# Geomechanical studies of an alpine rock mass

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ABSTRACT: The study refers to an area of about 70 km2, extended in the Italian Central Alps along the the San Giacomo Valley where different civil and mining works are present The regional geological setting is related to the Pennidic Nappe arrangement, characterized by the emplacement of sub-horizontal gneissic bodies resulting from the Mesoalpine isoclinalic folding of crystalline basements, emplaced throw East, and separated by matasedimentary cover units. The investigated geological rocks, belong to the "Tambò"Unit, overlapped by its meta-sedimentary cover and by the "Suretta" Unit. The tectonic contact gently dips to the E–NE. The valley, furrowed by the Liro Torrent, follows a N–S striking tectonic lineament, almost parallel to the nappe contact. A number of more then 70 sites, distributed in the studied area, were chosen and detailed structural and geomechanical field surveys were performed to characterize the rock masses, its intact rock and discontinuities. The procedure identifies the number of joint sets, their representative orientation, the set spacing, the type of movement, the amount of dilatation, the degree of alteration, the roughness coefficient, the presence and nature of infill. Rock mass quality indexes, such as the Rock Mass Rating (Bieniawski, 1989) or the Geological Strength Index (Hoek et al. 2002) have been evaluated in each surveyed site. The work is a contribute in assessing how the geometrical and geomechanical properties of the rock masses can be regarded as regionalized variables. The spatial distribution of these properties is a function of the geological and structural phenomena at which the rock masses have been subjected. The presented geostatistical analysis regards the spatial variation of the orientation of the most representative joint set.

## 1 GEOLOGICAL AND STRUCTURAL FEATURES OF THE AREA

The study refers to an area of about 70 $km^2$, extended in the Italian Central Alps along the San Giacomo Valley where different civil and mining works are present.

The Central Northern Alps are a fold and trust system. The major trust sheets were created during the Alpine compressional phase and are imbricated from South to North, forming, in the region of interest, the Pennidic Nappe arrangement (Figura 1).

The investigated geological rock masses belong to the Upper Pennine Nappe: the Tambò Unit, overlapped by the Suretta Unit, each constituted by crystalline basement and metasedimentary cover. The tectonic contact between the two nappes, on the left side of the San Giacomo Valley, gently dips to E–NE. The geological features of the studied are sketched in Fig 2.

The Tambò basement is mainly constitute by polycyclic and polymetamorphic rocks: two micas paragneiss, micaschist and metagranite with subordinated anphibolitic levels, and it is overlapped by a metasedimentary cover formed by highly laminated micaschist, phillades and mylonitic rocks. Levels of hard metavolcanic rocks are included in the cover and subordinately in the basement. It is worth to cite the appreciated metaquarziti exploited as "Quarzite verde dello Spluga". The cover unit reaches hundred meters of thickness. The lithological features of the Suretta basement are almost the same. Alpine pressure-dominated metamorphism did not reach conditions higher than blueschist facies, and the eclogite facies present in the Upper Pennine Units (Tambo and Suretta) are ascribed to the Pre-alpine metamorphic events.

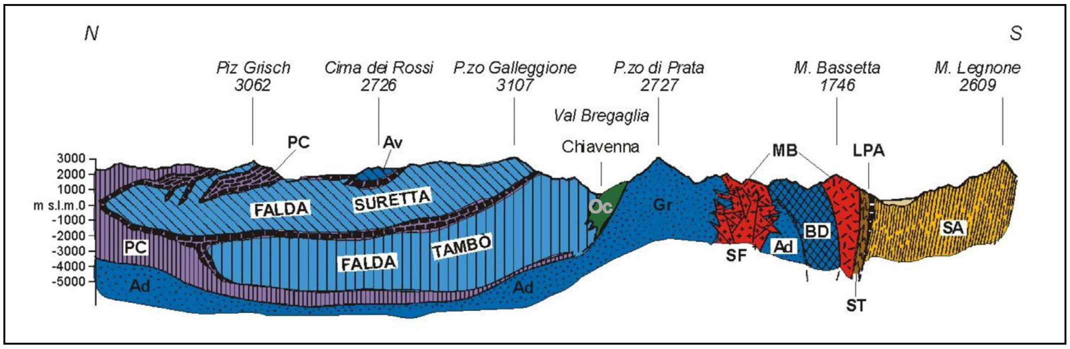



Figure 1: Schematic geological section through the Central Alps and the zone of interest.

