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The Neolithic greenstone industry from Chiomonte (northwestern Italy): mineralogy, petrography and archaeometric implications

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Abstract. The polished stone industry of Chiomonte (Piedmont region, northwestern Italy), dating back to the Middle-to-Late Neolithic, was studied with a multi-analytical approach, including mineralogical, petrographic and morpho-typological issues, with the aim of providing information about the supply sources of the raw materials and determining the function of the settlement in the prehistoric Western Alps setting. Most of the lithic tools are made of stricto sensu greenstones (i.e., 'Na-pyroxene rocks' and 'Na-pyroxene + garnet rocks'), though a large amount of serpentinites (25 %) also exists. The combined application of XRPD, polarizing microscopy and SEM-EDS led to the detection of specific mineral/chemical 'markers', pointing to a likely provenance of the Chiomonte tools from the Monviso area. However, other closer supply sources – e.g., small meta-ophiolite units in the Orsiera-Rocciavré mountain range or in the lower Susa valley – cannot be ruled out. The presence, on the many retrieved roughouts and broken tools, of raw, yet unpolished surfaces ascribable to pebbles and cobbles from alluvial or glacial deposits, suggests that these rocks had been picked up from local 'secondary' sources. The abundance of roughouts and broken tools identifies Chiomonte as a second-order/manufacturing site, although it is still unclear whether such an activity was restricted to the local needs or rather contributed to the circulation of greenstone implements on a wider scale.

1 Introduction

In the Neolithic, mankind abandoned nomadism and settled permanently in flat lands, dedicating to agriculture and stock raising and passing from the use of the splintered to the polished stone. Most lithic implements (axes, chisels and hatchets) have been found in archaeological sites spread all over Europe – and especially in the Po plain and Western Alps. These tools underwent a vast circulation – as similar relics have been found in southern France, southern Italy, Great Britain (Pétrequin et al., 2002), Slovakia, Czech Republic, Hungary, (Spišiak and Hovorka, 2005; Pétrequin et al., 2011; Bendő et al., 2014; 2019), Austria, Bulgaria, Denmark, Germany, Spain (Tsonchev, 1946; Přichystal and Trnka, 2001; Errera et al., 2006; Pétrequin et al., 2008) and Malta (Mancusi, 2017). They are mostly made of stricto sensu greenstones, i.e. high-pressure (HP) metaophiolites marked by toughness and high density (Ricq-de-Bouard, 1993; Giustetto et al., 2008; D'Amico and Starnini, 2009; 2011), mostly consisting of Na/Ca-pyroxenes, i.e. solid solutions of jadeite (Jd), omphacite and aegirine (Ae). Giustetto and Compagnoni (2014) divided these rocks in two groups: 1) ‘Na-pyroxene rocks’, commonly referred to as ‘jades’, including jadeitite (with 95-100 vol% jadeite), omphacitite (with 95-100 vol% omphacite) and mixed Na-pyroxenite (with intermediate amounts of jadeite and omphacite); 2) ‘Na-pyroxene + garnet rocks’, made of omphacite plus garnet, including eclogite (with omphacite and garnet in 25 to 75 % mutual amounts), garnet-omphacitite (with 5-25 vol% garnet) and omphacite-garnetite (with 5-25 vol% omphacite). Actually, the term ‘jade’ includes ‘jadeite jade’ (made of jadeite, NaAlSi2O6) and ‘nephrite jade’ [made of an amphibole of the tremolite–ferro-actinolite series: Ca2(Mg,Fe)5Si8O22(OH)2]. Only the former will be treated here, though ‘omphacite jade’ [made of omphacite, (Ca,Na)(Mg,Fe2+,Al)Si2O6] will be considered too (D’Amico et al., 2004; Ou Yang, 2006; Ou Yang et al., 2011; McClure, 2012).

These greenstones occur in the alpine geological context as rare and small ‘primary’ outcrops (few m3) at high altitude, mainly in the Monviso and Voltri massifs (D’Amico, 2005; Pétrequin et al., 2005a, 2005b, 2006; Compagnoni et al., 2007; 2012), or as boulders and pebbles/cobbles in ‘secondary’ alluvial deposits, derived from the dismantlement in the neighboring downhill regions (Compagnoni et al., 2006; D’Amico and Starnini, 2006; D’Amico and De Angelis, 2009). The pioneering studies of Gastaldi (1871), Damour (1846) and Franchi (1900) have shown that these greenstones belong to the Internal Piemonte Zone, which includes meta-ophiolite units derived from the Liguria–Piemonte oceanic domain, characterized by alpine metamorphism under eclogite-facies conditions (Compagnoni, 2003). Moreover, jadeitites and omphacitites are also found in Queyras, a typical blueschist facies area located in the External Piemonte Zone (Caron and Saliot, 1969; Harlow et al., 2014). Locating the supply sources of the raw materials used to produce these artifacts (whether from the Monviso or Voltri ‘massifs’) and their nature (whether from ‘primary’ outcrops or ‘secondary’ deposits) represent important issues, as they might allow reconstructing the manufacturing techniques and ancient migratory fluxes or trade routes (Chiarenza and Giustetto, 2010; D’Amico et al., 1992, 1997, 2013; Pétrequin et al., 2017b). Such a goal can be pursued only by comparing the distinctive mineralogical and petrographic features of these tools with those of analogous geological samples of known origin, searching for common traits that may hint the same provenance. Other lithotypes – such as serpentinites, prasinites and chloritites (occasionally also termed as greenstones, due to their hue) – were seldom used to produce these tools. However, due to their ubiquitous distribution in the Western Alps, they have limited archaeometric relevance. This study deals with the characterization of the polished greenstone industry from the archaeological site of Chiomonte – La Maddalena, near Torino, northwestern Italy (Figs. 1.a, b). Over 130 stone implements were investigated with a well-established analytical protocol, thus allowing archaeometric considerations.

