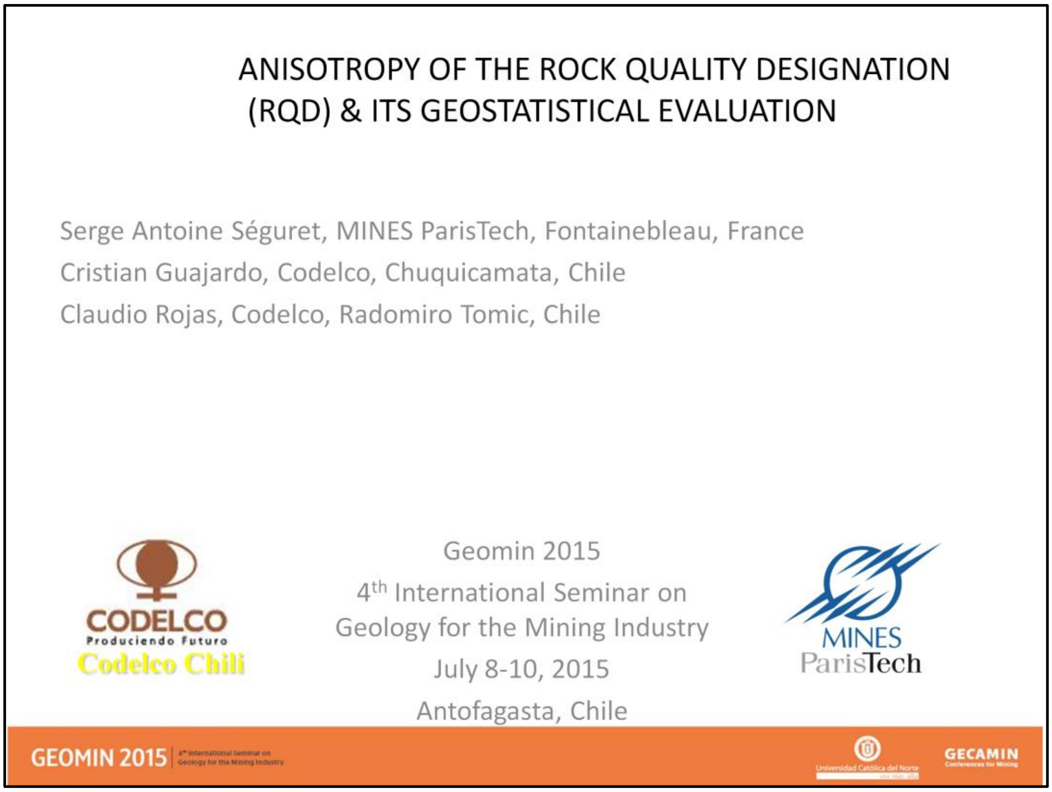
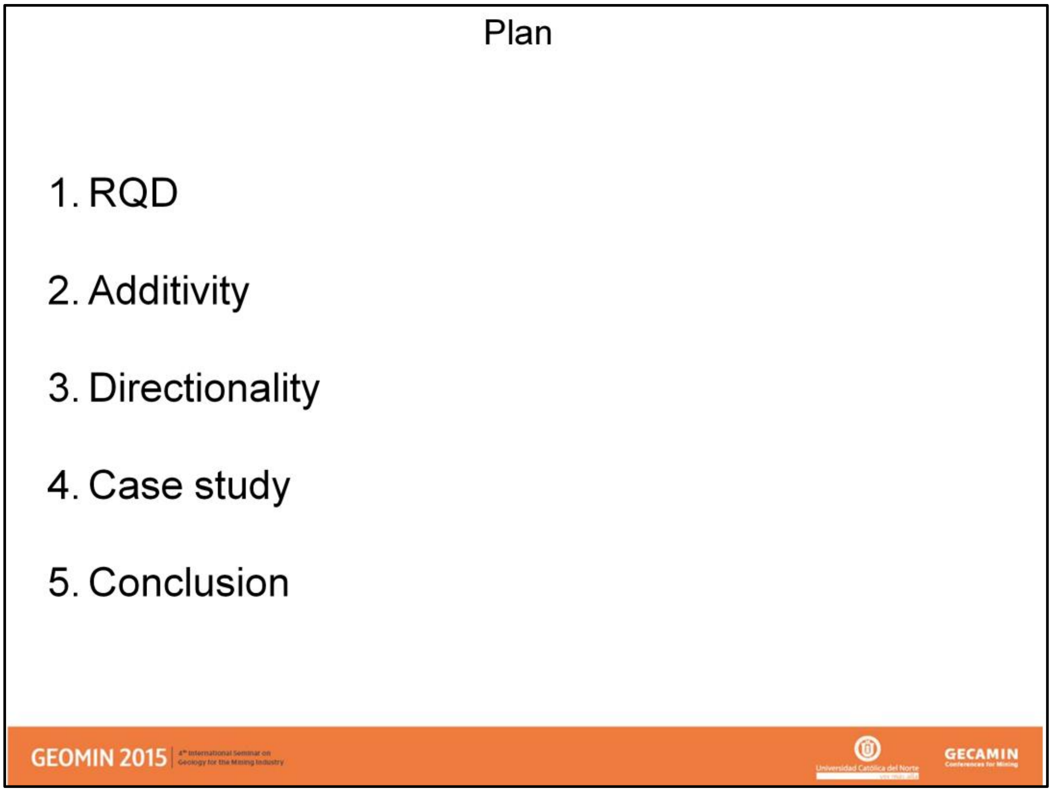


It is my pleasure to present the work done jointly by my collaborator Doctor Serge Séguret from France, and myself, on data provided by my team and by my colleague Claudio Rojas

