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Mechanical stratigraphy of fractured chalks: evaluation of bias associated with fracture density through artificial fracture networks (AFN)

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ABSTRACT Reservoir systems with both fracture and matrix porosity are labelled as dual porosity systems. The latter recently became a major topic of interest. Fracture density has major implications for chalk deposits, affecting permeability, as well as cliff and tunnel stability. This paper proposes a new methodology to evaluate fracture data from outcrops. The dataset described in this paper deals with outcrops of Santonian chalk, located in Flamborough Head (UK). This dataset was acquired based on manual scanlines of which the representative length was verified by Representative Elementary Length analysis. Due to the outcrop orientation and the presence of different fracture families, the dataset might be biased. For datasets dealing with strictly defined fracture families, the Terzaghi correction is often applied. However, in heterogeneous and polygonal fracture networks this correction often leads to high and erroneous fracture densities. This paper introduces Artificial Fracture Networks (AFN) to evaluate whether uncorrected data from scanlines truly underestimate fracture density of heterogeneous fracture networks. Based on the evaluation of these AFNs, it is concluded that raw scanline data are most representative for fracture spacing in heterogeneous and polygonal fracture networks. In this specific case dealing with a polygonal fracture network, it is thus best to use uncorrected scanline data to infer mechanical stratigraphy.

1 INTRODUCTION

Chalk deposits have a major economic importance worldwide, ranging from fresh water aquifers to reservoirs for hydrocarbons (Faÿ-Gomord et al. 2016). In addition, chalk is abundantly present in the subsurface of Europe. making chalk a challenging and interesting topic in the field of engineering, with applications such as tunnelling and foundations (Clayton et al. 2003; Mortimore & Duperret 2004). In general, chalk is characterised by a range of porosities from 5% to 40% and permeabilities down to 0.01 millidarcy (mD) (Faÿ-Gomord et al. 2016). The low primary permeability makes the presence of a well-developed fracture network crucial in reservoir geology. Therefore, a well understood quantification of this fracture network is essential in order to better constrain fluid-flow within low-permeability reservoir rocks.

The chalk cliffs of Flamborough Head are located at the Yorkshire coast in the UK, highlighted in Figure 1. The sediments were deposited during the Santonian and Campanian stages and were buried up to a depth of 1500 metres (Hillis 1995). The latter lead to

Figure 1. Location of Flamborough and the study area of South Landing, highlighted by a white box.

strongly cemented and stylolitised, tight chalks outcropping today along the coast (Childs et al. 1996). Concerning the structural setting, these outcrops are located close to the eastern end of the E-W trending Howardian-Flamborough Fault Belt (Sagi et al. 2016). The E-W trending cliffs of South Landing thus display numerous normal faults, often characterised by small offsets and multiple orientations.

These observations were recently confirmed by Faÿ-Gomord et al. (2017), who analysed the geometries of the fault network, concluding with the occurrence of a Polygonal Fault System (PFS) in the area of Flamborough Head. The intrinsic heterogeneity of fracture orientations in a PFS, make it impossible to strictly define fracture families.

In the frame of this study, these fracture networks were quantified based on manual scanlines. For homogeneous fracture networks the Terzaghi correction is an often applied technique to account for bias associated with non-oblique oriented fractures (Terzaghi 1965). However, applying this correction to non-homogenous, polygonal fracture networks often introduces significant errors. To evaluate whether manual scanlines are truly underestimating fracture density, Artificial Fracture Networks (AFNs) are introduced in this paper.

2 METHODOLOGY

The described dataset was gathered based on manual scanlines at the Flamborough Head chalk outcrops. Acquisition was based on the concept of mechanical stratigraphy, which states that fracturing behaviour of rocks is determined by the thickness of a corresponding mechanical unit (Underwood et al. 2013). In the frame of this study, mechanical units were defined as a set of beds that were characterised by a similar fracturing behaviour. Each mechanical unit was constrained by two mechanical interfaces, which border mechanical units displaying a different sedimentologic and tectonic style, as is visualised in Figure 2.

