

The Monviso Massif and the Cottian Alps as Symbols of the Alpine Chain and Geological Heritage in Piemonte, Italy

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Abstract In order to promote geosite conservation in the project entitled ‘PROactive management of GEOlogical heritage in the PIEMONTE Region’, we propose a comprehensive study involving the Monviso Massif (MM) geothematic area, one of the most outstanding symbols of the Alps and particularly of the Cottian Alps. Specifically, at the MM, the inventory of a number of different geosites whose conservation and development require different geologic and some additional non-geological expertise is considered: (1) some of the best preserved ophiolites in the Alps and the associated Cu–Fe mineralizations; (2) the lithostructural units in the Germanasca Valley; (3) the first primary source of jade in the Alps at the MM and its importance in terms of Neolithic to Bronze Age-polished stone implements; (4) the world-famous minerals such as coesite and giant pyrope, as well as type localities for new minerals (including carlosturanite); (5) the area, now buried under a debris flow, where Hannibal is

thought to have regrouped his army while crossing the Alps; and (6) the biodiversity of lichens, microfungi and cyanobacteria colonizing the ophiolites, which can give additional value for the environmental assessment and evaluation of the MM outcrops. Following geodiversity identification, further stages will be devoted to develop appropriate plans for geodiversity conservation in this area.

Keywords Monviso Massif · Cottian Alps · Piemonte · Geological heritage · Geotourism

Introduction

The ProGEO association was established in 1993 and devoted to diffusion activities on earth sciences and to the establishment of an international network for geosite inventory and conservation. A number of authors developed different methodologies and techniques for identifying, characterizing and managing geodiversity at the national, international and global scale (e.g. Brilha et al. 2005; Wimbledon 1996). It is of general agreement that the first and essential starting point for the geoconservation of geological heritage and geosites has to be an inventory of suitable resources and their detailed characterization and evaluation. Inventory and evaluation procedures play a decisive role on the implementation of subsequent conservation, valuing and monitoring of the geological heritage and may correspond to a sort of ‘basic geoconservation’ (Henriques et al. 2011).

In 2011, following the methodological approach of the ProGEO association (<http://www.progeo.se>), a multidisciplinary research group assembling various expertise in earth sciences, biology, economics, informatics, social sciences and engineering was created, involving 58 participants from 8

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academic research institutions of the University of Torino, Italy. This group focused its activities on the research project ‘PROactive management of GEOlogical heritage in the PIEMONTE Region’, aiming to achieve a new conceptual and operational protocol in the management of geoheritage in Piemonte, NW Italy (Fig. 1). The research group also aimed to develop new techniques for recognizing and managing the rich geodiversity of the Piemonte region at different scales by following the ‘protocol on geoconservation principles, sustainable site use, management, fieldwork, fossil and mineral collecting’ proposed by the ProGEO association (ProGEO 2011).

Within the project, nine strategic geothematic areas have been chosen to represent the geodiversity of the Piemonte region, each one being characterized by high potential for scientific studies, enhancement of public understanding of science, recreation activities and economic support to local communities (Giardino et al. 2012).

In the framework of the ‘PROactive management of GEOlogical heritage in the PIEMONTE Region’ project, the Monviso Massif (MM) geothematic area (Rolfo et al. 2012) may well be considered as one of the most outstanding symbols of the Alps, particularly of the Cottian Alps (Fig. 1). The MM peculiar skyline above the Piemonte basin already impressed the ancient Romans more than 20 centuries ago. Moreover, the Monviso base at Pian del Re gives birth to the

Po river, the historically most important source of life and welfare in northern Italy. From a geological point of view, the MM is an extraordinary well-preserved composite ophiolite nappe, which represents the remnants of a former ocean that disappeared during the orogenic processes due to the collision of Africa and Europe, which led to the building of the Alps (e.g. Lombardo et al. 1978; Philippot 1988; Rolfo et al. 2011).

The Monviso ophiolite nappe will be a great starting point for a comprehensive inventory of the most promising geosites involving the MM area itself together with nearby, geologically related areas. More specifically, a number of different geological topics involving different expertise and some additional non-geological disciplines are considered.

A Whole Ocean in a Small Pebble: the Monviso Meta-Ophiolite Complex

Ophiolites are portions of both the oceanic crust and underlying upper mantle, uplifted and emplaced onto continental crustal rocks in collisional orogens. Their etymology is quite straightforward: ‘ophio-’ is Greek for ‘snake’ (ὄφις), while ‘-lite’ means ‘stone’ from the Greek lithos (λίθος), after the typical variably green colour of lithologies that make up many ophiolites. Brongniart (1813) first used the term ophiolite for an assemblage of green rocks (serpentinite, diabase) in the Alps. About a century later, Steinmann (1927) introduced his famous ‘Steinmann trinity’ and included from the bottom upwards peridotite and serpentinite, gabbro and dolerite, basaltic pillow lava and chert, still based on occurrences in the Alps. The term ophiolite was little used outside the Alps until the early 1960s, when this assemblage of lithologies was recognized as an analogue for modern oceanic crust (Vine and Matthews 1963). Moreover, the interpretations of a sheeted dike complex within the Troodos ophiolite (Cyprus) as formed by continuous extension of crust and intrusion of magma which could only form by a process similar to the seafloor spreading (Gass 1968), added a new important member to the ophiolitic sequence. Thus, it became widely accepted that ophiolites represent oceanic crust that had been emplaced onto land (Coleman 1977).

The great geotectonic significance of ophiolites relates to their occurrence within mountain belts such as the Alps or the Himalayas, where they document the existence of former ocean basins that have now been consumed by subduction and included in the collisional belt. This insight was one of the pillars of plate tectonics, and ophiolites have always played a central role in plate tectonic theory and the interpretation of ancient mountain belts. Because of their profound involvement in collision tectonics, ophiolites are commonly metamorphosed, and the study of their metamorphic evolution gives important constraints to the evolution of mountain chains where they are emplaced.

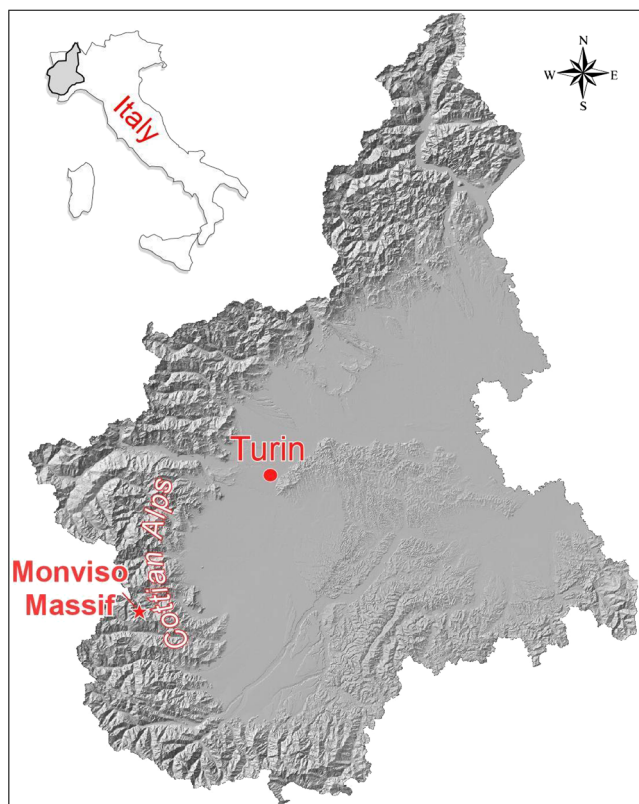


Fig. 1 Geographic location of the studied areas

Among ophiolite bodies in the Alps, the Monviso Massif (MM) is one of the most representatives. The MM forms a prominent rocky pyramid, up to 3,841 m above sea level (Fig. 2) and is a N–S trending body, 35 km long and up to 8 km wide, tectonically emplaced between the underlying continental-derived Dora-Maira thrust units and the ocean-derived Piemonte Zone metasedimentary units. The MM is one of the best preserved relics of oceanic crust in the Western Alps that formed during the Mesozoic opening of the Western Alpine Tethys and that underwent high-pressure (eclogitic) metamorphism during Alpine subduction (e.g. Lombardo et al. 1978; MONVISO 1980; Philippot 1988). The MM encompasses the whole lithological spectrum of the Piemonte-Ligurian ophiolites: metamorphic rocks after former peridotite, gabbro, dolerite, basalt, as well as cover sediments, will thus be found (Fig. 3a, b). Interestingly, the metagabbros derive from two types of protolith (Mg–Al-rich gabbro and Fe–Ti-rich gabbro) probably produced by fractional crystallization from tholeiitic melts at different fractionation stages (MONVISO 1980).

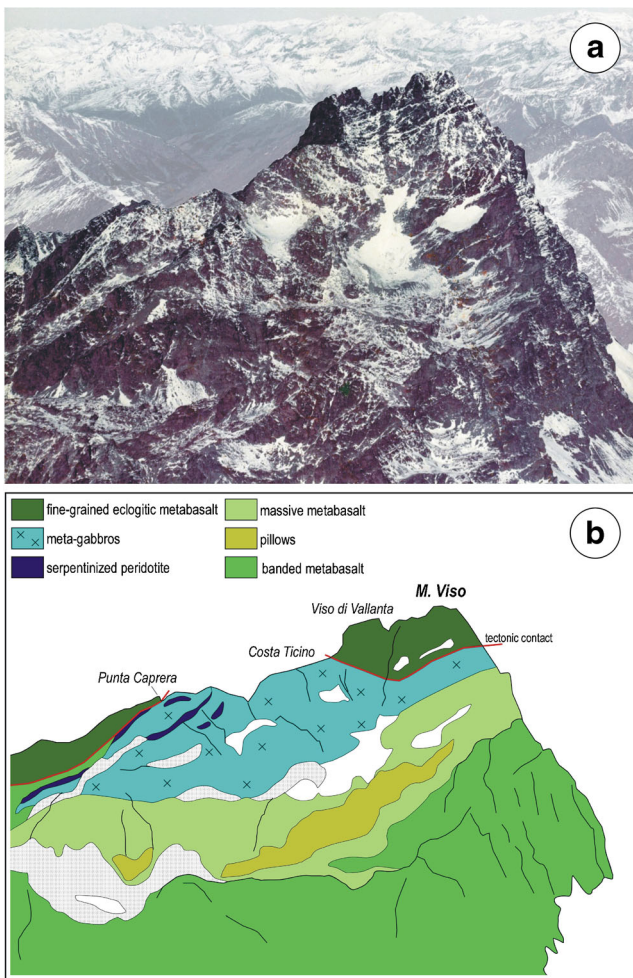


Fig. 2 a Aerial view of the SE face of Monviso. b Geological interpretation

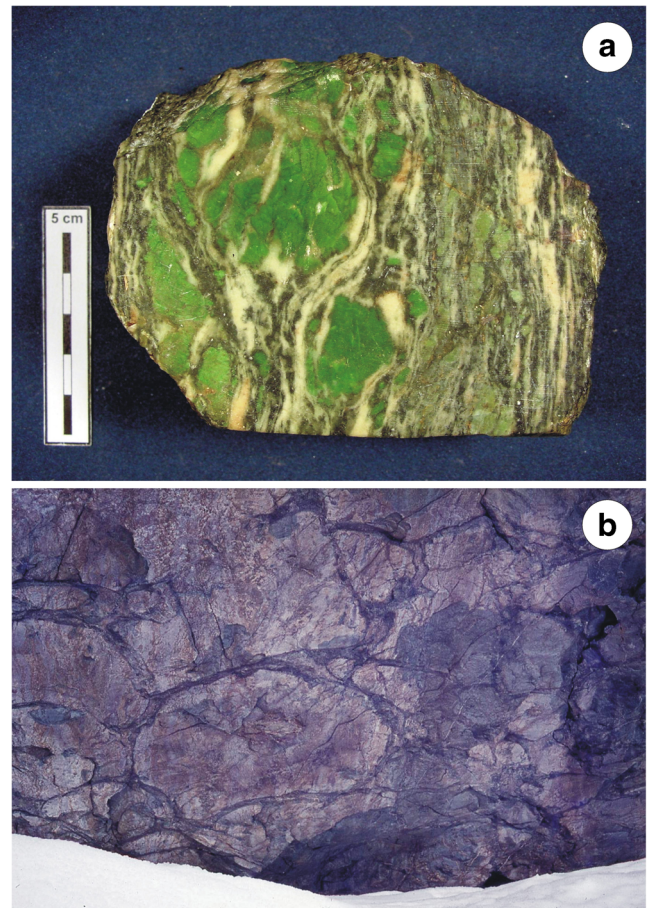


Fig. 3 a Smaragdite metagabbro from the MM; emerald green phenocrysts of ‘smaragdite’ (the local name for Cr-omphacite) are very well preserved. b Basaltic pillow lava of the MM; in spite of pervasive high pressure, eclogite-facies metamorphism, the original magmatic texture is extremely well preserved. Vallone dei Duc site, at the foot of Cima delle Lobbie. The picture is 2-m wide

As a whole, the MM comprises two major tectonometamorphic units, trending north–south and dipping to the west, separated by a major shear zone: the ‘Monviso upper unit’ to the west (overturned according to its original geometry) and the ‘Lago Superiore lower unit’ to the east (Angiboust et al. 2012).