2 Materials and methods

2.1 Archaeological case study and materials

The archaeological site of Chiomonte – La Maddalena (The Magdalene) was discovered in 1985, while excavating for the Fréjus highway, and explored by the local Archaeological Superintendence during three campaigns. The site, inhabited from the Middle Neolithic until the Medieval age, is positioned in the high Susa valley (718 m a.s.l.) at the base of a slope on the left side of the Dora Riparia river (Fig. 1.b), sheltered by big boulders of an ancient landslide deposit. The so-called 'La Maddalena' site corresponds to a terraced surface on fluvioglacial deposits close to the Clarea stream, which flows 60-80 m downstream. The archaeological materials (ceramics, splintered and polished stone) lay directly on landslide and fluvioglacial deposits, showing two separate colluvial layers: i) a lower, muddy/sandy level, conserving traces of anthropic activity; ii) a superficial, gravelly/pebbly layer, with landslide blocks in the upper portion and strongly muddled up archaeological goods. An area of about 12500 m2 at the base of the slope was stratigraphically investigated, thus uncovering a significant number of structures and artifacts, pertinent to a multiphase settlement dating back to the Middle/Late-Final Neolithic. The importance of the site is due to the frequent relationships that occurred between the end of the 5th/first half of the 4th millennium BC with other cultures on the French and Swiss sides of the Western Alps, especially in the high and medium Rhône valley (Padovan, 2017). The polished stone industry of Chiomonte consists of 132 objects, mostly in greenstone, mainly represented by instruments for cutting (i.e., axeheads, with some hatchets and scalpels). All different steps of the manufacturing chain are represented, including several tool fragments and/or roughouts. Few are the finished objects, whilst some pebbles are also present. The collection was held in the archaeological museum of 'La Maddalena – Chiomonte', recently closed due to the turmoil connected with the construction of the high-speed train line from Turin to Lyon. Since then, it has been transferred to the deposits of the Antiquity Museum in Turin.

2.2 Methods

All 132 retrieved implements were analyzed with a well-established protocol, involving archaeological (morpho-typological exam) and archaeometric (non-invasive mineralogical-petrographic analyses) methods, aimed at obtaining a statistical screening about their functionality and lithology. Furthermore, a more restricted number of tools – basing on their lithotype and mineral-petrographic features – was selected for micro-invasive mineral-petrographic analyses. Although alternative non-destructive approaches have been recently used (e.g., SEM-EDX to infer the chemistry from the tools surface and prompt-gamma activation to obtain their bulk elemental composition without any sampling: Bendő et al, 2014; 2019; Váczi et al., 2019), a micro-invasive protocol was preferred, so as to avoid severe limitations on the area of analysis and dispose of unbiased data. This sacrifice was counterbalanced by restricting such exams, which include X-ray powder diffraction (22 specimens), optical polarizing and scanning electron microscopy (12 specimens, representative of the previous ones; Chiari et al., 1996; Compagnoni et al., 2006; Giustetto et al., 2008), only to roughouts and broken/fragmented artifacts, in order to preserve the integrity of the few finished tools. Small cores (10 mm diameter) – representative at best of the rock composition – were extracted with a diamond crown drill and used to prepare powders and 30 µm polished thin sections. These analyses were aimed at pointing out typical mineral-petrographic 'markers', to be compared with those already described in the literature for analogous geological samples of known origin.

X-ray powder diffraction (XRPD) data were collected in the 3-70° 2θ range, using an automated Siemens D-5000 diffractometer with $\theta/2\theta$ setup in Bragg-Brentano geometry, CuKα radiation and zero-background, flat sample holder. Data were processed with the Diffrac Plus (2005) software (EVA 11,00,3).

Polarizing microscopy was performed on a Zeiss WL Pol optical instrument. Scanning electron microscopy (SEM) was performed with a SEM Stereoscan 360, Cambridge Instrument, on carbon-coated thin sections. Chemical characterization was performed by an EDS Link Pentafet, Oxford Instrument (operating conditions: 50 s counting time, 15 kV accelerating voltage, 25 mm working distance, 300 pA beam current). The collected data were processed with the INCA 200 Microanalysis Suite Software, version 4.08, calibrated on natural mineral standards using the ZAF correction method.

3 Results

3.1 Morpho-typological examination

The raw processing state and fragmentary conditions of the Chiomonte tools (especially axes and hatchets) allow only preliminary typological considerations, due to difficulties in checking their effective dimensions (length, width and thickness), upon which the existing classifications are based (Pedrotti, 1996). However, the studied tools and roughouts (132, some of which are shown in Fig. 2a) can be classified, basing upon their functionality and traces of manufacture/use, mostly as implements for cutting (axes, 52 % – but also hatchets and chisels, 10 %), with a few apt for striking (percussors, 5 %) or abrading (grindstones and millstones, 3 %). Some instruments with ornamental or playing purposes (pendants and taws, 5 %) have also been found. Finally, numerous splinters, unspecified fragments and/or pebbles (22 %) and a few residual samples with no plausible function (3 %) are found (Fig. 2b). As far as instruments for cutting are concerned, few complete and finished artifacts exist (8 out of 82 total), with small to moderate dimensions, whilst the number of roughouts and fragmented tools (probably broken during manufacture and/or after use) is significant (58). Table S1 (freely available online in the Supplementary Material linked to this article at https://pubs.geoscienceword.org/eurjmin) lists, for each implement, the inventory label(s) and presumed typological function.

3.2 Density measurements and stereomicroscopy examination

Density values were determined with a precision balance (weighing each tool in air and in water; Compagnoni et al., 2006) for 119 (out of 132) artifacts, by excluding those too small to obtain reliable measurements. All implements were also examined with a stereomicroscope in reflected light, on wet and polished surfaces (if present), in order to evaluate their mineral grain-size, heterogeneities and microstructural features. A preliminary lithotype determination was thus achieved (see Supplementary Material, Table S1).

The density histogram for greenstones (Fig. 3.a) shows a sharp distinction between HP-metaophiolites stricto sensu (i.e., 'Na-pyroxenites' and 'Na-pyroxene + garnet rocks', usually > 3 g/cm3) and other lithotypes – similar to the naked eye (i.e., serpentinites and prasinites, with densities usually □ 3 g/cm3). Eclogites show higher densities (mostly between 3.4 and 3.6

g/cm3), partially overlapping the slightly lower ones for jadeitites, omphacitites and mixed Na-pyroxenites (varying between 3.2 and 3.5 g/cm3). The lithotype distribution (Fig. 3.b) is rather heterogeneous, with serpentinite as the most abundant rock (25 %). Globally, stricto sensu greenstones represent 50 % of the tools; among them, mixed Na-pyroxenite (almost 24 %) is the most abundant rock, followed by eclogite (19 %). Jadeitite and omphacitite are scarce (2 and 3 %, respectively), as well as garnet-bearing omphacitite (2 %). Basing on the average distribution, 22 samples were selected among the roughouts and broken/fragmented tools for micro-invasive analyses (Table 1).

3.3 X-ray powder diffraction

With this technique, the mineralogical composition of the 22 selected samples was determined and confirmed their lithotypes. A rough measurement of the reflections intensities for the crystalline phases is also reported, prompting semi-quantitative evaluations (Table 2).

