Per. Mineral. (2004), *73*, 85-97 http://go.to/permin
SPECIAL ISSUE 3: A showcase of the Italian research in applied petrology

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY, ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment, Archaeometry* and *Cultural Heritage*

The Beola: a dimension stone from the Ossola Valley (NW Italy)

ALESSANDRO CAVALLO[1]*, BIAGIO BIGIOGGERO[2]† (deceased), ANNITA COLOMBO[2] and ANNALISA TUNESI[2]

[1] Dipartimento di Scienze della Terra, Università degli Studi di Milano, Via Botticelli, 23, 20133 Milano, Italy
[2] Dipartimento di Scienze Geologiche e Geotecnologie, Università degli Studi di Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy

ABSTRACT. — The Ossola Valley (north-western Italy) is well known in Italy both for its geological features and for the exploitation of various rock types. Among these the most valuable gneiss is the *Beola* used as building or ornamental stone since the Roman Age. The different varieties of *Beola* are exploited in four main areas according to their geological and structural setting: Vogogna (Fobello-Rimella mylonitic schists - Austroalpine), Beura-Villadossola (Monte Rosa nappe orthogneisses – Upper Penninic), Trontano-Domodossola (Orselina-Moncucco-Isorno orthogneisses – Upper Penninic) and Montecrestese-Crevoladossola (Monte Leone nappe orthogneisses – Lower Penninic). This paper deals with the historical use of the *Beola* and its quarries and presents new data on the petrographical, geochemical and mechanical features of the different varieties. The mineralogical composition of the *Beola* varieties is quite homogeneous: Qtz+Kfs+Pl+Bt+WM; the main differences are related to the rock fabric and to the presence of accessory/secondary minerals. The *«Quarzite» Verde* from Vogogna has the worst value of wear resistance (14.17 mm; Amsler), the *Beola Argentea* from Montecrestese-Crevoladossola has the best one (4.06 mm); whereas the other rock types have quite homogeneous values (5-8 mm). The flexural strength is remarkably different as function of the load applied parallel or perpendicular to the rock fabric (foliation or lineation) ranging from 19.5 to 11.3 MPa for the *Beola Grigia* and from 16.1 to 6.0 MPa for the *Beola Ghiandonata* of the Beura-Villadossola area. The water absorption value is usually low (0.27-0.44%) for all the *Beola* types. Based on the geo-mechanical features and the aesthetic parameters, the *Beola Bianca*, *Favalle* and subordinately the *Beola Grigia* are the most valuable varieties of the Ossola district.

RIASSUNTO. — La Val d'Ossola (Piemonte settentrionale) è una tra le aree più importanti in Italia non solo per l'assetto geologico, ma anche per lo sfruttamento di particolari litotipi, fra i quali la *Beola*, usata come pietra da costruzione o ornamentale fin dal tempo dei Romani, è l'esempio migliore. Con il nome *Beola* si intendono varietà provenienti da unità strutturali e litologiche diverse. Per questa ragione in questo lavoro sono state distinte quattro sub-aree di estrazione: Vogogna (scisti milonitici dell'unità Fobello-Rimella - Austroalpino), Beura-Villadossola (ortogneiss della Zona Monte Rosa – Pennidico Superiore), Trontano-Domodossola (ortogneiss della Zona Moncucco-Orselina-Isorno – Pennidico Superiore), Montecrestese-Crevoladossola (ortogneiss della Falda Monte Leone – Pennidico Inferiore). Il lavoro si propone di valutare per ogni area l'utilizzo storico delle beole, sia rurale che ornamentale e la situazione delle cave (sia attive che «storiche»).

* Corresponding author, E-mail: alessandro.cavallo@unimi.it

Vengono inoltre presentati nuovi dati sulle caratteristiche petrografiche, geochimiche e sulle proprietà fisico-meccaniche dei materiali cavati. La composizione mineralogica dei litotipi è piuttosto omogenea (Qtz+Kfs+Pl+Bt+WM), le principali differenze si riscontrano nel fabric e nei minerali accessori e/o secondari. Le prove fisico-meccaniche hanno dato i seguenti risultati: la *«Quarzite» Verde* ha il valore peggiore nelle prove di usura (14,17 mm), la *Beola Argentea* quello migliore (4,06 mm), mentre le altre tipologie presentano valori abbastanza omogenei (5-8 mm). Le prove di flessione hanno evidenziato una forte anisotropia nella *Beola Ghiandonata, Striata* e *Grigia* di Beura-Villadossola dovuta alla marcata lineazione che presentano le tre tipologie. I coefficienti di imbibizione sono piuttosto bassi ed omogenei per tutte le varietà (0,27-0,44 %). Sulla base delle caratteristiche geomeccaniche e dei parametri estetici, le varietà più pregiate risultano essere la *Beola Bianca* e la *Beola Favalle,* in misura minore la *Beola Grigia.*

KEY WORDS: *Beola, Ossola Valley, quarries, petrographical and geochemical features, mechanical properties.*

INTRODUCTION

The Verbano-Ossola district is well know in Italy and abroad for its great variety of ornamental stones represented by granites, marbles, gneisses (Bigioggero and Zezza, 1997). The quarrying activity is widespread all over the province and many small laboratories process block and slabs to prepare finished products trading all over the world. The stone industry is the main economic sector in the Ossola Valley together with tourism. Among the exploited ornamental stones, the *Beola* is one of the most famous and valuable rock types and is used as building stone since the Roman Age.

From a commercial point of view fourteen varieties of *Beola* are known. The different types are strongly foliated polymetamorphic gneisses that come from different lithological and structural units. In this paper four main quarrying sub-areas are distinguished (Fig. 1):

Vogogna area: the *Beola* quarries are located in the Fobello-Rimella mylonitic schists. The varieties extracted are: «*Quarzite» Bianca, Verde Vogogna* improperly *«Quarzite» Verde, Bianca Cremosina, Ghiandonata Vogogna, Grigia Vogogna*;

Beura-Villadossola area: the *Beola* varieties are *Bianca, Grigia Beura-Villadossola, Ghiandonata Beura-Villadossola* and *Striata* and come from the Monte Rosa Zone orthogneisses;

Trontano-Domodossola and Val Vigezzo area: in this area the quarries are located in the orthogneisses of the Moncucco-Orselina-Isorno Zone; the varieties are *Grigia Trontano-Domodossola* and *Grigia Grossolana*;

Montecrestese-Crevoladossola area: the *Beola Favalle*, *Argentea* and *Isorno* are orthogneisses of the Monte Leone nappe.