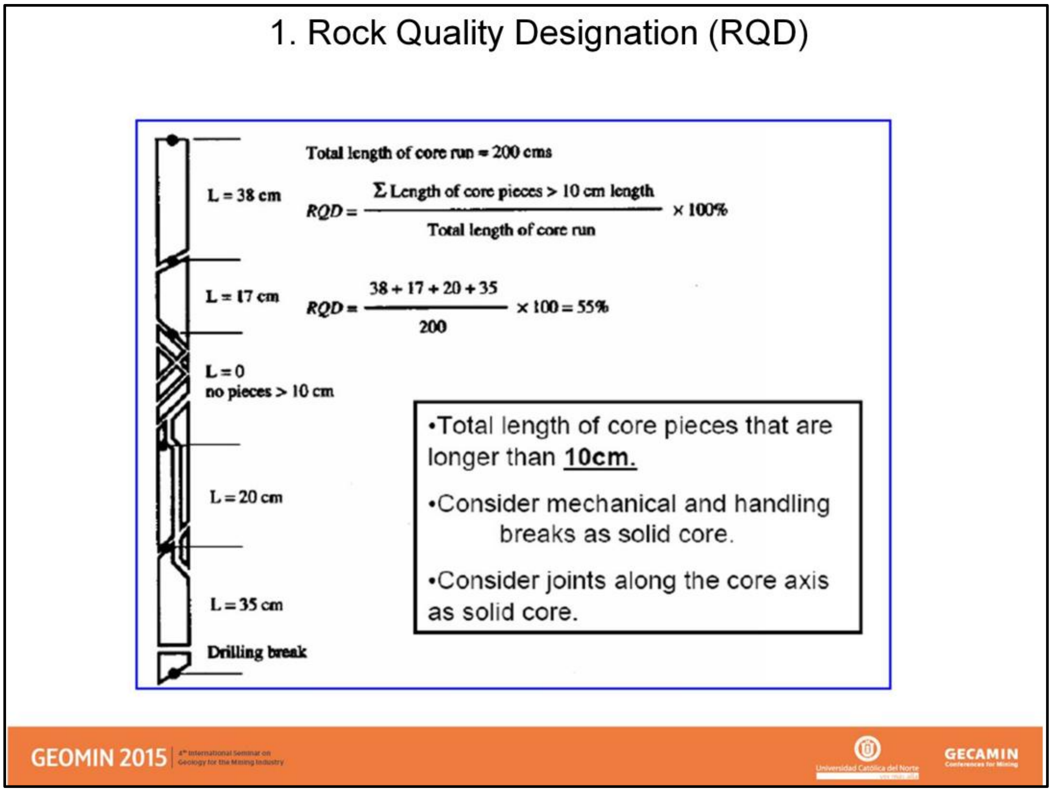
The presentation is entitled

“ANISOTROPY OF THE ROCK QUALITY DESIGNATION & ITS GEOSTATISTICAL EVALUATION».

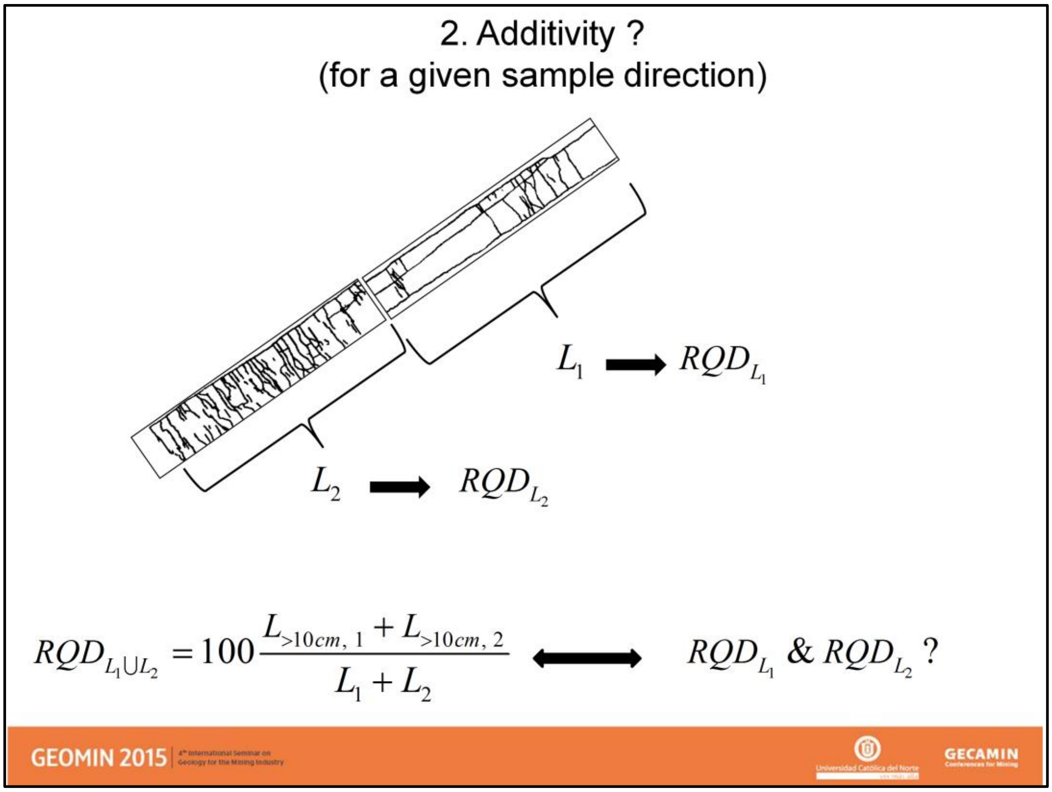
… a work supported by the Chilean company Codelco and the Paris School of Mines where Serge has worked for over thirty years in the Geostatistical laboratory founded by Georges Matheron at Fontainebleau.



Here is the program that we propose to follow.



The aim of RQD is to measure the degree of jointing or fracturing in a rock mass. It is one of the main attributes incorporated in RMR 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.



➢The first question concerns the additivity of RQD i.e. the ability to estimate it 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 in space 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, respectively equal to L1>10 and L2>10...

Additivity
(for a given sample direction)

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

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

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

→ Kriging possible
(same support & sample direction)

