) at depth vs Distance to closest corresponding surface fracture/fault

5. CONCLUDING REMARKS

This study provided a view of the main possible permeability trends in the Laugaland geothermal field, showing how the information available can be integrated to later investigate the impact of fractures characteristics on productivity and injectivity.

Due to the connection between surface and subsurface lithological characteristics in the area, it is possible to understand and explain the reservoirs by looking at the likelihood of their expression as surface features, such as lineaments, to explore them as possible fracture traces exposures.

The current production area in Laugaland has indications of being dominated by a main central fault of NS to NNE strike, which might be a likely controller of fracture intensity and thus permeability at the regional and local scales, both at the surface and at depth. This is indicated by the variations on major fracture trace lengths from its location, as measured by circular scanlines along a line perpendicular to it and the subsurface fracture populations measured in near-vertical and vertical wells.

For the geothermal resource targeting, it is important to increase the radius of the study to the closest volcanic system and/or heat sources, including the addition to volcanic typical fracturing mechanisms detection in the field fracture typing scheme, along with temperature logs of wells, by integrating them with feedzones locations and fracture logs.

Subsurface fracture density, P10, as observed in the borehole televiewer logs, is directly proportional to the distance from the closest fault of similar orientation, following the typical behavior parallel and conjugate fault-related fractures and hence, validating the Laugaland reservoirs as tectonic, fault-related naturally fractured.

The maximum horizontal stress direction in Laugarland is favorable for production from NS, NNE and NE fractures, as it appeared to be aligned parallel or quasi-parallel to them.

The fracture orientation and spatial distribution expertise is essential for slanted wells drilling planning, as these should be aimed to drill as efficiently as possible, through the highest intensity open fracture families.

It is recommended to continue these investigations by incorporating fracture dynamic characteristics and more refined static fracture vs. feedzones analyses through the integration of additional datasets.

6. ACKNOWLEDGEMENTS

This section is to show appreciation to the teamwork spirit of the collaborators at the Research & Development division at Reykjavík Energy allowing this project to occur during a short span of time. Additionally, the recent structural geology field work by Khodayar (2020) made possible to start advancing on the permeability and productivity understanding.

7. APPENDIX – A NOTE ON FRACTURE MEASUREMENTS NOTATION

In the commonly used Pxy notation for fracture abundance measurements, the two subscripts ‘x’ and ‘y’ refer to the dimension of the sampling space and dimension of sample measure (respectively), with ‘3’ as volume, ‘2’ as area, ‘1’ as length, and ‘0’ as count. Refer to Figure A 1 for further explanation.

		Dimension of Measurement				
		0	1	2	3	
Dimension of Sample	1	P10 *No of fractures per unit length of borehole*	P11 *Length of fractures per unit length*			***Linear Measures***
	2	P20 *No of fractures per unit area*	P21 *Length of fractures per unit area*	P22 *Area of fractures per area*		***Areal Measures***
	3	P30 *No of fractures per unit volume*		P32 *Area of fractures per unit volume*	P33 *Volume of fractures per unit volume*	***Volumetric Measures***
		Density		***Intensity***	***Porosity***	

Figure A 1. Pxy notation explanation (From Fracman software Manual)

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