Modeling 3D Fracture Network in Carbonate NFR: Contribution from an Analogue Dataset, the Cante Perdrix Quarry, Calvisson, SE France*

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General Statement

The full 3D characterization of fracture networks is a key issue in naturally fractured reservoir modeling. Fracture geometry (e.g., orientation, size, spacing), fracture scale (e.g., bed-confined fractures, fracture corridors), lateral and vertical variations, need to be defined from limited, generally 1D, data. In order to populate a 3D reservoir model, one needs to define, at the field scale, how the fracture network is distributed in between wells and, at the reservoir cell scale, how the fracture properties can be summarized to fully represent the matrix-fracture flow exchange. With well data only, the problem is clearly undersized and we need to define other sources of information, such as relationships between fracturing at well and large-scale drivers, for example, or derive the missing gap from outcrop data, which provide qualitative concepts or quantitative relationships between fracture parameters.

The study presented in this article aims at modeling, at the reservoir cell scale, 3D fracture networks from quarry outcrops. An innovative data collection method is used; this allows a full characterization of the fracture network in 2D, which provides the basic inputs required for the construction of DFN models. In turn, the reality of the fracture network can be compared to the simplification that we make while drilling through these networks and ultimately summarizing them as a double porosity reservoir cell, and some basic lessons can be learned.

Data collection

Calvisson is located in the Southeast Provence Basin on the western, upthrown, side of the NE-trending Nimes fault. The “Cante Perdrix” quarry is a circa 300x300m working area (i.e.,one or two typical reservoir cells) excavating 30 m of fairly homogeneous, Hauterivian marly limestones along three different step levels (Figure 1). The quarry is located away from the main regional faults with only a northward gentle tilt, suggesting that it has been gently deformed by the Paleogene and Neogene main phases of deformation. Burial depth (and subsequent uplift) is not known.

Fracture data have been collected along 11 vertical quarry walls, varying from 3m to 16m in height, using the Digifract tool developed at TU Delft. This tool can georeference outcrop photographs, on which fractures can be traced and their corresponding attributes such as strike, dip, size and infill interpreted. In the field, nearly 1800 fractures, 20 fracture corridors and bedding surfaces have been manually measured in order to calibrate these 11 so called "digisurfaces". A data processing software can then compute 1D and 2D fracture property distributions (e.g., height, P10, P21, etc.) from automatic scanline or surface analysis.

Fracture network characterization (Figure 2)

Two fracture scales are present in the quarry: diffuse fractures (HPF) and fracture corridors (FC). Within the FC's, the presence of horizontal slickensides suggests that they originated or have been reactivated by the main compressive paleo-stress field. Due to the limited amount of FC's, this study focuses mainly on the HPF scale.

Two orthogonal fracture sets are observed: N130 (Set 1) and N045 (Set 2). Due to the preferential orientations of the sampling quarry walls, Set 1 is under sampled compared to Set 2. Set 2 also shows a rotation in from NE-SW to almost N-S striking fractures from the west to the east of the quarry, respectively. Only Set 2 FC's have been observed.

Fracture height distribution of all HPF fractures in the 11 digisurfaces shows a negative exponential distribution with 85 % of the fractures below 3m in height, the smallest digisurface height.

There is no relation of bed thickness neither with height nor with spacing. This suggests non strata-bound fractures at the HPF scale related to an early initiation (i.e., before sedimentary bedding stratification) similarly to the Provence study (Lamarche et al., 2012).

Fracture frequency has been analyzed from both 1D (scanlines) and 2D (digisurfaces) measurements, using the PXY nomenclature, where X represents the dimension of the sampling domain and Y the dimension of the measured feature (see Figure 4). All PXY values have been corrected for the bias between the orientation of the quarry wall and that of the average fracture orientation. Fracture frequency has been analyzed through P10 and P21 distributions at the single digisurface and entire quarry scales. At the entire quarry scale, P10 fits a Gaussian distribution of average 2 m-1 and Stdev 0.73 m-1. This distribution suggests that the network is at saturation level according to the evolution of fracture frequency distribution as function of fracture set development. When looking at the variations in space, we note that the western and eastern parts of the quarry have higher fracture frequencies but also a larger spread than the central part. For all the digisurfaces, the average P21 values are similar to that of the P10.