THE HISTORICAL USE OF BEOLA STONES

The *Beola* or *Bevola* is a typical gneissic dimension stone extensively quarried in the lower-medium part of the Ossola Valley (north-western Italy), between the small villages of Vogogna and Montecrestese-Crevoladossola.

The historical and commercial term *Beola* comes from the name given in the XV century to the village of Beura, as reported in a letter dated 1487 A.D.. In this letter the Duke of Milano forced the Commander of Bevola to restore the defence tower. Also an old tombstone (dated 1513 A.D.), once in the Franciscan convent in Domodossola and now in a chapel in Pallanzeno, reports the words «HVNC LAPIDEM BEVRA DEDIT» («Beura gave this tombstone»).

The quarries of *Beola* are probably the oldest of the Ossola Valley, although the precise period in which the stone started to be exported is unknown. The *Beola* trade probably started at the end of the XIII century, with the opening of the Naviglio Grande channel (a Leonardo da Vinci's project) connecting the Ticino river to the town of Milano. However, during the Roman Empire these stones were already exploited and exported, as testified by the

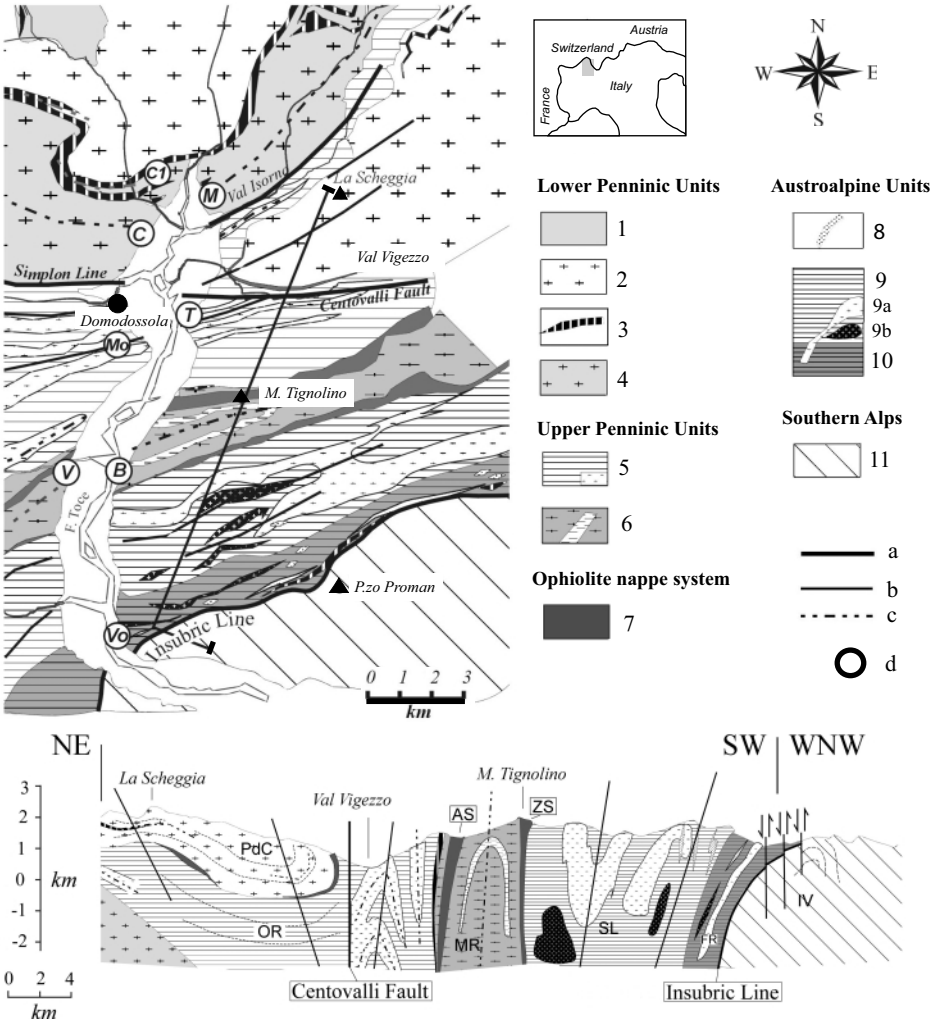

Fig. 1 – Geological sketch-map and cross-section of the middle part of Ossola Valley. 1) Baceno schists; 2) Antigorio (AN) and Pioda di Crana (PdC) orthogneisses; 3) Undifferentiated cover units, mainly calc-silicate marbles; 4) Monte Leone nappe; 5) Orselina-Moncucco-Isorno Zone (OR); 6) Monte Rosa Zone (MR); 7) Amphibolite and serpentinite from the Zermatt-Saas (ZS) and Antrona (AS) units; 8) Alpine porphyritic dykes; 9) Sesia-Lanzo Zone (SL), 9a = orthogneisses, 9b = metagabbros; 10) Fobello-Rimella Schists (FR); 11) Undifferentiated Southern Alps, Ivrea-Verbano Zone (IV).
a) Main faults; b) Axial plane trace of late-alpine folds; c) Axial plane trace of post-nappe, meso-alpine folds; d) Main quarry areas, C1 = Crevoladossola (marble), C = Crevoladossola, M = Montecrestese, T = Trontano, Mo = Moncucco (Domodossola), B = Beura, V = Villadossola, Vo = Vogogna.

ancient Roman road visible near the village of Beura (Gruppo Archeologico Mergozzo, 1978).