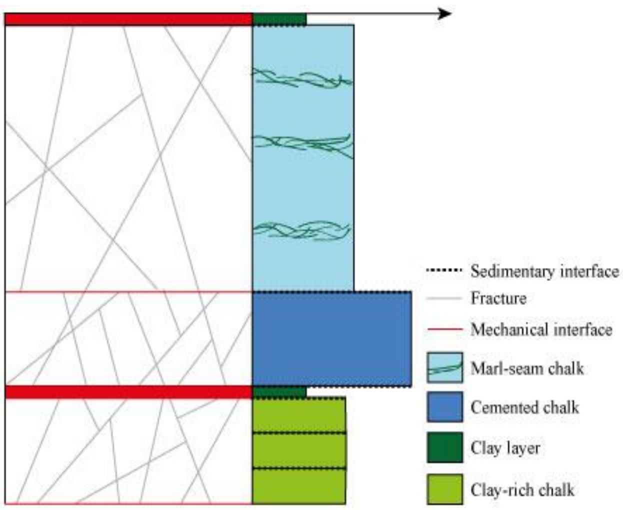

Figure 2. Conceptual model used during this study, based on mechanical units bordered by clear mechanical interfaces (modified after Underwood et al., 2013).

Mechanical properties were acquired through manual scanlines, placed in the centre of each mechanical unit in order to evade deviating fracture behaviour, often occurring near mechanical interfaces (Spence & Finch 2014). The distance in between each fracture and its respective orientation was measured during this procedure. To assure that each scanline yielded representative information for each mechanical unit, Representative Elementary Length analyses (REL) were performed. The latter are based on the theory described by Borges et al. (2011), stating that a representative value is achieved once the parameter itself stabilises with additional acquisitions. In this study, this concept translates to a stable average fracture spacing with increasing scanline length.

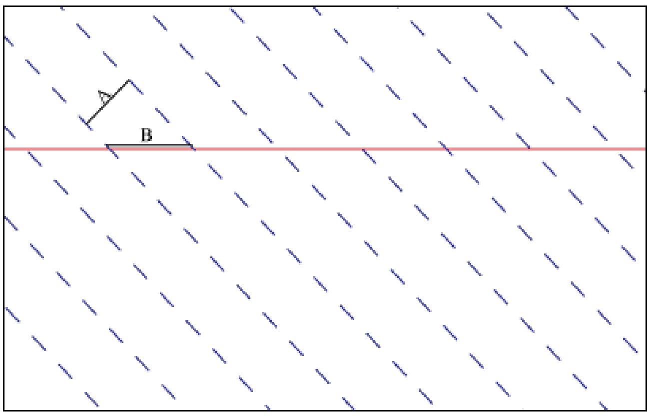

Figure 3. Fracture families presented by blue lines, while a scanline is highlighted in red. The Terzaghi correction accounts for the overestimation (B) of the actual maximal average fracture spacing (A) in homogenous fracture networks.

In fracture networks with clearly defined families, acquired datasets are often corrected for their orientation with respect to the scanline. The latter correction is known as the Terzaghi correction that accounts for the overestimation of the fracture spacing due to non-oblique oriented fracture families, as illustrated in-Figure 3. However, Davy et al. (2006) and Watkins et al. (2015) noted that for heterogeneous fracture networks, the Terzaghi correction introduces more bias to the acquired dataset than is naturally present in the uncorrected data. To verify the latter theory in the heterogeneous fracture networks of Flamborough Head, this paper introduces the concept of Artificial Fracture Networks (AFNs), which enable quantitative testing along artificial scanlines.

The initial step of the presented method is to reconstruct the studied fracture network through a self-written script, based on fracture measurements along the manual scanline, within the software package R (Version 3.3.3, Another Canoe). The script generates a 2D fracture network, based on the extrapolation of fractures measured by the manually acquired scanline, as visualised in Figure 4. In a second step, the AFN generates a total of 19 primary and 38 secondary scanlines of which the length is respectively to 50% and 25% of the manually acquired scanline. Finally, the average fracture spacing is calculated for these artificial scanlines, enabling to verify whether uncorrected scanline data truly overestimates average fracture spacing.

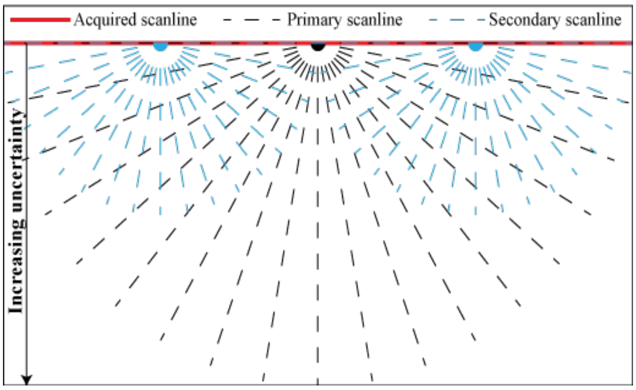

Figure 4. Conceptual model of an Artificial Fracture Network. The AFN is generated from the fracture measurements acquired along the scanline itself, simulating the measured fracture network starting from the acquired scanline (red). Both primary (black) and secondary artificial scanlines (blue) yield information on the average fracture spacing within this generated fracture network.