- There are several ways to look at the spatial distribution of fractures. One approach is to consider the number versus size (i.e., height here) relationship in log-log space. The power-law exponent of this relationship indicates whether the fracture set is self-similar or whether small or large fractures are dominant in the distribution. If Set 1 fractures are under-sampled for a realistic exponent, Set 2 fractures show an exponent close to 1, indicating that large fractures (i.e., non strata-bound) dominate the population. The second approach is to compute the fractal dimension of the network, using the fracture mass distribution method which shows that Set 2 fractures have a fractal spatial distribution.

Discrete Fracture Network modeling

3D DFN models are created with a modeling tool which generates disc shape fractures using fracture size distribution, P10, length-height ratio and fracture dip/orientation as input parameters. In space, fractures are located using a Poisson-based distribution of uniformly spaced fracture, which is representative for our dataset as we have a low degree of clustering (outside FC's) and no relation with bed thicknesses. P21, fractal dimension and fracture spacing of simulated DFN's serve as a calibration exercise, to check how accurate the match is between the Digifract data and the DFN's.

- First, small DFN's are created around each Digifract surface. The fit between simulated and observed data is reasonably good. These DFN's can be used to simulate wells drilled along different trajectories
- Then, a quarry-scale DFN can be constructed. Due to the limitation of the software used in modeling lateral variations of input statistical parameters, the final quarry-scale model was built using the FC as deterministic limits separating zones of average fracture properties. This model could be used as the basis for a fluid flow model where the effect of fracture corridors and BCF fractures on fluid flow can be studied.

Lessons Learned

Local DFN's have been used to assess some of the key issues we need to address when modeling fracture networks in 3D from a limited number of well-line fracture data.

Sampling uncertainty analysis: our modeling enabled us also to analyze in detail the 1D (e.g., well) sampling uncertainty. P10 values from 3500 horizontal scan lines have been computed over the 9 digisurface models of Set 2, which fit the Gaussian distribution described in Figure 2. This represents the intrinsic variability of the P10 at the scale of the quarry. In other words, a well drilled at random in this distribution could show any P10 value between 0.25 m^{-1} and 4.0 m^{-1}. It was found that 9 and 50 horizontal wells would be necessary to start (i.e., steady mean) and to fully (i.e., steady variance) capture the natural variability of this reservoir cell analogue, respectively. Therefore, even excluding orientation sampling bias or tool-acquisition quality, well-fracture data should not be considered as hard data, as it is often the case in our fracture modeling workflows.

The pertinence of the classic Terzaghi correction to account for fracture-well orientation bias has been evaluated by computing scanlines at various angles to the surfaces and resulting raw P10 values corrected using the Terzaghi correction (Figure 3). Globally, we observe that for correction angle below 40°, we lose the Gaussian nature of the P10 distribution and Terzaghi does not correct for it. A systematic analysis of the Terzaghi correction as function of the sampling bias angle for each digisurface shows a quite erratic behavior of the correction, some surfaces being well corrected down to 10° angle, whereas others quickly deviate from the "true" perpendicular P10 value. This result suggests that The Terzaghi correction might be erroneous below 30° sampling bias.

Stereological relationships enable us to estimate P32 (i.e., surface of fractures per volume) as function of P21 (length or height of fractures per surface of outcrop) and P21 as function of P10. It is found generally for theoretical fracture network (long and parallel fractures) that we have P32 > P21 > P10. The quarry data provide access to both P10 and P21, and we found that in this case, P10 = P21 (Figure 2). The local DFN's were used to evaluate these stereological relationships for P32 (Figure 4). For measurements made perpendicular to one of the fracture set, we have more or less the theoretical relationship, but for arbitrary measurement within the DFN volumes, we have P10=P21=P32. These results suggest that the natural dispersion of the fracture network equalizes the stereological relationships; this should help when modeling the 3D properties of subsurface fracture networks.

