GEOSTATISTICAL EVALUATION OF ROCK QUALITY DESIGNATION & ITS LINK WITH LINEAR FRACTURE FREQUENCY

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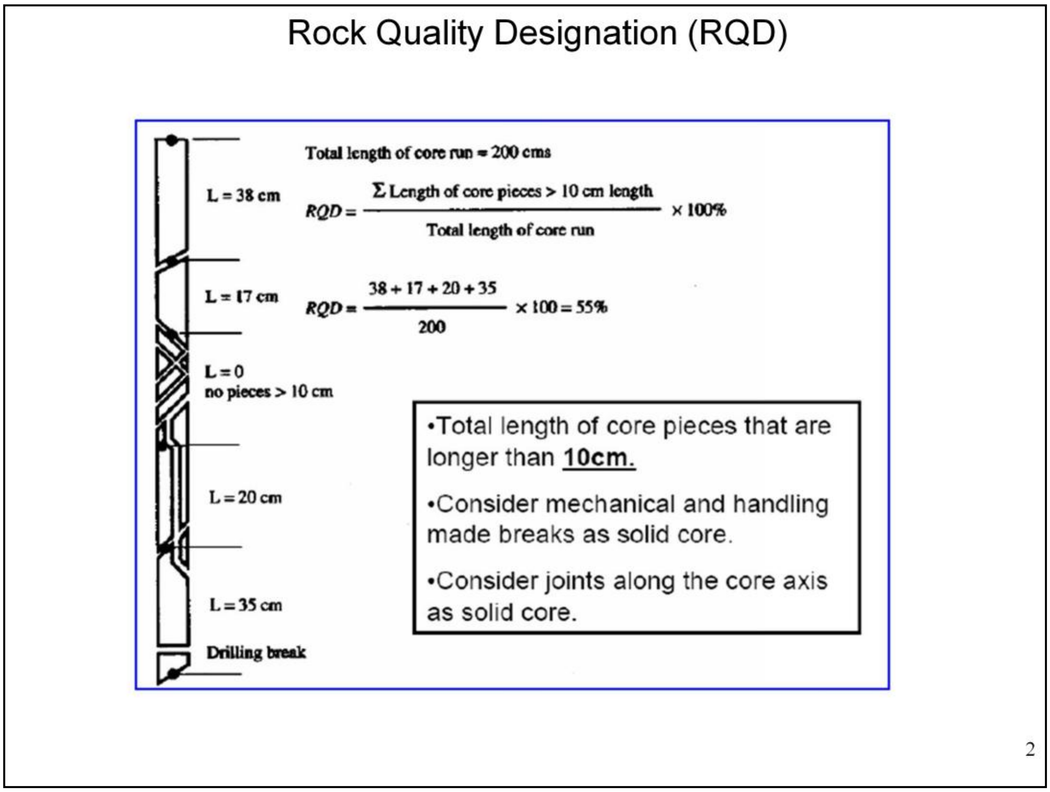
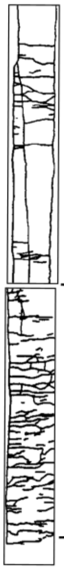


➢Rock Quality Designation aims at quantifying the degree of jointing or fracturing in a rock mass

➢It measures the borehole core recovery percentage incorporating only pieces of solid core that are longer than 10 cm in length measured along the centerline of the core

➢It is one of the main attribute incorporated in the Rock Mass Rating which is a comprehensive index of rock mass quality used for the design and construction of excavations in rock, such as tunnels, mines, slopes and foundations

Additivity ?
(for a given sample direction)



$L_1 \longrightarrow RQD_{L_1}$

$L_2 \longrightarrow RQD_{L_2}$

$$RQD_{L_1 \cup L_2} = 100 \frac{L_{>10cm,\,1} + L_{>10cm,\,2}}{L_1 + L_2}$$

$$= \frac{L_1 100 \frac{L_{>10cm,\,1}}{L_1} + L_2 100 \frac{L_{>10cm,\,2}}{L_2}}{L_1 + L_2}$$

$$= \frac{L_1 RQD_{L_1} + L_2 RQD_{L_2}}{L_1 + L_2}$$

→ Kriging possible (same support & sample direction)