It is important to notice that the uncertainty of an AFN rises with increasing distance away from the acquired scanline, acting as controlling data from where the AFN is extrapolated. This uncertainty is higher for primary scanlines, which underestimate fracture density since they reach further into the AFN. Secondary scanlines have a limited length and thus mainly assess the AFN in close proximity of the scanline, where it is well constrained. Finally, this method enables statistical evaluation whether the uncorrected scanline dataset truly overestimates the average fracture spacing, by analysing the statistical distribution of the results of these artificial scanlines. This distribution is key to concluding whether or not manually uncorrected scanline data is underestimating the true fracture density. If this would be the case, a significant amount of artificial scanlines would measure lower fracture densities compared to the manually acquired scanline.

3 RESULTS

Nine manual scanlines were acquired at the South Landing site near Flamborough Head, yielding information on orientations, mechanical bed thickness and average fracture spacing. The latter was calculated for mechanical units ranging from 20 cm to 115 cm in thickness. The raw and uncorrected dataset is presented in Figure 5.

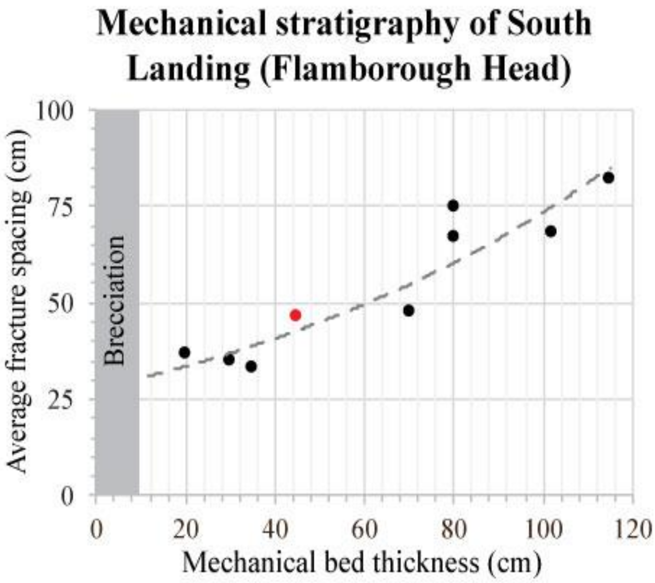

Figure 5. The mechanical stratigraphy of South Landing expresses an exponential relation between mechanical bed thickness and average fracture spacing. Tectonic brecciation was observed for all beds up to 10 cm thickness.

These data indicate an exponential relation between average fracture spacing and mechanical bed thickness. In addition, representative elementary length (REL) analyses indicated that all scanlines can be considered to be representative for the studied mechanical units, with the exception of scanline 1 in Figure 5, indicated by a red dot. Mechanical beds thinner than 10 centimetres were characterised by tectonic brecciation. Therefore, this value is defined as the brecciation threshold. The latter generates a chaotic fracture network, preventing quantification of fracture spacing. Mechanical units below this threshold value are thus not considered in Figure 5.

In order to verify that fractures were distributed homogenously throughout the outcrops, cluster analysis was performed based on the coefficient of variation (C_v). This coefficient was defined by Gillespie et al. (1999, 2001) as the ratio of the standard deviation to the mean value of fracture spaces ($C_v = SD(s)/s_{mean}$) and quantifies the degree of clustering along scanlines. Clustered fracture networks will have a low fracture spacing within each cluster, with a significant larger spacing in between two clusters. An elevated intercluster spacing, will translate itself in a greater standard deviation in contrast to a lower average fracture spacing, due to the overall dominance of intracluster fractures (Figure 6). The latter will translate itself in a coefficient of variation above 1.

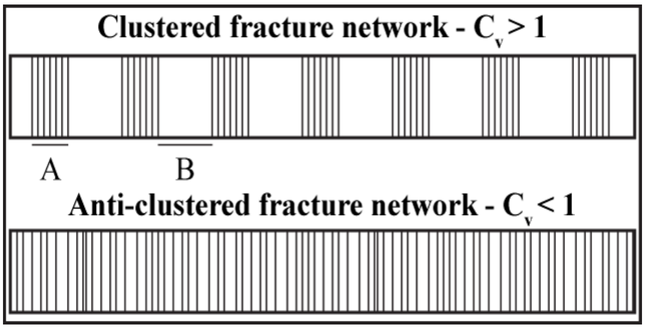

Figure 6. Representation of clustered and anti-clustered fracture networks, as defined by the coefficient of variation (C_v).