Recent advances in petrology, geochemistry and geochronology all suggest a short duration of igneous activity in the MM and a short time span (from ca. 170 to ca. 150 Ma) for the entire Piemonte-Ligurian Tethys, portraying a scenario with an embryonic ocean (max 380 km wide; Piccardo et al. 2001) rather than a mature, slow spreading, Atlantic-type ocean model (Lagabrielle and Cannat 1990). The oceanic crust preserved in the Monviso meta-ophiolite complex experienced first an oceanic hydrothermal alteration (Nadeau et al. 1993) and then, during the Alpine subduction, a high-pressure eclogite-facies metamorphism (e.g. Lombardo et al. 1978). Later exhumation produced re-equilibration under progressively lower pressure conditions at blueschist and greenschist facies.

The MM gives the almost unique opportunity for a general public to see and appreciate different portions of the ancient ocean along a mountain trail. From the Po river springs at Pian del Re to Lago (lake) Fiorenza, Lago Lausetto and Lago Superiore, a path rises from 2,000 m up to about 2,350 m a.s.l. and shows all different lithologies described above within a few kilometres.

Starting from a small hut along a road accessible by vehicle (km 7.5) from Pian Melzè to Pian del Re (Fig. 4, stop 1), a general view of the MM internal structure is evident by looking southward to the ridge from Monte Grané (2,314 m) to Viso Mozzo (3,019 m) and Monviso (3,841 m). Along this section are exposed, from left to right and from bottom to top: the serpentinite at Monte Grané and in the lower ridge above Pian Melzè; the metagabbro at the foot of Viso Mozzo and the low ridge above Pian del Re; and the Viso Mozzo metabasite and the Colle di Viso serpentinite, which crops out in the low ridge between Viso Mozzo and Monviso. This latter serpentinite sliver separates the two main tectonometamorphic units composing the MM.

Once left the car park, along the path from Pian del Re to Lago Fiorenza, the first outcrop of serpentinite can be reached within a few minutes' walk (Fig. 4, stop 2). The serpentinite, deriving from primary spinel lherzolite, is either massive or sheared. It mainly consists of antigorite, with variable amounts of clinopyroxene, brucite, Mg-rich chlorite, Ti-clinohumite, metamorphic olivine and chrysotile; the ore minerals are magnetite, Fe–Ni alloys and sulphides. Different generations of metamorphic veins crosscut the serpentinite.

About 500 m SSE of Lago Fiorenza, the path crosses a folded elongated body of metasediments tectonically embedded within serpentinite (Fig. 4, stop 3). This sliver, about 50-m

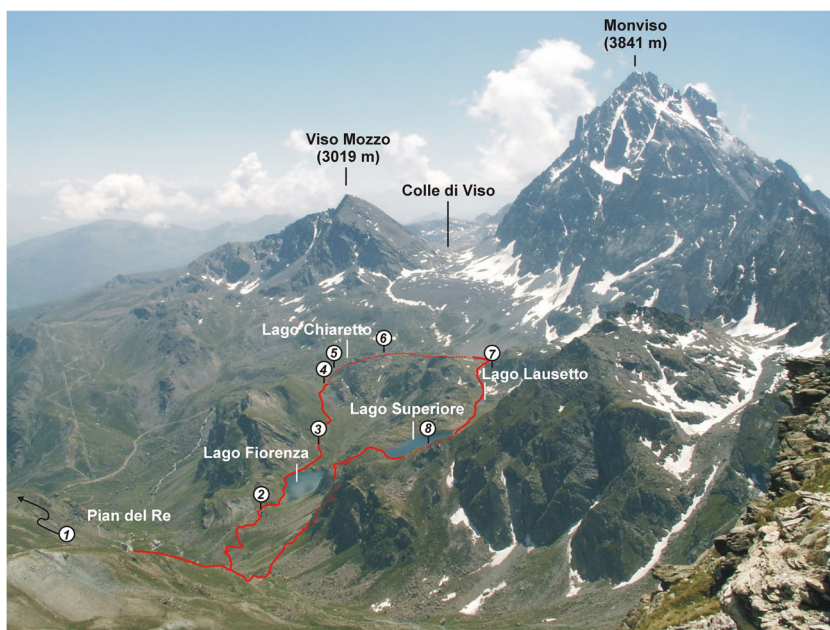
thick, belongs to an eclogite-facies shear zone which passes through Colletto Fiorenza. The metasediments consist of impure marbles, calcschists and micaschists ('calcescisti' in Italian) grading to quartzite. Rare centimetre-thick layers of metabasite are interbedded with metasediments.

At Colletto Fiorenza, a tectonic contact between calcschists and the overlying metagabbro is marked by a zone from a few metres to a few tens of metres thick of strongly sheared serpentinite and talc-carbonate-amphibole-schist, with tectonic inclusions of banded eclogitic rocks (Fig. 4, stop 4).

Between Colletto Fiorenza and Lago Chiaretto, beautiful smaragdite metagabbro locally includes transposed centimetre- to decimetre-thick dykes of metabasalts (Fig. 4, stop 5). The metagabbro shows a well-developed foliation and consists of a whitish matrix, in which emerald green phenoclasts of 'smaragdite' (the local name for Cr-omphacite) are preserved (Fig. 3a). Locally, a layering in the smaragdite metagabbro suggests a cumulus structure. The greenish grey to pinkish metabasaltic dykes, now eclogite, are very fine grained and locally preserved remnants of a porphyritic structure. Few boulders preserve igneous-layering textures, with emerald green bands (enriched in Cr-omphacite) corresponding to layers with high-modal clinopyroxene.

West of the smaragdite metagabbro, along the path leading to Lago Lausetto and Rifugio Giacoletti, layered eclogitic rocks polished by the glacier are exposed (Fig. 4, stop 6). They consist of alternating layers of eclogite and metagabbro from a few centimetres to several decimetres thick. Eclogite largely prevails over metagabbro. The melanocratic layers (now eclogite) derive from primary Fe–Ti oxide gabbro, whereas leucocratic layers derive from Mg–Al gabbro

Fig. 4 Panoramic view of the MM from Mount Meidassa, with location of the outcrops described in the text. Modified after Castelli et al. (2014)



protoliths. The eclogitic foliation is cut by different generations of metamorphic veins.

South of Lago Lausetto, along the path leading to Rifugio Giacoletti (Fig. 4, stop 7), a narrow alluvial plane hides a shear zone separating Fe–Ti metagabbro mylonites (to the E) from foliated prasinite (to the W). No primary features, such as pillow structure or porphyritic texture, are preserved within the prasinite (nice pillows can be observed not far from here, for instance, in the Vallone dei Duc, at the foot of Cima delle Lobbie; Fig. 3b). However, the prasinite may be considered as the metamorphic product of original basaltic flows. Homogeneous prasinite is fine grained and mainly composed of albite, clinozoisite/epidote, chlorite, amphibole, and accessory rutile, titanite, apatite and opaque ores.

Finally, at the western side of Lago Superiore, a layered eclogitic sequence preserves small (10×10 cm) lenses of low-strain domains still preserving the igneous microstructure and surrounded by large volumes of eclogite-facies mylonites. Cigar-shaped boudins of eclogite within the metagabbro outline a complex interference pattern of folds (Fig. 4, stop 8). Eclogite-facies veins are spectacular, and witness the fluid migration during subduction. They contain mostly Na–pyroxene and minor garnet, rutile and apatite. In tension gashes, most pyroxene is fibrous.

Less than 30 km NW from here, in the Viafiorcia area (upper Germanasca Valley), ophiolites are associated to Cu–Fe mineralizations and are considered a wonderful evidence of hydrothermal activity of the Jurassic age. The Cu–Fe mineralizations are the products of an exhalative activity on the palaeo-ocean floor, strongly similar to that occurring in the present-day ocean domains. In the Viafiorcia area, calcschists produced by the reworking of sediments deposited in the Piemonte ocean palaeodomain are associated with metaophiolites. The sediments, belonging to the oceanic realm, are represented by large volumes of carbonatic rocks (metamarls) and carbonate-rich pelites and marbles, with scattered lenses of metagabbro, serpentinite and metabasite. These lenses have been interpreted as olistoliths, i.e. large exotic blocks of the oceanic crust included in the sedimentary sequence (Dal Piaz et al. 1978). Sulphide mineralizations, mostly consisting of pyrite, chalcopyrite, bornite, pyrrhotite and minor magnetite, are associated with some of these exotic rock bodies. The adits of a few galleries represent a record of a small-scale mining activity developed for copper in the past (Grill 1925, 1926). Even if the underground workings are generally not accessible because they are flooded by water and unstable, the mineralized rocks are well visible in some outcrops and dumps.

The mineralization is observed as a heterogeneous-deformed layered body overlying a metagabbro and associated serpentinite lens. It consists of layers, 1- to 30-cm thick, of quartz–sulphide-rich rocks that may also contain blue amphibole, deerite and stilpnomelane. Chlorite- and serpentine-rich

layers, carboniose phyllites and calcschists with marbles are associated to the quartz–sulphide-rich layers (Fig. 5a–d). In spite of the Alpine deformation and metamorphism, some quartz–sulphide-rich layers display an inner millimetre-scale lamination that closely resembles the present-day sulphide-rich precipitates on the ocean floor; also, at the microscale, colloform bands at the core of pyrite crystals (Dal Piaz et al. 1978) likely represent relict hydrothermal textures.

All these features suggest that the mineralizations took place at the Jurassic ocean floor, due to the hydrothermal circulation of fluids that leached metals from the ocean crust and deposited them as soon as they emerged in the cold ocean water. This would be similar to occurrences in present-day ocean domains, where the emergence of the enriched hot fluids (mostly in the 250–350 °C, T range) gives birth to the so-called black smokers. This is also in agreement with the association with gabbroic rocks and serpentinite, as also observed in present-day ocean settings at major fault zones and at the ridge axis.