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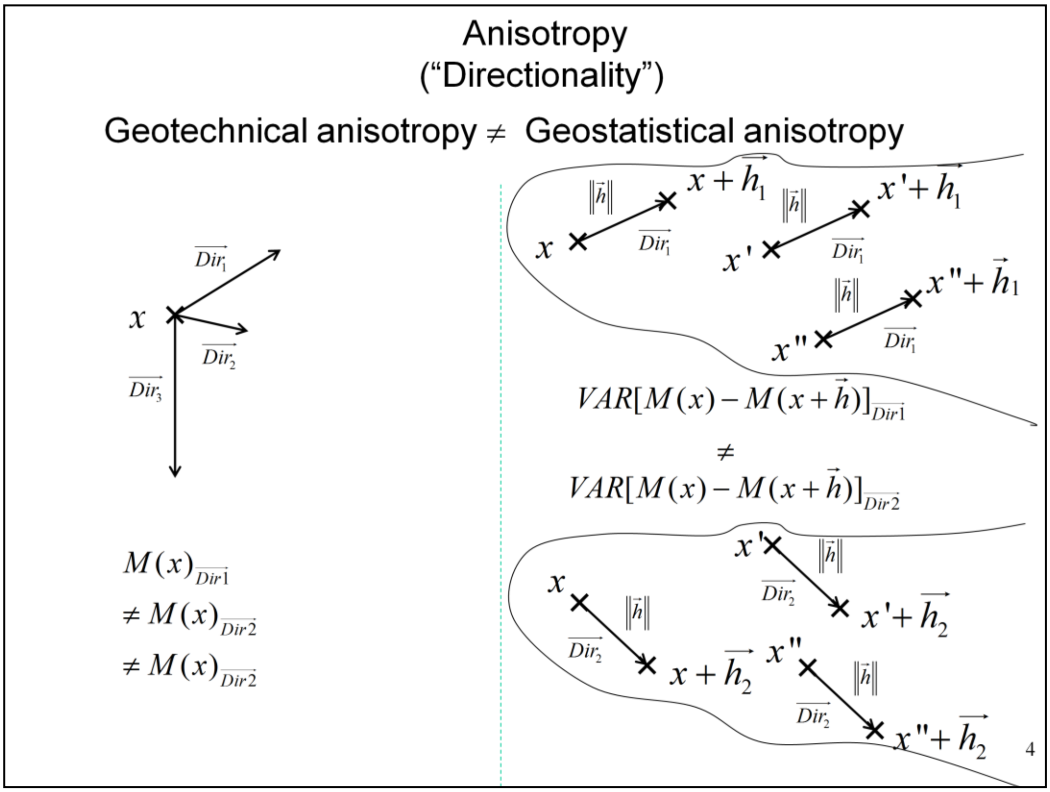
- The first question concerns the ability to estimate RQD at any location by a linear combination of measurements like kriging in geostatistics

- Suppose that all the samples have been drilled along the same direction and take two values collected along two different supports L_1 and L_2, each with its own sum of core pieces longer than 10 cm

- One can see here that the value of RQD over the two supports is a linear combination of the two quantities, equal to the average when the supports are similar

- So in this case kriging RQD is authorized, at punctual or block scale, using classical geostatistical tools when RQD is order-two stationary

- Although the estimation is easy, the interpretation is not: as RQD is a 1D measurement, estimating it at block scale using 1D samples just gives the average behavior of 1D samples over a block, and this is not a 3D property



➢ Now, we have to face this problem: the samples have different drilling directions

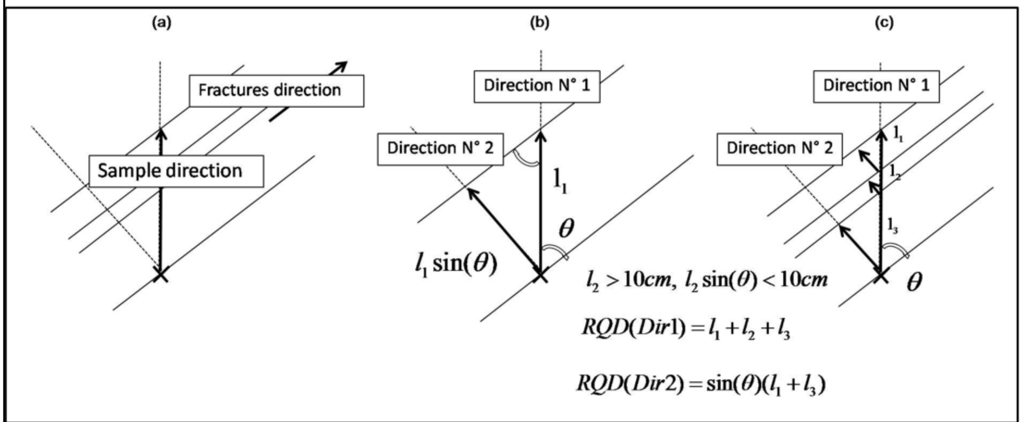
➢ It is important, at this stage, to distinguish between the interpretation of the word "anisotropy" when used by a geostatistician, and the same word, when used by a geotechnician or a hydrogeologist

➢ In geostatistics, this word means that when we calculate a variogram, based on differences of the variable of interest , the variance of such increments depends on the direction and this leads to concepts like "zonal" or "geometric" anisotropies

➢ In Geotechnics and in Hydrogeology, when one says that the phenomenon is anisotropic, it means that the measure itself depends on the direction, not only the increment

➢ The two anisotropies are linked, but the underlying concepts differ fundamentally and this is the reason why we employ the word "directionality" as a synonym for anisotropy as used by the geotechnicians and hydrogeologists