Reference

Lamarche, J., A.P.C. Lavenu, B.D.M. Gauthier, and Y. Guglielmi, 2012, Relationships between Fracture Patterns, Geodynamics and Mechanical Stratigraphy in Carbonates South-East Basin, France: Search and Discovery Article #120071 (2012). Web accessed xx December 2012. http://www.searchanddiscovery.com/documents/2012/120071lamarche/ndx_lamarche.pdf

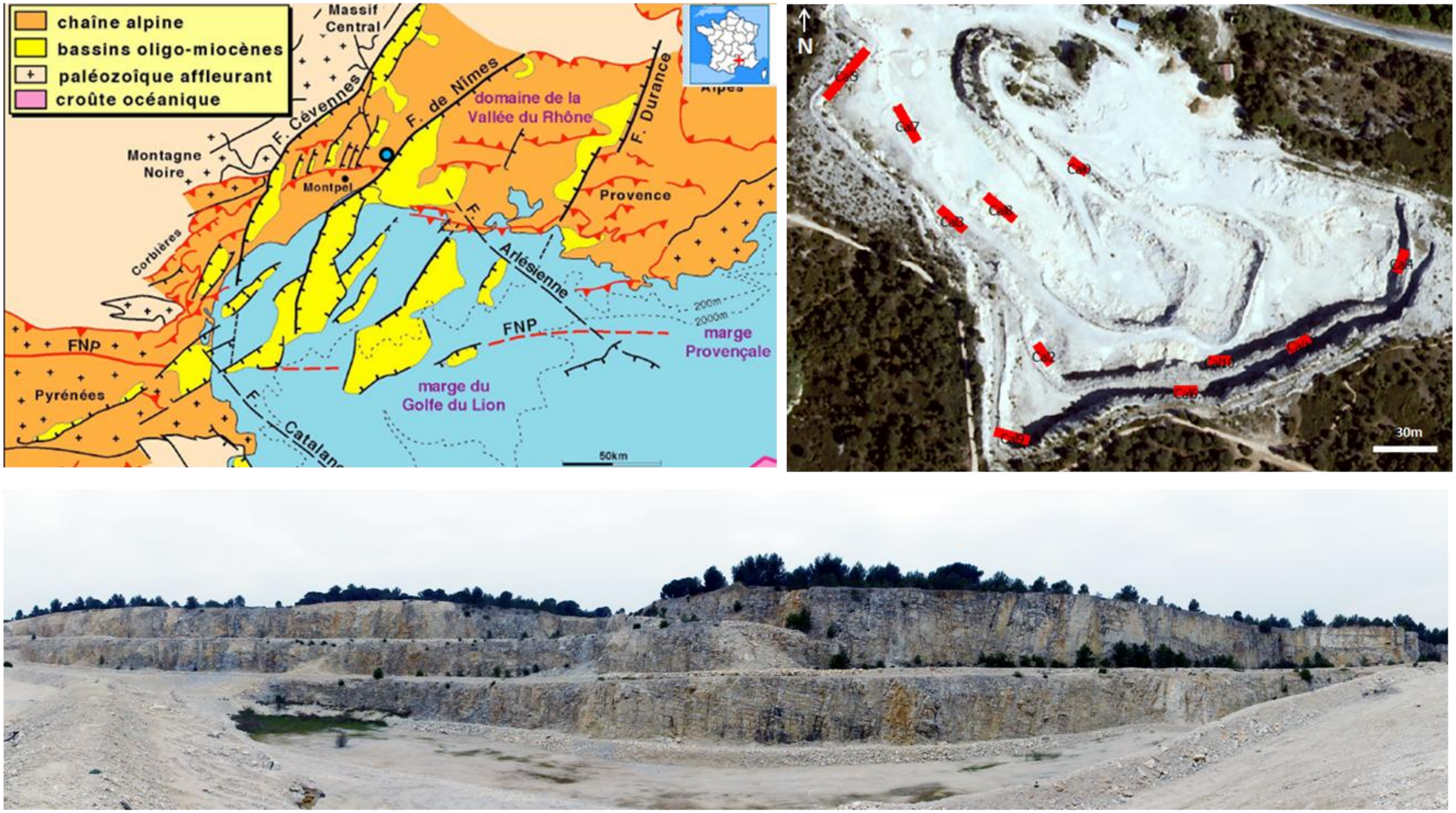

Figure 1. Calvisson location, quarry overview and study outcrop positions.