The Viafiorcia mineralization also preserves records of the travel that the ocean floor rocks underwent when they were involved in the Alpine orogenesis, subducted to great depths and eventually exhumed. It is well known that the Alps are a collisional orogen that was formed when the African and European plates collided after the consumption of the ocean that divided them. The oceanic lithosphere was consumed in a subduction zone, and some of the rocks of the ocean floor where then exhumed, their journey being recorded by minerals that developed at high pressure and low temperature. The mineralizations at Viafiorcia and their enclosing rocks confirm this journey with the development of mineral assemblages, comprehensive of deerite, glaucophane and stilpnomelane. These paragenetic sequences suggest a re-equilibration under blueschist facies conditions, indicative of a temperature gradient typical of subduction zones. The depths recorded by these rocks are smaller than those registered by the MM ophiolites, allowing to recognize different PT paths for the two units, and providing insights on the mechanisms acting in subduction zones and in the formation of collisional chains.

The Germanasca Valley: a Geological Cross Section Through the Inner Part of the Western Alpine Chain

At the border between France (Briançonnais and Maurienne regions) and Italy (Susa, Sangone, Chisone, Pellice and Germanasca valleys), different types of metamorphic rocks record the geological history of the collision among African and European continents and the interposed Mesozoic ocean. This collision occurred about 30 million years ago and formed the Alpine orogenic belt.

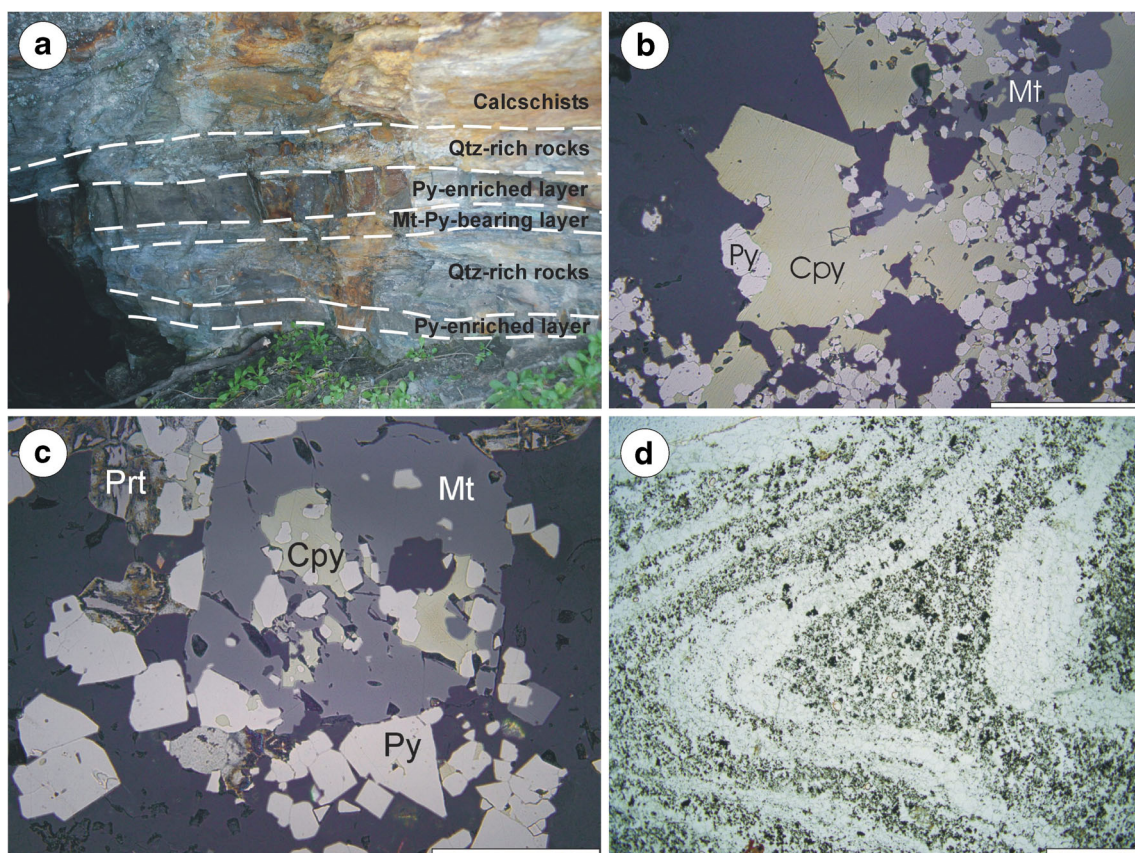


Fig. 5 **a** Mineralized lithologies at the Viaforcia mine. **b** Chalcocopyrite–pyrite–magnetite intergrowth under the microscope. Dark grey areas are quartz and silicates. Cpy chalcocopyrite, Py pyrite, Mt magnetite. Scale bar 0.2 mm. Plane-polarized reflected light. **c** Magnetite–pyrite–chalcocopyrite–pyrrhotite intergrowth at the microscale. Mt magnetite, Py pyrite,

Cpy chalcocopyrite, Prt pyrrhotite. Dark grey areas are quartz and silicates. Scale bar 0.2 mm. Plane-polarized reflected light. **d** Finely bedded and folded pyrite-rich sample at the microscale. Pyrite is white, dark spots are mainly quartz grains. Plane-polarized reflected light. Scale bar 2 mm

The Germanasca Valley represents a notable natural geological section, about 20-km long, along which are wonderfully preserved and exposed metamorphic rocks of both the Piemonte zone (oceanic crust) and the Dora-Maira Massif (European continental crust) (Fig. 6). The different stages of the Alpine geological history can be easily observed along the Germanasca stream and are particularly well shown both in the quarry of the Rocca Bianca area and in the tunnels of the Fontane talc mine (now partially restored for the ‘ScopriMiniera’ geosite exposition). The Dora-Maira Massif represents part of the upper continental crust of the ancient European margin facing on the Piemonte ocean palaeodomain and consists of two different superposed rock complexes (Sandrone et al. 1993) (Fig. 6).

The lower complex, named Pinerolo Graphitic Complex, consists of metamorphic rocks derived from a detritic sedimentary succession of the Late Paleozoic Age (Carboniferous?) originally made up of conglomerate and arenite, with plant remains. The metamorphic processes occurred during the Alpine orogeny transformed these sedimentary rocks into metaconglomerate (Fig. 7a) and fine-grained micaschist with embedded graphite lenses (Bussy and

Cadoppi 1996). Magmatic rock intrusions (i.e. granitic and dioritic bodies) were transformed to *augen* gneiss and metadiorite (Fig. 7b). Peculiar of the metasedimentary rock succession is the diffuse occurrence of graphite, both in lenses and dispersed within the rock mass, that have been exploited in different sites scattered along the lower Germanasca and Chisone valleys. The mining activity started at the beginning of the 18th century and definitively stopped in 1983. Deformation and metamorphic transformations that affected the original sedimentary rock succession are well shown into the metaconglomerate outcrops along the Germanasca stream (e.g. close to Ponte Battarello locality). At present day, the original rounded conglomerate pebbles of the protolith show an E–W striking highly stretched ellipsoidal shape (Fig. 7a).

The upper complex, named Polymetamorphic Complex, consists of rocks metamorphosed before the Alpine orogeny that correspond, at present, to coarse-grained micaschist (Fig. 7c), impure marble (Fig. 7d and e), metabasite and *augen* gneiss. These rocks, of the Paleozoic Age or older (Bussy and Cadoppi 1996), differ from those of the Pinerolo Graphitic Complex on the basis of the occurrence of relics of pre-Alpine

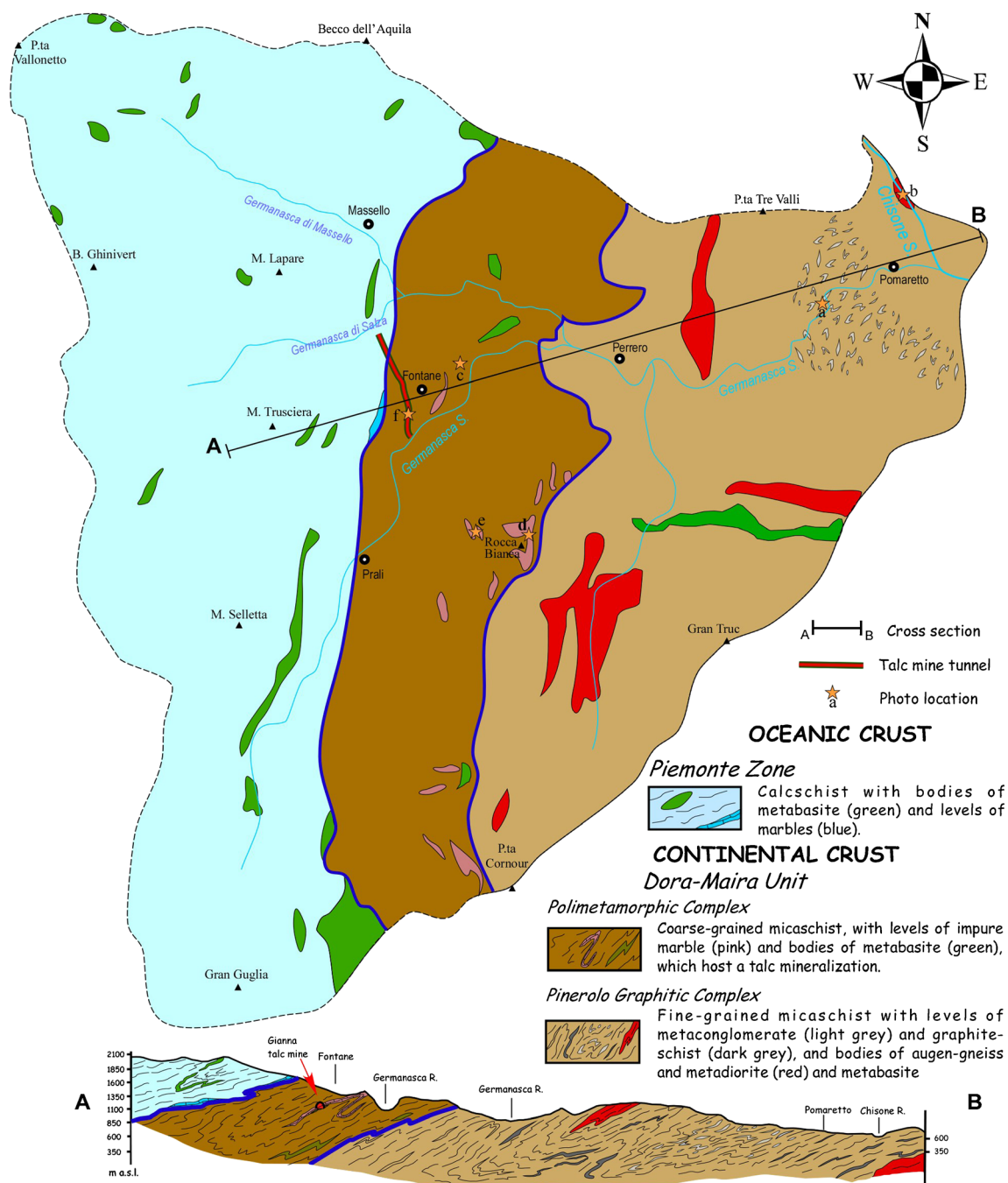


Fig. 6 Geological sketch map and cross section of the Germanasca Valley area

paragenesis (e.g. the garnet-bearing micaschist cropping out close to Fontane village, Fig. 7c). The most interesting feature of the Polymetamorphic Complex is the occurrence of a diffuse talc mineralization hosted in the micaschist and marble association. The talc mineralization quality is one of the best in Europe, and is thus still exploited in the Fontane area. The tunnels of previous mining activities (named Gianna and Paola) have been re-established in 1998 thanks to the ‘ScopriMiniera’ project that aimed to enhance and restore the mining heritage of both the Chisone and Germanasca valleys. The Gianna tunnel,

whose entrance is located at 1,211 m a.s.l. along the left side of the valley, is approximately N–S trending and comes out after more than 2 km in the Salza Valley (Germanasca di Salza) at the same altitude (Fig. 6). Along the Gianna tunnel, the talc mineralized rocks preserve the traces of a long deformation history which occurred during the Alpine orogeny. The folded schistosity highlights the tectonic processes active at deep crustal levels while faults, fractures and fault breccias are related to processes active at shallow crustal levels (Fig. 7f). Of high interest is the fact that, within the Gianna tunnels, the tectonic