*Av: Avers calcischist; Pc: Pennidic metasedimentary cover; Ad: Adula Nappe; Gr: Mte. Gruf Complex; Dd: Bellinzona-Dascio Zone; St: Austrid indifferenziate; Sa: Sud Alpine basement; Mb: Masino-Bregaglia Complex (Oligocenic intrusive complexes); FALDA' SURETTA: Suretta Nappe; FALDA TAMBO': Tambò Nappe; Oc: Ophiolitic complex; LPA: Periadriatic lineament. (Redrawn from Bedognè et al., 1995).*

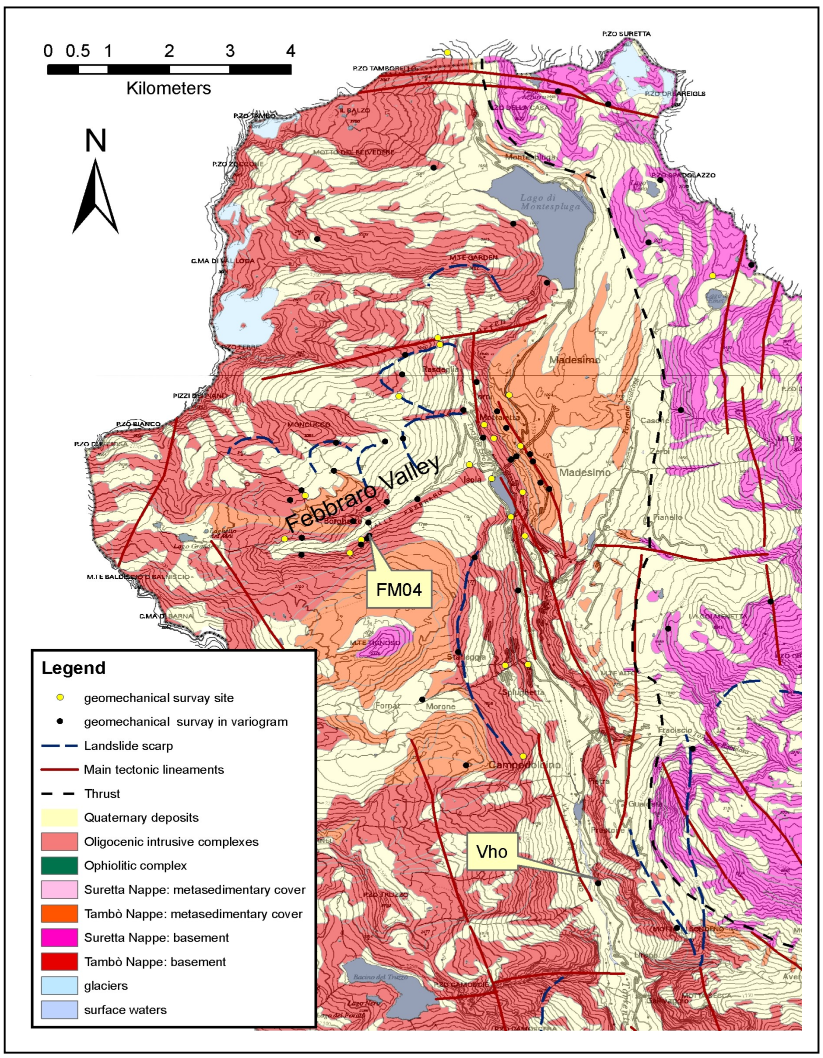



Figure 2: Geological sketch map of the San Giacomo Valley. Location of the geomechanical surveyed sites.