RQD Directional



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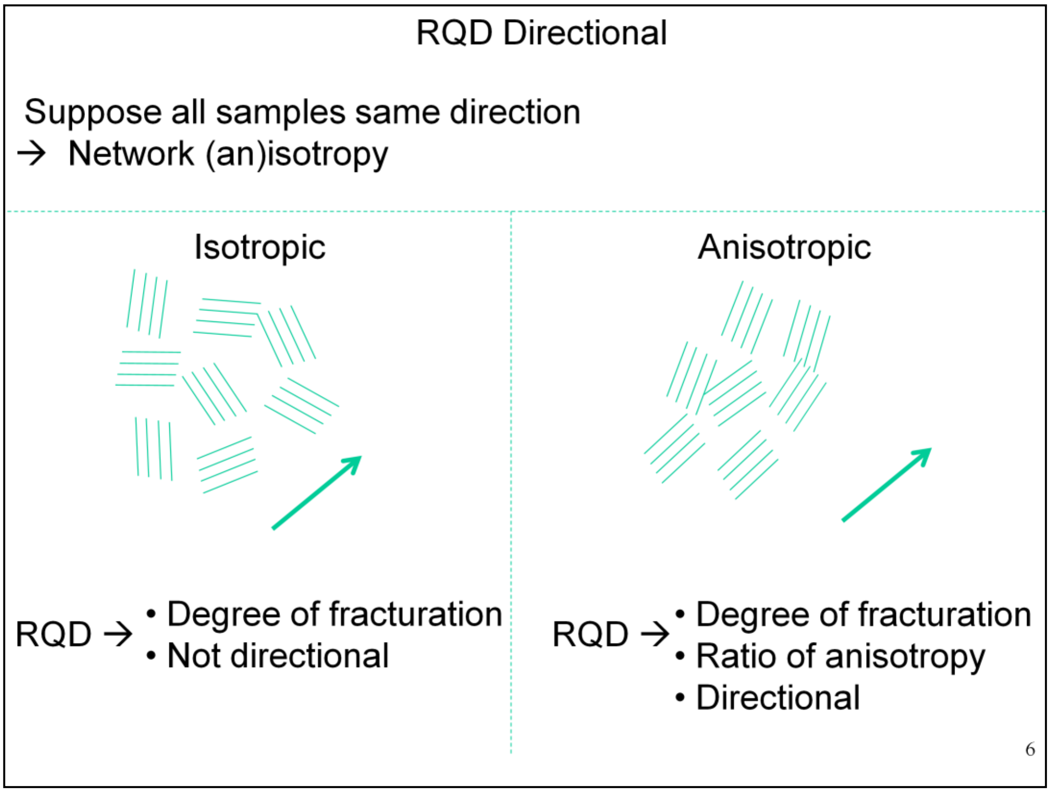
➢The main reason of RQD directionality is that the spacing between the fractures is subject to bias

➢Suppose that all the fractures are parallel planes aligned along a single direction and consider two consecutive fractures

➢ The spacing measured along direction n°1 is l_1 while it should be "l1Sinus thetha" if we want to make the measurement independent of the sample direction by referring to direction n°2 perpendicular to the fracture direction

➢This correction must be applied to each segment but it cannot be applied directly to its sum with the common factor "sinus thetha" because after correction, some segments may be shorter than 10 cm. This is the case of segment l_2 in the right-hand figure which will not be included in the summation

➢The problem becomes more complex when we consider that a direction in three dimensions requires two angles (azimuth and dip)

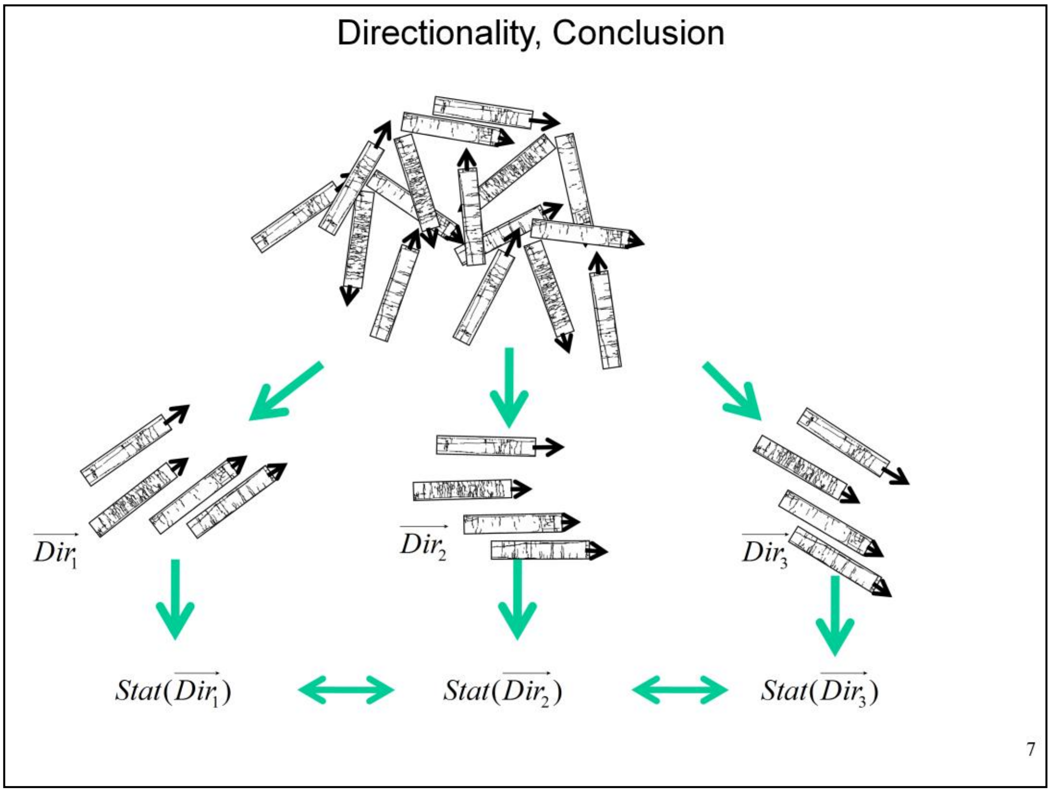


- Samples are directional, but fractures too

- If we assume that all the samples have the same direction, and the fracture network is isotropic, the directionality of RQD can be neglected, whereas if there are local anisotropies in the fracture network, the local value of RQD at a given location will depend on their angles and will not be comparable to another value of RQD at an another location even close