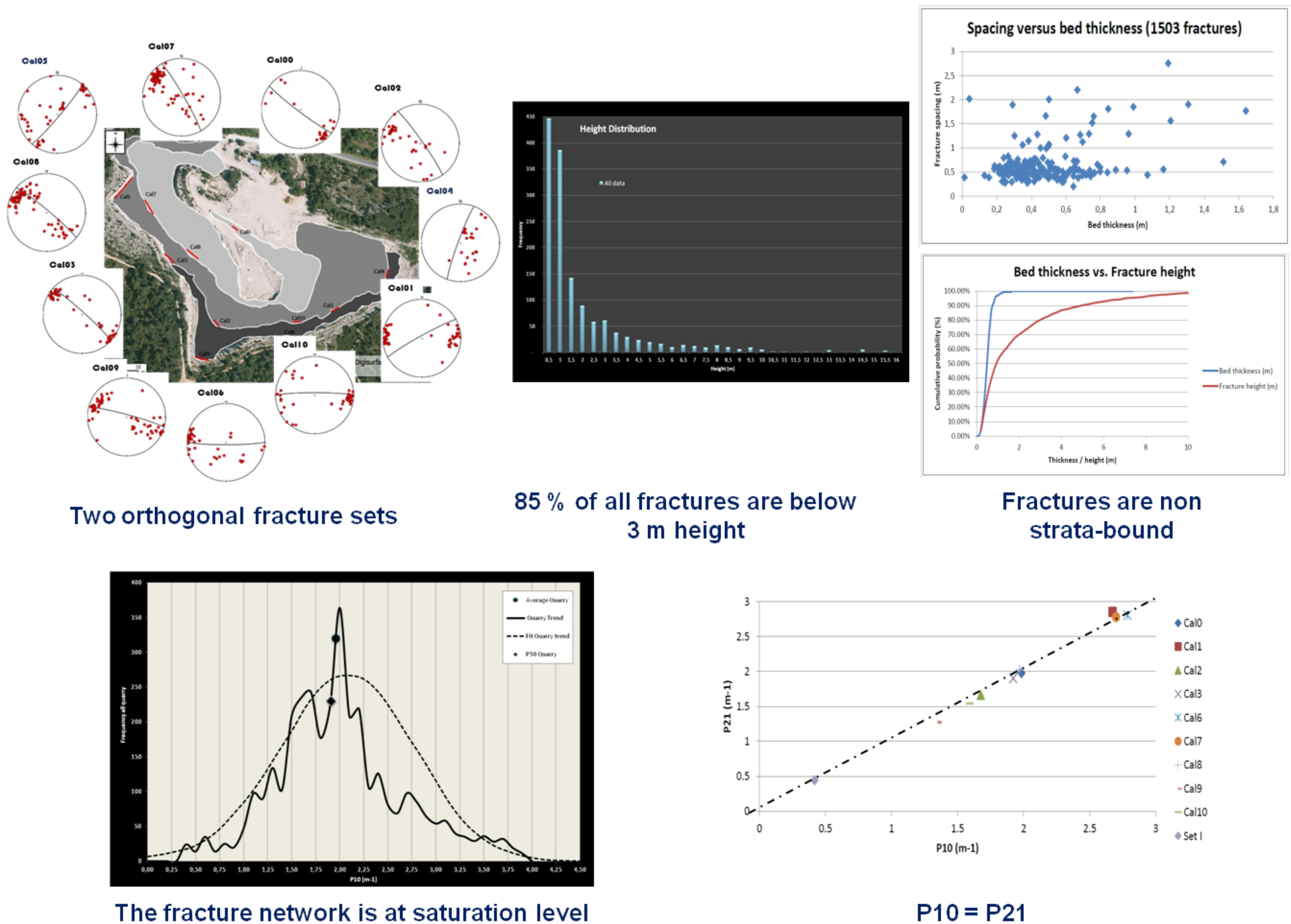

Figure 2. Fracture network characterization.