Four main Alpine deformation phases were recognised in the upper eastern Pennine Units (Huber and Marquer, 1988) related to: the closure of the Valais Pennine basin, the northwestward thrust structure formation during the Eocene subduction; the Oligo–Miocene collision accompanied with a syn-collisional E–W extension. This second deformation phase induced the most penetrative ductile structures and is responsible of the main regional schistosity which is, expecially along the flank of the isoclinal fold, parallel to the contact beetween the Suretta and Tambò nappes. Major ductile detachment zones cross-cut the nappe tectonic contact. Subsequent deformation structures are related to the late and Post-alpine deformation and are due to vertical extrusion of the crustal block at the north of the Insubric lineament and to the brittle–ductile E–W extension parallel to the Forcola line. The two late deformation pheses overprinted and steepened the previous structures, and produced an extensive fracturing pattern, dominated by two sets orientated NW-SE and NE-SW, mainly expressed by normal faults cross-cutting all previous structures. Figure 3a) shows the regional orientation of the structural lineaments, derived from digital elevation model (DEM) and photoaereal analysis.

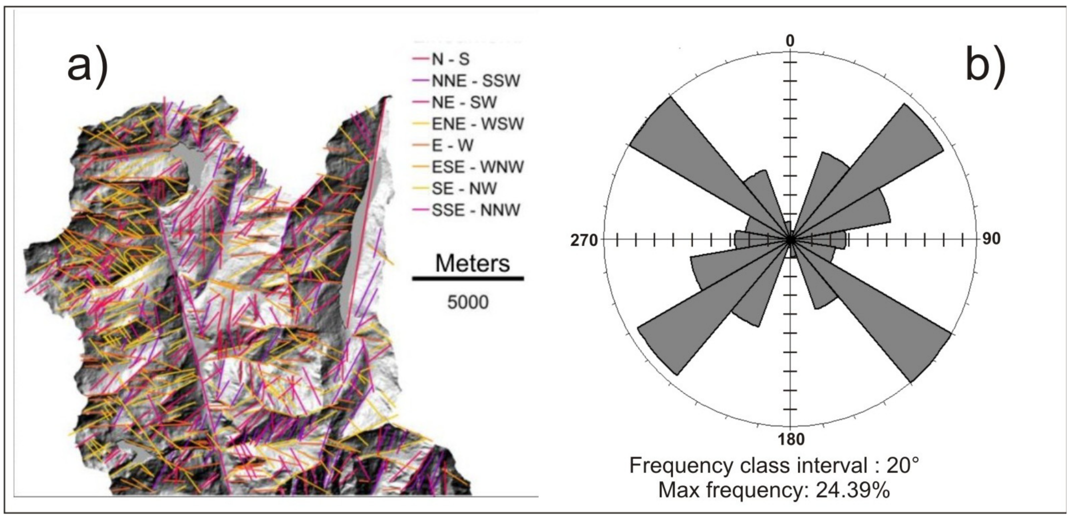



Figure 3. a) Shaded release map and tectonic lineaments observed in the regional contest of the studied area. b) Rose diagram of the tectonic lineaments revealed by photoaereal interpretation and in situ survey in the Febbraro Valley. (Source: M.Rossi, 2008)

The San Giacomo Valley, furrowed by the Liro Torrent, follows an almost N–S striking tectonic lineament, which is accompanied with minor parallel sub vertical structural elements responsible for a series of geomorphologic terraces on both sides of the valley. Deep seated flank deformations, structurally controlled, are present especially on the upper portion of the valley.
The Liro tributary valleys are mainly elongated in the NE-SW direction. The Febbraro Valley which is one of them, with a hydrographic catchment of about 15 $km^2$, presents well exposed outcrops of the Tambò nappe both basement and cover. A detailed analysis of the structural lineament orientation was carried out in this area, by photoaereal observations, DEM interpretation, and in situ surveys. The rose diagram in Figure 3b) shows the maximum frequency of lineament direction in the range between 300°-320°.