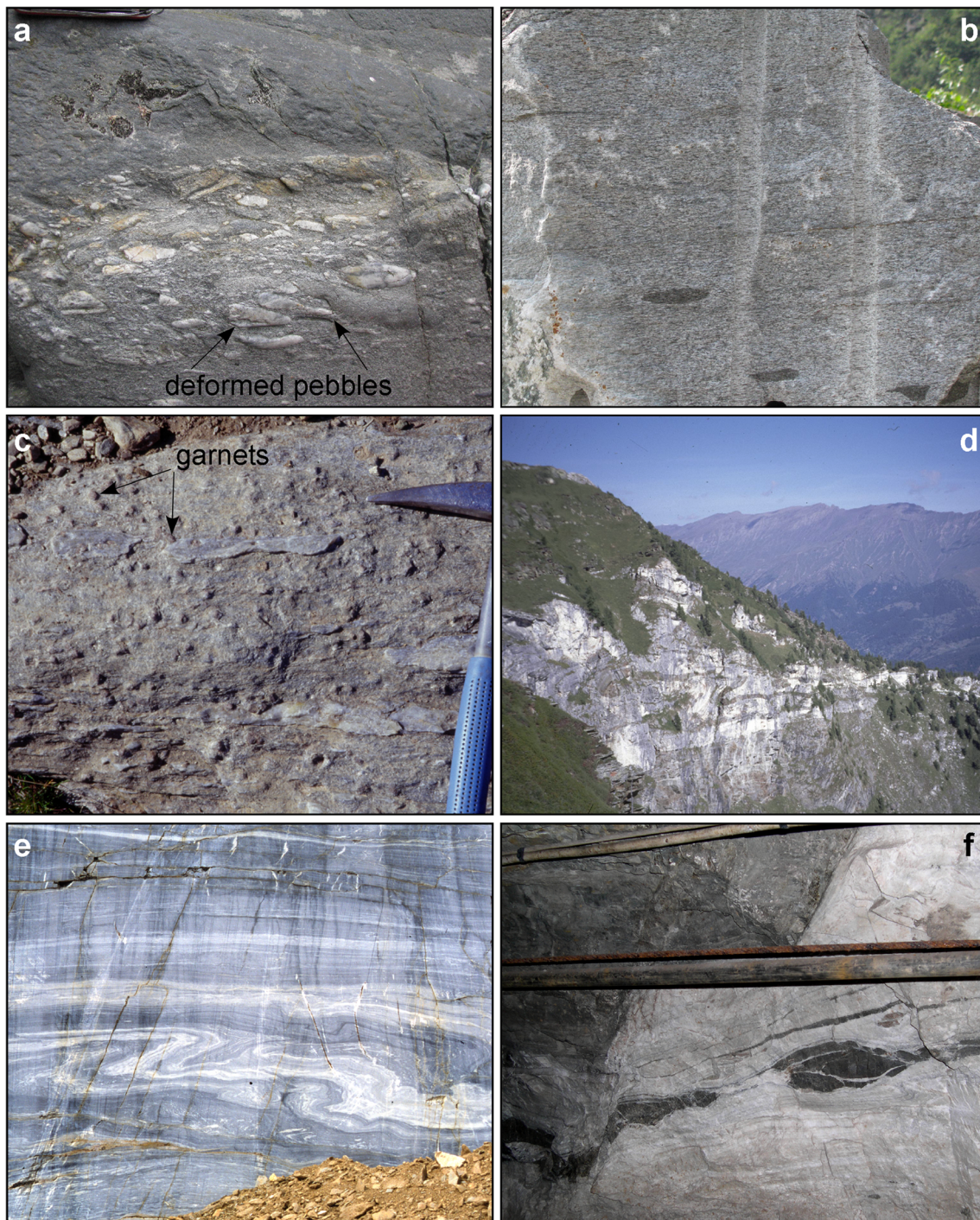


Fig. 7 The spectacular variability of rocks and structures of the Germanasca Valley. **a** Metaconglomerate with highly stretched pebbles at Ponte Battarello. **b** Metadiorite exploited in a quarry located at the confluence of Germanasca and Chisone valleys. **c** Coarse-grained garnet micaschist of the Polymetamorphic Complex (Fontane locality). **d** The

eastern slope of Rocca Bianca peak, showing the white marble exploited in the past. **e** Folding and deformation of the impure marbles visible in the Maiera quarry located in the western slope of Rocca Bianca peak. **f** Ductile and brittle deformation in the marble with boudins of metabasite visible along the Gianna tunnel of the Fontane deserted talc mine

contact between the Dora-Maira Massif and the Piemonte Zone is very well exposed and represents a relevant record of the orogenic juxtaposition between the European continental crust and the oceanic crust. The Piemonte Zone in the upper Germanasca Valley, consists of calcschist originated by

metamorphic transformation of a carbonate sedimentary succession that embeds basic rocks (metagabbro and metabasalt) deriving from the oceanic crust.

Another notable feature of the Polymetamorphic Complex is the so-called Rocca Bianca marble (Fig. 7d). It is a white

statuary marble employed in the building of many historical monuments located in the Torino city (e.g. Palazzo Madama in 1675 and Palazzo Carignano in 1681) and extensively exploited from the 17th century until 2003, in two different quarries at an altitude of ca. 2,000 m a.s.l. The marble forms several transposed layers (up to a few metres thick) embedded within garnet- and chloritoid-bearing micaschist (Cadoppi et al. 2008 and references therein) and is characterized by centimetre-thick layered bands of tremolite-rich green levels in dolomite-rich marble (known as ‘calcefiro zonato verde’), alternating with a mylonitic marble with grey levels due to the grain size reduction of the carbonate. The distribution of the Rocca Bianca marble is mainly controlled by mega-folds (Fig. 7d) and is well exposed on the eastern slope of the Rocca Bianca peak (‘White Rock’ peak from the milky white colour of marble). The exploited marble levels of the Maiera quarry, located on the western slope of Rocca Bianca, provide a good opportunity to directly observe the complex deformation of these metamorphic rocks (Fig. 7e), locally marked by the occurrence of thin metabasite levels embedded in the marble (Fig. 7f).

Petrography together with Prehistory: Jade at the Monviso Massif

From the Early Neolithic to the Bronze Age, i.e. from the sixth to the second millennium BC in Western Europe, axes and chisels were often made of polished stones, collectively known as ‘green stones’ (Ricq-de-Bouard and Fedele 1993). The green stones mainly consist of serpentinite, fine-grained eclogite and Na-pyroxenite, mostly omphacite and jadeite (Fig. 8a). A systematic petrographic study of the polished stone implements from Mediterranean France (Ricq-de-Bouard et al. 1990) and Northern Italy (D’Amico et al. 1995) has shown that, especially in the Neolithic period, jadeite was at least 15–20 % of the raw material used.

More than a century ago, Damour (1881) analyzed a sample from a private collection labelled ‘Green Jasper from Monviso, Piemonte’, and concluded that it was made of jadeite and invited geologists and mineralogists to check carefully the Monviso area and search for this mineral. Over 100 years passed and jadeites were found only as pebbles or boulders from ‘secondary’ deposits, such as the alluvial post-orogenic Oligocene to Quaternary conglomerates. Eventually, a systematic field survey of the area led to the discovery of a jadeite boudin on the northern side of Punta Rasciassa, Po Valley. This finding was first reported by Compagnoni and Rolfo (2003a) and studied in detail by Compagnoni et al. (2007, 2012).

The first jadeite was found at about 2,400 m a.s.l. in a small cirque on the northern side of Punta Rasciassa in the MM. It occurs as a loose block, of about 1-m cubed, within the

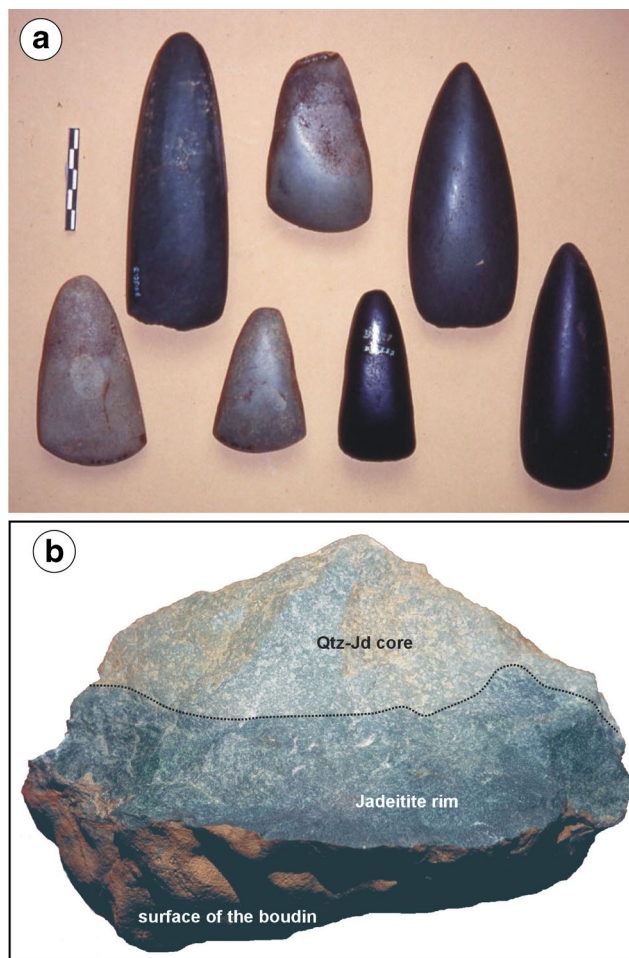


Fig. 8 a Jadeite, eclogite and omphacite Neolithic axes from the Museo di Antichità (archaeological museum) of Torino, Piemonte region, Italy. b Mesoscopic view of a composite sample of jadeite from Monviso Massif (Colle di Luca, between Val Varaita and Valle Po). The rock fragment is about 50-cm wide

massive or sheared antigorite serpentinite of the MM metaphtiolite (Lombardo et al. 2002). Though not in its primary setting, the jadeite was a boudin originally located a few tens of metres upstream within the same serpentinite. Following the discovery of the Punta Rasciassa jadeite (Compagnoni et al. 2007) a further, extensive search in the surrounding area led to the discovery of about a dozen jadeite bodies, most of them occurring as loose blocks suggesting short transport processes, and three of them cropping out ‘in situ’, in the Vallone Bulè and Vallone Chiot del Porco leading upstream to Colle di Luca and Punta Rasciassa (Compagnoni et al. 2012).

In hand specimen, the jadeite is a very pale grass green, fine-grained massive rock surrounded by a darker retrogression margin (Fig. 8b). The jadeite locally contains irregular centimetre-sized, coarse-grained, phlogopite-rich pockets and veins. Locally, coarse-grained portions with peculiar pegmatoid grain size occur and consist of centimetre-sized crystals of bright green clinopyroxene and light grey chlorite

flakes. Most jadeitite blocks are mantled by darker retrogression margins from 10- to 20-cm thick.

On a geochemical and petrologic basis, the jadeitite protolith was an oceanic plagiogranite, most likely a dyke cutting across upper-mantle peridotites, later hydrated to serpentinites. The jadeitite experienced a metasomatic process involving a significant desilication and Mg and Ca enrichment, connected to the host peridotite serpentinitization (Harlow et al. 2007). This process occurred during prograde Alpine high-pressure (eclogite-facies) metamorphism.