Sixteen samples are made of stricto sensu “greenstones”, the rest being related to other less representative (e.g., chloritites and serpentinites) or peculiar lithologies. ‘Na-pyroxene rocks’ are made of a single pyroxene with a well-defined composition (jadeitite and omphacitite), or two pyroxenes in almost equal amounts (mixed Na-pyroxenite), with scarce or no minor phases. The three main pyroxene reflections – -221, 310 and 002 – are well defined in jadeitite (Fig. 4a) and omphacitite (Fig. 4b), while in mixed Na-pyroxenite they are split due to presence of both jadeite and omphacite, each with a complex zoning (Fig. 4c). In ‘Na-pyroxene + garnet rocks’, the reflections of garnet also appear – evident in eclogite (Fig. 4d) but hardly visible in garnet-bearing omphacitite (Table 2). In sample 5747, the reflections of garnet prevail over those of other phases (omphacite, plagioclase and minor clinochlore and amphibole) – thus suggesting a peculiar composition.

The chemistry of Na-pyroxene solid solutions may be estimated from the dhkl values of their main reflections (-221, 310, 002). When transferred on the grid proposed by Giustetto et al. (2008), superposed to the Jd-Q-Ae diagram of Morimoto et al. (1988), these values lead to an average composition affected by a mostly restricted error (Fig. 5a, b and c).

3.4 Polarizing microscopy and SEM-EDS

The petrographic approach, despite its micro-destructivity, is fundamental to identify compositional mineral zoning and micro-structural heterogeneities of these rocks, together with the chronological relationships among different pyroxene (and garnet) generations. Moreover, the petrographic study allows identifying minor phases, undetected by XRPD. All these features are essential for the comparison between data collected on prehistoric tools and geological specimens of known provenance, in order to trace the origin of the raw materials (Giustetto et al., 2017). Twelve thin sections were obtained from as many tools in stricto sensu greenstone already inspected by XRPD, namely:

• 5 ‘Na-pyroxene rocks’ [2 jadeitites, 1 omphacitite and 2 mixed Na-pyroxenite];

• 7 ‘Na-pyroxene + garnet rocks’ (4 eclogites and 3 garnet-omphacitites).

The chemistry and zoning of pyroxene and garnet were studied by plotting EDS data in the ternary diagrams of Morimoto et al. (1988) (Fig. 5a, b and c) and almandine (Alm) + spessartine (Sps) – grossular (Grs) – pyrope (Prp), respectively (Fig. 6).

Table 3 provides the semi-quantitative mineralogical composition obtained for each sample by combining XRPD, polarizing microscopy and SEM-EDS. Selected EDS analyses for pyroxene and garnet are reported in the Supplementary Material (Tables S2 to S20).

3.4.1 Na-pyroxene rocks: jadeitites

The 3788 axehead fragment is a typical jadeitite with granoblastic structure and faint foliation, marked by jadeite crystals with a complex zoning and including greener omphacite domains. Locally, the Jd crystals show 'dusty' cores or small, iso-oriented linear exsolutions of omphacitic nature (Fig. 7a), together with scarce opaque ores. The SEM-EDS analyses proved that these omphacitic domains have a rather low Ae content (< 20 %; Table S2). Green-to-bluish amphibole coupled to apatite, titanite, zircon and biotite occur as minor or accessory phases. The other sample (CMIX/81; axe heel) is marked by crumbled Jd crystals (hundreds of μm across), partly retrogressed with a 'dusky' aspect (Fig. 7.b), and albite. SEM-EDS investigations indicated that the jadeitic matrix includes tiny and irregular omphacite exsolutions, with no (or little) Ae. White mica (paragonite), together with clinozoisite, nepheline and titanite also occur.

3.4.2 Na-pyroxene rocks: omphacitites

The studied artifact (4360; axehead fragment) is quite homogenous and fine-grained, with an incipient mylonitic microstructure. Small green and zoned omphacite crystals (≈ 50 μm) locally have tiny, iso-oriented darker inclusions (Fig. 8.a). The SEM images show a complex pyroxene zoning, with older Ca/Mg richer domains (brighter in BSE) being surrounded by a younger, Na/Al richer matrix (darker; Fig. 8.b). Spot analyses clearly indicate an omphacitic composition, with a wide range of Ae content (10 to even 40 %; Table S4). Zircon is the only accessory phase.

3.4.3 Na-pyroxene rocks: Mixed Na-pyroxenites

The two studied specimens are similar. The 6636 axe heel exhibits an evident foliation, defined by the alignment of abundant rutile, commonly forming aggregates. The very fine grained pyroxene matrix shows a complex zoning, appreciable only at high magnifications, with a dual distribution of colourless jadeite and greenish omphacite (Fig. 9.a). At SEM, such a zoning shows in some areas the presence of darker jadeite 'relics', corroded by a younger omphacite (Fig. 9.b).

The 7179 axehead fragment is also fine-grained, though some stumpy pyroxene crystals locally occur, commonly wrapped out by shear zones marked by the preferred orientation of finer-grained, iso-dimensional crystals. The only accessory minerals are rutile and zircon. The distribution of EDS spot analyses covers an almost continuous range between the jadeite and omphacite fields. The aegirine content is usually less than 20 % (Table S6).

3.4.4 Na-pyroxene + garnet rocks: eclogites

Three (out of the four) analyzed eclogites (3088, 5653 and 67142/8936) show fine to very fine-grained omphacite matrix, commonly with mylonitic structure. When observed at the polarizing microscope, pyroxenes show a strong zoning – their colours varying from pale to deep green (Fig. 10.a). The EDS data confirm this heterogeneity, the related spot analyses being scattered in the omphacite field (Wo + En + Fs20-50 with Ae10-40; Tables S7, S9 and S13). Jadeite is rare: only in sample 3088, small domains of impure Jd, including small 'blebs' of exsolved omphacite, are surrounded by an omphacite matrix. Locally, pyroxene crystals show a peculiar yellowish to green/bluish pleochroism. A foliation is evident, marked by the abundant rutile (or pyroxene) crystals. Garnet (≈ 100 μm across) forms packed aggregates and show a typical atoll-like aspect; a greener pyroxene is locally observed inside the atoll (Fig. 10.a, b). The garnet chemistry is quite constant, with higher Alm + Sps content (70-80 %) and minor pyrope (20-30%) and grossular (< 10 %; Tables S8, S10 and S14). Occasionally, retrogression zones are observed converting both omphacite and garnet into green amphibole. White mica, ilmenite, (rare) sulfides and apatite occur as minor or accessory phases.

The last sample (7144; axehead fragment) differs from the others due to the larger pyroxene grain-size (hundreds of μm across), including both omphacite and jadeite. Fractured garnet crystals, with no atoll-like habit, form scattered aggregates; large and scattered rutile crystals (hundreds of μm across) occur as an accessory phase (Fig. 10c). SEM-EDS analyses showed that relict Jd crystals, including tiny exsolved omphacitic 'blebs', are corroded by younger zoned omphacite (Fig. 10d). Jadeite is rather pure (≈ Jd90), with no or very small Fe-content. The distribution of omphacite analyses is quite scattered (Ae10-20), confirming its marked zoning; garnets are almandine (Alm-Sps80), with minor pyrope (around 10-20 %) and grossular (< 10 %; Tables S11 and S12).