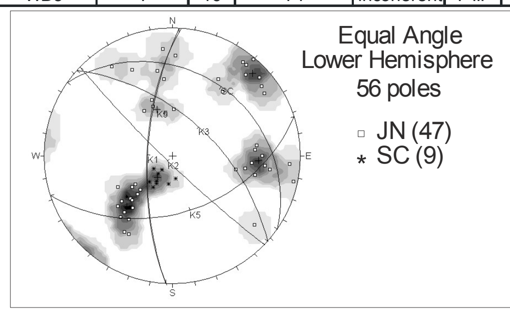
## 2 GEOMECHANICAL FEATURES OF THE ROCK MASSES

A number of 73 sites, distributed along the San Giacomo Valley, mainly located on the right side of the Liro Torrent were chosen: 52 involving the Tambò basement, 12 the Tambò meta-sedimentary cover, and 9 the Suretta basement (Figure 2).

A conspicuous number of geomechanical surveys were carried out along the Febbraro basin, and on the left side of the San Giacomo valley around the Isola village, where the metasedimentary cover of the Tambò nappe extensively outcrops.

Detailed structural and geomechanical field surveys were performed according to the ISRM suggestion methods (ISRM, 1981) to characterize the rock masses, its intact rock and discontinuities. The procedure allowed to identifiy the number of joint sets, distinguishing the one coincident with the main regional foliation, and their representative orientation, the set spacing, the type of movement, the amount of dilatation, the degree of alteration, the roughness coefficient, the presence and nature of infill. From the collected data the rock mass quality indexes, such as the Rock Mass Rating (Bieniawski, 1989), and the Geological Strength Index (Hoek et al., 2002) were evaluated in each surveyed site. As example, Figure 4 reports a synthesis of data collected and elaborated at the site FM04, located in Val Febbraro.

| Geomechanical rock mass properties | | | | | | | | | | | | | FM 04 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| set TYPE | Orientation | | Average Spacing [cm] | Persistence | Average Aperture [mm] | Weathering | Raughness | | Wall Strength JCS [MPa] | Filling | Seepage | Friction angle [°] | |
| | Dip [°] | Dip Dir. [°] | | | | | waviness | JRC | | | | | |
| K1 = SC | 23 | 35 | 7 | High | 3 | WD2 | IX | 7 | 56 | Absent | U III | 38 | |
| K2 = JN1 | 68 | 273 | 27 | Low | 30-40 | WD2 | II | 5 | 74 | Absente | U III | 35 | |
| K3 | 85 | 224 | 7 | Medium | 2 | WD2 | | 6 | 72 | Absent | U V | 37 | |
| K4 | 56 | 42 | 20 | Medium | 2 | WD2 | IV | 6 | 64 | Absent | U IV | 37 | |
| K5 | 47 | 155 | 34 | Medium | 10 | WD3 | I | 16 | 71 | incoherent | F III | 56 | |


| ROCK MASS RATING (Bieniawsky, 1989) | Parameter | | Ratings |
|---|---|---|---|
| | STRENGTH OF INTACT ROCK MATERIAL | | 7 |
| | ROCK QUALITY DESIGNATION - RQD | | 3 |
| | SPACING OF DISCONTINUITIES | | 5 |
| | CONDITIONS OF DISCONTINUITIES | persistence | 6 |
| | | aperture | 1 |
| | | roughness | 0 |
| | | infilling | 6 |
| | | weathering | 5 |
| | GROUNDWATER CONDITIONS | | 15 |
| | | RMR | 48 |