The massive use of the *Beola* as a dimension stone is due to its excellent technical properties, in particular its high wear resistance and its high flexural strength. Being this material easy to split in thin slabs, it was widely used in the last two centuries for local building in every village and town of the Ossola Valley (staircase steps, balconies,

skirting boards, pavements and roof covering). Domodossola is an excellent historical example: the *Beola* was the main stone used in the buildings of the old town centre since the XII century. Paving, walls, balconies, architraves and roofs are all built up with *Beola Grigia* (Rodolico, 1953).

The first example of *Beola* use is represented by the ancient Roman roads. When the Romans arrived in the Ossola Valley at the end of the first century b.C. they built a sophisticated system of roads and muletracks. The paths run on the mountains flanking the Toce plain and in the adjacent valleys. The Romans preferred half-way roads, to avoid the river beds because of the danger of frequent floods. Roman tracks in the Ossola Valley have no equals in other places because they are paved with large slabs of *Beola* stones, arranged transversally to the way. The stone slabs are located 10 centimetres higher with respect to the «dry-placed» walls below, in order to avoid damage by torrential rains. The existence of Roman roads is confirmed by a Latin epigraph engraved in a stone near the village of Vogogna, dated 196 A.D., that reports the name of two Consuls: Caio Domizio Dextro and Publio Fusco. Between the villages of Beura and Cuzzego a 500 meters long paved track excavated in the rock is still preserved, 100 m above the Toce plain.

Since the Roman period *Beola* slabs were used for roof covering, but transport problems confined their use to areas close to the quarries. Only at the end of the XVII century the *Beola* slabs were massively utilized for building houses in the Ossola Valley (Dematteis, 1985). The typical Ossola house presents a massive structure, the roof has commonly two high-sloping decks with small eaves, small windows and generally no balconies (Fig. 2a). Due to the small size of the slabs, the covering percentage of each single slab is about 70% of its planar surface. The configuration of the roof and its covering with *Beola* slabs make the rural house of the Ossola Valley extremely different from other typical alpine houses.

Besides roofs, masonry, sheds and rural houses, *Beola* stones have been used in the Ossola Valley to border private lands (with rows of slabs fixed in the ground, size about 0.5 x 1 m), as a support for grape vine (rectangular stone slabs approximately 1.5 m high) and for countryside paths. *Beola* has also been used for ornamental purposes and for the construction of churches, palaces and monuments, widely documented in many towns and villages of the Ossola Valley and in Milano. During the period of the medieval communes the buildings of Milano present the combined use of bricks, *Beola* (usually *Grigia* or *Ghiandonata*) and Serizzo (another ornamental stone from the Ossola Valley). These materials, probably recycled, can be recognized in columns, capitals and ashlars of many churches, for example San Ambrogio, San Simpliciano and San Eustorgio churches, in the Ragione Palace and in the ruined Santa Maria di Aurona church. On the contrary, during the Visconti age, the use of the *Beola* was progressively replaced by Serizzo from the Ossola Valley and Ghiandone from the Masino Valley: these were massively used to build up Porta Nuova, Porta Ticinese and Casa Borromeo. In some streets of Milano downtown, (e.g. Via Montenapoleone or Via della Spiga), *Beola* stones were used for exterior wall facing. Recently, *Beola Grigia* has been used for floors and facings of the «C. Cattaneo» University in Castellanza (VA), at the «Duca» Hotel and at the «Dal Verme» Theatre in Milano.

GEOLOGICAL SETTING

The thickest geological section (20 km) of the Alpine belt can be found in the Ossola Valley; this belt is formed by several nappe systems with subvertical attitude to the south in the lower valley and subhorizontal to the north in the Antigorio Valley, where the deepest units crop out. The basement and cover units were metamorphosed during the alpine event under prevailing amphibolite facies conditions. For detailed studies about this area, see Polino

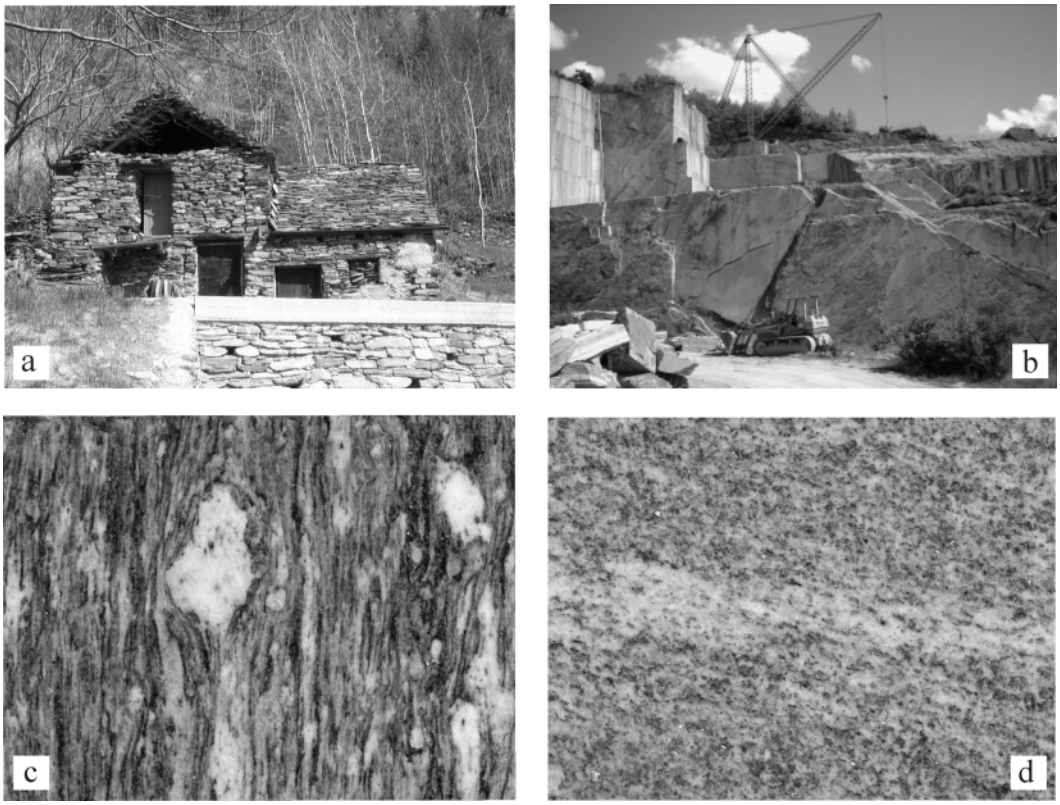

Fig. 2 – a) Rural house in the Ossola Valley near Vogogna. b) *Beola Grigia* quarry in Trontano: the «Croppo» quarry. Some commercial varieties of *Beola:* c) *Beola Ghiandonata* from Beura, d) *Beola Favalle* from Crevoladossola. Base of c) and d) photos = 11 cm.

et al. (1990), Pfiffner (1993), Steck and Hunziker (1994), Boriani (2000), Engi *et al.* (2001) and their references.