- In the first case RQD measures the degree of fracturation in an objective way

- In the second case it also measures the anisotropy of the fracture network and this is not really its objective



➢For all these reasons we recommend the following procedure:

➢the samples must first be classed according to their directions, and structural analyses must be conducted by direction

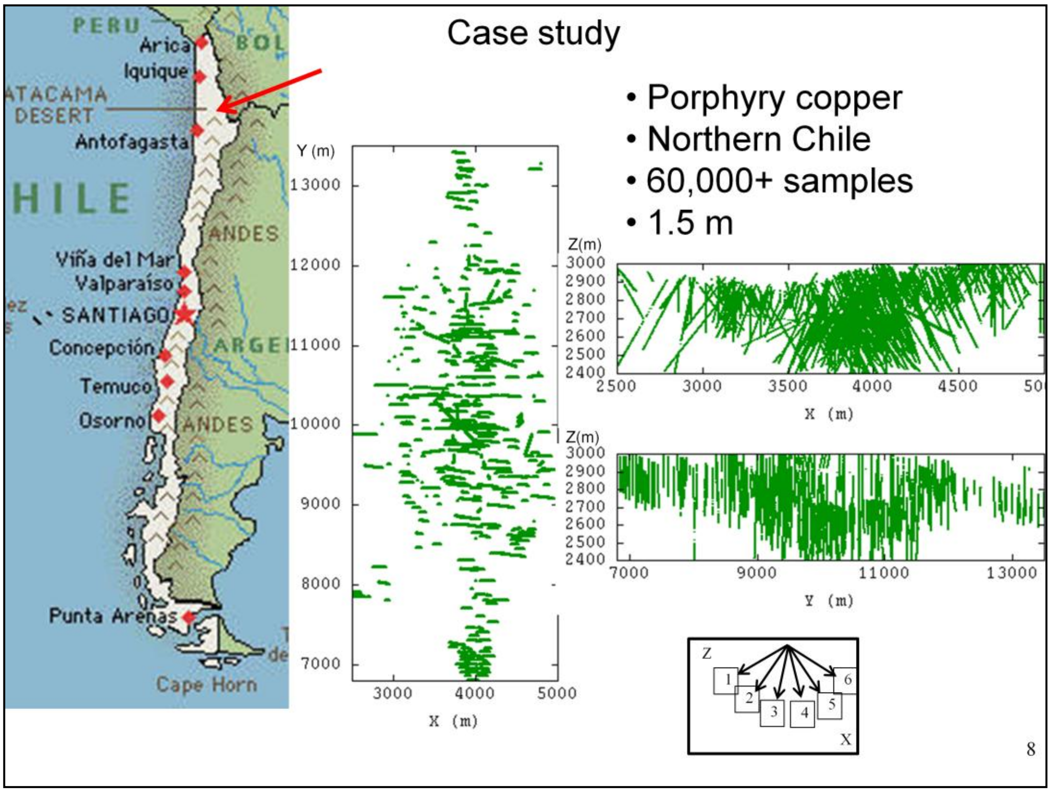
➢If the variograms by sample directions are close to each other, and close to the variogram obtained with all the samples, there is no reason to distinguish between the directions because the fracture network looks isotropic

➢If this is not the case, kriging must be conducted only with the samples of a given directional sampling class, yielding as many directional results as there are classes

➢If, for each location where the estimation is conducted, the results are always the same, it means that the directionality of the measurement can be neglected and kriging can be conducted with all the samples without distinction between the classes

➢If the differences are large, the result is directional, which is important for the geotechnicians because it means that, when looking at the rock-strength prior to drilling a tunnel, for example, they must account for the drilling direction

