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RSCM THERMOMETRY IN THE ALPI APUANE (NW TUSCANY, ITALY): NEW CONTRAINTS FOR THE METAMORPHIC AND TECTONIC HISTORY OF THE INNER NORTHERN APENNINES

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Highlight:
- First RSCM data for the Northern Apennines
- Peak temperature in the Alpi Apuane metamorphic core and surroundings region
- New definition of the thermal structure and nappe architecture of the inner Northern Apennines

ABSTRACT

In this study, Raman spectroscopy on carbonaceous material (RSCM) is applied, for the first time, in the Northern Apennines with particular focus on the Alpi Apuane (NW Tuscany, Italy) and surrounding areas in order to constrain peak metamorphic temperatures and their variability in the different continent-derived units of the nappe stack.

Peak temperatures in the range of ~ 530-320 °C were found in the Alpi Apuane, whereas in the neareby metamorphic core of the Monte Pisano and Punta Bianca lower peak temperatures of 305-315 °C and 350 °C were found, respectively. The Tuscan Nappe in La Spezia area (west of Alpi Apuane) shows temperatures in the range of 295-246 °C, whereas the same unit in the Lima Valley (east of the Alpi Apuane) shows temperatures lower than 230 °C.

The collected data allowed refining the thermal architecture of the belt and the relationships between deformation (early and late folds and low angle normal detachments) and the metamorphic architecture of the Alpi Apuane core. These results provide new contraints for the thermo-mechanical evolution and exhumation history of the inner Northern Apennine and its geodynamic setting. In particular our data support the interpretation of the Alpi Apuane as a cold metamorphic core complex in which the preserved paleothermal structure and part of the exhumation are related with crustal thickening while the final exhumation stages (depth ≤15 Km and at ambient crustal temperature ≤350 °C) are associated with crustal thinning still ongoing in the area.

1. Introduction

The thermal structure and the field metamorphic gradient in mountain belts may be first order parameters directly related to the tectonic setting and the crustal-scale architecture of the orogens (between others Chopin et al., 1991; Hervegh and Pfiffer, 2005, Brown, 2009, Vitale Brovarone et al 2013, Agard and Vitale Brovarone, 2013 and references). Data on the thermal structure of metamorphic units combined with those constraining kinematic history delineates the extent to which heat and mass are transferred from mid to upper crust (e.g. Allemand, Lardeaux, 1997; Selverstone, 1988; Platt et al., 1998; Jolivet et al., 1998; Ring et al., 1999; Berger et al., 2011; Chen et al., 2011; Cottle et al. 2011; Bousquet et al., 2012). Therefore, the understanding of the thermal structure of the internal part of mountain belts is a key element to unravel the tectonic and kynematic frame of orogenic systems and the reconstruction of past geological boundary conditions as inputs for large-scale thermokinematic and geodynamics simulations (Aygüll et al., 2015; Beyssac et al., 2007; Simoes et al., 2007; Avouac et al., 2012; Scharf et al., 2013; Wiederkehr et al., 2011, Rosenberg et al., 2015).

The thermal characters of the inner Northern Apennines and the evolution of its main units were defined through a series of the classical methods including clay mineralogy, vitrinite reflectance, fluid inclusions and illite cristallinity for the shallowest units of the nappe stack (Cerrina et al., 1983; Carter and Dorwkin, 1990; Carosi et al., 2003; Reutter et al., 1978; Reutter et al., 1983; Ellero et al., 2001; Montomoli et al., 2001; Montomoli et al., 2002; Botti al., 2004; Dellisanti et al. 2010, Caricchi et al., 2014; Ventura et al., 2001), and Al-silicates, chloritoid-chlorite thermometry, calcite-dolomite, stable isotope geothermometers, and conodonts color in the lowermost metamorphic units (Franceschelli et al., 1986; Franceschelli et al., 1997; Franceschelli and Memmi, 1999; Molli et al., 2000a,b; Molli et al., 2002; Cortecci and Orlandi, 1975; Cortecci et al., 1994; Costagliola et al., 2002; Consani, 2002). More recently, thermodinamical modeling was also applied in the Paleozoic basement terms of the Tuscan metamorphic units (Lo Po' and Braga, 2014; Lo Po' et al., 2017).