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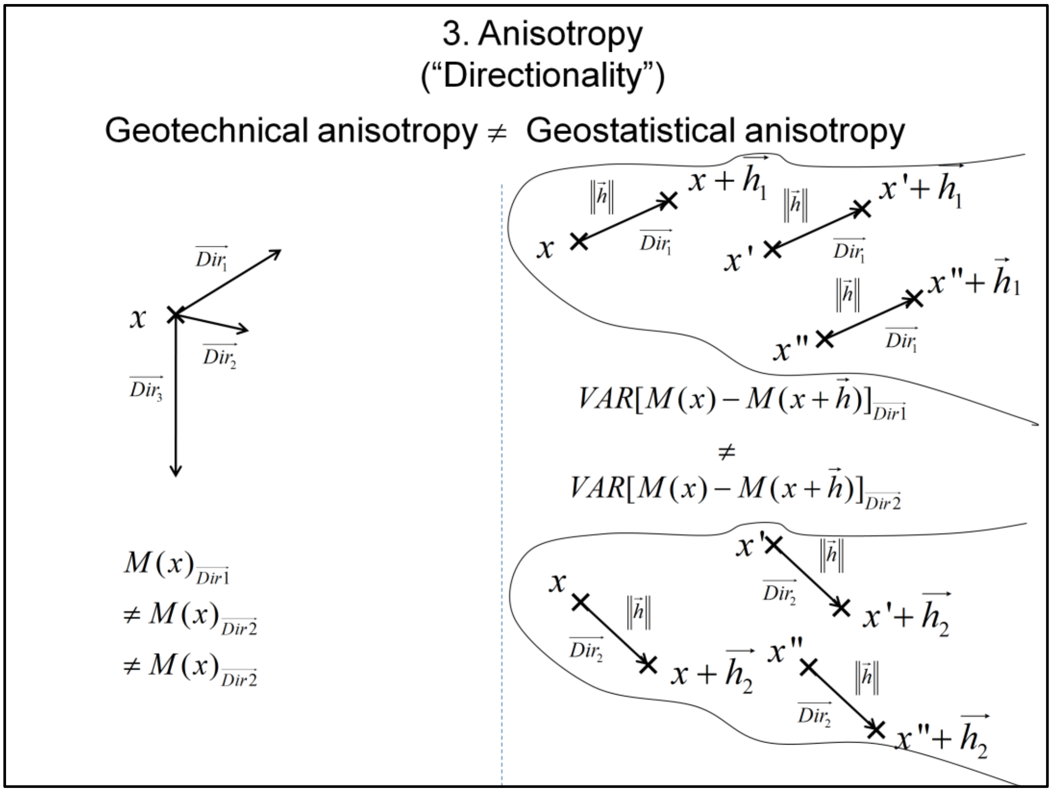
- The value of RQD over the support L1 and L2 is…

- And when we develop, we obtain…

- This is by definition the way to combine additive quantities, equal to the average when L1=L2

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

- Although the calculation 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

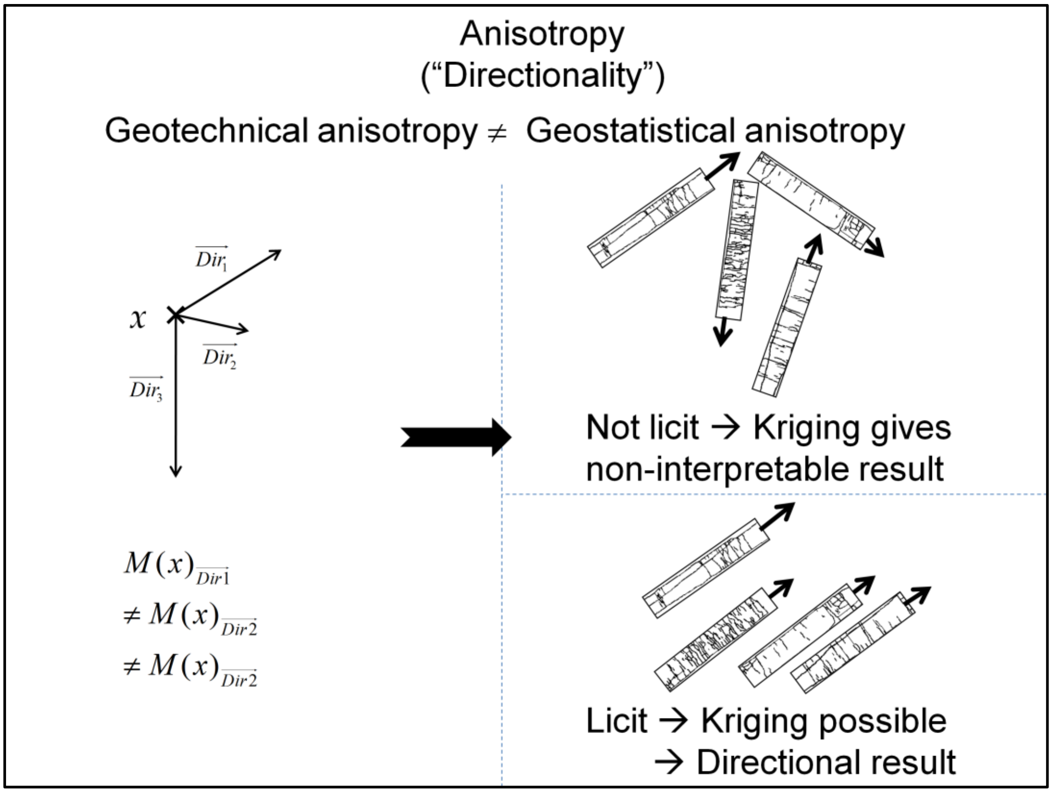
➢ This is a very general problem that occurs when geostatical tools are applied to tensors: the quantity that we measure may depend on the direction of the measurement

➢ 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 ("M" on the slide), 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 obviously 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

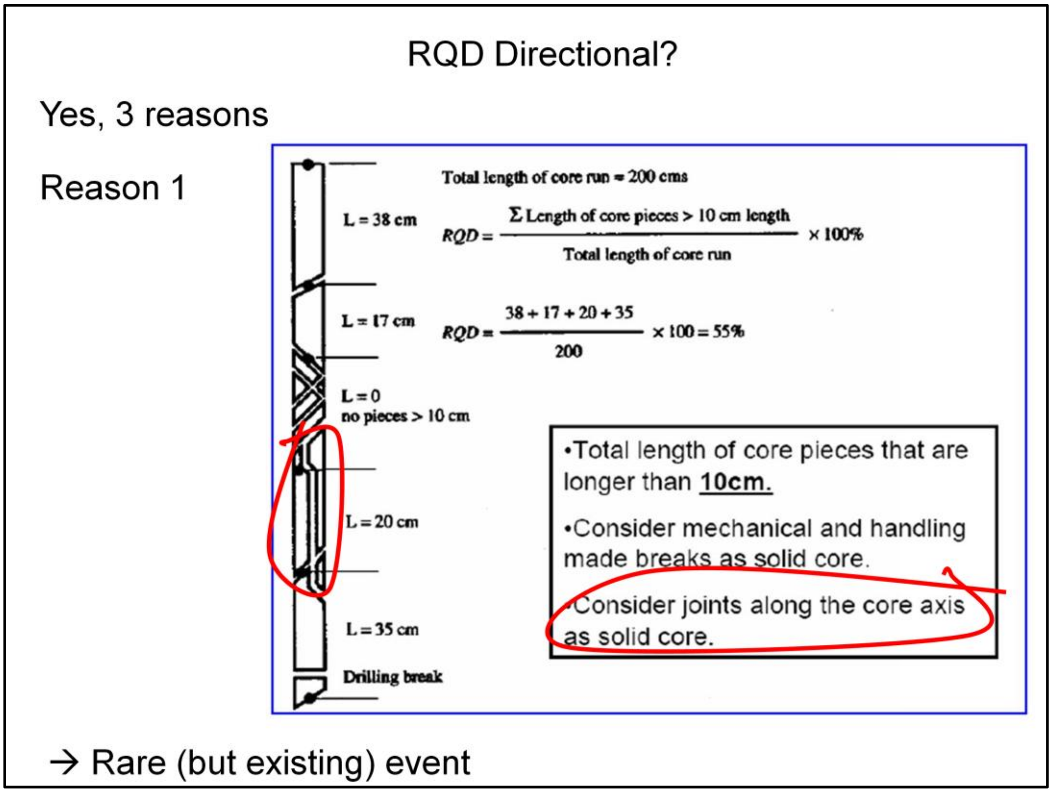


- If, for a given estimation, based on a given amount of samples – typically the measurement used in the kriging neighborhood – we mix samples with different directions, we obtain a result that is not useful, and even incorrect, because we mix quantities that are not comparable, due to their directionality