For each scanline, the coefficient of variation (C_v) was below the threshold value of 1 and is therefore not clustered (Table 1). This confirms the suitability of this dataset to infer the mechanical stratigraphy of the South Landing chalk deposits.

Table 1: Cluster analysis based on the coefficient of variation (C_v) indicate that all scanlines were not-clustered and are therefore suitable to infer the mechanical stratigraphy of the studied deposits.

Scanline	Average fracture spacing (cm)	Standard deviation	Cv
SL 01	67	33	0.49
SL 02	68	39	0.57
SL 03	35	24	0.68
SL 04	37	13	0.35
SL 05	48	19	0.40
SL 06	75	25	0.33
SL 07	82	38	0.47
SL 08	33	22	0.67

In addition, artificial fracture networks (AFNs) were generated for each of these scanlines. These AFNs enable visualisation of the fracture network and acquire artificial scanlines in all possible directions. The latter permits confirmation that the raw datasets are not underestimating average fracture density. For each individual scanline only 25% of the simulated scanlines yielded an average fracture spacing lower than the uncorrected dataset (Table 2).

Table 2: Summary of the AFN analysis for each scanline, presented as the corresponding average spacing to percentile quartiles (Qx.xx) of the simulated scanlines. The uncorrected data correctly estimates the average fracture spacing. Based on a comparison with Q(0.01) the potential natural bias is thought to be lower as the error which is associated with the weighted correction of Terzaghi.

Scanline	Average spacing (cm)	Q(0.01)	Q(0.25)	Q(0.50)	Q(0.75)	Q(0.99)
SL01	66.86	49.29	64.04	76.83	85.40	276.25
SL02	68.28	57.50	73.83	88.41	128.51	327.44
SL03	34.88	27.12	36.73	47.07	56.96	255.64
SL04	36.57	27.21	36.95	46.85	54.66	76.37
SL05	47.72	19.81	44.07	57.20	74.20	103.61
SL06	75.22	52.41	73.95	83.32	102.86	270.53
SL07	82	56.66	71.68	83.88	92.53	136.01
SL08	33.34	22.77	32.38	39.57	45.70	246.50

4 DISCUSSION

The uncorrected dataset is characterised by an exponential trend, meaning that the average fracture spacings increases with increasing thickness of mechanical units. In addition, a plateau effect is observed for thin mechanical units, leading to a stabilisation of the average fracture spacing at approximately 30 centimetres. Mechanical boundaries in the South Landing chalks generally corresponded to multi-centimetre thick, clay layers. The latter are likely to be sedimentological in origin, but were further enhanced by pressure-dissolution during diagenesis.

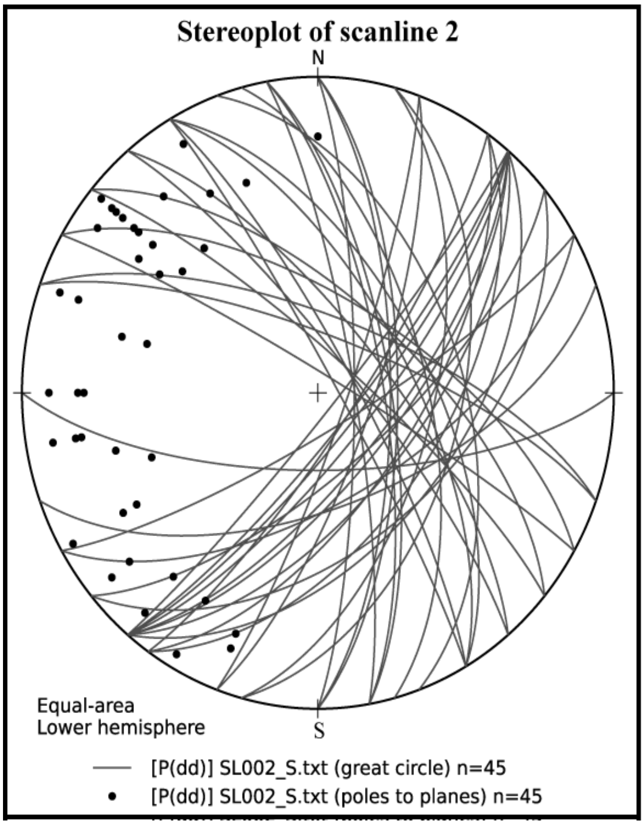

Figure 7. Fracture measurements of scanline 2 in South Landing (Flamborough Head), characterised by their multidirectional orientations.

Fracture orientation data indicates that the studied fracture networks are heterogeneous in nature, complicating to identify strict fracture families. An illustrative stereoplot of scanline 2, acquired in South Landing, is given in Figure 7, highlighting the polygonal character of the studied outcrops.