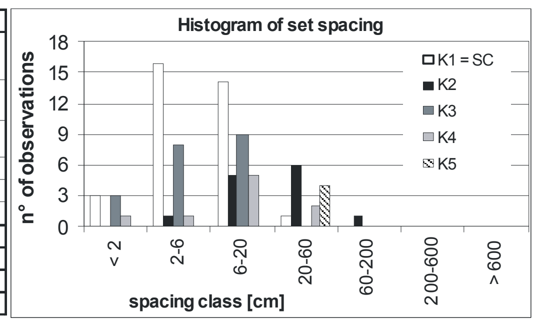



Figure 4: Synthesis of the geomechanical properties of the rock mass at site FM04 (location in Figure 2).

Some general considerations can be outlined to describe the analogies and differences in the investigated rock masses. The studied rock masses, belonging to the Tambò and Suretta basement Units, show to behave in a similar way. Joint orientations and conditions are similar, and the little variability in lithological characters do not control significantly the discrepancy in rock mass quality. The rock masses of the metasedimentary cover show a general greater state of deformation. The high lithological variability is obviously responsible for a wide variation in rock mass quality, but it is to note that the groundwater condition appears to be an important controlling factor, together with the proximity to local fault systems.

The RMR values ranges between 44 and 70; 63 % of the sites follow in the class of "fair good quality" (RMR 61-80), and 36 % in the class of "good quality"( RMR 41-60) (Bieniawski, 1989), mostly bellow 70, with the highest value equal to 77 in correspondence of a quartzite outcrop. The joint spacing and consequently the index of volumetric fracturing are the factors mainly responsible for the rock mass quality regional variation. The distance from local tectonic lineament, (faults or tectonic contacts) seems to play a significant role in joint intensity of fracturing.

For each of the 73 geomechanical surveyed sites, a mean of 50 joints, were measured and plotted on stereographic projection, obtaining the mean orientation value of each set of joints.
In consideration of the wide number of measures (about 3650 poles) only the mean orientation values of the recognized joint sets were plotted to analyse the regional variation of joint orientation (Figure 5b). 260 poles, 71 of which are relative to joint on foliation plane, are considered in the stereograph projection representative of the joint sets in the San Giacomo Valley.

The joint set SC, coincident with the more pervasive foliation, is orientated 18°/91° (dip/dip direction), and shows a wide dispersion of value along the great circle 73°/260°(dip/dip direction). The strike of this orientation is quite parallel to the nappe contact.

Then, at least further 3 sets of joints are recognised, with mean orientation as follow: JN1 77°/276°; JN2 69°/155°; JN3 71°/215°. The JN1 set is the most frequent in the area. It is present in 50 sites over 73. Its orientation is quite parallel to the valley with a sub vertical dip. It is sometimes coupled with a conjugate set. It has been noted that in much of the cases in which the JN1 set is not present, it is substituted by the conjugate set. In other cases the absence can be due to the unfavourable orientation of the outcrop, quite parallel to the set.
On the base of these considerations, it was chosen to study the regional variability of the orientation of the JN1 set by means of geostatistical analysis.