From south to north, the Ossola district shows two important structural domains separated by the Periadriatic lineament, here known as Canavese Line (Schmid *et al*., 1989): the pre-alpine crystalline basement of the Southern Alps (Africa-verging belt) and the Alpine nappe systems of the Europe-verging belt (Fig. 1).

The Southern Alps include: a) the Serie dei Laghi (upper continental crust), composed by pre-alpine metamorphic rocks under low grade amphibolite facies conditions; it is intruded by lower Permian granitoids, the so called Graniti dei Laghi (e.g., Baveno-Montorfano). b) the Ivrea-Verbano Zone (lower crust), formed by pelitic to psammitic siliciclastic metasediments with lenses of marbles and mafic/ultramafic rocks. The pre-alpine metamorphism was under high grade amphibolite to granulite facies conditions. The tectonic setting of this Zone is now sub-vertical, as a consequence of tectonic alpine events (Schmid *et al*., 1987; Schmid *et al*., 1989).

The Alpine nappe systems consist of polymetamorphic sequences of pre-alpine continental crust, intruded by several Variscan metagranitoids, which suffered the alpine events. In the medium part of the Ossola Valley the nappe systems form the *southern steep belt*; the various types of *Beola* pertain to some structural units of this belt.

In the Ossola Valley from the SE to the NW the following nappe systems are recognizable:

1) Fobello-Rimella Schists, a thick shear zone (1-2 km) in greenschist facies occurring in the internal border of the Sesia-Lanzo Zone, close to the Canavese Line (Sacchi, 1977; Schmid *et al*., 1987). The protoliths are rocks pertaining both to the Southern Alps and Austroalpine domain and also to the Canavese Zone, traditionally considered the Permo-Mesozoic cover of the Austroalpine units. The prevailing rock types (orthogneisses and paragneisses) are hardly recognizable due to the strong alpine deformation: chlorite-epidote or white mica-epidote phillonites are interlayered with laminated Qtz-feldspar gneisses, amphibole-rich schists, lenses of foliated marbles and minor graphite schists. The origin of the Fobello-Rimella Schists is not well known: according to Schmid *et al*. (1987), these mylonites are due to the back-thrusting alpine phase followed by a dextral transcurrent movement. The varieties *«Quarzite» Bianca* and *«Quarzite» Verde* from Vogogna area belong to the Fobello-Rimella Schists.

2) Sesia-Lanzo Zone (Austroalpine domain), mainly represented (in the Ossola Valley) by paragneisses with minor orthogneisses (late-Paleozoic age) and metabasites, bounded to SE by the Canavese Line; it is considered the southern steep belt of the Gran S. Bernardo system.

3) Piemontese Zone, only represented in the Ossola Valley by thin layers of amphibolites, but widespread to the west in the Aosta Valley and Wallis with the presence of the Combin Zone and the eclogitized Zermatt-Saas Zone.

4) Upper Penninic units, represented by the Monte Rosa Zone and the Camughera and Moncucco-Orselina-Isorno Zone. These two zones are separated by a continuous ophiolitic unit, the Antrona Zone. The Monte Rosa is one of the most complex alpine tectonic unit of the Upper Penninic domain, pertaining to the palaeo-Europe continental margin of the Tethys. In the Ossola area it is composed of a pre-alpine metamorphic basement with high-temperature relicts and a huge mass of Variscan meta-granitoids (Engi *et al*., 2001) characterized by K-feldspar megacrysts up to ten centimetres in size. The most evolved rock types are fine grained aplitic gneisses. The *Beola Bianca* and *Beola Ghiandonata* pertain to the Monte Rosa Zone. The Camughera unit is lithologically very similar to the Monte Rosa Zone whereas the Moncucco-Orselina-Isorno Zone consists of prevailing metasediments with minor orthogneisses, amphibolites and serpentinites (Bigioggero *et al*., 1982-83 with references) that show amphibolite facies conditions of alpine age. It is attributed to the Gran San Bernardo nappe and is located between the Monte Rosa Zone to the south and the Monte Leone/Pioda di Crana units to the north, both made up of metagranitoids. The orthogneisses of the Moncucco-Orselina-Isorno Zone are late-Variscan granites (intrusion age 271.6±4.8 Ma; Bigioggero *et al*., 1982-83) which were metamorphosed during the alpine event. The *Beola Grigia*, exploited near Trontano (Croppo village), is a typical orthogneiss of this Zone.

5) Lower Penninic units, cropping out in the upper part of the Ossola Valley to the north of Domodossola. From top to bottom, they are constituted by the Monte Leone, Lebendun and Antigorio nappes. The deepest element known in the Alpine belt is the Verampio «granite» (emplacement age 291±14 Ma; Romer *et al*., 1996). The lower Penninic nappes are now interpreted as large isoclinal folds (locally recumbent) post-dating the nappe emplacement. The Monte Leone, Antigorio and Verampio units are constituted by prevailing granitic orthogneisses (the protoliths are pre-alpine granitoids), whereas the Lebendun nappe consists of psefitic to psammitic siliciclastic metasediments of probable Permo-Carboniferous and/or Mesozoic age. In particular, the Monte Leone also includes polymetamorphic schists and the mafic-ultramafic complex of Cervandone-Geispfad; in the Ossola Valley the Monte Leone unit is represented by fine grained banded orthogneisses frequently interlayered with hornblende gneisses and amphibolites. The *Beola Favalle*, *Argentea* and *Isorno* are orthogneisses belonging to the Monte Leone unit.