Applying the Terzaghi correction to these heterogeneous datasets leads to erroneous fracture spacing, strongly overestimating the fracture density of the South Landing chalks. This overestimation is due to the abundance of low-angle fractures with respect to the measured scanlines. As visualised in Figure 8A, these low-angle fractures pose no problem in homogenous fracture networks. However, for heterogeneous fracture networks the uncorrected average fracture spacing is most accurately representing the studied fracture network as long as the scanline itself is representative. In heterogeneous networks, the Terzaghi correction is applied as a weighting factor to each fracture, which is defined as W = cosec(α) (Terzaghi 1965). This weighting factor becomes large for fractures with a low α-angle, overestimating their presence within a heterogeneous fracture network. The latter is schematically presented in Figure 8B.

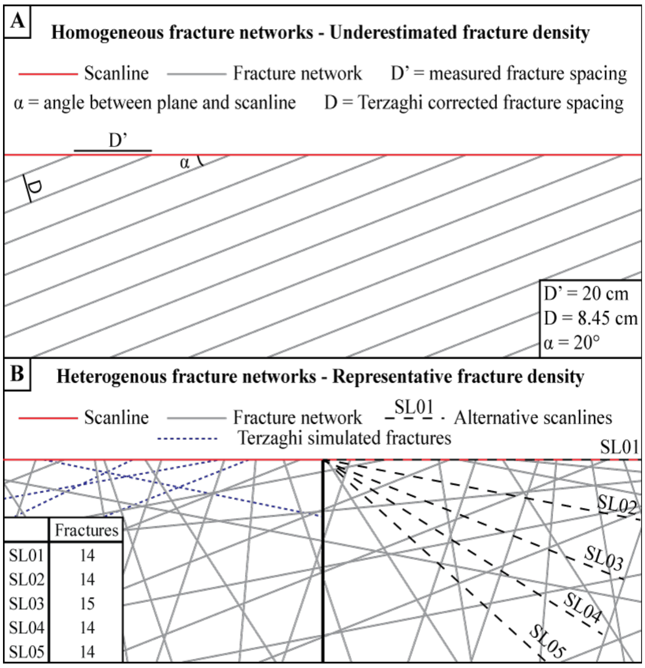

Figure 8. Homogeneous fracture networks require the Terzaghi correction, especially for small values of α as in Figure 8A. Identification of fracture families is impossible in heterogeneous fracture networks, requiring to apply a weighting factor to each individual fracture. In heterogeneous networks, this weighting factor artificially increases fracture density, illustrated by blue lines in Figure 8B.

All of the acquired scanlines are verified to be representative for the studied mechanical beds. Therefore, the Terzaghi correction is unnecessary and even introduces a strong error to the datasets. Artificial Fracture Networks can be used to verify whether the uncorrected dataset is representing the maximal fracture density. In general, 75% of the artificial scanlines measure a lower or similar fracture density compared to what was manually determined in South Landing. The majority of the artificial scanlines with higher simulated densities correspond to the secondary scanlines, presented in Figure 4 by blue lines. The latter are characterised by a limited length, equalling to only ¼ of the length of the manually acquired scanline. In addition, the respective REL curves indicate that for these secondary scanlines, the calculated average fracture spacing is not representative for the studied fracture network. The latter occurs if secondary scanlines are transacting densely fractured zones, which are often local in nature.

These AFNs thus show that for the heterogeneous fracture networks of South Landing, uncorrected datasets are the most accurate approach to study fracture networks. This in contrast to Terzaghi corrected datasets, yielding a strong overestimation of the actual fracture density.

5 CONCLUSIONS

A mechanical law (**I**) is proposed for the South Landing chalk deposits, which is based on the quantification of the fracture network with manual scanlines. This trend is exponential in nature and is characterised by a plateau-effect for thin bedded mechanical units (Figure 5). In addition, a brecciation threshold was defined for mechanical beds thinner than 10 centimetres.

Secondly, it was observed that these chalk deposits are characterised by a heterogeneous fracture network (**II**). The latter was also confirmed by observations of Faÿ-Gomord et al. (2017). The heterogeneous nature of these fracture networks complicated data-processing. For homogenous networks the Terzaghi correction is used to correct for bias, however, in heterogeneous network this correction is debated.

Therefore, this study introduces the concept of Artificial Fracture Networks (AFNs), which reconstruct the measured fracture network (**III**). Within these AFNs, several artificial scanlines evaluate fracture densities in all possible directions. With these artificial scanlines, it was possible to confirm that uncorrected scanline data can be considered as the most suitable to present heterogeneous fracture networks.

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