3.4.5 Na-pyroxene + garnet rocks: garnet-omphacitites

All findings of this lithology – a broken axe heel (3975) and two fragments (5319, 7736) – were analyzed. The 3975 sample has granoblastic structure with mylonitic portions, in which porphyroclasts (hundreds of μm across) of a relict magmatic pyroxene exhibit dusky cores and contain deformed ilmenite inclusions (Fig. 11.a). The matrix, rather homogeneous, has omphacitic composition with Ae10-20 (Table S15). In the mylonitic domains, a moderate zoning occurs with scattered spots in the aegirine-augite field. Single, fractured Alm+Sps rich (70-80 %) garnets with relict appearance, possibly developed after the mylonitic fabric, occasionally overgrow the porphyroclasts. Pyrite, rutile and ilmenite are the only accessory phases. In sample 5319, the microstructure is isotropic, with fragmented and irregularly shaped omphacite crystals (hundreds of μm wide) having a rather homogeneous chemistry. Garnet is scarce and fractured. Apatite and titanite are accessory phases. In 7736, the fine-grained pyroxene matrix shows coexistence of both jadeitic and omphacitic domains, with complex mutual relationships. Locally, omphacite seems older than jadeite, because it appears in the core of larger crystals (Fig. 11.b) – in opposition to what observed elsewhere (e.g., in 6636 and 7144; Sections 3.4.1.3 and 3.4.2.1). The scattered distribution of EDS analyses confirms the observed zoning, with Ae up to 30 %. Scarce and isolated garnets are rich in Alm-Sps (up to 90 %) and poor in Grs (< 5 %; Tables S19 and S20). Rutile and interstitial ilmenite occur as accessory phases.

4 Discussion

4.1 Mineralogical/petrographic considerations and provenance issues

In the Chiomonte lithic industry, the fraction made of stricto sensu greenstones (‘Na-pyroxene rocks’ and ‘Na-pyroxene + garnet rocks’) is large (around 50%) though less conspicuous than elsewhere (e.g., in Brignano Frascata; Giustetto et al., 2017). Serpentinites are quite abundant. This is an uncommon occurence, rarely observed in other sites (e.g., Villaromagnano; Giustetto et al., 2017), and may suggest a certain scarceness of HP-greenstones in the areas surveyed for the retrieval of raw materials. Such a possibility has been suggested by Mancusi (2016) and contextualized by D’Amico (2012), who pointed out the scarcity of these tougher lithotypes in the northern Monviso ‘massif’ (close to the inspected site; Fig. 1.b). An alternative explanation might be a reduced skill of the local gatherers in tracing those rocks apt to produce better tools. A further oddity in Chiomonte is represented by the assorted fraction of tools made of rocks other than greenstones (25%, including quartzite and marble, hardly found in other sites), which may further support the inference about the local scarcity of more suitable lithotypes.

‘Na-pyroxene rocks’ prevail on ‘Na-pyroxene + garnet rocks’ (29 vs. 21 %). Such a trend, though locally seen elsewhere (e.g., Brignano Frascata; Giustetto et al., 2017), is opposite to what observed in most sites (i.e., Alba, Castello di Annone, Gaione, Ponte Ghiara, Rivanazzano, Rocca di Cavour, Sammardenchia and San Lazzaro di Savena; Mannoni and Starnini, 1994; D’Amico et al., 1995; 1997; 2013; D’Amico and Ghedini, 1996; D’Amico and Starnini, 2000, 2012b; Andò, 1998; Bernabò Brea et al., 2000; Borgogno, 2000; Giustetto et al., 2016) – in which eclogites dominate, even reaching 66 %. ‘Na-pyroxene rocks’ (with ‘mixed Na-pyroxenite’ being the prevailing rock) are quite abundant with respect to other sites (e.g., Sammardenchia and Rivanazzano), where these ‘jades’ are □ 10 %.

From a mineral/petrographic point of view, accurate comparison can be done between the Chiomonte tools and those from other coeval sites. Besides, the same data can also be related to analogous geologic material of known provenance, in order to infer analogies or differences and retrieve information about the location of the raw material supply sources. Of course, the reliability of such a survey increases if samples analyzed with analogous protocols are compared. This is the reason why, in the following, studies that followed analytical procedures similar to those adopted here (e.g., D’Amico, 2012; Giustetto et al., 2016; 2018) will be kept into account more than others, based on different approaches (i.e., visual appearances to the naked eye or non-invasive analytical methods, such as spectroradiometry; Errera et al., 2012, Pétrequin and Errera, 2017). The latter studies, although providing databases with hundreds of entries (Pétrequin et al., 2012b), offer less reliable mineral/petrographic information. Also, it is known that, on average, jadeitites, omphacitites and mixed Na-pyroxenites are hard to discriminate with no instrumental support (XRD, at least) and virtually indistinguishable by visual methods alone (D’Amico, 2012). Similar difficulties arise for eclogites, their garnet often being fine grained (especially in greenstone tools). Moreover, eclogites are hardly recognizable from omphacitites with spectroradiometry, their spectra not being distinctive enough (Errera et al., 2012; Pétrequin et al., 2012b; Pétrequin and Errera, 2017). In this perspective, the high number of roughouts and broken implements becomes an important issue, as micro-invasive mineral/petrographic analyses might be restricted to these ‘unfinished’ or