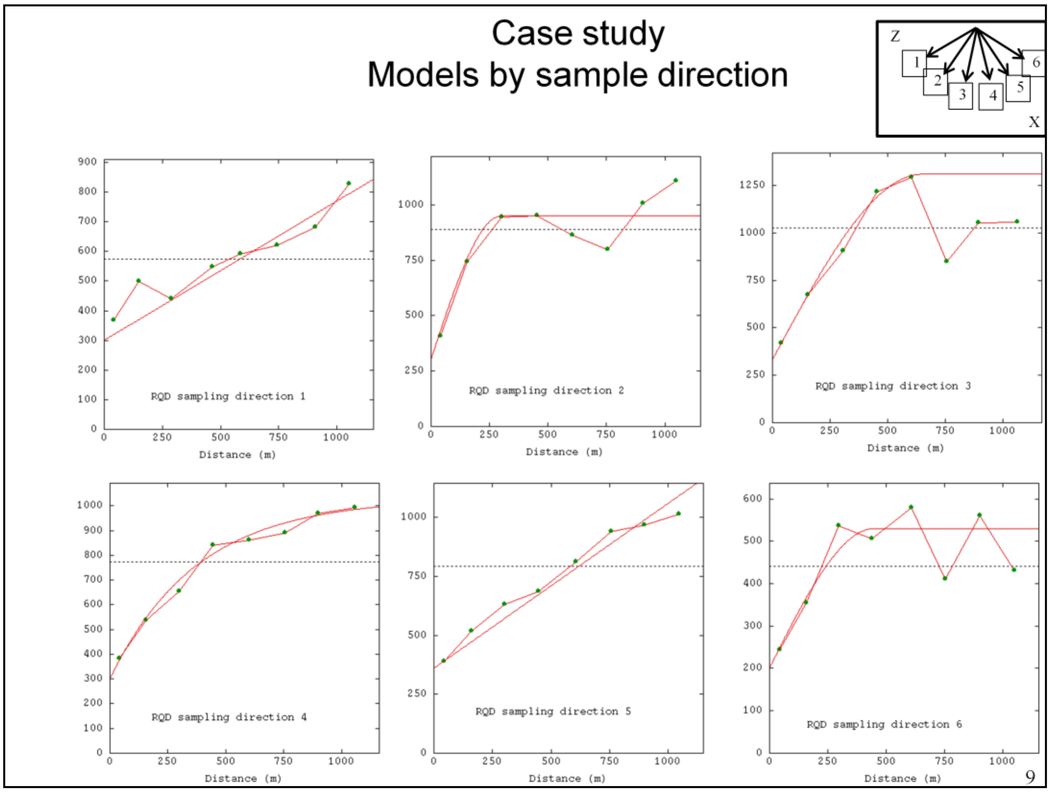
➢These ideas are illustrated below by a case study



➢ The data are from a copper mine in northern Chile. We have used more than 60,000 samples with RQD information

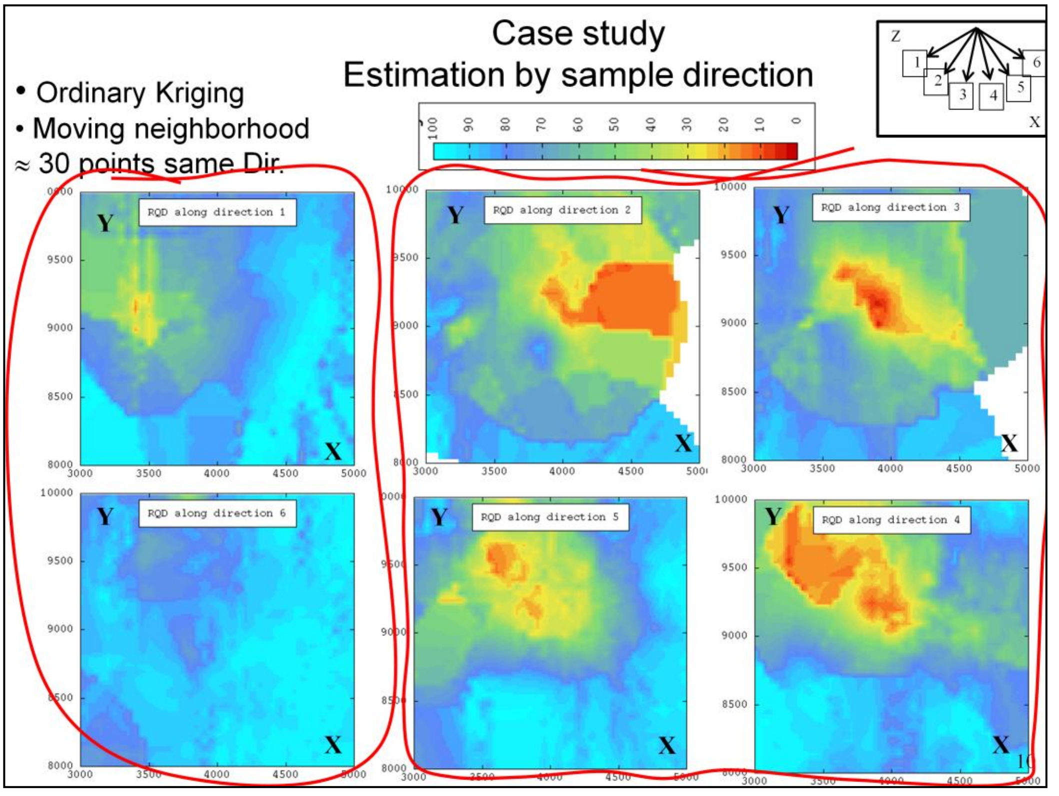
➢All the samples are 1.5 m long

➢We have at our disposal six sampling directions all belonging to East-West vertical plans and a dip is enough to characterize the sampling directions



➢We fit a model for each one of the six directions, and a seventh one taking into account all the samples

➢Estimations are conducted by sampling direction, each time using only the samples associated with the direction



➢We present here a typical horizontal cross-section of the results

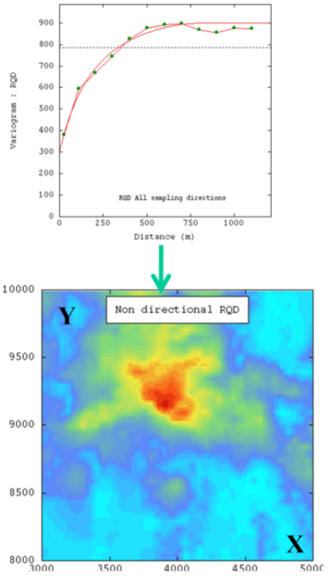
➢ The directional RQD maps can be regrouped into two sets: {1, 6} and {2, 3, 4, 5}