Features of Beola varieties

The quarries

A detailed field work was performed in all the *Beola* quarries of the Ossola Valley, both active and historical, in order to compile a structural map and describe the slope stability, quarrying technology and exploitation potentiality for each quarry.

In the area of Vogogna (Vo in Fig. 1) 11 quarries were investigated. At present only one of these is active whereas the others ceased the activity twenty years ago. «I Piod» quarry extracts small amounts of *«Quarzite» Bianca* and *«Quarzite» Verde* commercial varieties. The most important historical quarry is located near Alpe Cremosina, where the *Beola Bianca Cremosina* (the most valuable variety of *Beola*) was extracted up to 1980. The *Beola Verde* (improperly called *«Quarzite» Verde*) was extracted in two quarries near Genestredo. All the quarries within the Fobello-Rimella Schists of the Vogogna district present strongly fractured fronts, poor slope stability and serious problems of accessibility (in the past, cableway was used). The Vogogna town council has planned to construct a new access road to the quarries, in order to revaluate the *Beola Bianca Cremosina* and *Beola Grigia Vogogna*.

In the Beura-Villadossola district (B and V in Fig. 1) 23 quarries were surveyed, 6 of which are still active. The main quarries extract the *Beola Grigia* and *Ghiandonata* (Fig. 2c) commercial varieties, while the most valuable *Beola Bianca* is now considered niche product because the production of this stone is restricted to very few outcrops. The quarry areas present fracture systems mainly oriented NW-SE. Most of the quarries present slope morphology problems and need a re-profiling of the quarry fronts in case of massive further extraction.

In the area of Trontano-Domodossola (T and Mo in Fig.1) there are 10 quarries, 4 of them active (Fig. 2b), while in Vigezzo Valley the extraction ceased many years ago. The Calvario quarry, now closed, located near Domodossola at Sacro Monte del Calvario, is one of the most ancient quarries in the Ossola Valley, as indicated by some documents that testified its activity since the XII century. The stones extracted in this area have different commercial names (*Beola Grigia Calice, Beola Grigia Servezzo, Beola Grigia Calvario*, etc…) but all of them show similar aspect and properties. This district has a quite good extraction potentiality, although there are slope stability problems and quarry fronts need to be re-profiled.

In the Montecrestese-Crevoladossola district (M and C in Fig. 1) there are 4 quarries and only one is closed. The *Beola Favalle* (Fig. 2d), the most valuable commercial variety together with *Beola Bianca*, is extracted in the Favalle quarry (Crevoladossola). As in the other areas, the most important fracture systems are oriented NW-SE and NNW-SSE. In some places, as in the area of Montecrestese, these joint systems make difficult the mining works and particularly in the Favalle quarry it will be necessary a new planning project of the quarry front.

Most of the companies use a similar quarrying technique based on explosives, or mainly explosives (gunpowder and detonating fuse) locally associated with diamond wire. Rarely the diamond wire is the principal or exclusive tool (e.g. Roldo and Favalle quarries near Montecrestese). Because of brittle tectonic setting and extractive techniques, quarries are not always straight forward and the wastage factor is commonly high. The waste material finds applications in the environmental restoration of the quarries.

Petrographic characteristics

Ten to fifteen samples were collected in each quarry in order to obtain a representative view of all the historical and commercial varieties of *Beola*. The mineralogical composition is quite uniform. All the varieties contain Qtz, Kfs (microcline), Pl, Bt and WM although in different proportion. The difference among the types is due to the different rock fabric and to the presence or absence of specific accessory or secondary minerals.

The varieties from the Fobello-Rimella Schists present fine (*«Quarzite» Bianca* and

Ghiandonata Vogogna) to very fine (*«Quarzite» Verde, Bianca Cremosina* and *Grigia Vogogna*) grain size, greenish color due to abundant Chl and Ep (except the *Beola Bianca* and the *Beola Bianca Cremosina* varieties), strong mylonitic foliation and low-temperature minerals such as Ab, Chl, Ep. The *Beola Grigia Vogogna* and in a lesser account the *Beola Ghiandonata Vogogna* preserve small garnet crystals and are characterized by relicts of isoclinal folds. Pyrite is a common accessory mineral in the *«Quarzite» Verde*.

The varieties from the Monte Rosa nappe are fine-grained and characterized by a strong mineralogical lineation mainly due to white mica and tourmaline alignments. Biotite is rare and K-feldspar is porphyroclastic, locally dissected by microfaults (*Beola Ghiandonata Beura-Villa*). In these rock types Chl and Ep are rare and localized in small fracture zones.

The orthogneisess of the Orselina-Moncucco-Isorno Zone are grey in colour, have medium to fine grain size and present biotite (several millimeters in size) and white mica in the same proportion. A mineralogical lineation is present but less pronounced than in the varieties of the Monte Rosa nappe. Polycrystalline layers of quartz and feldspars are common and are usually parallel to the main foliation. Chl and Ep are more abundant and widespread than in the rock types of the Monte Rosa Zone.

The Monte Leone types present homogeneous fine-grain size and a slight mineralogical lineation (mainly in the *Beola Isorno*). White mica is medium grained (e.g. *Beola Argentea*); Chl and chloritized biotite are widespread.

Geochemical features[1]

The orthogneisses of the Monte Rosa-Camughera Zone, the Orselina-Moncucco-Isorno Zone and the Monte Leone nappe are originated from peraluminuos granites (A/CNK ratios of 1.1 to 1.4). All the samples are subalkaline, particularly high-K calcalkaline with silica contents ranging mainly from 68% to 78%. A compositional gap is observed in the Monte Leone rocks: two different groups are present, one between 62 and 66% and the other between 70 and 78% of SiO_2. On the contrary, the orthogneisses of the Monte Rosa nappe (D'Amico and Mottana, 1974) and Orselina-Moncucco-Isorno Zone (Bigioggero *et al.*, 1982-83) have more homogeneous chemical composition and small silica variation: 70-75% and 70-73% respectively. Major and trace elements are well correlated with SiO_2 except Na_2O and K_2O that cluster around values of 3% and 5% respectively.