- If the different directions are represented in the same way, one could say that the obtained result represents the average behavior of the quantity along all the possible directions…

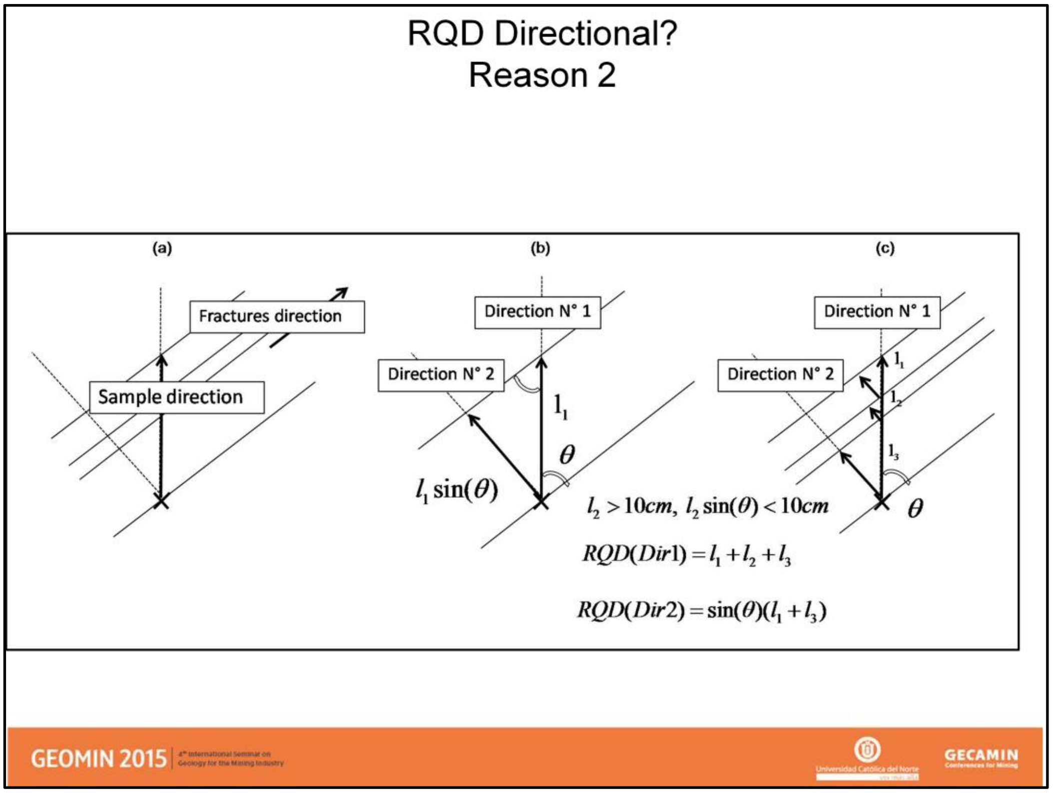
- … but in practice, locally, the sampling of the directions is never homogeneous and the result just reflects the anisotropy of the sampling

- This is the reason why we recommend classing the samples according to their direction, and calculating direction by direction



➢Now let us analyze the directionality of RQD

➢ The primary reason is that a core with a joint running along it, is considered solid (see figure, in red circles). If the sample direction is slightly changed, the joint is no longer aligned with the sample and a core, previously considered to be longer than 10 cm and incorporated into RQD, can be rejected, which changes the final value of the attribute. But this is a rare event that can be neglected in most cases.



➢The second reason is that the spacing between the fractures is subject to directional bias.

➢Suppose that all the fractures are parallel planes aligned along a single direction (left figure) and consider two consecutive fractures (middle figure)

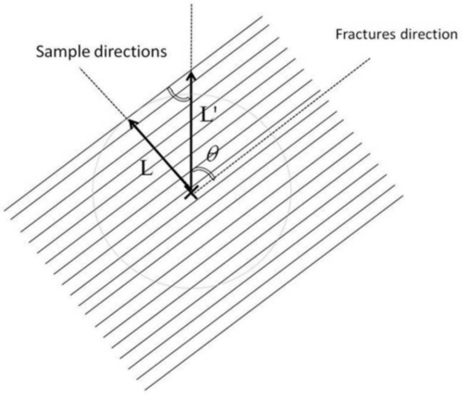
➢ The spacing measured along direction n°1 is l_1 while it should be “l1Sinus thetha” if we want to make the measurement independent of the sample direction by referring to direction n°2 perpendicular to the fracture direction.

➢This correction must be applied to each segment (right-hand figure) 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 (case of segment l_2 in the right-hand figure) and consequently, they 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).

RQD Directional?
Reason 2

Same problem for Fracture Frequency



$$L' = \frac{L}{\sin\theta}$$

$$FF = \frac{N_{tot}(x)}{L} = \frac{N_{tot\_corrected}(x)}{L'}$$

$$\rightarrow N_{tot\_corrected}(x) = \frac{N_{tot}(x)}{\sin(\theta)}$$

(*Terzaghi*, 1965)