Given the great petrographic (and most probably also genetic) variability shown by archaeological jadeitites, data are still too few to dissert on the origin of the raw material of prehistoric implements (see e.g. Pétrequin et al. 2006), and it is just possible to conclude that the MM meta-ophiolite is one of the most promising source areas from the Western Alps. However, because similar rocks are reported from other localities from the Western and Maritime Alps (see Castelli et al. 2002 and references therein), it is likely that the raw materials of most jadeitites used to make stone axe heads, which are spread all over Western Europe, have a similar origin and derive from the Western Alps as long suggested (Damour 1881; Franchi 1900).

World-Famous Minerals and New Type Localities

In order to improve knowledge about type localities for new minerals in the surroundings of the MM (Varaita and Po valleys, Piemonte region), we describe their occurrence and characterize other peculiar mineral varieties below.

At present day, approximately 4,800 mineral species are known in the world. In Italy, there are more than 1,800 valid mineral species (more than 650 recorded in the Piemonte-Aosta Valley district alone). Italy has a well-established tradition in the study of minerals, and since 1546, 303 mineral species were discovered for the first time in Italy (and are thus called ‘Italian-Type Minerals’). The locality of their first finding is called the ‘type locality’ (acronym TL). The Piemonte region is the TL of 36 mineralogical species (it is the richest after Campania and Tuscany regions). Among these 36 TL, 6 are in the Dora-Maira Massif (DMM) in lower Varaita and Po valleys (bearthite, ellenbergerite, phosphoellenbergerite, hydroxylwagnerite, magnesioidumortierite, magnesiostauroilite) and 1 (carlostanurite) is associated with chrysotile in the serpentinites of the MM ophiolite (Sampeyre, Varaita Valley) (Ciriotti et al. 2009). In order to raise awareness of these minerals as well as other peculiar ones, the Museum of Pyrope at Martiniana Po opened in July 2008 in collaboration with the Po park and the municipality of Martiniana Po (which is located almost at the mouth of the Po Valley). The museum consists of three rooms: the first one describes the Earth and the genesis of the Alps, with special

regard to the Po Valley; the second one hosts a number of minerals, mostly of regional importance; and the third one has multimedia tools. The museum was founded with the aim of raising awareness amongst visitors about the geological resources of the Po park and of promoting and disseminating knowledge of the exceptional crystals of pyrope discovered here and described below. Pyrope as pure as that of Martiniana Po is very rare and is, therefore, a geological heritage of inestimable international scientific value, though virtually unknown to the general public. The museum of Pyrope offers to the public the opportunity to learn about this mineral, and at the same time, contributes to its preservation. All these features make Martiniana Po a very important mineralogical site.

Carlosturanite

Carlosturanite is a hydrated silicate of Mg, Fe, Ti, Mn and Al, with fibrous habit, recognized for the first time in serpentinites in Auriol asbestos mine near Sampeyre in Varaita Valley (Compagnoni et al. 1985). The chemical formula is $(\text{Mg}, \text{Fe}^{2+}, \text{Ti})_{21}(\text{Si}, \text{Al})_{12}\text{O}_{28}(\text{OH})_{34}\cdot\text{H}_2\text{O}$, and the crystal system is monoclinic. The name is to honour Carlo Sturani (1938–1976), Professor of Palaeontology at the University of Torino, whose untimely death occurred in a fatal accident during field work. Crystals of carlosturanite are fibres, 0.2- μm width, up to several centimetres long (Fig. 9a), commonly gathered in folded bundles intergrown in parallel with brucite and chrysotile. Physical properties are light brown colour, vitreous or pearly luster, whitish streak, transparent, good cleavage and flexible. Hardness (H) = 2.5. Specific gravity (G) = 2.63. Specimens of carlosturanite were first collected on the working face of a chrysotile-asbestos mining prospect, located some 5 km west of Sampeyre (Auriol asbestos mine). The mine is situated in a metamorphic serpentinite belonging to the southern portion of the MM. Carlostanurite is quite common in the Sampeyre serpentinite and occurs over an area of a few square kilometres. The serpentinite underwent a polyphase metamorphic evolution characterized by an early Alpine event under greenschist facies conditions. Structural and mineralogical relics suggest that the antigoritic serpentinite derives from an upper-mantle spinel lherzolite partly re-equilibrated under the plagioclase peridotite facies, like most serpentinites of the ophiolitic belt of the Western Alps. Carlostanurite develops in a close network of veins (from 0.1 mm to several centimetres thick) randomly cross-cutting the serpentinite. It usually occurs together with chrysotile (Fig. 9b), diopside, opaque ore minerals (magnetite and native Ni–Fe alloys), clinohumite, perovskite and a green uvarovite garnet (Grosso and Compagnoni 2007). Microscopic observations suggest that carlosturanite, as well as the other serpentine minerals, is frequently replaced by brucite. Beside the TL at Auriol asbestos mine, carlosturanite

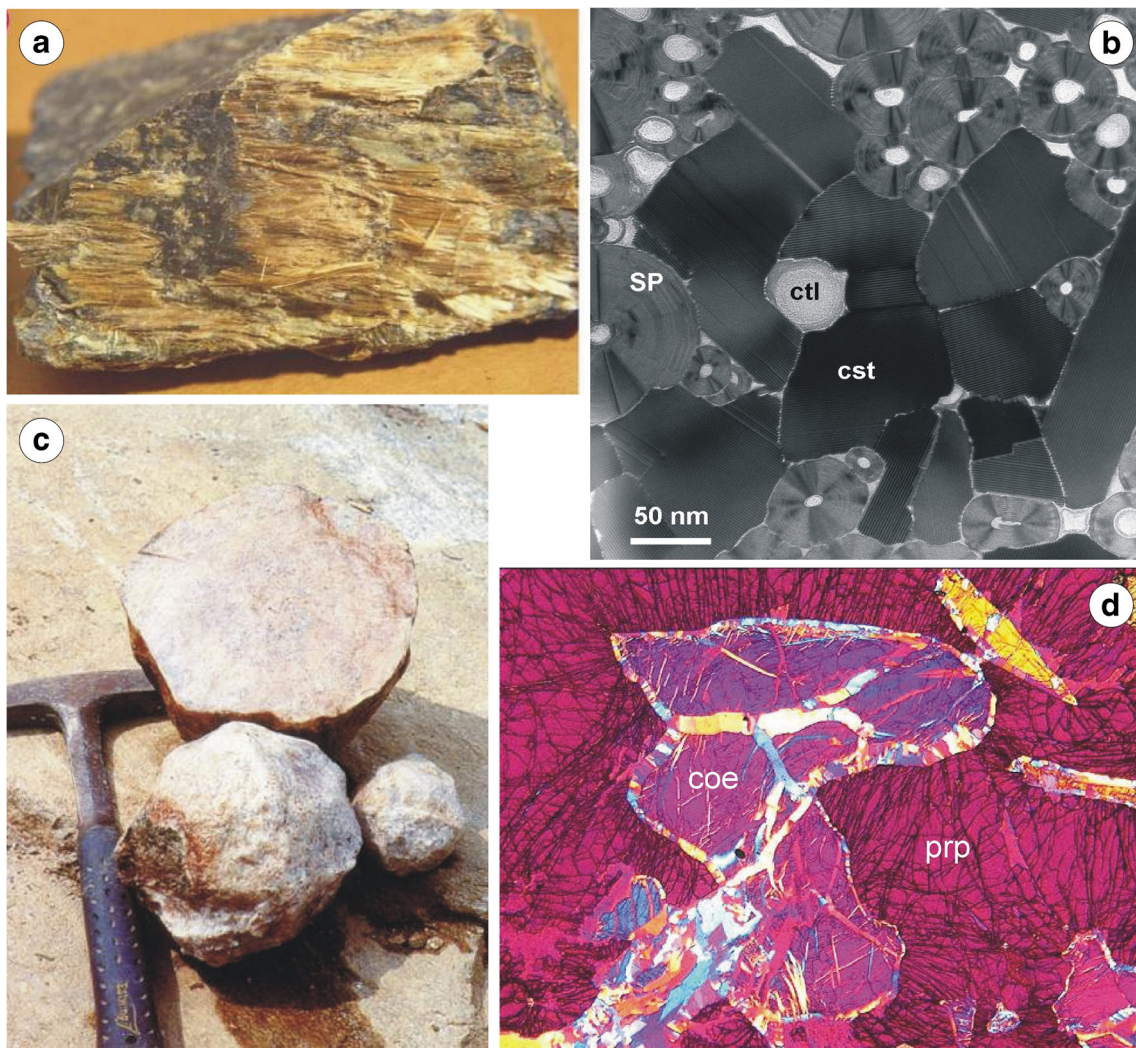


Fig. 9 **a** Mesoscopic view of asbestiform carlosturanite (*gold brown*) on serpentinite (TL). **b** High-resolution transmission electron microscope (HRTEM) image of a fibrous bundle cross section showing an intergrowth of carlosturanite (*cst*), chrysotile (*ctl*) and ‘polygonal’ serpentine (*SP*) fibres (TL). **c** Idioblastic pyrope megablasts, ca. 20 cm across, from the Case Paris coesite-bearing whiteschists of the DMM (Martiniana Po). The light pink colour is due to its unusual composition, very close to the pure pyrope endmember. These garnets of exceptional size (up to 20 kg in weight) and unusual chemical composition were formed by HP metamorphism to a depth of about 100 km. This deep origin is confirmed by

the presence of inclusions of coesite (Rolfo 2003). **d** Photomicrograph of coesite (*coe*) inclusions in pyrope (*prp*) from a kyanite–phengite–pyrope whiteschist subjected to UHPM (Ultrahigh pressure metamorphism), Brossasco-Isasca Unit, DMM. In the centre, a crystal of coesite about 3 mm across is included in pyrope. Coesite is surrounded and transected by quartz, which developed during decompression, as a product of coesite destabilization at a low pressure. Radial cracks in the pyrope around the inclusion appear, due to the volume increase associated with the inversion of coesite to quartz during uplift. Crossed polarizers with first-order red plate (Compagnoni and Rolfo 2003b; Rolfo 2003)

also occurs in a number of localities around Sampeyre and Casteldelfino, Varaita Valley; around Crissolo, Po Valley; at Monte Nebin, Maira Valley, Cuneo Province, Piemonte region (Compagnoni et al. 1985; Mellini et al. 1985; Piccoli et al. 2007).

Pyrope Megablasts

A number of new mineral species have been discovered as inclusions in the world-famous pyrope megablasts of Martiniana Po (Chopin 1984; Compagnoni et al. 1995;

Compagnoni and Rolfo 2003b; Piccoli et al. 2007). Pyrope is a variety of garnet with formula $Mg_3Al_2 [SiO_4]_3$ (acronym Prp), belonging to the orthosilicates. The name derives from the Greek word ‘πυροπης’ which means ‘having the appearance of fire’ for its commonly bright red colour. Pyrope is the Mg-member of the ‘pyralspite’ garnet series (pyrope + almandine + spessartine) and is usually mixed with the almandine garnet $Fe_3Al_2 [SiO_4]_3$ (Alm). It occurs in ultrabasic rocks (such as peridotites, kimberlites, serpentinites) and eclogites, and typically contains 70 % Prp and 30 % Alm. Pyrope

garnets containing more than 80 % Prp are very rare. The crystals of pyrope found in the DMM, in small outcrops between Brossasco in Varaita Valley and Martiniana in Po Valley, have extraordinary features: abnormal in size (Fig. 9c) (up to 25 cm in diameter and up to 20 kg in weight), and with a very peculiar colour; they are not red but a very pale pink or even colourless, because of the purity of their chemical composition (98 % Prp); included in pyrope crystals, other new species of minerals have been detected for the first time in the world. Vialon (1966) first described in DMM lithologies resembling conglomerates with rounded pebbles ('les facies pegmatitique noduleux'), which proved to be crystals of pyrope, in a matrix of quartz and shiny flakes of white mica. In 1984, Chopin described tiny inclusions of coesite, partially transformed into quartz (Case Paris, near Martiniana, lower Po Valley). The presence of coesite (the high-pressure polymorph of silica formed at pressures above 2.6 GPa, corresponding to about 100 km in depth) and the extremely pure composition of pyrope indicated that crustal rocks (gneiss and granite) were brought to the depth typical of the mantle during subduction and then brought back to the surface, thanks to orogenic movements, without losing the minerals crystallized in depth, at very high-pressure (HP) conditions. These rare minerals were protected on the way to the surface by the shield of pyrope, which prevented metamorphic retrogression (Fig. 9d). Until the discovery of coesite in DMM, the more deeply subducted rocks known in the Alps were not known to have exceeded 50 km (e.g. Sesia-Lanzo Zone). The discovery of Chopin has opened a new field in the study of metamorphism, namely, the petrology of the rocks recrystallized at 'very high pressures' (Ultrahigh-pressure metamorphism, UHPM). Besides its importance for the studies of metamorphism, this discovery had also important implications for systematic mineralogy. For instance, the pyropes of the Martiniana Po site were the first observed to include conspicuous inclusions of a violet mineral, ellenbergerite, which is a new silicate of Mg, Al, Ti and Zr. Further mineralogical studies have identified in the pyrope-bearing rocks a series of new minerals, of which Martiniana Po and Gilba Valley (Brossasco) are TL: bearthite, phosphoellenbergerite, magnesioidumortierite, magnesiostaurolite and hydroxylwagnerite (Compagnoni et al. 1995; Compagnoni and Rolfo 2003b; Piccoli et al. 2007).