Spider diagram with incompatible elements (Fig. 3a) displays the typical pattern of orogenic calcalkaline rocks: enrichment in Rb and Th

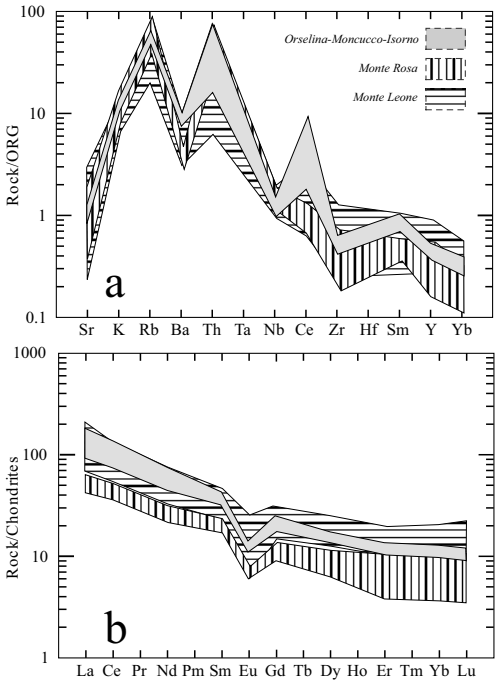

Fig. 3 – a) ORG-normalized incompatible elements (normalizing values of Pearce *et al.*, 1984) and b) REE distribution patterns (normalizing values of Nakamura *et al.*, 1974) for the Penninic orthogneisses of the Ossola Valley.

[1] This part is based on more than 150 analytical data performed by the authors on Penninic orthogneisses. A detailed work is in progress.

and negative anomaly in Nb and Ba. A smooth depletion in HFSE is also observed. Rb/Zr ratios are well correlated with SiO_2 and show the highest values in the Monte Rosa samples.

The patterns of the RE elements of the Penninic orthogneisses (Fig. 3b) show enrichment in LREE over HREE (mainly La_N/Yb_N= 4-20) and Eu/Eu*= 1.10-0.3. All samples display an incompatible behaviour for LREE with increasing silica contents. The more evolved rocks (higher Rb/Sr ratios – Monte Rosa nappe) are LREE depleted with respect to the other samples and display a shallower profile with La_N/Yb_N from 6 to 13. Within these samples strong plagioclase fractionation is indicated by the more pronounced negative Eu anomalies (Eu/Eu*= 0.3-0.4). The less fractionated rocks are the Monte Leone orthogneisses that have a smooth REE profile (La_N/Yb_N 6-10) with the highest overall REE abundance.

In the Rb vs. Nb+Y (not shown) discrimination diagram of Pearce *et al.* (1984) the Penninic othogneisses of the Ossola Valley plot across the field of VAG, Syn-COLG and WPG suggesting a complex tectonic environment (work in progress).

Physical and mechanical properties

All the *Beola* varieties from the Ossola Valley were analysed in order to determine some physical and mechanical properties (Table 1) that are compared with those of other

TABLE 1

Mineralogical composition, physical and mechanical properties of Beola *commercial varieties*

Beola variety	Exploitation area	Mineralogical composition	Water absorption (% by weight)	Wear resistance (mm)	Flexural strength (MPa)
"Quarzite" Bianca	Vogogna	Qtz+Pl+Kfs+WM±Chl±Ep	0.33	6.34	22.5
Bianca Cremosina #	Vogogna	Qtz+Kfs+Pl+WM±Ep±Chl	0.29	9.05	31.1
"Quarzite" Verde	Vogogna	Ab+Chl+Ep+WM±Qtz±Cal	0.37	14.17	27.5
Grigia #	Vogogna	Qtz+Pl+WM+Bt±Kfs±Chl±Ep	0.30	6.35	25.2
Ghiandonata #	Vogogna	Qtz+Pl+Kfs+WM±Bt±Chl±Ep	0.29	5.41	25.8
Bianca	Beura-Villadossola	Qtz+Kfs+Pl+WM±Bt±Tur	0.31	7.14	21.2*
Grigia	Beura-Villadossola	Qtz+Kfs+Pl+WM+Bt±Tur±Ap	0.31	5.81	19.5*/11.3**
Ghiandonata	Beura-Villadossola	Qtz+Kfs+Pl+WM+Bt±Tur±Ap	0.42	8.36	16.1*/6.0**
Striata	Beura-Villadossola	Qtz+Kfs+Pl+Bt±WM±Tur	0.37	7.01	17.9*/11.4**
Grigia	Trontano-Domodossola	Qtz+Kfs+Pl+WM+Bt±Ep±Chl	0.45	8.36	15.1*
Grigia Grossolana	Trontano-Domodossola	Qtz+Kfs+Pl+WM+Bt±Ep±Chl	0.30	5.38	9.7
Favalle	Montecrestese-Crevoladossola	Qtz+Kfs+Pl+Bt±WM±Chl±Ep	0.33	5.50	18.1*/16.1**
Isorno	Montecrestese-Crevoladossola	Qtz+Kfs+Pl+Bt±WM±Chl±Ep	0.43	5.36	18.2*/14.1**
Argentea	Montecrestese-Crevoladossola	Qtz+Kfs+Pl+Bt±WM±Chl±Ep	0.27	4.06	16.1*/13.8**

#: out of the market; *: load perpendicular to mineralogical lineation; **: load parallel to mineralogical lineation

ornamental stones (*Serpentino Classico Valmalenco, Quarzite di Barge, Quarzite dello Spluga, Pietra di Luserna,* Table 2) with similar uses. Because of strong anisotropy in some varieties of *Beola*, the properties were considerably influenced by the orientation of the test samples. For this reason some tests were performed both parallel and perpendicular to the main foliation or lineation of the samples. The tests performed are wear resistance (Amsler test), flexural strength and water absorption.