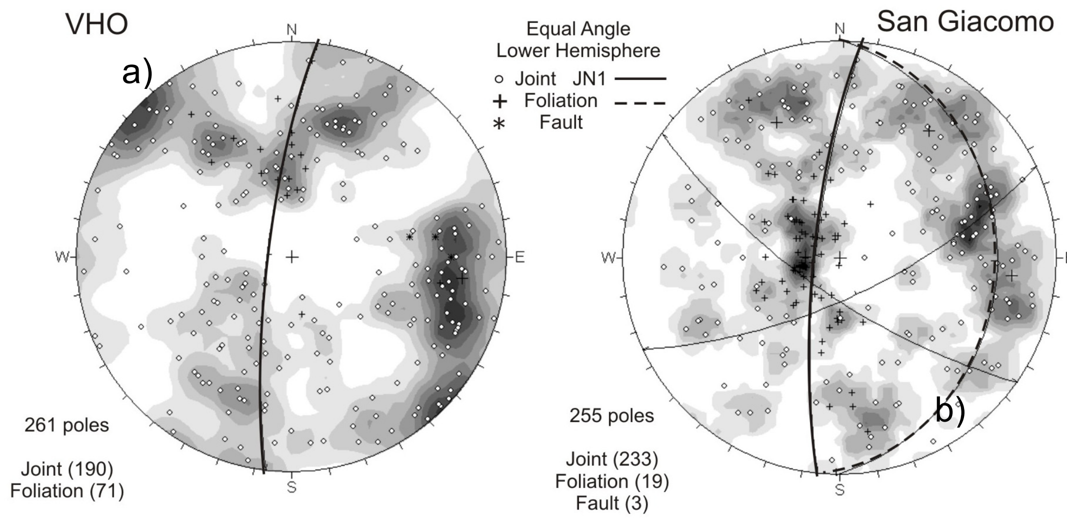



Figure 5: Stereograph projections on Schmidt's net of the joint orientation measured at the geomechanical surveyed site named Vho (a) and of the mean orientation values of each joint set for all investigated sites in the San Giacomo Valley (b).

## 3 GEOSTATISTICAL STUDIES

The distribution of rock joint parameters of a rock mass can be partly structured and partly random. Depending on the complexity of the different geological processes which leaded to the rock mass fracturation, the geometrical features of the discontinuities can be analyzed by using Geostatistical methods able to take the structural and random characteristics of the natural phenomena into account (Journel et Al. , 1978).

Geostatistics is therefore applied to the reconnaissance of the structure or pattern of the spatial distribution of a rock joint set orientation of the examined rock mass. This orientation becomes the regionalized variable of the problem, and this study has the purpose to assess the variability of this joint set orientation in the three dimensional rock mass field.

Since the orientation of a discontinuity plane is defined by the angle of dip direction and dip, in this application the discontinuity orientation is defined by unit vector perpendicular to the discontinuity plane (i.e. pole of the plane). The variation of the orientation in the examined space is therefore defined by the angular distance between the unit vectors which define the discontinuity plane in each point and its “regional mean value”.

The Geostatistical application is based on the fact that the variability of the angular distance between two unit vectors representing two discontinuity planes are auto-correlated and this auto – correlation depends on both the distance between the two planes and the discontinuity structure. The independence of two unit vectors beyond a certain distance is a particular case of this auto – correlation.

The tool applied to assess the structure of the joint orientation distribution is the variogram. The variogram function is defined as the expectation of the random variable:

$$2\gamma(x,h) = \mathrm{E}\left\{\left[\theta(x) - \theta(x+h)\right]^2\right\} \qquad [1]$$

where $\theta(x)$ and $\theta(x+h)$ are the angular distances between the unit vector in the $x$ and $x+h$ position.

This Geostatistical application is carried out by assuming the validity of the intrinsic hypothesis which states that the variogram function $2\gamma(x,h)$ depends only on the distance $h$ and not on the position of the mean value of the regionalized variable.

The variogram can be estimated by using the surveyed data: a variogram estimator is defined as the arithmetic mean of the square differences between two angular distance unit vectors at any two points separated by the distance $h$,

$$2\gamma * (h) = \frac{1}{N(h)} \sum_{i=1}^{N(h)} \left[\theta(x_i) - \theta(x_i + h)\right]^2 \qquad [2]$$

where $N(h)$ is the number of experimental pairs $[\theta(x), \theta(x+h)]$ of data separated by the distance $h$.

In a given direction the variogram may become stable beyond some distance $|h|$ called the range. Beyond this distance, the mean square deviation between two quantities $\theta(x)$ and, $\theta(x+h)$ no longer depends on the distance $|h|$ between them and the two quantities are no longer correlated. When this range is different in some direction of the space, the examined regionalized variable exhibits an anisotropic structure.