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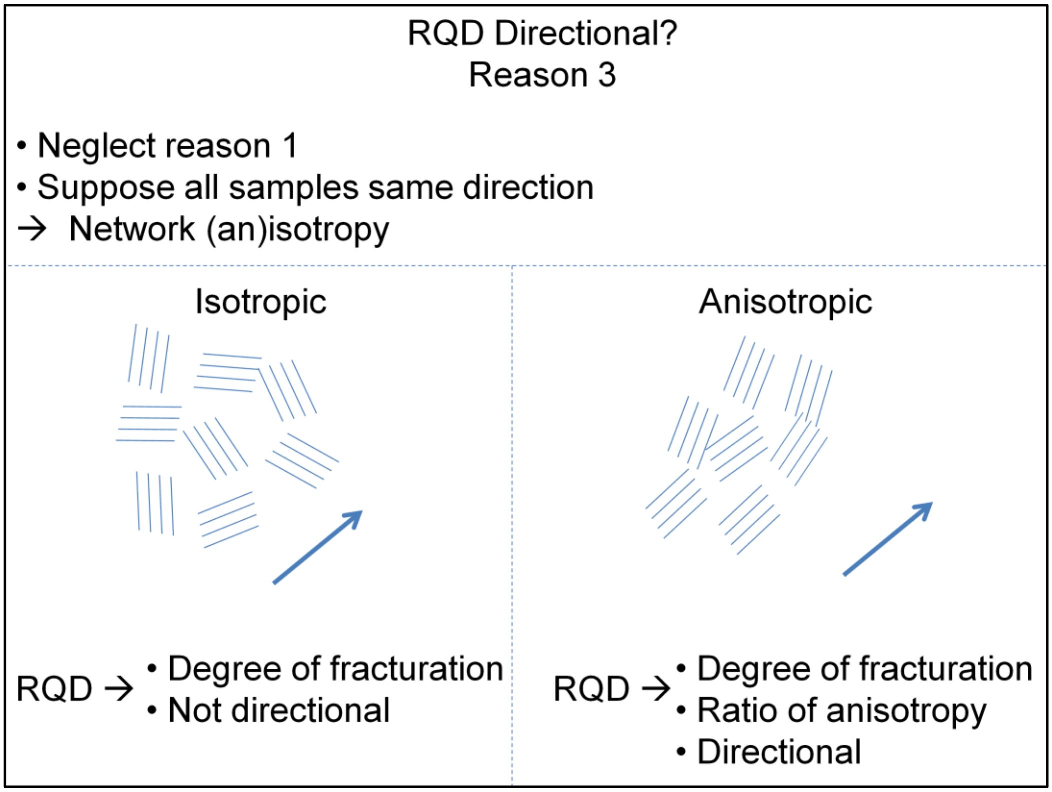
- Like RQD, FF is subject to a bias which depends on the angle θ between the fracture and the sample direction

- While this angle tends to zero (sample axis parallel to the fractures), the counting tends to under-evaluate the number of fractures

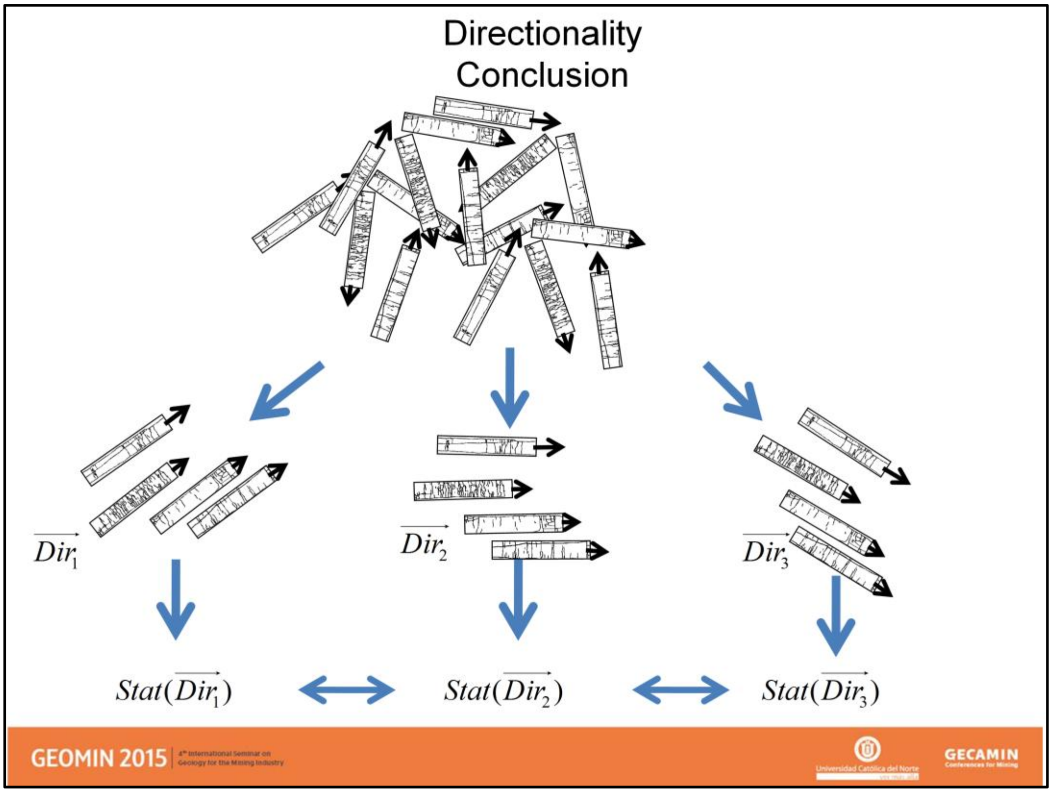
- Terzaghi (1965) proposed to correct this bias by multiplying the number of fractures by « 1/sinus thetha ». As opposed to RQD, this correction is possible because the fractures are classed.



➢ If we assume that all the samples have the same direction, and the fracture network is isotropic (left-hand figure), the directionality of RQD can be neglected, whereas if there are local anisotropies in the fracture network, the local value of RQD at location “x” will depend on their angles and will not be comparable to another value of RQD at an another location “x’” even close to “x” (right-hand figure)