incomplete tools – more ‘expendable’ than their complete counterparts. This might allow the detection of distinctive (albeit not easily traceable) ‘markers’, essential to provide hints about a possible provenance – hardly attainable otherwise.
A remarkable feature of the Chiomonte greenstone tools concerns the scarcity of white mica(s), almost absent in all studied samples (with the exception of CMIX/81, in which paragonite occurs in moderate amounts) albeit regularly detected (by XRPD and SEM-EDS) in tools from the sites of southern and southeastern Piedmont (Castello d'Annone, Brignano Frascata, Momperone and Villaromagnano; Giustetto et al., 2016; 2017). The systematic presence of white mica has also been ascertained in most greenstone geologic specimens from the ‘secondary’ deposits of the Beigua ‘massif’ (feasible supply sources for the southeastern Piedmont sites; Giustetto et al., 2018). Also, such a mineral has been hardly reported in samples from ‘primary’ and/or ‘secondary’ deposits in the Monviso ‘massif’ and Po valley (Váczy et al., 2019) – i.e., the areas that might better suit, geographically, the reservoir for the supply of raw materials by the local gatherers; only in the southern Monviso ‘massif’ (i.e., opposite to Chiomonte), K-micas (such as phengite and muscovite) were seldom observed (D'Amico, 2012). Hence, the absence of white mica(s) might support an origin of the Chiomonte tools from the Monviso. In this respect, detection of white micas (even by XRPD) might indeed represent a general ‘marker’ in order to preliminarily infer the provenance of a given implement from a certain supply area – i.e., the Beigua (Voltri) or Monviso ‘massifs’ – where they are either abundant or rare, respectively. However, such an opinion is not shared by others, according to which this issue (especially when muscovite is concerned) should not be considered discriminant (Pétrequin et al., 2012b). Similarly, chlorite is frequently observed in geological samples and artifacts of Beigua origin (Giustetto et al., 2017; 2018), but rare in the Chiomonte tools (Tables 2 and 3). Even then, detection of chlorite as a ‘marker’ for an origin from Monviso is debated (Pétrequin et al., 2012b).
The mineralogy of CMIX/81 (axe heel) is intriguing: in addition to tiny omphacitic exsolutions (reminiscent of those described by Schertl et al., 2012) and paragonite, discrete amounts of albite also appear. Its marked alteration and low density (3.18 g/cm3) is consistent with those of a ‘retromorphosed jadeitite’ (D'Amico, 2012) – an issue typical of geological samples from the southern Monviso or the central Voltri ‘massifs’. Similar features occur also in 67138/4148 [Fig. 2a, (iii), Table S1], not analyzed in depth being one of the few complete artifacts.
Another ‘marker’ might be represented by the pseudomorphs of (white mica + epidote) after lawsonite, systematically observed in greenstone tools from the lower Piedmont and Lombardy sites (e.g., Castello di Annone, Brignano Frascata and Rivanazzano: D'Amico and Starnini, 2012a; Giustetto et al., 2016, 2017) as well as in geologic samples from the areas of presumed supply (Giustetto et al., 2018), but apparently lacking in the Chiomonte artifacts. Presence of these pseudomorphs in greenstone rocks from the Monviso ‘massif’ is disputed: according to some authors, they should be typical of this area (especially in omphacitites and eclogites; Pétrequin et al., 2012b), whereas others do not report them neither in the Monviso nor from ‘secondary’ deposits in the Po valley (Váczi et al., 2019). Moreover, the presence of rutile and apatite in the Chiomonte greenstone tools (Table 3) is open to interpretation: the former, considered as a ‘marker’ of Monviso provenance (D'Amico, 2012), is also observed in most Brignano Frascata tools of presumed Voltri (Beigua) origin (Giustetto et al., 2017); the latter, believed as symptomatic of a Beigua source (Pétrequin et al., 2012b), was also detected in greenstone pebbles from alluvial sediments of the Po valley (Váczi et al., 2019). Green-to-bluish pyroxene crystals, similar to those observed in

Chiomonte, have also been reported in the Castello di Annone tools (Giustetto et al., 2016). This may suggest either a common source for the raw materials or that trade relationships occurred between these sites, which is consistent with their coeval dating (from the Middle Neolithic on). However, similar pleochroic crystals appear also in the tools of other sites located eastwards (Giustetto et al., 2017). Moreover, the bluish hue of the Castello di Annone pyroxenes is justified by relatively high Ti-contents (TiO_2 up to 5 wt%), whereas lower ones (TiO_2 < 1 wt %) appear in the Chiomonte artifacts.

Garnets with an atoll-like habit similar to the eclogite tools from Chiomonte are also described in the Castello di Annone artifacts, further supporting the hypothesis of a common origin or occurred trade/exchanges. Such a habit is quite common in garnets from the Monviso, albeit rarer in those from Beigua. Moreover, lack in the Chiomonte tools of Qtz-Ab-jadeitites and omphacite schists – rocks found only in the Voltri massif (D'Amico and Starnini, 2006; D'amico, 2012; Pétrequin et al., 2012b) – corroborate a possible origin from the Monviso. The most compelling evidence about the provenance of the Chiomonte artifacts is the total absence of glaucophanite in the many heterogeneous artifacts made of rocks other than greenstones (Fig. 3.b). As inferred by Pétrequin et al. (2012a), the lack of this lithotype, which is found only in the Voltri 'massif' (D'amico, 2012), strongly supports an origin from the Monviso area.

Most mineral/petrographic features of the Chiomonte tools indicate therefore the nearby Monviso 'massif' as the feasible area of provenance. However, some closer areas cannot be ruled out a priori, such as the Rocciavré and the lower Susa-Lanzo valleys-Orsiera (SLO) meta-ophiolite units (e.g. Cadoppi et al., 2002), cropping out on the left (northern) side of the middle and lower Susa Valley and in the Orsiera-Rocciavré mountain range, between the Susa and Sangone valleys – within 20 km as the crow flies from Chiomonte (Fig. 1b). These units were also affected by eclogite-facies metamorphism during the Alpine orogeny. 'Primary' outcrops of Na-pyroxene rocks are rarely reported there: a dm-thick omphacitite layer occurs at Balangero mine, at the contact between the gneisses of the Sesia–Lanzo Zone and the serpentinites of the northern part of the Lanzo ultramafic 'massif', belonging to the SLO Unit (Compagnoni and Sandrone, 1986); there is no known occurrence of jadeitite. Nonetheless, scarce and small 'jade' boulders have been reported from the alluvial and glacial deposits of the Susa Valley and of the Rivoli-Avigliana end moraine system at the outlet of the same valley (Piolti, 1898-1899; 1901-1902; Franchi, 1903; Pétrequin et al., 2012a, 2012b).

A peculiarity of Chiomonte is the retrieval of ornamental and playing objects, hardly found in other sites, made of chloritite [pendants; Fig. 2.a, (v) and (x)] and serpentinite [taws; Fig. 2.a, (ix)] – 'softer' lithotypes easier to model. A careful selection of raw materials might thus have been operated by the Chiomonte craftsmen, depending on their purposes: probably, stricto sensu greenstones were intended for instruments for cutting, because of their particular toughness (still, the abundance of serpentinite in these tools suggests that this interpretation should be taken cautiously). Finally, the 5747 axehead fragment shows a peculiar mineralogical composition with abundant garnet, predominant over plagioclase, chlorite and amphibole, with only few omphacite. Such a composition may be ascribed to an 'omphacite-garnetite' (see Table 2) – a peculiar lithology actually considered by Giustetto and Compagnoni (2014) in their petrographic classification of HP-metaophiolites, but never found before in a greenstone archaeological implement (Giustetto et al., 2018).