➢The greatest differences concern the northern part which contains low RQD for the second set of directions

Case study
No direction selection

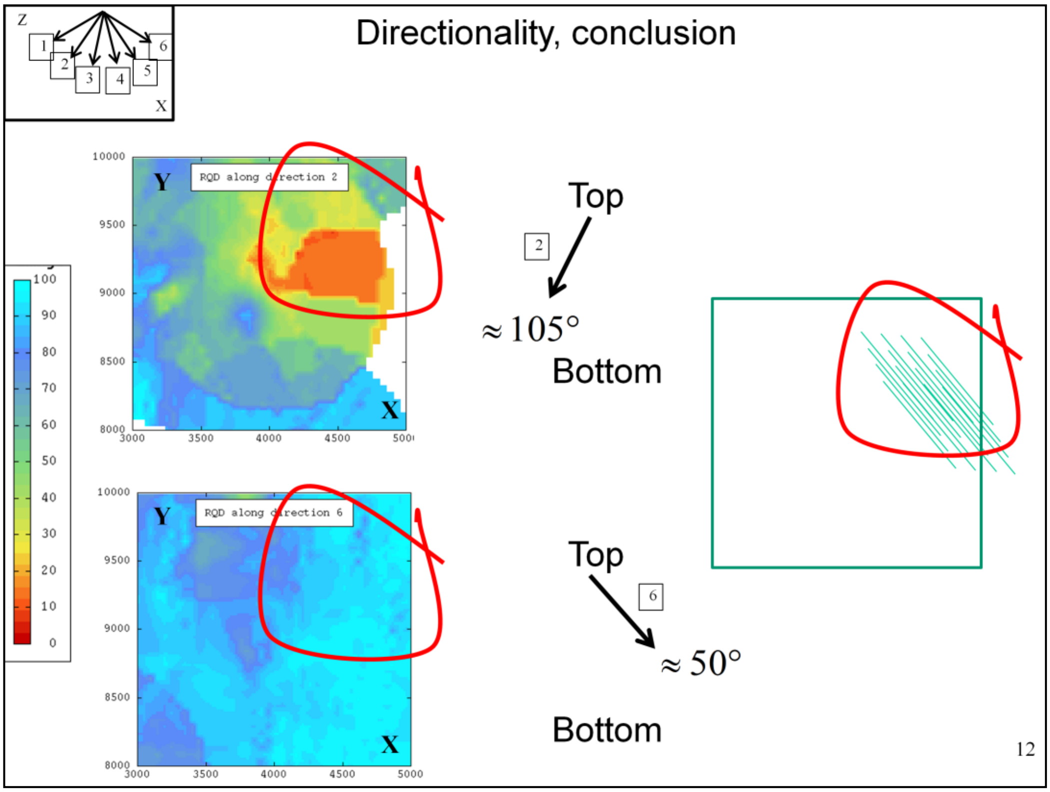
- Ordinary Kriging
- Moving neighborhood

≈ 30 points ANY Dir.



➢This map is obtained when no distinction of the sample direction is considered

➢ Such a map is of no interest because it just shows the dominant directions of the sampling



➢So direction 50° differs strongly from direction 105°

➢Along 50° (and in a West-East plan), RQD is equal to 70% on average while it becomes lower than 20% when sampling is along 105°

➢ 70° correspond to 1 meter for the length of solid core; 20% corresponds to only 30 centimeters

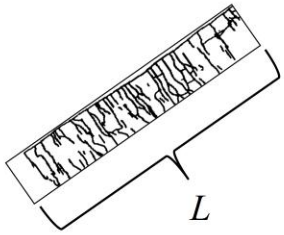
➢ One can deduce that in this part of the deposit, the fractures tends to be parallel to 50°, with a high density

➢Such analyses, made plane by plane and by direction may help to detect particular domains that go unnoticed if the sample direction is not taken into account

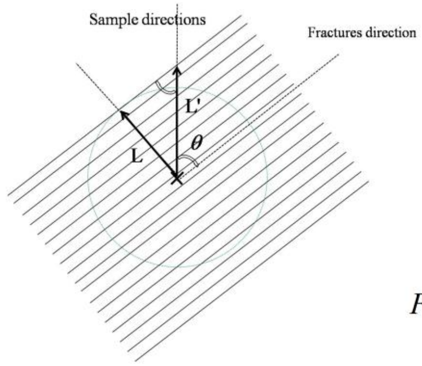
➢Finally, while RQD aims at measuring the degree of jointing or fracturing in a rock mass, its spatial variations measure mainly the anisotropy of the fracture network

➢ The conclusion is that the directionality of RQD must be accepted and used and it means that attributes like Rock Mass Rating must become directional too

FF



$$FF = \frac{\sum_{n_\theta} n(\theta)}{L}$$



$$FF_{corrected} = \frac{\sum_{n_\theta} \frac{n(\theta)}{\sin(\theta)}}{L} \qquad (Terzaghi, 1965)$$