In the Martiniana Po site (after the name of the municipality), the historic outcrop of pyrope is located at Case Ramello: here, two lenses of whiteschist contain large crystals of pyrope, the most pure in the world (98 % Prp). The pyrope-bearing whiteschist occurs within granitic orthogneiss of a

coesite-bearing terrane (Brossasco-Isasca Unit of the southern DMM), as layers from a few centimetres to ca. 20-m thick and from a few metres to hundreds of metres long. The whiteschist mainly consists of pyrope embedded in a matrix of quartz (inverted from former coesite), phengite, talc, kyanite, rare jadeite, and accessory rutile, zircon and monazite. The size of pyrope grains ranges from a few millimetres up to about 25 cm in diameter. Pyrope developed a trapezohedron habit, but edges are frequently rounded by later post-crystalline deformation or possibly incomplete growth, and/or partial resorption. The colour of pyropes varies from white to light pink or lilac to brown (the crystals are poorly zoned with a pale reddish core and pale pinkish rim). Pyrope porphyroblasts are systematically crowded with others minerals: the surface of the crystals is often opaque and completely covered with vermiculite, phlogopite, talc, chlorite, phengite, coesite and kyanite. The interior of the crystals is often turbid because of the inclusions. In addition to relatively common minerals, they also include rare minerals: among these are particularly interesting coesite and other new species as bearthite, ellenbergerite, hydroxylwagnerite, magnesiostaurolite and magnesioidumortierite. Other inclusions in the pyrope are dravite, wagnerite and magnesiochloritoid (Compagnoni et al. 1995; Compagnoni and Rolfo 2003b; Chopin and Ferraris 2003).

In the Gilba Valley (Brossasco, Varaita Valley), pyrope is smaller than in Martiniana Po, but the crystals' interiors preserve pink or slightly red zones so transparent to have been cut as gemstones up to several carats. Here, the pyropes are especially interesting for their mineral inclusions with the greatest inclusion of coesite found so far and the mineralogical species for which this is the TL (bearthite, hydroxylwagnerite, magnesioidumortierite, magnesiostaurolite and phosphoellenbergerite). The best outcrops are found along the road from Masueria village leading to the Chapel of St. Bernard. The surface of the pyrope crystals is green after transformation to chlorite (Piccoli et al. 2007).

Bearthite

Bearthite is a hydrated phosphate, belonging to the brackebuschite group. Its chemical formula is $\text{Ca}_2\text{Al}(\text{PO}_4)_2(\text{OH})$, and the crystal system is monoclinic. The name is to honour Peter Bearth (1902–1989), Swiss petrologist and mineralogist, Professor of Petrology at the University of Basel, for his pioneering petrologic studies of the high-pressure terranes of the Western Alps. Bearthite occurs rarely as aggregates of partly euhedral, flat prismatic millimetre crystals; more typically, it occurs as smaller, usually corroded anhedral grains. Physical properties are pale yellow colour, white streak, transparent, poor cleavage and uneven fracture. $H < 5$. $G = 3.25$. Experimental studies indicate that the stability

of bearthite is restricted to very Ca-poor or P-rich rocks under moderate to high-temperature conditions. Associated minerals are lazulite, apatite, kyanite, coesite, pyrope, paragonite, muscovite, almandine, rutile, augelite, wardite, goyazite, hydroxylherderite, quartz, albite and talc. Bearthite occurs in the pyrope megablasts as tiny inclusions. It is characterized by a high content of rare earths elements and thorium. The TLs are Case Paris (very near to Case Ramello) at Martiniana Po and Case Tapina in Gilba Valley (Chopin et al. 1993; Brunet and Chopin 1995; Piccoli et al. 2007).

Ellenbergerite

A hydrated Mg–Al–Ti silicate with extensive Ti–Zr substitution, ellenbergerite has the ability to incorporate phosphorus which makes it one of the most P-rich silicates known. It is a HP phase, stable at $P > 2.7$ GPa at $T = 725$ °C. Its chemical formula is $\text{Mg}_6(\text{Mg}, \text{Ti}, \text{Zr})_2\text{Al}_6\text{Si}_8\text{O}_{28}(\text{OH})_{10}$, and the crystal system is hexagonal. The name is to honour François Ellenberger (1915–2000), Professor of Geology at the University of Paris, for his geological work in the Western Alps. Ellenbergerite crystals are millimetre sized and anhedral; they rarely form elongated, up to 10 mm prisms, with a hexagonal cross section. Physical properties are purple to lilac colour (sometimes with smoky or pink cores), vitreous luster, transparent, faint blue cathodoluminescence, no cleavage and brittle. $H = 6.5$. $G = 3.15$. Ellenbergerite occurs in composite inclusions within pyrope porphyroblasts as purple millimetre-sized grains associated with talc, kyanite, clinocllore, rutile, zircon and sodic amphibole. The colour zoning is due to nearly complete Ti–Zr substitution. In addition, ellenbergerite may contain more than 8 wt.% P_2O_5 with strictly correlated changes of Si, Mg, Al and Ti+Zr contents, over 80 % of which represent the SiAl-PMg substitution. The TL is Case Paris (Case Ramello) at Martiniana Po (Chopin et al. 1986; Piccoli et al. 2007; Ciriotti et al. 2009).

Phosphoellenbergerite

Phosphoellenbergerite is a Mg–phosphate isostructural with ellenbergerite. It is a HP phase, stable at $P > 0.85$ GPa at $T = 650$ °C and $P = 2.25$ GPa at $T = 900$ °C. Its chemical formula is $\text{Mg}_{14}(\text{PO}_4)_6[(\text{PO}_3\text{OH}), (\text{CO}_3)]_2(\text{OH})_6$, and the crystal system is hexagonal. The name is after its chemical composition and structural relationship with ellenbergerite. Phosphoellenbergerite forms anhedral inclusions, up to 0.5-mm long, rarely centimetric crystals, tabular to pseudo-octahedral. It may be fibrous to massive. Physical properties are pale green, olive green, brownish green colour; reddish brown if oxidized; vitreous to subresinous luster, white streak, translucent to transparent, non-fluorescent, no cleavage and conchoidal fracture. $H = 6.5$. $G = 3.2$. The

mineral occurs as blue elongated prismatic crystals up to 0.5-mm long in pyrope megablasts, associated to ellenbergerite. The TLs are Case Canova (Masueria—Chapel of St. Bernard), Gilba Valley, Brossasco and Pratoluogo, Isasca Valley (Brunet et al. 1998; Piccoli et al. 2007; Ciriotti et al. 2009).

Magnesioidumortierite

This mineral is a borosilicate isostructural with dumortierite. Its chemical formula is $(\text{Mg}, \text{Ti})(\text{Al}, \text{Mg})_2\text{Al}_4(\text{SiO}_4)_3(\text{BO}_3)[\text{O}(\text{OH})]_3$, and the crystal system is orthorhombic. The name is after its chemical composition and structural relationship with dumortierite, named after Eugène Dumortier (1802–1873), French palaeontologist. The rare prismatic hexagonal crystals can reach 1 cm in length. Physical properties are pink to red colour, vitreous luster, white streak, transparent and poor cleavage. $H = 7.5$. $G = 3.22$. Magnesioidumortierite occurs in pyrope porphyroblasts, either in polymineralic inclusions (anhedral grains a few tens to 300 μm in size, deep pink in colour, together with kyanite, magnesio-staurolite, talc, clinocllore, ellenbergerite, rutile) or in narrow cracks fillings. The TL is Case Tapina, Gilba Valley, Brossasco (however, the best samples are from Case Paris, Martiniana Po) (Chopin et al. 1995; Ferraris et al. 1995; Chopin and Ferraris 2003; Piccoli et al. 2007).

Magnesio-staurolite

Magnesio-staurolite belongs to the staurolite group. Its chemical formula is $[\text{Mg}_4\text{Al}_{16}(\text{Al}_2[\text{Si}_8\text{O}_{40}[(\text{OH})_2\text{O}_6])]$, and the crystal system is monoclinic. The name is after its chemical composition and structural relationship with staurolite (the Fe analogue). Staurolite takes its name from the Greek word for cross, in allusion to the common cruciform twins. Physical properties are yellow to brown colour or colourless, vitreous to resinous luster, white streak and transparent. $H = 7.5$. $G = 3.54$. Magnesio-staurolite occurs exclusively as inclusions of anhedral isolated grains, with size ranging from a few tens to 250 μm , in pyrope megablasts, typically associated with talc, clinocllore, kyanite, rutile and magnesiochloritoid, in polymineralic inclusions. Rarely, it occurs as single-crystal inclusions that contain armoured relics of corundum. The TL is Case Canova (Masueria—Chapel of St. Bernard), Gilba Valley, Brossasco, Varaita Valley. Recently, magnesio-staurolite has been found in centimetric prismatic yellow-brown crystals at Case Paris, Martiniana Po (Chopin et al. 2003; Piccoli et al. 2007; Ciriotti et al. 2009).

Hydroxylwagnerite

This mineral is the OH-analogous of wagnerite and is named after Franz Michael von Wagner (1768–1851), German

mining official. Its chemical formula is $Mg_2(PO_4)(F, OH)$, and the crystal system is monoclinic (Raade and Romming 1986). Physical properties are tan colour, vitreous or glassy luster, white streak and transparent. It is a very rare mineral, found as yellowish crystals in the whiteschist of Gilba Valley, both in the matrix of quartz, and as inclusions within pyrope megablasts. Centimetric aggregates formed by anhedral crystals, creamy white, are found at TL. Aggregates, up to a few millimetres across, of more yellow-brown micro-lamellae are found at Case Ramello, Martiniana Po, with wagnerite. The TL is San Giacomo, Gilba Valley, Brossasco, Varaita Valley (Piccoli et al. 2007; Ciriotti et al. 2009).

A Geomorphologic Aid to Reconstructive Geoarchaeology

During the second Punic War, Hannibal's army crossed the Alps in the autumn of 218 BC, to invade the Roman Republic with a surprise attack from the rear. This event is particularly noted for the use of elephants, which has inspired popular imagination. The route across the Alps followed by the troops (30,000 soldiers with 5,000 holders, 7,000 horses, 15,000 baggage animals and 37 elephants) is an old debated historical question, its resolution not having yet been supported by decisive archaeological finds.