Two variograms were constructed at different scale in this study: the first variogram was drawn at the surveyed discontinuity scale of about 70 meters, the second variogram was drawn at the San Giacomo Valley scale of some kilometers.

The first variogram was constructed by using the joint orientation (77°/276°, dip/dip direction) belonging to the joint set (JN1) surveyed on the scanline placed on the outcropping rocks in the Vho station (location in Figure 3 and stereonet projection of joints in Figure 5a).

The second variogram was constructed by using the same value, which is the mean values of the joint set (JN1) orientation obtained in all the examined stations selected in the San Giacomo Valley.

The variogram analysis carried out for the two variograms (Figure 6) can allow us to assess:

- the behavior near to origin;
- the structure of the variograms;
- the range of the variograms;
- the way to model the variogram;
- the principal axes of anisotropy.

The semivariogram $\gamma(h)$ does not tend towards zero when $h$ tends towards zero. This discontinuity of the variogram at the origin is called *“nugget effect”* and can be due to the roughness and the waviness of the joints.

The variogram can be viewed as the variance of the error committed when the joint orientation in $x$ is estimated by the joint orientation in $x + h$. Near to the origin the *nugget effect error* variance is of about 50 for the scanline scale variogram and of about 10 for the valley scale variogram.

The resulting variogram behavior, before reaching the absence of auto–correlation, can be characterized by a non linear trend, which has been modeled by an exponential function: the auto correlation decreases in an exponential way while the distance $h$ increases.

The *exponential scale*, representing the vertical scale for the structured component of the variogram, are 72 and 200 respectively for the scanline and regional variogram. The variograms tend to reach a sill, which is the sum of the nugget effect plus the exponential scale, at 122 for the first semivariogram and at 210 for the valley scale variogram.

The scanline variogram was constructed on a discontinuity survey carried out along a fixed direction of 340°-160°. The structural variation of the joint set distribution shows that the direction along which the valley scale variogram exhibits greatest auto – correlation is about 315°: this direction is one of the most significant revealed by the analysis of the regional structural lineament (Figure 3a) and those most frequent in the basin of the Febbraro Valley, area of structural detailed study (Figure 3b).

The study carried out up to now shows as the auto – correlation of the regionalized variable joint orientation is different at different scale and in order to represent the complete behavior of joint orientation from the scanline scale up to the valley scale an intermediate scale should be still considerate.