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➢Now let us recall the Fracture Frequency (FF), a number of fracture divided by a sample length L

➢The fracture counting depends on the angle of the fracture and the sample direction, as shown by Terzaghi in 1965, and it must be corrected by a sinus

➢This is the same problem as for RQD but here with a concrete solution as the fractures are usually classified according to their direction

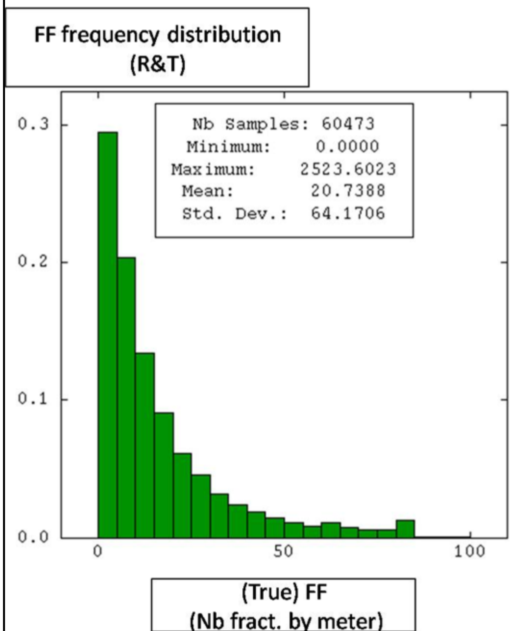
➢Question is: by applying such a correction on FF (and not RQD) do not we break some relationship and change results when integrating both measures in attributes like Rock Mass Rating ?

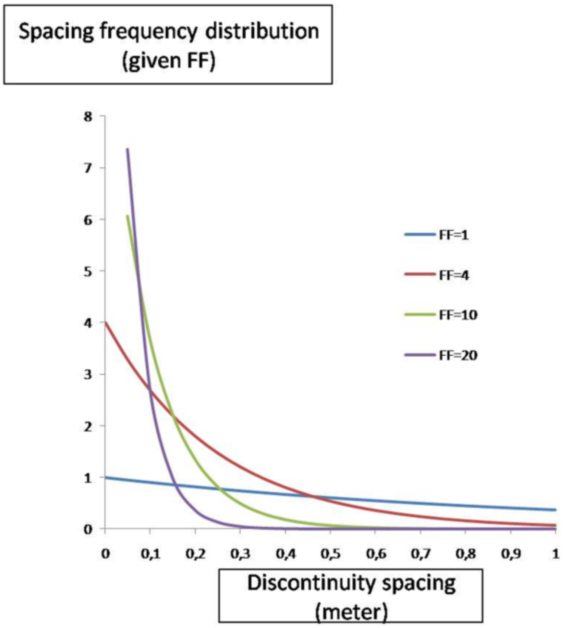
RQD & FF
(Priest & Hudson 1976)

$$RQD = 100e^{-0.1FF}(0.1FF + 1)$$

$$f(x) = FFe^{-FFx}$$

→ Frequency of the spacing x





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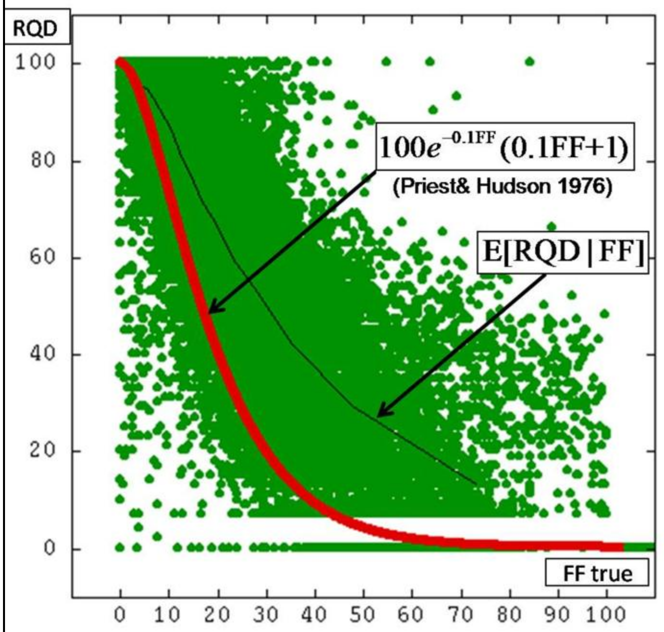
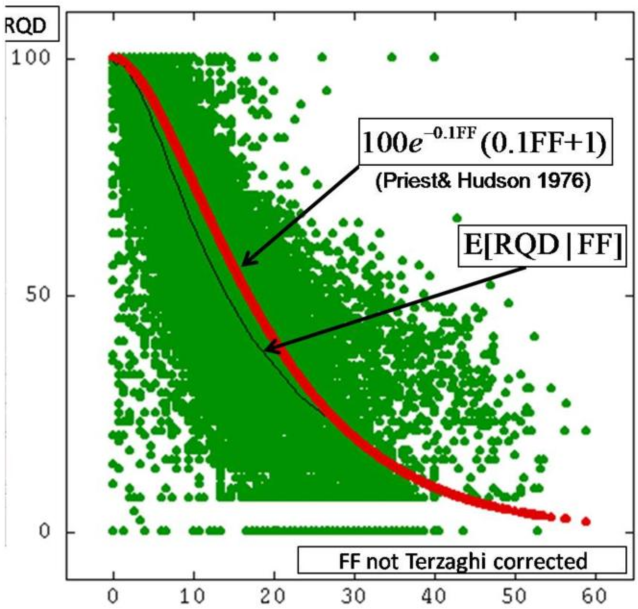
➢In 1976, Priest and Hudson established a link between FF and RQD