Due to the patchy distribution of suitable rock types in the different units and within the nappe stack, however, we still lack a precise definition of the regional thermal structure and of the paleothermal field gradients. As a consequence the overall tectonic setting shaping the present day nappe-architecture is still a matter of debate, with crustal contractional and crustal extensional models being alternatively supported by different studies (Carmignani and Kligfield, 1990; Carmignani et al., 1994; Storti, 1995; Jolivet et al., 1998; Boccaletti et al., 1999; Carosi et al., 2003, 2004; Bonini and Sani, 2002; Brogi and Liotta, 2008; Thomson et al., 2010; Sani et al., 2014;

Musumeci et al., 2015). This in turn leaves open some relevant questions, for instance the relationships between exhumation processes and the mode of crustal deformation (thickening vs. thinning) as well as the timing, thermal and structural record of crustal/litospheric stretching, which shaped characteristic features of the inner Northern Apennine in Tuscany such as the present day Moho depth and thermal anomaly (Carminati and Doglioni, 2012; Della Vedova et al., 2001; Di Stefano et al., 2011; Spada et al., 2013 and references).

In this study, we present a regional-scale set of paleo-thermal estimates obtained by means of Raman spectroscopy on carbonaceous material (RSCM), including a large range of lithologies from the main units of the inner Northern Apennines, with special focus on the Alpi Apuane metamorphic core and nearby areas. Thanks to the irreversible process of graphitization of carbonaceuos material (CM), this geothermometer can provide peak temperature (T) estimates for CM-bearing metasedimentary rocks independently from their mineralogical assemblage, and is therefore aplicable to a wider range of rock types in the considered units compared to previous studies.

Our data allow constraining the thermal structure and the exhumation-related paleogradients, thereby improving our understanding of the orogenic processes recorded in the inner Northern Apennines. Moreover, our data document the thermal architecture and metamorphic signature of a mid-shallow orogenic wedge and its relationships with the regional structures, the nappe and thrust stack styles and their internal deformation.

2. Regional Geology

The Northern Apennines (Fig.1) are characterized by a pile of thrust-sheets and fold nappes derived from the distal part of the Adria continental margin (the Tuscan Domain), which presently rests below the remnants of a former intraoceanic accretionary wedge represented by the Ligurian and sub-Ligurian units relicts of the former Mesozoic western alpine Tethys ocean (Elter, 1975; Marroni and Pandolfi, 1996; Bortolotti et al. 2001, Bernoulli, 2001; Butler et al., 2006; Molli, 2008; Malavieille et al., 2016; Schmid et al., 2017). The recent to active tectonic framework of the Northern Apennines is characterized by crustal-scale extension in the inner-western (Tyrrhenian) side of the orogen, and shortening in its external eastern side (Po Plain and Adriatic) (e.g. Elter et al., 1975; Barchi et al., 1998; Doglioni et al., 1998; Liotta, 2002; Bennett et al., 2012; Cuffaro et al., 2010; Eva et al., 2014; Faccenna et al., 2014; Molli et al., 2016; Le Breton et al., 2018).

In the NW of Tuscany, the Alpi Apuane complex forms the largest tectonic window in the inner

Northern Apennines and expose the deepest crustal units of the belt (Tuscan Metamorphic Units) (Fig.1). Three major stratigraphic and tectono-metamorphic units are traditionally distinguished in the region, the Tuscan Nappe, the Massa unit and the Apuane unit, all derived from the Adria continental paleomargin (Fig.2). The Tuscan Nappe consists of Mesozoic carbonate rocks and Tertiary deep water and turbiditic sequences mainly detached from their original basement along the décollement level of the former Carnian and Norian evaporites (Ciarapica and Passeri, 2002 and references therein). These anydrites and dolostones are transformed almost everywhere (with some relevant exceptions) into cataclastic breccias called Calcare Cavernoso or "cellular" limestone (Baldacci et al., 1967; Gandin et al., 2000). The post-Norian sequence continues with Rhaetian to Hettangian shallow water limestones (Rhaetavicula Contorta and Calcare Massiccio), Lower Liassic to Cretaceous pelagic limestones, radiolarites and shales (Calcare selcifero, Marne a Posidonomya, Diaspri, Maiolica), grading to hemipelagic deposits of the Scaglia (Cretaceous-Oligocene), to end with the siliciclastic foredeep turbidites of the Macigno (Late Oligocene-Early Miocene). The entire sequence has a thickness between 2000 and 4000 m (Fazzuoli et al., 1986; Ciarapica and Passeri, 2002; Molli and Meccheri, 2012).