4.2 Archaeological issues and archaeometric implications

The Piedmont region represents an important area for analyzing the trade and exchange circuits of greenstone artifacts that spread over Europe during Neolithic, being bordered at the West and South by the Monviso and Voltri 'massifs', respectively (the two main sources of supply in the Western Alps; Pétrequin et al., 2005a; 2006; Lunardi, 2008a; Pétrequin and Pétrequin, 2012; Pétrequin et al., 2012b; 2012a; 2012c; Forno et al., 2015). The relatively small set of polished tools from Chiomonte is considered to have utilitarian purposes in a sort of 'habitat' environment (Pétrequin and Pétrequin, 2017). A peculiarity is represented by the absence of disc-rings, retrieved instead elsewhere (e.g., Brignano Frascata, Villaromagnano, Momperone; Giustetto et al., 2017), coupled to the recovery of playing objects (taws) in serpentinite, seemingly exclusive of this settlement. Unfortunately, little can be inferred about their provenance, due to the ubiquitous distribution of this rock in the Western Alps (D'Amico et al., 2004; D'Amico and Starnini, 2006). Recently, most attention was devoted to the bigger (15-36 cm long), ultra-polished jade axes, used for trade and ceremonial purposes in the Western and Northern Europe (France, Germany, Benelux, and Great Britain; Pétrequin et al. 2005a, 2005b; 2017a; Zamagni, 1996, Lunardi, 2008b, Lunardi and Starnini, 2010/2011). Another important factor is the examination of the roughouts, essential in those sites where a consistent record exists (Mancusi, 2016), which may retain clues about the nature and shape of the raw materials, providing information about their origin (whether detached by thermal shocks from 'primary' outcrops at high altitude or moulded from pebbles/cobbles from 'secondary' alluvial deposits; D'Amico and Starnini, 2012b; Pétrequin et al., 2017b). The morpho-typological examination of the roughouts, splinters and broken blades marks Chiomonte as a manufacturing site. The presence of elongated chisels with parallel sides and narrow blades (mostly in eclogite) is symptomatic of an economy aimed at production purposes. On some roughouts, superficial portions (untouched by moulding and shaping) show raw surfaces, reminiscent of the cobbles or pebbles from which they had been obtained. Moreover, greenstone pebbles – raw material to be destined to further production – were found among the artifacts. Such lines of evidence indicate that most (if not all) of the materials used for these artifacts was collected from 'secondary' deposits. Their small-to-modest size further supports this assumption, also backed by chronological issues, as from the late Neolithic onwards the exploitation at high altitudes of these lithologies apparently started to decline (Mancusi, 2016). The Chiomonte site must be contextualized in the Western Alps setting, where shaping of the roughouts was carried out in areas close to the supply sources (Thirault, 2005), once collected from 'secondary' deposits in the nearby geological units. Reasonably, the period testifying the bigger expansion of the Chiomonte site stands between 4200 and 3500 B.C., similarly to what was observed in other close long-occupation settlements in France (Savoy, Tarantaise and Maurienne; Padovan, 2017).

5 Concluding summary

A thorough study was performed on the polished stone industry from the archaeological site of Chiomonte – La Maddalena, dating back to the Middle-to-Late Neolithic, with both archaeometric and morpho-typological issues. Particular care was devoted in studying the greenstone artifacts, which represent by far the most significant rock types used in the Po plain in prehistory for the production of tools – distributed even in areas very far from their sources.

A theory has been raised by archaeologists, according to which the exploitation of supply sources (from the Monviso and Voltri 'massifs') and production of greenstone tools might have induced, from the early Neolithic on, a sort of hierarchical organization. First-order sites (e.g., Alba; Venturino-Gambari and Zamagni, 1996; D'Amico and Ghedini, 1996) were meant to be important centres of supply (from both 'primary' and 'secondary' sources) and distribution, with an intense and refined production that exceeded the local needs. In Second-order sites, instead (e.g., Brignano Frascata, Giustetto et al., 2017), all the production steps (splintering, shaping and bush-hammering) were carried out, but the supplies were limited by their own needs, stocked up from local 'secondary' deposits – as testified by the moderate dimensions of the tools and roughouts derived from pebbles (the surfaces of which are somewhat preserved; Mancusi, 2016). The abundance of roughouts and broken tools indicates that Chiomonte was a second-order/manufacturing site, although it is hard to assess whether such an activity was confined to the local needs or involved in the trade, circulation and diffusion on a wider scale.

Most mineralogical and petrographic 'markers' of the Chiomonte tools suggest that the raw materials might originate from the Monviso 'massif' – though other 'local' areas cannot be ruled out. The presence of many roughouts with unmanufactured, raw surfaces and even pebbles, suggests that these rocks might have been picked up from 'secondary' sources, represented by the glacial and alluvial deposits of the adjoining valleys.

6 Author contribution

R. Giustetto and R. Compagnoni performed the mineral/petrographic analyses; S. Padovan took care of all morpho-typological descriptions; L. Barale provided an accurate characterization of the inspected geological contexts. R.Giustetto also assembled the manuscript, with contributions from all co-authors.

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Table captions

Table 1. Characterization of the 22 polished stone implements from the Neolithic site of Chiomonte *La Maddalena*, analyzed by XRPD, optical polarizing microscopy (PM) and SEM-EDS.

Table 2. Mineralogical composition of the 22 polished stone implements ('Na-pyroxene rocks', 'Na-pyroxene + garnet rocks' and 'other lithotypes') from the Neolithic site of Chiomonte – *La Maddalena*, according to XRPD [XXX: very strong reflections; XX: strong reflections; X: weak reflections; X(?): dubious].

Table 3. Mineralogical composition (vol%) of 12 polished stone implements in H*P*-meta-ophiolites (5 'Na-pyroxene rocks' and 7 'Na-pyroxene + garnet rocks') from the archaeological site of Chiomonte – *La Maddalena*, obtained by combining X-ray powder diffraction, polarizing microscopy and SEM-EDS on thin sections.