➢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

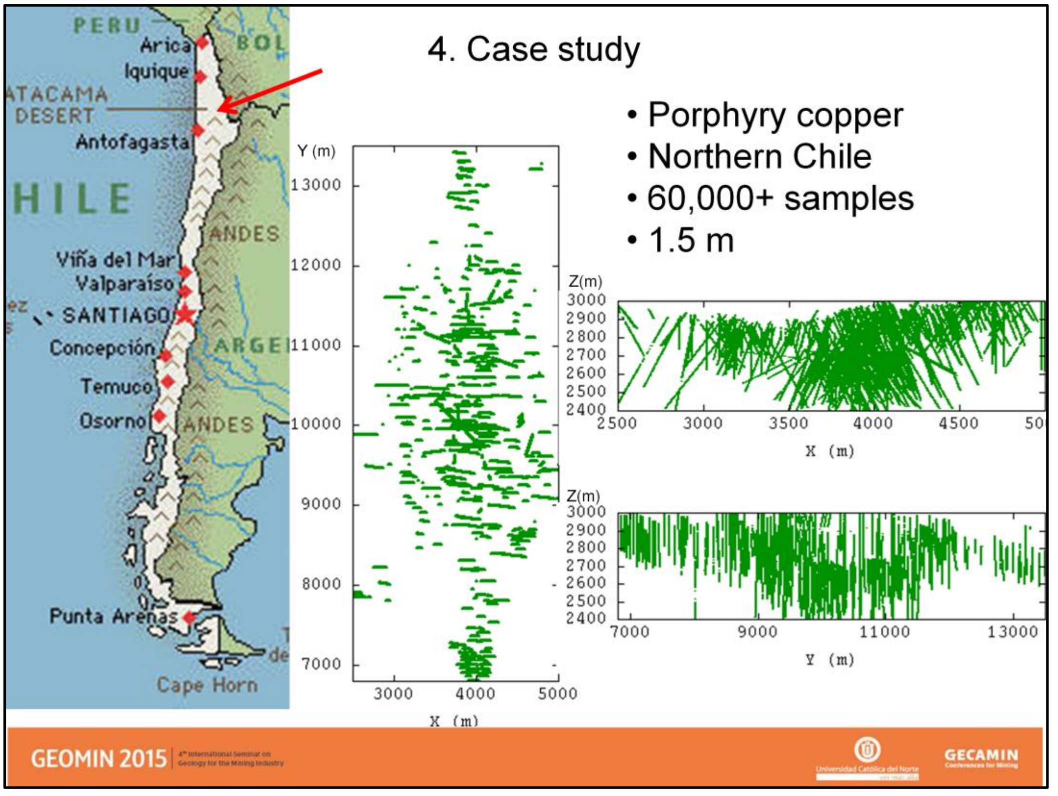
➢If the variograms by sample directions are close to each other, and close to the variogram obtained with all the samples, there is no reason to distinguish between the directions because the fracture network looks isotropic

➢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 x, 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

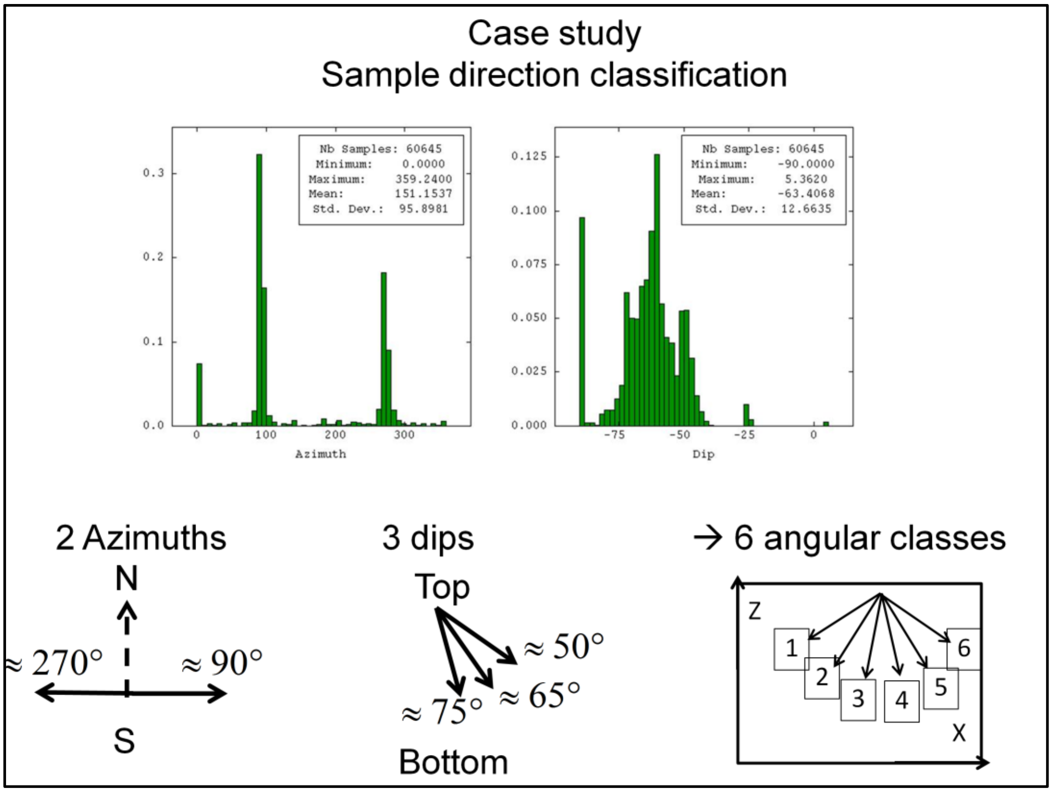


➢We are at Antofagasta and everybody knows the map of Chile but this presentation will also be done in France and Germany, the reason why this map is here

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

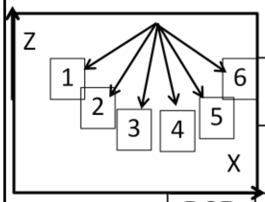
➢All the samples are 1.5 m long

➢They cover a 7 km by 3 km by 600 m domain

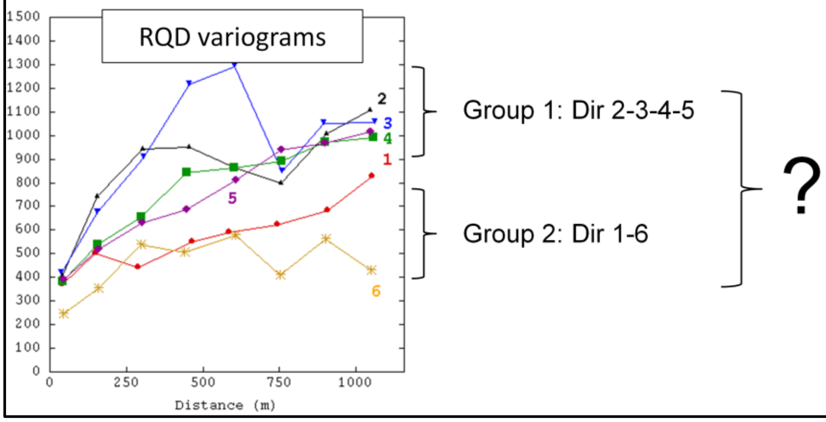


➢ All the drill holes belong to vertical West-East oriented planes and the sample directions can be summarized by six angular classes

Case study
(Geo)statistics by sample direction



	1		2		3		4		5		6	
	m	σ^2	m	σ^2	m	σ^2	m	σ^2	m	σ^2	m	σ^2
RQD	84.6	573	72.4	888	68	1024	73	774	73	793	87.4	440