Three passages from the Transalpine to the Cisalpine Gaul have been assumed by researchers, either historians or archaeologists, mainly on the basis of interpretation of the Polybius (1979; 1993) and the Livy (1965; 1997) reports, i.e. the two main historical sources about the Punic Wars (Fig. 10a).

1. A southern route across the Colle delle Traversette (2,950 m a.s.l.), from the Queyras (Durance basin) to

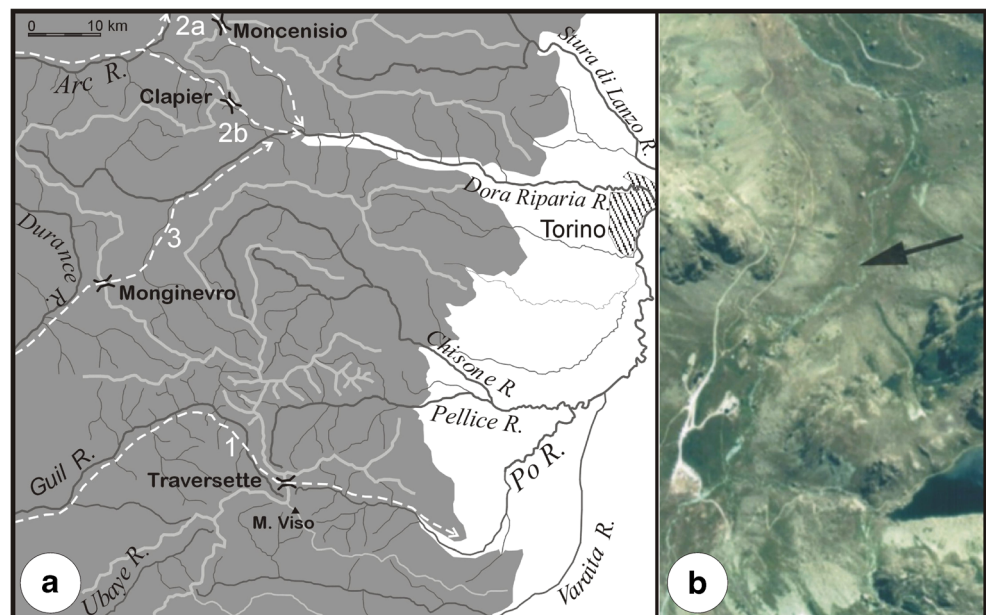
the Po Valley and the Po Plain south of Torino, is supported by de Beer (1967), Prevas (1998) and Mahaney et al. (2008a, 2008b).

2. A northern route, from the Arc Valley (Isère basin) to the Dora Riparia Valley and the Po Plain at Torino, is hypothesized across the Colle di Moncenisio (2,083 m) by Napoleon (de Montholon 1905), the Col du Clapier (2,497 m) by Lazenby (1998) and Kuhle and Kuhle (2012), or one of the above-mentioned pass by Annequin and Barruol (2004).
3. An intermediate route across the Colle del Monginevro (1,830 m), from the Drac Valley to the Dora Riparia Valley, is preferred by Connolly (1981).

Geomorphology can offer support to historical and archaeological studies for tracing Hannibal's routes, by means of targeted application of landform field mapping and environmental reconstruction. The description made by Polybius, who repeated the trek 70 years after Hannibal, indicates some distinctive features of the pass, accepted by all researchers: presence of finpack, very steep descent along the Italian side and a long view over the Po Plain. Some other indications are more debated, such as the passage impeded by a landslide (Mahaney et al. 2008a) or by a 'break-off' in the slope (Kuhle and Kuhle 2012). The first interpretation best fits with the Colle delle Traversette landslide features (Mahaney et al. 2008a); this passage could correspond to the Hannibal's pass that the Roman historians Varro, Servius and Strabo located south to the Colle del Monginevro. The second, alternative interpretation, best fits with Col du Clapier (Kuhle and Kuhle 2012), characterized by erosional/gravitational scarps.

According to the Polybius statement, the Punics crossed the highest pass in the Alps, and the Colle delle Traversette is

Fig. 10 **a** Hypothetical routes followed by Hannibal's army across the Alps. Numbers are explained in the text. **b** Air imagery of the Po Valley at the 2,000 m contour. The arrow shows the location of the Hannibal's stone wall system (Mahaney et al. 2010)



indeed a very high pass (2,950 m high) on the main watershed northwest of Monviso (3,841 m), at the head of the Po Valley. Moreover, the 25-km long mountain basin of the Po river is one of the shortest main valleys of the Western Italian Alps. These elements suggested to us to first examine the possible southern route (1) of the Hannibal invasion. In this context, our plans are to focus on the area where Hannibal is thought to have regrouped his army while crossing the Alps in the upper Po Valley, downstream from the Colle delle Traversette mountain pass and about 1,000 m below it (e.g. Mahaney et al. 2008a, 2008b).

The ‘regrouping area’ should coincide with a series of three gently sloping morainic and alluvial landforms of the glacially moulded valley floor, named Pian del Re (2,070–2,020 m), Pian Fiorenza (1,900–1,840 m) and Pian della Regina-Pian Melze (1,750–1,700 m).

A series of stonewalls, made of rocky angular boulders, was observed in the intermediate plain (Pian Fiorenza) in 1994 and later investigated but never excavated (Mahaney 2004). This area is now buried under debris flow deposits (Fig. 10b), linked to the heavy rains of summer 2008 (Mahaney et al. 2010).

We aim to show the role that earth sciences can play in identifying and characterizing this archaeological area, using geomorphological mapping supported by digital techniques and information technologies (IT), lichenometry and geophysical surveys. We will also make a historical and linguistic review of the original Polybius text, in order to correctly interpret the described landforms.

The Rock-Dwelling Organisms on the Ophiolitic Rocks

Often thought to be virtually bare of life, rock outcrops and boulders everywhere represent valuable niches of biodiversity. Rock surfaces are environments that not only support low-temperature geochemistry but also major metabolic processes in several microorganisms (Gorbushina and Broughton 2009). Phototrophic and chemotrophic bacteria, as well as algae, lichenized- and non-lichenized fungi are the main components of epilithic and endolithic rock-dwelling communities (Sterflinger 2000). These lithobiontic microorganisms promote biogeophysical and biogeochemical processes which support pedogenesis and the recycle of elements essential for life on Earth (Piervittori et al. 2009). In extreme environments, where plant cover is sparse or absent, rock-dwelling communities are characterizing elements. For this reason, they have been widely examined in hot and cold deserts (e.g. Onofri et al. 2007), while only some groups of microorganisms, such as lichens, have been significantly investigated in alpine areas (e.g. Favero-Longo and Piervittori 2009; Nascimbene et al. 2012). Investigations on lithobiontic microorganisms on the Monviso Massif (MM) not only give an additional value for

the environmental assessment and evaluation of this geosite but also open new insights on the biodiversity in the Alps. Moreover, the rich geodiversity of the Monviso ophiolite nappe offers the possibility to analyze the influence of mineralogical and structural features of the different lithotypes on the colonization patterns of microorganism communities, both in terms of species composition and interactions with the substrata (Fig. 11a–d).

In this context, several topics linking geodiversity and biodiversity on the MM have been identified for geodiffusion actions aiming to make people aware of the complexity and richness of alpine environments and to support conservation programmes.

- (a) Rock habitats and microorganism communities—on the MM, black patinas of cyanobacteria are often obvious on periodically washed, steep walls of metagabbros, as well as lichen xerophytic communities and colonies of microcolonial fungi on horizontally exposed outcrops and boulders of serpentinites, nitrophilous lichen communities on calcschist outcrops, slightly emerging from the soil layer. These examples highlight the influence of mineralogical and structural features of rock outcrops and boulders, mediated by geomorphological processes at various scales, on the development of microniches displaying different microclimatic and ecological features which eventually control the colonization by various microorganism communities.
- (b) Community diversity on different lithotypes—outcrops or boulders of the MM metagabbros and calcschists, even at a distance of a few metres and in similar microclimatic conditions, host very different lichen communities in terms of species composition. Lichens, as many organisms, are indeed affected by the calcium contents of their substratum, high contents being more or less tolerated or required depending on species (Brodo 1973). The recognition of silicicolous vs. calcicolous lichen communities exemplifies the influence of rock chemistry on the specific compositions of microfloras.
- (c) Species richness on serpentinite rocks—while plant communities on ultramafic lithologies commonly display a low number of species in response to geochemically induced stresses, as high concentrations of heavy metals (Ni, Cr, Co), a scarcity of macronutrients and high Mg/Ca ratios, other groups of organisms, as lichens, commonly display a high species richness just on serpentinites (Favero-Longo et al. 2004). On the MM, hot spots of lichen diversity can be observed on serpentinite boulders, more than 30 species being detectable on surfaces of 10 m² or less.
- (d) Colonization and deterioration patterns on ophiolites—the extent of the biotic colonization on the MM ophiolites can be easily appreciated on the rock surfaces,

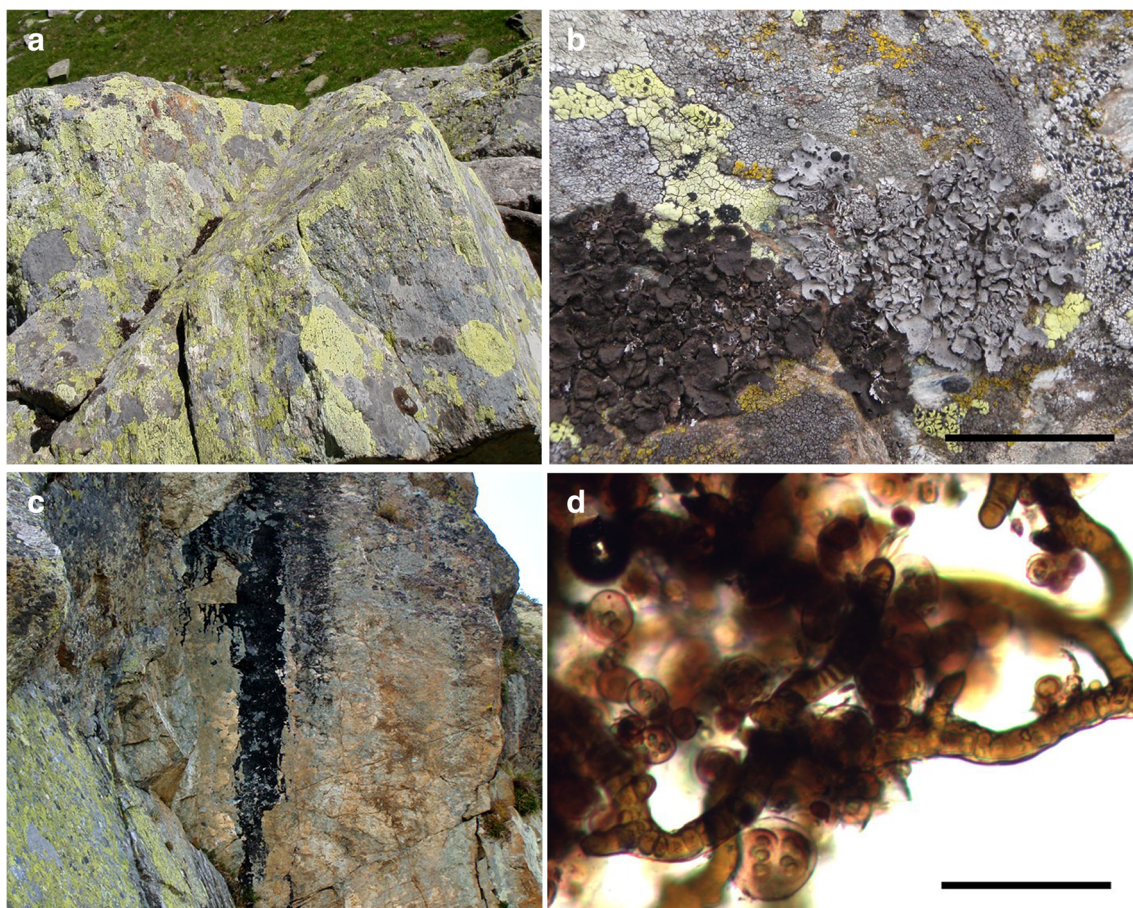


Fig. 11 Microorganism communities on the MM ophiolites. **a** Silicolous lichen community on a Mg–Al-rich metagabbro boulder. **b** Richness of foliose and crustose lichen species on a serpentinite (*scale*

2 cm). **c** Black patina on a Mg–Al-rich metagabbro steep wall. **d** Coccoid and filamentous cyanobacteria from the black patina in (c) (*scale* 100 μm)

in particular, in the case of patinas of dark-coloured microorganisms, as cyanobacteria, or bright coloured lichens with yellow or orange thalli. Lichenized- and non-lichenized fungi, however, also colonize the rock interior, where the mineralogical and textural features strongly control the extent and the patterns of hyphal penetration (Favero-Longo et al. 2005). For example, in foliated serpentinites, the foliation along which discontinuities form delineates the plane of weakness which can be attacked by penetrating hyphae down to more than 2 mm from the surface. This biotic growth and release of metabolites within the rocks are involved in mineral disaggregation and leaching processes supporting pedogenesis (Piervittori et al. 2009).