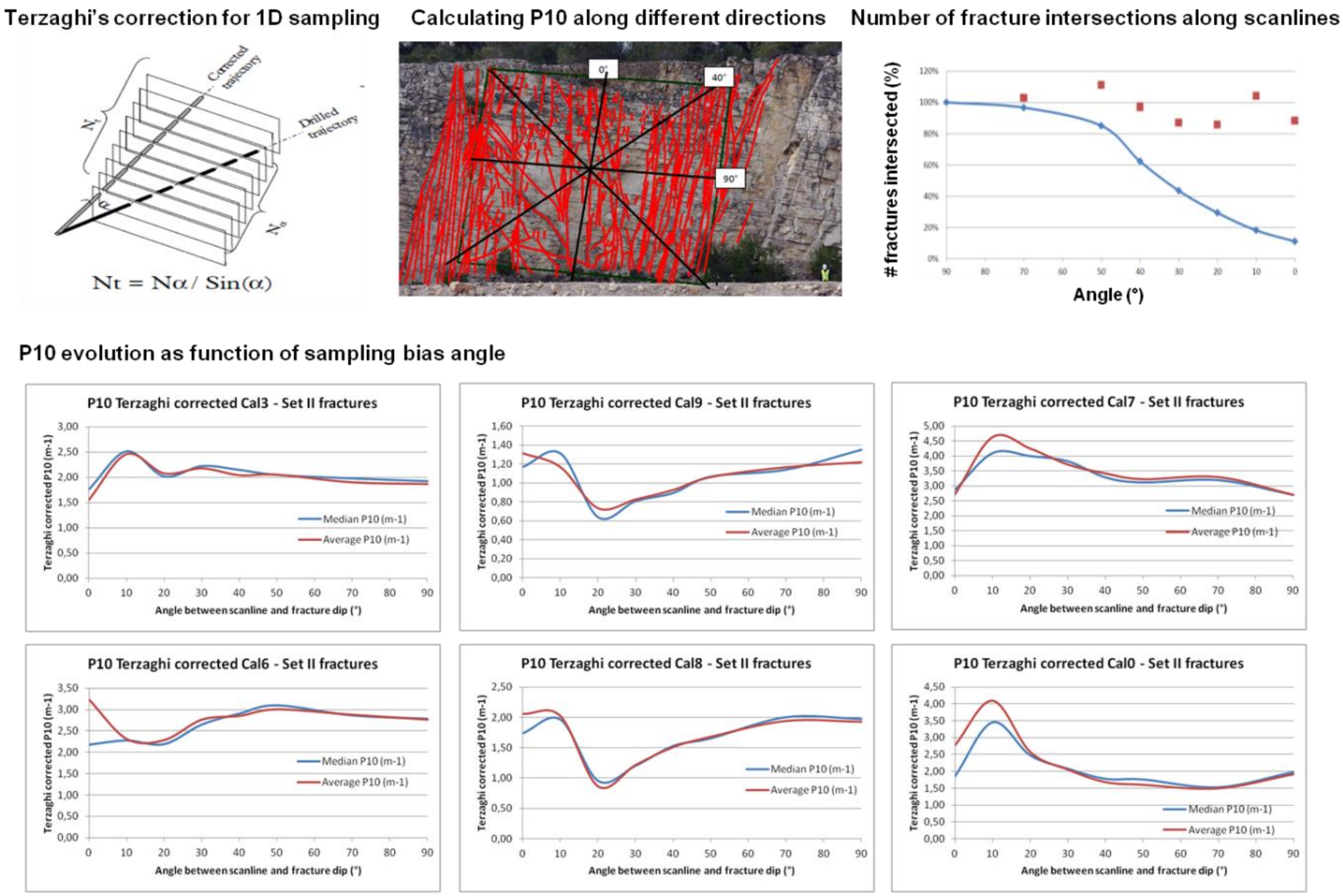

Figure 3. Evaluation of the Terzaghi correction.