Tables

Na-PYROXENE ROCKS								
Inventory code	Excavation code (sample label)	Functional typology	Notes (from macroscopic and stereomicroscopy observations)	Density (g/cm^3)	XRD	P.M.	SEM-EDS	Picture (Fig.2a)
JADEITITE:								
=	3788	Axehead fragment	= = =	3.34	X	X	X	=
CMIX	81	Axe heel	= = =	3.18	X	X	X	=
OMPHACITITE:								
=	4360	Axehead fragment	= = =	3.36	X	X	X	=
=	6602	Splinter	Too small to obtain a reliable density	=	X	=	=	=
=	6830	Axe cutting edge	= = =	3.37	X	=	=	=
MIXED Na-PYROXENITE:								
=	6636	Axe heel	= = =	3.38	X	X	X	=
=	1548	Splinter	= = =	3.48	X	=	=	=
=	7179	Axehead fragment	Approximate equal amounts of jadeite and omphacite	3.34	X	X	X	=
Na-PYROXENE + GARNET ROCKS								
Inventory code	Excavation code (sample label)	Functional typology	Notes	Density (g/cm^3)	XRD	O.M.	SEM	Picture
ECLOGITE:								
=	3088	Axehead fragment	Eclogitic portions with atoll-like garnets and sulfides	3.36	X	X	X	=
=	4217	Small chisel	Presence of a small superficial groove (perhaps modern)	3.58	X	=	=	=
=	5653	Hatchet	= = =	3.57	X	X	X	=
=	7144	Axehead fragment	= = =	3.55	X	X	X	=
67142	8936	Axehead fragment	= = =	3.57	X	X	X	=
GARNET-OMPHACITITE								
=	3975	Axe heel	= = =	3.33	X	X	X	=
=	5319	Unidentif. fragment	= = =	3.30	X	X	X	=
=	7736	Axehead fragment	= = =	3.48	X	X	X	=
OTHER LITHOTYPES								
Inventory code	Excavation code (sample label)	Functional typology	Notes	Density (g/cm^3)	XRD	O.M.	SEM	Picture
SERPENTINITE:								
=	5515	Small chisel	Presence of fibrous antigorite	2.51	X	=	=	=
CHLORITITE:								
86451	3256	Pendant	Showing a peculiar banding; exclusively chlorite-containing	2.71	X	=	=	X
86453	1000	Pendant	Exclusively chlorite-containing	2.56	X	=	=	X
META-DIABASE:								
=	7645	Axehead fragment	With omphacite, garnet, chlorite, feldspar and amphibole	3.21	X	=	=	=
ROCK WITH PREDOMINANT CHLORITE AND ACTINOLITE:								
=	3018	Splinter	Accessory plagioclase and omphacite; scarce jadeite	=	X	=	=	=
ROCK WITH PREDOMINANT GARNET AND PLAGIOCLASE:								
=	5747	Axehead fragment	Accessory pyroxene and amphibole	3.25	X	=	=	=

Table 1

Minerals / Sample label	omphacite	jadeite	garnet	amphibole	hornbl./actinol.	clinochlore	plagioclase	ilmenite	rutile	antigorite	Lithotype	Notes
Na-PYROXENE ROCKS												
3788	x	xxx									jadeitite	shoulders account for scarce presence of omphacite
81		xxx					x				jadeitite	plagioclase is possibly albite
4360	xxx										omphacitite	weak shoulders account for possible presence of jadeite
6602	xxx										omphacitite	weak shoulders account for possible presence of jadeite
6830	xxx					x		x(?)			omphacitite	peak at 2θ=32.53°; d_{hkl} = 2.751, possible ilmenite
6636	xxx	xx									mixed Na-pyroxen.	jadeite reflections less intense than omphacite
1548	xx	xxx									mixed Na-pyroxen.	reflections not distinct but 'fringed' (zoned pyroxenes)
7179	xxx	xx									mixed Na-pyroxen.	reflections not distinct but 'fringed' (zoned pyroxenes)
Na-PYROXENE + GARNET ROCKS												
3088	xxx		xxx								eclogite	garnet is mainly almandine and pyrope
4217	xxx	x(?)	xxx								eclogite	weak shoulders account for possible presence of jadeite
5653	xxx	x(?)	xxx			x					eclogite	weak shoulders account for possible presence of jadeite
7144	xxx	x(?)	xxx						x(?)		eclogite	weak shoulders account for possible presence of jadeite
8936	xxx		xxx								eclogite	garnet is mainly almandine
3975	xxx		x(?)								garnet omphacitite	weak shoulders account for feasible presence of aegirine
5319	xxx		x(?)								garnet omphacitite	splitting of omphacite peaks suggests pyroxene zoning
7736	xxx		x			x					garnet omphacitite	splitting of omphacite peaks suggests pyroxene zoning
OTHER LITHOTYPES												
5515										xxx	serpentinite	antigorite is the only phase
3256						xxx					chloritite	clinochlore is the only detectable phase
1000						xxx					chloritite	clinochlore is the only detectable phase
7645	xx		xx		xx	xx	xx				meta-diabase	plagioclase is possibly albite
3018	xx	x(?)	x(?)		xxx	xxx	xx				chlorite/actin. rock	Unidentified reflection at d=2.675 Å; possible garnet
5747	x		xxx	xx		xx	xx				garnet/plagiocl. rock (omphacite-garnetite?)	Garnet spessartine; splitting of omphacite peaks (zoning)

Table 2

Legend: ○ < 5 % ◗ 5 % - 20 % ● 20 % - 60 % ⬤ > 60 %

Minerals / Sample label	omphacite	jadeite	garnet	amphibole	zoisite	clinozoisite	white mica	biotite	clinochlore	plagioclase	rutile	ilmenite	titanite	zircon	apatite	sulfides	Notes
Na-PYROXENE ROCKS																	
JADEITITES																	
3788	◗	⬤						○					○	○	○		Presence of biotite is dubious
81	○	⬤			○	○	◗			◗							White mica is paragonite; coarse grained
OMPHACITITES																	
4360	⬤													○			Fine-grained; mylonitic structure
MIXED Na-PYROXENITES																	
6636	⬤	●									◗			○	○		Foliation marked by abundant rutile
7179	⬤	●									○			○			= = =
Na-PYROXENE + GARNET ROCKS																	
ECLOGITES																	
3088	⬤	○	●	○			○				○			○			Jadeite undetected at polarizing microscope
5653	⬤		●						○		○	○			○		Atoll-like garnets
7144	⬤	◗	●								○			○			Jadeite shows small omphacitic exsolutions
8936	⬤		●								◗	○			○		Atoll-like garnets in rounded aggregates
GARNET-OMPHACITITES																	
3975	⬤		○								○	○				○	Clinopyroxene has intense green colour
5319	⬤		○										○		○		= = =
7736	⬤		◗								○	○					Jadeite younger than omphacite