- (e) Lichen growth and age of colonization—although the growth of saxicolous lichens is not constant, but articulates with a duration which is species specific, lichenometric dating is considered a valuable dating tool for geoscientists (Piervittori 2004; Roberts et al. 2010). The measure of the growth rate of certain lichen species on outcrops, debris slopes and boulder fields of MM allows the calculation of the approximate age of thalli

displaying the highest dimensions. This knowledge is informative on the minimum age of lichen colonization and, indirectly, on the time in which the rock surfaces were already available for the colonization. It is worth remembering that the early stages of lichen colonization cannot be contemporary to the exposure of the rock surfaces which follow a glacial retreat or a landslide event. Accordingly, lichenometry does not allow an absolute dating, but only gives a semi-quantitative information on the minimum age of rock surfaces.

Discussion and Conclusions

The multidisciplinary research project ‘PROactive management of GEOlogical heritage in the PIEMONTE Region’ aims to implement a new conceptual and operational discipline in the management of geoheritage in the Piemonte region by developing new techniques for recognizing and managing its rich geodiversity at the local and regional scale (Giardino et al. 2012). Several activity steps are planned: review and

Geodiversity contents	Scientific research actions	Research methods	Geological concepts and geodiffusion interests	Geodiffusion actions	Local partners	Geodiffusion techniques and products
1) The Monviso ophiolites and the associated Cu-Fe mineralizations.	Origin and tectonometamorphic evolution of the MM ophiolites; new geologic and petrologic data on selected mineralizations, evidence of Jurassic hydrothermal activity.	Bibliographic research; fieldwork and geologic-stratigraphic, structural, geomorphologic mapping; field survey of biodiversity; structural analysis and tectonostratigraphy; digital techniques and Information Technologies (IT) applications; petrography (transmitted and reflected light optical microscopy); mineral chemistry (SEM-EDS, μ -Raman spectroscopy, μ -fluorescence); geochemistry; petrologic modeling; fluid inclusion study; mineralogy; crystal chemistry; diffraction analyses; structural and submicrometric morphological investigations by TEM-EDS	To show, describe and explain the preserved evidence of the fossil ocean, as well as the birth and development of an orogenic chain. To place Cu-Fe mineralizations in the framework of the paleo-ocean floor.	Concepts and design of panels and of a number of geological paths along the most interesting and representative cross sections of the MM. Description of representative geosites of the different phases of the alpine evolution. Description of geological transformations in space and time in talc mine galleries of the Germanasca Valley. Organization of a database to be used for museal purposes. Selection of representative samples for expositions.	Parco del Po Cuneese (Saluzzo). Museo Regionale di Scienze Naturali (Torino). Comunità Montana Valli Chisone e Germanasca. ScopriMiniera – Ecomuseo Regionale delle Miniere e della Val Germanasca. "ScopriAlpi" in the framework of the Alpi Cozie geopark project. Museo del Piroppo (Martiniana Po). Italian Micro-mineralogical Association (AMI). Rifugio Quintino Sella (Lago Grande di Viso).	Geologic, petrographic and mineralogic database; web page; scientific papers; thematic chapters in a Geosite volume; cartoons representing the geological structure and evolution of the Alps; exposition of investigated samples and laboratory activities during "The Nighth of the Researchers"; definition of contents for the popular diffusion of knowledge (brochures, information panels, etc.)
2) Lithostructural units of the Dora-Maira Unit and Piemonte domain from Susa to Varaita Valley.	Palaeogeographic reconstruction of the Alpine realm in the Piemonte-Ligurian domain and its paleomargin; evolution and geometry of the most important mineralizations (eg talc and graphite) of the CA.	To explain how rocks deform and change their fabric and mineralogy during the building of the alpine chain.				
3) Jadeite at the MM and its prehistoric significance.	Characterization of MM jadeite and related lithologies.	To describe the first primary source of jade in the Alps, and to determine the source area of neolithic axes widespread in all Europe.				
4) Type localities for new minerals.	New minerals type localities in Val Varaita and surrounding areas.	To describe the occurrence and diffusion of jade in the Alps, first found in Val Varaita, and the Ellembergerite, Bearthite, Mg-staurolite, Mg-dumortierite in lower Val Varaita.				
5) Geomorphology of Hannibal crossing the Alps	Geomorphologic analysis of the area where Hannibal is thought to have stationed in upper Po valley.	To show the role geology may play in identifying the area, now buried under a debris flow, where Hannibal is thought to have regrouped his army while crossing the Alps.				
6) The rock-dwelling organisms on the ophiolitic rocks	Assessment of biodiversity on the different ophiolitic lithologies.	Microscopical and molecular techniques to identify the rock-dwelling organisms	Identification and ecological characterization of hot spots of biodiversity along the geologic trail.			

Fig. 12 Activities and actions for the management of the geological heritage in the Monviso Massif (MM) and the Cottian Alps (CA)

improvements of the regional geosite inventory, assessment of main thematic areas of the Piemonte region geodiversity, specialized analysis on related critical issues of earth sciences knowledge, experiments on visual representation of geological environments and processes, development of geodiversity action plans including educational impacts and promotion of a 'geodiversity economics'.

As a starting point, the first stage should be completed to inform later stages. A systematic review of inventoried geosites in the Regional Geosite Inventory by the Documentation Centre for Geodiversity and Geoconservation (Regional Natural Sciences Museum, Turin) selected, among others, the strategic geothematic area described in this paper with an approach related to 'basic geoconservation' (as defined by Henriques et al. 2011).

After this initial fundamental step, further actions described in detail by Giardino et al. (2012) will include coupling of scientific concepts and techniques with didactic interests and products focused either on geosites or on museum collections, science exhibits and nature trails. The dissemination of earth science contents to the general public will be enhanced and granted with the cooperation of the Virtual Reality MultiMedia Park (VRMMP, Torino), by using 3D virtual environments with interactive and immersive audiovisual interfaces for shedding light over many issues concerning geodiversity and geoheritage. Finally, indicators for an

integrated management system of geosites (quality, environment, landscape, occupational health and safety, social responsibility) will be considered, following the ISO standards and the European Landscape Convention.

The MM geothematic area fully represents the complex geodiversity of the Piemonte region and is characterized by a high potential for scientific studies, enhancement of public understanding of science, recreation activities and, last but not least, economic support to local communities. Moreover, the MM and the Cottian Alps are wonderful places to test and promote different actions for the management of the geological heritage in the Piemonte region (Fig. 12).

Concerning the MM itself, a number of possible scientific research actions include: (i) to improve the knowledge about the geologic origin and the tectonometamorphic (P-T-X) evolution of the Monviso ophiolites and (ii) to acquire new geologic, petrographic and petrologic data on selected mineralizations, considered as evidence of hydrothermal activity of the Jurassic Age. Regarding geological concepts and 'geodiffusion' interests, we aim the following: (i) to show, describe and explain the preserved evidence of the fossil ocean; (ii) to explain the birth and development of an orogenic chain; and (iii) to emphasize that the Cu-Fe mineralizations are the products of an exhalative activity on the palaeo-ocean floor, strongly similar to that occurring in the present-day oceanic domains. Planned geodiffusion actions include

concepts and design of a number of geological paths along the most interesting and representative cross sections, mostly devoted to showing features of the palaeo-ocean floor. In the nearby area, where the first primary source of jade in the Alps was recognized at Punta Rasciassa, we aim to show and describe this recently discovered outcrop of jade by means of a detailed petrographic characterization of jadeite and related lithologies, in order to determine the source area of the characteristic neolithic axes which are widespread across Europe. Geodiffusion actions will also include concepts and design of a number of panels to be placed in the source area at the foot of Punta Rasciassa in the MM.

For the Cottian Alps, acquisition of new structural, lithostratigraphic and petrographic data are planned for: (i) a palaeogeographic reconstruction of the Alpine realm with special regard to the Piemonte-Ligurian domain and its palaeomargin and (ii) reconstruction of the evolution and geometry of the most important mineralizations (e.g. talc and graphite) of the Cottian Alps. Among the geological concepts and geodiffusion interests, we aim to explain how: (i) the Alpine chain was built and (ii) rocks deformed and changed their fabric, mineralogical composition and structural position during the building of the Alpine chain. Geodiffusion actions will include the description of representative geosites of the different phases of the Alpine evolution, as well as description of geological transformations in space and time in the disused talc mine tunnels of the Germanasca Valley.

In the realm of new minerals discovered in the MM and surrounding areas, the TL of carlosturanite at Sampeyre, Val Varaita and other minerals as for instance the ellenbergerite, bearthite, magnesio-staurolite and magnesiodumortierite in lower Val Varaita will be considered. We shall disseminate awareness about mineral TLs in Val Varaita and the surrounding areas to visitors and the local people, by describing the occurrence and origins of these minerals in the selected area, and by characterizing mineral varieties (e.g. asbestiform versus elongated). Geodiffusion actions will also include organizing and producing a database for museums as well as selecting representative samples for temporary or permanent exhibitions.

In order to emphasize the possible contribution of geomorphology to reconstructive geoarchaeology, we will consider the area, now buried under debris flow sediments, where Hannibal is thought to have regrouped his army while crossing the Alps (in the upper Po Valley, downstream from the mountain pass Colle delle Traversette in the Cottian Alps, north of MM). By means of geomorphological mapping supported by digital techniques and information technology (IT) applications, we aim to show the role geology may play in identifying this area.

Last but not least, the rock-dwelling organisms on the ophiolitic rocks can add a very interesting contribution to the development of geological heritage in the MM ophiolites. The

biodiversity of lichens, microfungi and cyanobacteria colonizing the ophiolites will be considered; they can give additional value for the environmental assessment and valorization of the MM outcrops. In order to assess the biodiversity on different ophiolitic lithologies, we plan to constrain the influence of structural and compositional petrographic features on the development of different (micro-) organism communities. Geodiffusion actions will also include identification and ecological characterization of hot spots of biodiversity along the geological trail.

As an ‘interim’ conclusion, this study is an initial stage for enhancing knowledge of the regional geodiversity in the Piemonte region, a fundamental requirement for successful management of its geoheritage. Following geodiversity identification, further stages of the ‘PROactive management of GEOlogical heritage in the PIEMONTE region’ project will be devoted to developing appropriate plans for geodiversity conservation in this unique, but fragile area, whilst promoting a range of social, economic and environmental benefits, including the establishment of geotourism in the MM geopark.

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