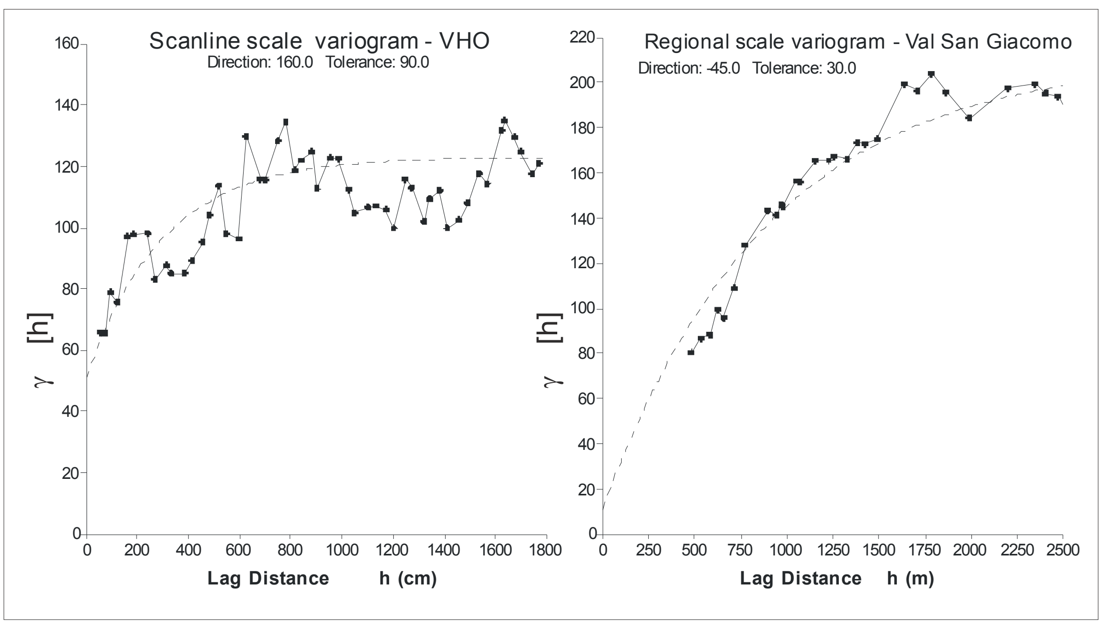



Figure 6: a) Scanline scale variogram, b) regional scale variogram.

## 4 CONCLUSION

A rock mass characterization of a Central Alps valley has been here presented. Geomechanical work was carried out by surveying rock discontinuities in 73 different sites and by classifying, according to Bieniawski RMR system, the examined rock mass. Rock mass exhibits both good qualities and similar geometrical and mechanical parameters in each surveyed sites.

For this purpose a Geostatistical application was carried out to examine the spatial variability of a geometrical parameter of one of the surveyed joint sets: the orientation. The structure of the distribution of the joint orientation parameter was investigated by means of a variogram analysis.

Some auto – correlation of the joint set orientation in space has been determine both at a small scale and at a regional scale.

The structural variation of the joint set distribution shows that the direction along which the valley scale variogram exhibits greatest auto – correlation is about 315°: this direction is one of the most significant revealed by the analysis of the regional structural lineament (Figure 3a) and those most frequent in the basin of the Febbraro Valley, area of structural detailed study (Figure 3b).

The definition of auto - correlations to evaluate the spatial variability of the mentioned geometrical properties, can represent an useful tool: first in implementing the comprehension of the geological and geomechanical features related to the rock mass history, and to support provisional evaluation where no direct investigations are available.

## 5 REFERENCES

Bedognè, F., Maurizio, R., Montrasio, A., and Sciesa, E., 1995. I minerali della provincia di Sondrio e della Bregaglia grigionese: V. Bregaglia, V. Masino, V. Codera e Valle Spluga. Sondrio: Bettini , p. 300.

Huber, R. K. and Marquer, D., 1998. The tectonometamorphic history of the peridotitic Chiavenna unit from Mesozoic to Tertiary tectonics: a restoration controlled by melt polarity indicators (Eastern Swiss Alps). Tectonophysics, Volume 296, Issues 1-2, p. 205-223.

Surfer 8, Golden Software Inc., Golden, CO, USA, 1994, user manual and online help.

Journel, A. G. and Huijbregts, C. J., 1978. Mining Geostatistics. Academic Press London 600 pp.

Rossi, M., 2008. Fenomeni di erosione di versante in ambiente alpino: sperimentazione, monitoraggio e modellazione del bacino pilota della Valchiavenna. PhD Thesis University of Milan –Dip. Earth oh Science , XXI Cicle Milan.

ISRM - International Society of Rock Mechanics, Commision on Standardization of Laboratory and field tests (1981), Rocks Characterization Testing and Monitoring. Suggested Methods. Brow E.T. (Editor). Pergamon Press.

Bieniawski, Z.T,. 1989., Engineering rock mass classifications. John and Wiley, New York, p.251

Hoek, E., Marinos, P. and Benissi, M., 1998. Applicability of the geological strength index (GSI) classification for very weak and shared rock masses. The case of the Athens Schist Formation. Bull. Eng. Geol. Env., 57, 151-160.

Hoek, E., Carranza, C., and Corkum, T. B., 2002. The Hoek-Brown Failure Criterion - 2002 Edition, 5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada , Conference: NARMS-TAC, 2002, 267-271.

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