➢This formula results from the assumption that the distribution of spacings between discontinuities along a line follows a negative exponential distribution

➢ The aim here is not to discuss this assumption but to use this formula as a reference

RQD & FF
(Terzaghi or not Terzaghi)





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➢What about RQD compared to FF? Left-hand figure shows a scatter diagram between FF (when Terzaghi-corrected) and RQD. The black curve represents the conditional expectation which is, for a given value of FF, the average of the different values of RQD. The behavior predicted by Priest & Hudson's formula is plotted in red. The least one can say is that this formula does not reflect the experimental average behavior. Does this mean that Priest & Hudson's hypotheses are not acceptable?

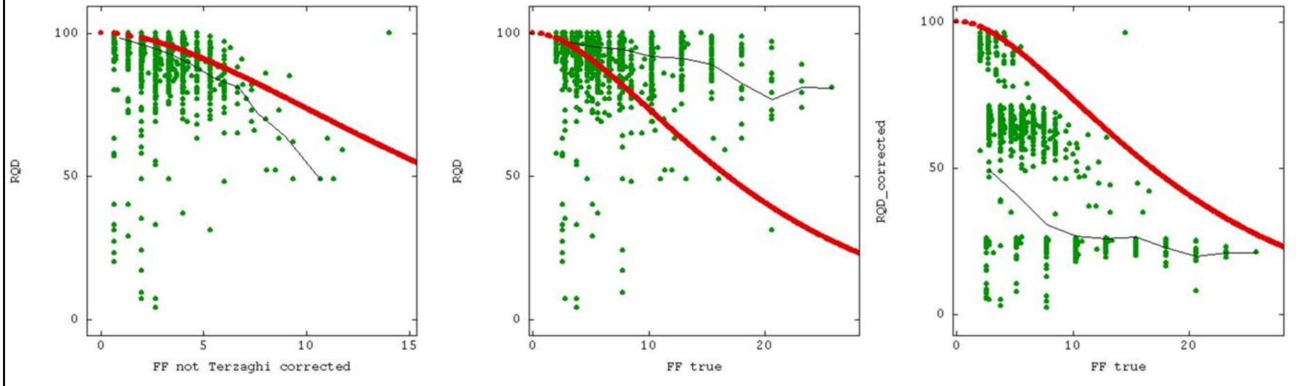
➢Not necessarily. Right-hand figure presents RQD versus FF without the Terzaghi-correction. One can see that the formula slightly over-estimates RQD in the FF range [0, 28], but the differences are not comparable to the previous differences when Terzaghi was applied

➢ What happens? When we correct FF, we induce a distortion of the distribution, a kind of anamorphosis which makes the values no more comparable to RQD

➢When FF is not corrected, we compare coherent populations because the bias in the counting is fully compatible with the bias in the associated length and then Priest & Hudson's formula is verified in an acceptable way

➢So we have to face a dilemma: Terzaghi correction is necessary to make the discontinuity counting comparable from one direction to another and finally transform the directional number into a counting systematically perpendicular to the fractures. But if we correct FF, we must also correct RQD

RQD & FF
(Try a correction)



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➢Let us try such a correction for RQD

➢From the total amount of data, a sub-set of more than 4,000 samples was selected because they have at least 3 fractures with the same direction. It then becomes possible to correct RQD in the same way as FF, as previously explained a crude calculation which over-estimates RQD. We focus on [0, 20] FF interval

➢ On the left-hand figure, FF is corrected, not RQD. In the middle, no correction is applied . On the right-hand figure, RQD and FF are corrected

➢When a correction is applied to RQD, it induces so strong a reduction of variability that this time, Priest & Hudson over-estimates RQD given FF when it is Terzaghi-corrected

➢So the correction is not efficient, if we refer to Priest & Hudson, and the best solution is certainly to not apply any correction, neither to RQD, nor to FF

Conclusion

- ➢RQD, FF, directional
- →RMR directional
- ➢ 5D Geostatistics?

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➢The first conclusion is that RQD, as well as FF, are directional measurements that must be estimated after classing the samples according to their directions. Otherwise we mix quantities that are not comparable, producing a not interpretable result

➢ It means that attributes like the Rock Mass Rating become directional too.

➢ But the procedure of classing the samples according to their directions is somewhat rudimentary as it proposes estimations only on the sampled directions and no interpolation between these directions

➢ This is a very general problem that occurs when geostatical tools are applied to tensors, and the solution, in the future, is to consider the real regionalization space involved by the problem, a 5D space, 3 for the usual coordinates and 2 for the dip crossed by the azimuth, a concept that requires considerable theoretical development because we do not have models for distances crossed by angles.

Acknowledgment

Codelco Chili

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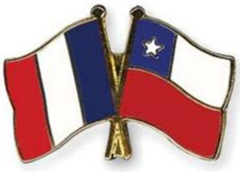

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