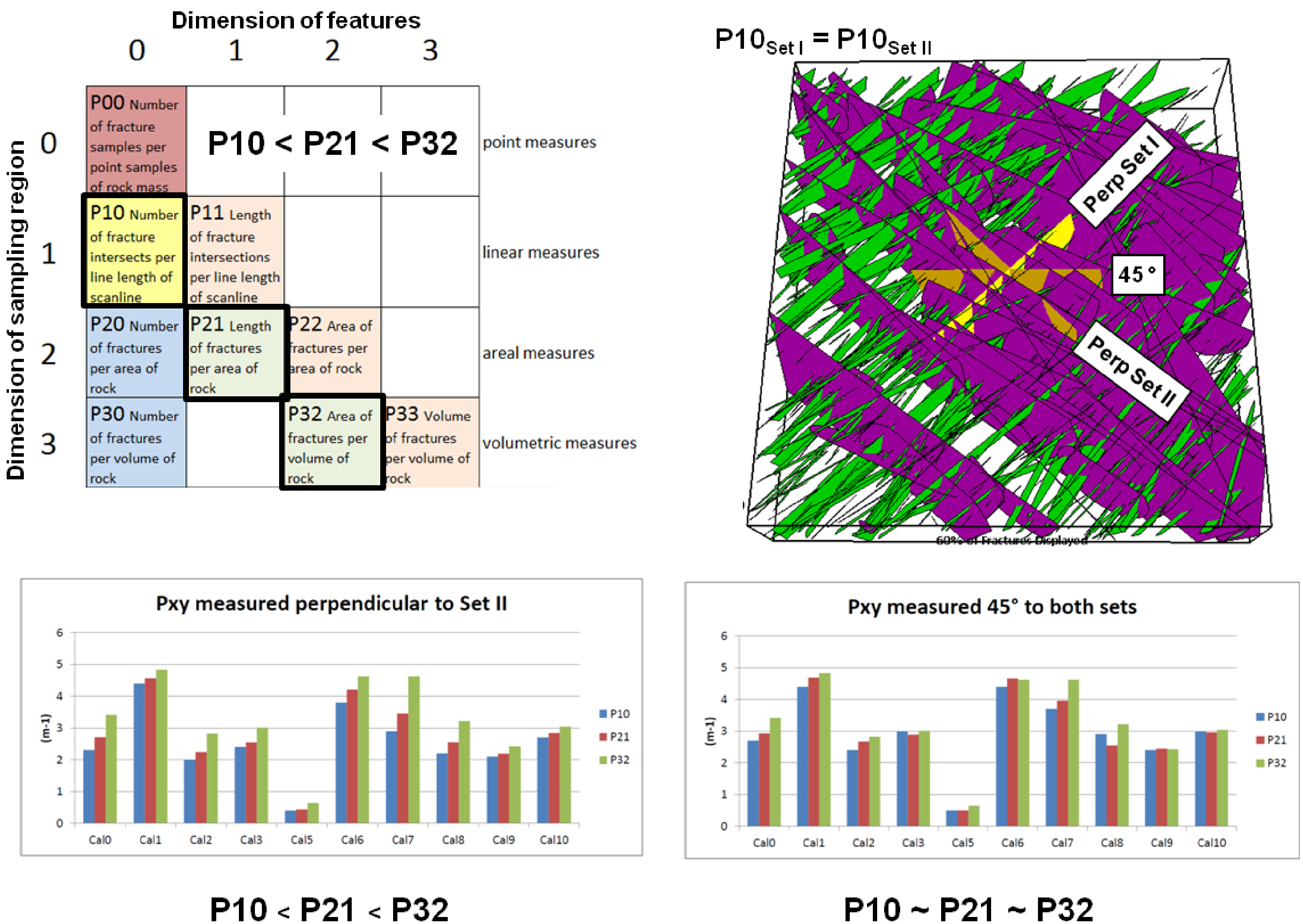

Figure 4. Stereological relationships evaluation.