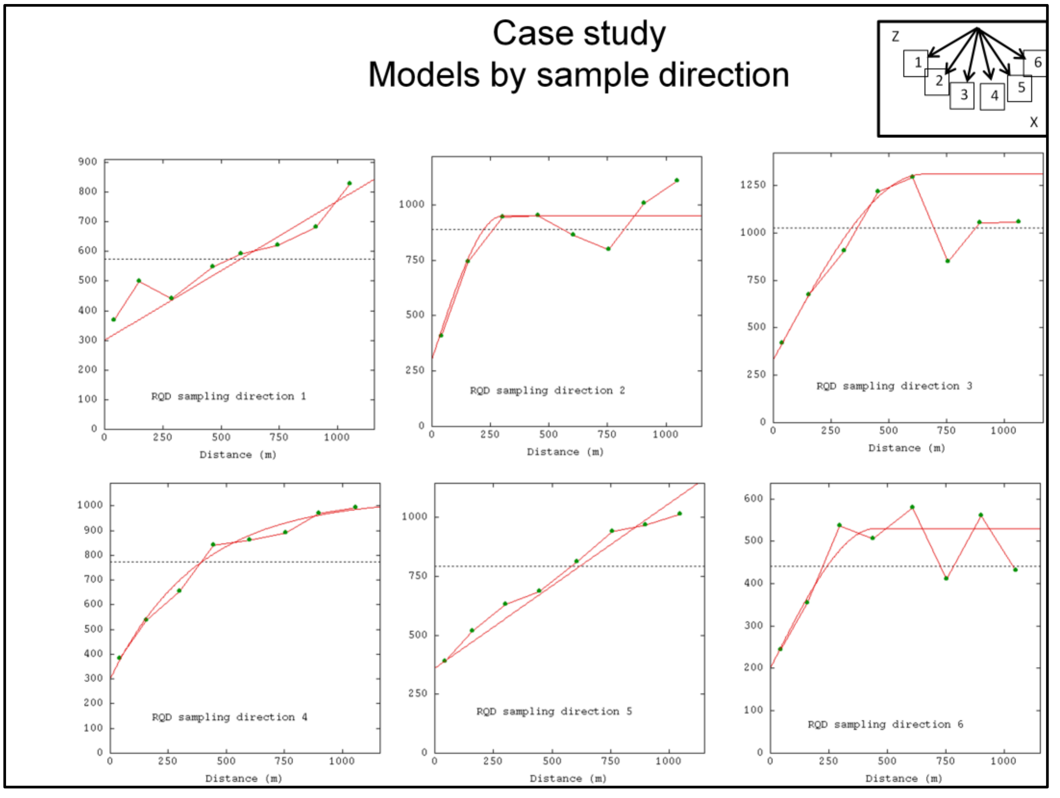
➢For each angular class a RQD variogram is calculated

➢As no geostatistical anisotropy is noticed, we use omnidirectional variograms

➢One notices two variogram groups: sampling directions 1 and 6 on the one hand, and sampling directions 2, 3, 4, 5 on the other

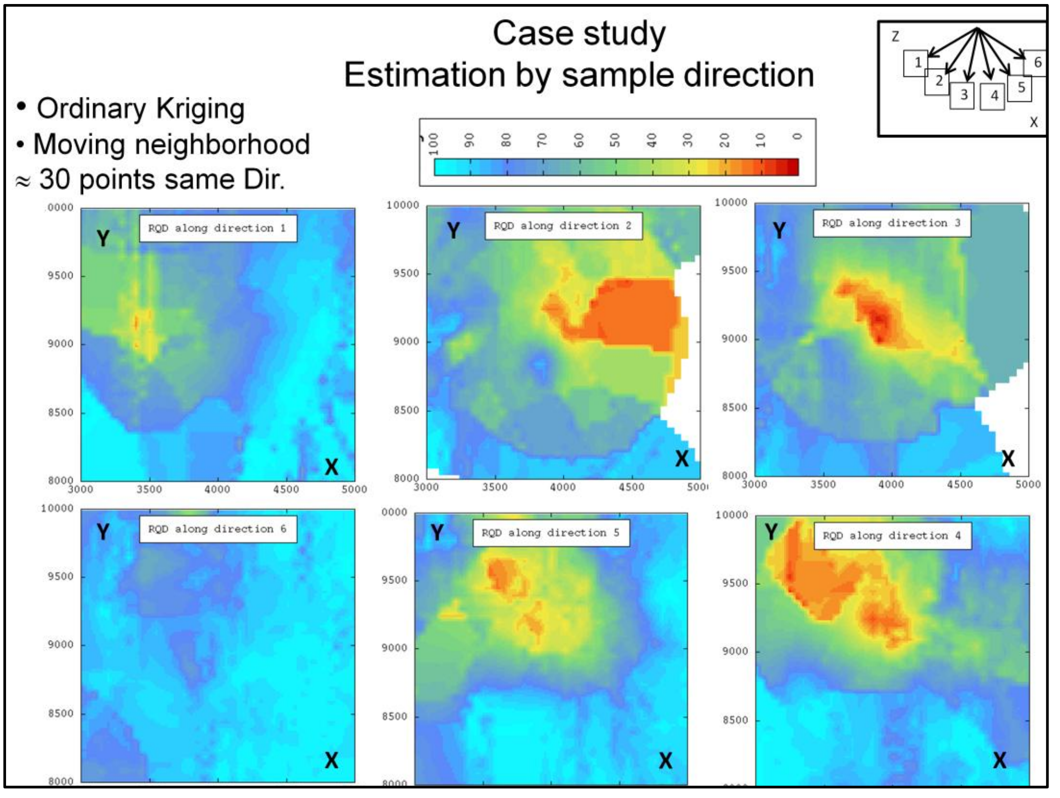
➢The variance increases with the dip

➢The first five directions share approximately the same nugget effect



- ➢We fit a model for each one of the six sampling 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