Wear resistance (Amsler) - Tests have been performed according to R.D. n. 2234. It is a very important test for all dimension stones used for paving. The tests showed that:

- wear resistance is influenced by fabric (rocks with more marked planar or linear anisotropy usually show the worst results) and by mineralogical composition (abundance of phyllosilicates reduces wear resistance);
- the various stones show wear values varying from 4.06 mm (*Beola Argentea*) to 14.17 mm (*«Quarzite» Verde*, the worst result); the last value blocks the use of the stone for flooring or paving;
- stones from the Monte Leone nappe present the most homogeneous wear values from 4.06 mm of *Beola Argentea* to 5.50 mm of *Beola Favalle*, similar to those of the ornamental stones reported in Table 2;
- all the other varieties of *Beola* present values between 5 and 8 mm and represent good paving materials.

Flexural strength - The flexural strength tests have been performed according to UNI 9724/5. This test is important for dimension stones used for paving, panelling and for load-bearing elements. For the varieties of Beola that show a strong mineralogical lineation, the tests have been carried out applying the load both perpendicular and parallel to the lineation, in order to quantify flexural strength anisotropy. In the other varieties the load was always perpendicular to the foliation. The tests pointed out that:

- the stones with the highest flexural strength come from the Fobello-Rimella Schists (*Beola Bianca Cremosina* and *«Quarzite» Verde*, 31.1 MPa and 27.5 MPa respectively). The high flexural strength value of the *«Quarzite» Verde* is due to its very fine and homogeneous grain size that inhibits cracks propagation. On the contrary, the phyllosilicates abundance which causes the worst wear resistance value, does not influence the flexural strength.
- the lowest values of flexural strength are registered when load is applied parallel to lineation, especially in the *Beola*

TABLE 2

Mineralogical composition, physical and mechanical properties of some northern Italy ornamental stones

Commercial variety	Mineralogical composition	Water absorption (% by weight)	Wear resistance (mm)	Flexural strength (MPa)
Pietra di Luserna[a]	Qtz+Pl+Kfs+Ms±Chl±Bt	0.31	4.44	21.7
Serpentino Classico Valmalenco[b]	Atg+Ol+Di±Chl±Mag±Ctl	0.3	4.88	63.9
Quarzite Verde Spluga[c]	Ab+Qtz+Chl+Phe±Ep	0.37	5.00	22.3
Quarzite Grigia di Barge[b]	Qtz+Phe±Ab±Kfs	0.2	5.97	40

[a] data from Manuale di Marmi, Pietre e Graniti (1996)
[b] data from Primavori (1999)
[c] data from www.graniticonrad.it

Ghiandonata from Beura-Villadossola. In this variety the resistance is reduced from 16.1 MPa (load perpendicular to lineation) to 6.0 MPa (load parallel to lineation). The major flexural strength anisotropy is observed in the *Beola* samples with the strongest mineralogical lineation (*Ghiandonata, Grigia* and *Striata* from Beura-Villadossola, *Beola Isorno*). The values of flexural strength of the *Beola* samples are partly comparable with those of *Pietra di Luserna* and *Quarzite Verde Spluga*, whereas they are much lower than those of the *Serpentino Classico Valmalenco* and the *Quarzite di Barge*.

Water absorption - Water absorption tests have been performed according to UNI 9724/2. This test is important for ornamental stones used for roof coverings, outdoor paving and staircases. The tests showed that:

- water absorption values are generally low and homogeneous, ranging from 0.45% (*Beola Grigia* from Trontano-Domodossola) up to 0.27 % (*Beola Argentea*);
- the stones with relatively high phyllosilicate contents have the highest water absorption values (e.g. *Beola Grigia* and *Beola Isorno* from Trontano-Domodossola or *Beola Ghiandonata* from Beura-Villadossola);
- rock fabric may influence water absorption: varieties with marked foliation or lineation usually exhibit higher imbibition coefficients;
- all the stones are suitable for external uses and the imbibition coefficient values are always comparable with those of other ornamental stones generally used for roof coverings or outdoor paving (*Serpentino Classico Valmalenco, Quarzite di Barge, Quarzite dello Spluga, Pietra di Luserna*).

Surface finishes and commercial value of stone materials

Generally the stone is processed in small factories, widespread in the valley, where blocks and slabs are transformed into finished products.

Because of its strong foliation and aptitude to split in thin slabs, the *Beola* was mainly worked by splitting and generally utilized for external use. Actually, in all the Ossola Valley most of the historical local buildings and rural houses utilized split slabs for roofs and external walls and nowadays the local regulation promotes the use of local stones for restoration works in respect to building traditions.

Modern processing involves many different types of works and the splitting is very subordinate. As most of the *Beola* stones are now converted into slabs for floors and coverings, the surface can be polished, honed, brushed, shock-treated (dot-like, sandblasted, bush-hammered), flamed, antiqued. Special techniques, based on water-jet or laser technologies, are also utilized. For some products more than one surface finishes could be used. For example, some companies coupled split and honed finishes to produce slabs for roof covering to conciliate a rustic roof appearance (split) with technical aspects. *Beola Bianca* and *Beola Grigia* from Trontano-Domodossola area are the most suitable varieties for special processing. *Beola Bianca* and *Beola Favalle* are ideal for internal flooring, usually with polished or flamed surfaces. Some companies combine thermal finishes with brushing, a treatment that gives a «soft» and weakly glossy appearance. *Beola* is also worked by hammering and drilling, most of all bush-hammering which is one of the most frequent historical surface treatments, suitable for external floors and coverings. Bush-hammering is used for most of the varieties of *Beola* from Beura-Villadossola area, for the *Beola Favalle* and for *Beola Isorno*. The varieties of *Beola* with abundant medium grained micas (e.g. *Beola Argentea* and *Beola Grigia Grossolana*) are not suitable for polishing, due to the low hardness of phyllosilicates and their possible erosion from the surface during processing.