Table 3

Figure Captions

Figure 1. a) Map of NW Italy showing the position of the Chiomonte archaeological site (*star*) and of the other coeval archaeological sites cited in the text (1- Rocca di Cavour; 2- Alba; 3- Castello di Annone; 4- Villaromagnano; 5- Rivanazzano; 6- Momperone; 7- Brignano Frascata; 8- Gaione; 9- Ponte Ghiara). The position of the Monviso (Vi) and Voltri (Vo) 'massifs' is also shown. The blue rectangle indicates the area of the geological map in b). The inset shows a simplified map of northern Italy, with indication of the sites of Chiomonte (*star*), San Lazzaro di Savena (10) and Sammardenchia (11). b) Simplified geological map of the Italian side of Cottian and southern Graian Alps (from Varaita Valley to Viù Valley), showing the position of the archaeological site of Chiomonte (*star*) and the distribution of the geological units, here considered as possible sources for the supply of raw materials (eclogite facies meta-ophiolites of the Liguria–Piemonte oceanic units, alluvial and glacial deposits). Geological boundaries redrawn from Piana *et al.*, 2017 (Italian part), Kerckhove *et al.*, 1980 (French part, south of 45°N) and Debelmas, 1980 (French part, north of 45°N). Legend: Quaternary deposits: all- alluvial deposits (Holocene–Present); fl- terraced alluvial and fluvioglacial deposits (Pleistocene–Holocene); lr- landslide, block stream and rock glacier deposits; gla- glacial deposits. Tertiary Piemonte Basin and Pliocene succession: tpb. European palaeomargin units: mms- Mesozoic meta-sedimentary units; amb- Ambin 'massif'; dma- Dora–Maira Unit, pre-Triassic basement rocks and associated meta-sedimentary cover. Liguria–Piemonte oceanic units: non-metamorphic units (Chenaillet Unit; ch_b- basalt; ch_g- gabbro; ch_s- serpentinite and serpentinite breccia); blueschist-facies units (bs_c- calc-schist, locally with gneiss intercalations; bs_b- metabasite; bs_s- serpentinite); eclogite-facies units (Monviso, Rocciavré, lower Susa Valley-Lanzo valleys-Orsiera Unit, SLO; ec_c- calc-schist; ec_b- metabasite; ec_g- metagabbro; ec_s- serpentinite; ec_p- peridotite of the Lanzo ultramafic 'massif'). Cargneules and metasedimentary rocks: bcc- main bodies of cargneules, evaporites and metasedimentary rocks preserved along tectonic contacts.

Figure 2. a) Examples of Neolithic tools from Chiomonte: i) 67140/3600 (axehead, serpentinite); ii) 3772 (axehead, eclogite); iii) 67138/4148 (axehead; jadeitite with albite?); iv) 4229 (axehead, mixed Na-pyroxenite; v) 86453/1000 (pendant, chloritite; studied with XRPD); vi) 67143/3208 (small axehead, mixed Na-pyroxenite); vii) 67141/5018 (small axehead, mixed Na-pyroxenite/eclogite) ; viii) 67144/8771 (axe fragment, mixed Na-pyroxenite); ix) 67161/5117 (taw, serpentinite); x) 86451/3256 (pendant, chloritite; studied with XRPD) (other details reported in the Supplementary Material, Table S1); b) diagram reporting the functional distribution of the polished stone tools from the archaeological site of Chiomonte, as resulting from morpho-typological studies;

Figure 3. a) Histogram of density measurements, performed on 119 (out of 132) lithic implements from Chiomonte; b) preliminary lithotype distribution of the 132 tools from Chiomonte, obtained by combining stereo-microscopic observations and density measurements.

Figure 4. X-ray powder diffraction patterns of selected tools from Chiomonte. In jadeitite (a: 3788) and omphacitite (b: 6602), the characteristic reflections of clinopyroxenes (-221, 310 and 002): see magnifications in the upper right corners] are sharp and mostly single. In mixed Na-pyroxenite (c: 7179), the coexistence of both jadeite and omphacite in almost equal amounts tend splits them in two, partially superposed, peaks. In eclogite (d: 67142/8936), reflections of garnets (i.e., almandine) also appear. (Jd, jadeite; Omph, omphacite; Alm, almandine; Cu-$K\alpha$ radiation).

Figure 5. a) Pyroxene classification diagram proposed by Morimoto *et al.* (1988) (a) reporting the compositional variation of clinopyroxenes in the Chiomonte tools; b) 'Na-pyroxene rocks' (5 specimens); c) 'Na-pyroxene + garnet rocks' (7 specimens). The bigger dots indicate the average composition of jadeite (light green) and omphacite (dark green) solid solutions, estimated by plotting the d_{hkl} values of the three characteristic clinopyroxenes reflections [-221, 310 and 002] on the compositional grid of Giustetto *et al.* (2008).

Figure 6. Compositional variation of garnet, plotteod in the diagram almandine (Alm) + spessartine (Sps) – grossular (Grs) – pyrope (Prp), in 'Na-pyroxene + garnet rocks' (7 specimens).

Figure 7. Photomicrographs of jadeitite: a) jadeite granoblast (Jd) includes in the core tiny oriented linear exsolutions of omphacite (Omp) (3788, plane-polarized light, PPL); b) partly retrogressed jadeite (Jd) matrix, including crumbled crystals (hundreds of μm across) intertwined with 'dusky' portions (CMIX/81, PPL).

Figure 8. Photomicrographs of omphacitite: a) pyroxene matrix, in which small omphacite crystals (Omp), green in colour and typically zoned, show tiny, darker and oriented inclusions in the core (4360, PPL); b) complex zoning of pyroxenes: a heterogeneous, darker matrix (richer in Na and Al) includes small lighter domains, richer in Ca and Mg (4360, SEM image, BSE; the numbered stars indicate the spots in which EDS analyses were collected – see Table S4).

Figure 9. Photomicrographs of mixed Na-pyroxenite: a) small zircon (Zrn) and rutile (Rt) in a matrix of pyroxenes (Jd; Omp) whose zoning is appreciated only at high magnification (6636, PPL); b) the complex zoning of pyroxenes is evident: small and 'relict' jadeite crystals (Jd) are surrounded by a younger omphacite matrix (Omp), commonly slipping inside and partly corroding them (6636, SEM image, BSE; the numbered stars indicate the spots in which EDS analyses were collected – see Table S5).

Figure 10. Photomicrographs of eclogite: a) and b) fractured garnet (Grt), with an atoll-like habit, forms aggregates included in a matrix consisting of mylonitic omphacite (Omp) and occasionally contoured by (brown) rutile (Rt) [67142/8936, PPL; 3088, SEM image, BSE; the numbered stars indicate the spots in which EDS analyses were collected – see Table S13 for pyroxenes (1, 4) and S14 for garnet (2)]; c) admixture of sub-millimetric, idioblastic crystals of jadeitic (light green; Jd) and omphacitic (dark green; Omp) pyroxenes, with scarce garnet; in the middle, a large rutile aggregate (Rt) (7144, PPL); d) restricted jadeite domains (darker), with a 'relict' appearance and including small 'blebs' of exsolved omphacite, are surrounded and crossed by an omphacitic matrix, showing a complex zoning (enhanced by the various shades of grey) (7144, SEM image, BSE).

Figure 11. Photomicrographs of garnet-omphacitite: a) porphyroclast of an omphacitic pyroxene (Omp), which shows a 'dusky' core with tiny inclusions of ilmenite (Ilm) (3975, PPL); b) an unusual zoning for pyroxenes, in which an older omphacitic core (light grey; Omp) is surrounded by a darker rim, richer in Na and Al (7736, SEM image, BSE; the numbered stars indicate the spots in which EDS analyses were collected – see Table S19).

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