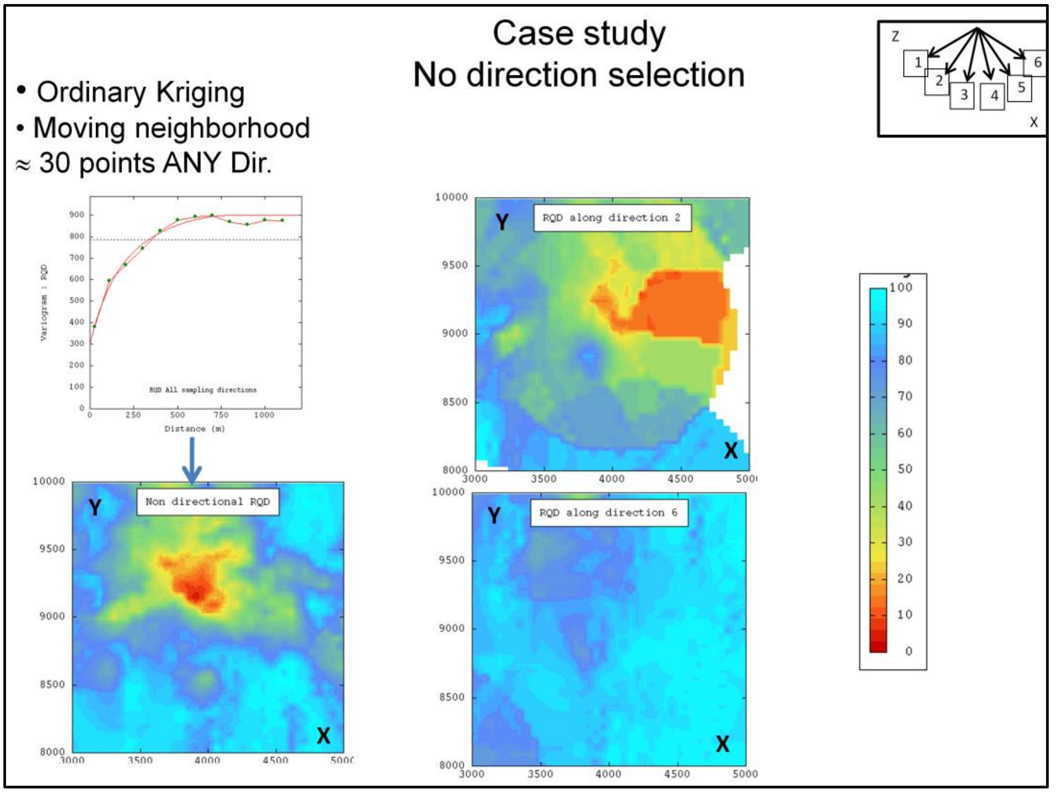
➢ Here we present a typical horizontal cross-section

➢ As for the variograms, the directional RQD maps can be regrouped into two sets: {1, 6} (i.e. close to a horizontal sampling direction) and {2, 3, 4, 5} (i.e. almost vertical)

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

➢. In this region, the contrasts are extreme: for an almost horizontal direction (and along West-East), RQD is equal to 70% on average while it becomes lower than 20% when sampling is perpendicular

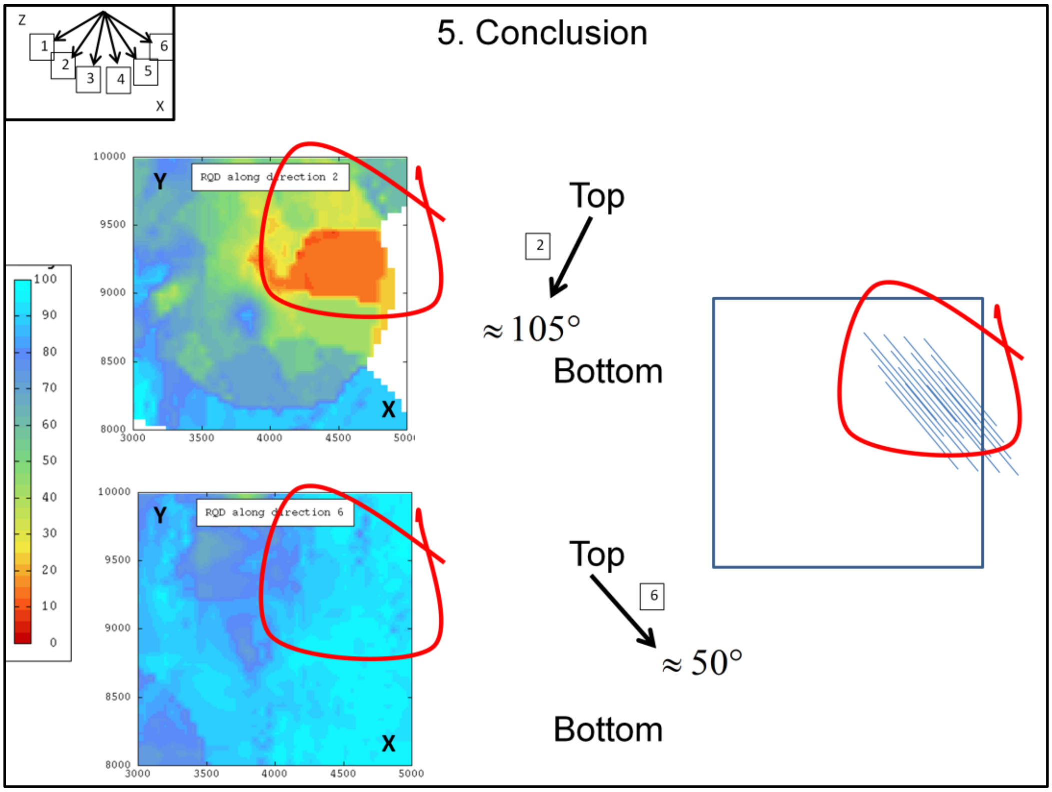
➢This domain is probably composed of a stack of horizontal planes separated by fractures



➢The left-hand 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

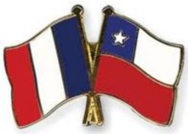
➢ The right-hand maps differ the most



- What is the truth?
- There is no truth
- RQD is directional and subjected to a bias linked to the angle between the sample and the fracture
- Previous results showed that direction 2 differs strongly from direction 6. What does that mean?
- We recall that the samples all belong to vertical East-West oriented planes . When we calculate RQD, we measure the intersection between these measurement planes and the planes defined by the fracture. For the horizontal cross-sections of the figure, RQD along direction 2 (105°) is close to 20% in the upper western part while along direction 6, RQD becomes close to 70%. One can deduce that in this part of the deposit, the intersection of the measurement planes with 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 the RQD aim is to measure the degree of jointing or fracturing in a rock mass, it is clear that it measures mainly the anisotropy of the fracture network and it seems very important to account for the sample direction to ensure that the results are useful
- The conclusion is that the directionality of RQD, as well as of FF, must be accepted and used and it means that attributes like RMR become directional too, which may disturb the practitioner's habits. But does it matter so much? After all, when drilling a tunnel, it seems natural to consider that the rock strength depends on the drilling direction.

Acknowledgment

CODELCO
Produciendo Futuro
Codelco Chili



- Codelco
- Chile
- France
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