Considering the good technical properties and the aesthetic features, the *Beola* is used as ornamental stones for floor and cladding in

- **Buildings:** internal and external covering and flooring, slabs for roofs, staircases, window cills, window rims, portals, balconies, shelves, columns and skirting boards, girders, architectural elements;
- **Urban décor:** recreation areas, kerbs, sidewalks, benches, fountains and planters;
- **Furnitures:** fireplaces, table tops, kitchen and bathroom tops;
- **Holy arts:** monuments, mortuary chapels and tombstones.

Some varieties of *Beola* as *Beola Bianca* from Beura-Villadossola and *Beola Favalle* are very appreciated stones due to their fine grain size and homogeneous white colour, together with the mechanical parameters. As a consequence, these two types have generally higher economic values than all the other *Beola* varieties. The *Beola* is trade with similar or lower prices with respect to *Pietra di Luserna, Serpentino Classico Valmalenco, Quarzite Verde dello Spluga, Quarzite Grigia di Barge.*

The extraction of many types of *Beola* and the various finishing processes suggest the possibility of larger trade and diffusion on the market with respect to the current state. Some varieties from Vogogna, particularly the *Beola Bianca Cremosina*, could have a wider market in case of re-opening of the quarries.

ACKNOWLEDGMENTS

This study was part of the first author's diploma thesis. Field work was partly supported by a special grant of the Rector of the Università degli Studi di Milano-Bicocca. We are grateful to L. Cortesogno and F. Carò for their valuable suggestions in improving the manuscript. This paper is dedicated to the memory of our co-author Biagio Bigioggero, in gratitude for fruitful cooperation over the past twenty years. With his premature death our research group has lost its principal leader and a remarkable friend and teacher.

REFERENCES

BIGIOGGERO B. and ZEZZA U. (1997) — *Il distretto estrattivo del Verbano-Ossola*. In PAGLIONICO A. (Ed.) - I materiali lapidei, con particolare riferimento alle pietre ornamentali. 1ª Scuola di Petrografia, Dip. Geomineralogico – Università di. Bari, Trani, 41-55.

BIGIOGGERO B., BORIANI A., COLOMBO A., TUNESI A., FERRARA G. and TONARINI S. (1982-83) — *Età e caratteri petrochimici degli ortogneiss della Zona Moncucco-Orselina nell'area ossolana*. Rend. Soc. It. Min. Petr., **38**, 207-218.

BORIANI A. (2000) — *The geo-petrological setting of the Verbano-Ossola domain in the frame of the Alps*. Quarry-Laboratory-Monument, Pavia 2000, Proceeding, **1**, 1-14.

D'AMICO C. and MOTTANA A. (1974) — *Hercynian plutonism in the Alps. A report 1973-74.* Mem. Soc. Geol. It., suppl. 1, **13**, 49-118.

DEMATTEIS L. (1985) — *Case contadine nelle valli dell'Ossola, Cusio e Verbano.* Quaderni di cultura alpina, **12**, 127 pp., Priuli & Verlucca Editrice, Ivrea.

ENGI M., GIERÉ R. and NIEVERGELT P. eds (2001) — *Contribution to the Geology of the Monte Rosa Nappe*. Schweiz. Min. Petr. Mitt., **81**, 269-393.

GRUPPO ARCHEOLOGICO MERGOZZO AA. VV. (1978) — *Ossola di pietra nei secoli.* Tipografia Cerutti, Intra, 183 pp.

MANUALE DI MARMI, PIETRE E GRANITI (1996) — CD-rom, Exnovo Edizioni srl

NAKAMURA N. (1974) — *Determination of REE, Ba, Mg, Na, K in carbonaceous and ordinary chondrites.* Geochim. Cosmochim. Acta, **35**, 953-968.

PEARCE J.A., HARRIS N.B.W. and TINDLE A.G. (1984) — *Trace element discrimination diagrams for tectonic interpretation of granitic rocks*. J. Petrol., **25**, 956-983.

PFIFFNER O.A. (1993) — *Palinspastic Reconstruction of the Pre-Triassic Basement Units in the Alps: The Central Alps*. In: VON RAUMER, J.F. and NEUBAUER, F. (Eds.): Pre-Mesozoic Geology in the Alps. Springer-Verlag, Berlin, 29-39.

PRIMAVORI P. (1999) — *Pianeta Pietra. G. Zusi Editore, Verona*, 326 pp.

POLINO R., DAL PIAZ G.V. and GOSSO G. (1990) — *Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny in the Alps.* Mem. Soc. Geol. France, **156**, 345-367.

RODOLICO F. (1953) — *Le pietre delle città d'Italia*, Le Monnier Editrice, Firenze.

ROMER R. L., SCHÄRER U. and STECK A. (1996) — *Alpine and pre-Alpine magmatism in the root-zone of the western Central Alps*. Contrib. Mineral. Petrol., **123**, 138-158.

SACCHI R. (1977) — *Gli Scisti di Fobello e Rimella, una reinterpretazione.* Mem. Sci. Geol. It., **32**, 3-20.

SCHMID S.M., AEBLI H.R., HELLER F. and ZINGG A. (1989) — *The role of the Periadriatic Line in the tectonic evolution of the Alps*. In: COWARD, M.P., DIETRICH, D. and PARK, R.G. (Eds.) – Alpine tectonics, Geol. Soc. Spec. Publ., **45**, 153-171.

SCHMID S.M., ZINGG A. and HANDY M. (1987) — *The kinematics of movements along the Insubric Line and the emplacement of the Ivrea Zone*. Tectonophysics, **135**, 47-66.

STECK A. and HUNZIKER J (1994) — *The Tertiary structural and thermal evolution of the Central Alps – compressional and extensional structures in an orogenic belt*. Tectonophysics, **238**, 229-254.

REGIO DECRETO (1939) — *R.D. N° 2234/5-39 – Prove di usura per attrito radente al tribometro Amsler*

UNI (1990) — *Normativa UNI N° 9724/2-90 - Materiali lapidei - Determinazione della massa volumica apparente e del coefficiente d'imbibizione*

UNI (1990) — *Normativa UNI N° 9724/5-90 - Materiali lapidei - Determinazione della resistenza a flessione*