The Apuane Unit forming most of the Alpi Apuane tectonic window is made up of a Paleozoic basement unconformably overlain by an Upper Triassic–Oligocene metasedimentary sequence. The Paleozoic basement is represented by metasedimentary and metavolcanic rocks including Upper Cambrian–Lower Ordovician phyllites and quarzites, Middle Ordovician metavolcanics and metavolcanoclastics, Upper Ordovician quartzitic metasandstones and phyllites, Silurian black phyllites and Orthoceras-bearing metadolostones (Gattiglio et al., 1989; Conti et al., 1993; Pandeli et al., 1994; Paoli et al., 2017). The Paleozoic lithostratigraphic units were deformed and metamorphosed under low-grade conditions, not well precisely defined, during the Variscan orogeny (Conti et al., 1991, 1993). The Mesozoic cover-rocks, where complete, include thin Triassic continental to shallow-water Verrucano-like deposits followed by Upper Triassic–Liassic carbonate platform metasediments comprising dolostone (Grezzoni Fm.), dolomitic marble, and marble (the Carrara Marble), in turn covered by Middle Liassic–Lower Cretaceous cherty metalimestone, cherts, and calcschists, and Lower Cretaceous to Lower Oligocene sericitic phyllites and calcschists with marble interlayers. Oligocene-early Miocene (?) metasediments related to turbiditic systems (Pseudomacigno Fm.) complete the sedimentary succession (Patacca et al., 2011 and reference therein).

The Massa unit is exposed in the westernmost part of the Alpi Apuane complex and includes a litho-stratigraphic sequence formed by a Paleozoic basement similar to that of the Apuane unit and a characteristic and distinctive Upper Permian–Upper Triassic metasedimentary succession, including a Mid Triassic continental (conglomerates and pelites) to marine (carbonate platform derived deposits) succession associated with intraplate alkaline basalts (Martini et al, 1985). Lithostratigraphic terms younger than late Mid Triassic are not described in the literature, although (see below) they are be locally found as tectonic lenses and small-scale remnants within a cataclastic fault zone below the contact with the overlaying Tuscan Nappe (Molli et al., 2002; Conti et al., 2004). Based on the similarities in stratigraphic contents of the pre-Late Triassic sequences, traditional literature correlated the P.Bianca and M.Pisano exposures to those of the Massa unit (Baldacci et al., 1967; Elter, 1975), whereas more recent papers defined different peak metamophic conditions (Storti, 1995; Leoni and Pertusati, 2003; Carosi et al., 2004; Molli, 2008).

The deformation structures of the Tuscan metamophic units of the Alpi Apuane and surroundings metamorphic cores may be referred to two main tectono-metamorphic regional events (D1 and D2 phases of Carmignani and Kligfield, 1990), which are regarded (Molli et al., 2000, 2002) as recording progressive deformation of the distal Adriatic continental margin during continental subduction and the syn- to post-contractional exhumation (Carmignani et al., 1990; Jolivet et al., 1998; Carmignani et al., 2001; Molli, 2008). The two main regional events D1 and D2 were related to different fold generations as illustrated by Molli and Meccheri (2012). The same deformation patterns may be also recognized in the Punta Bianca and Monte Pisano metamorphic cores (Storti, 1995; Montomoli, 2002; Carosi et al., 2007; Molli, 2008; Balestrieri et al., 2011).

Deformation event D1, which can be associated with underplating and antiformal stacking of the metamorphic units, is defined by a main axial-plane foliation of isoclinal folds observable on a micro- to kilometer-scale (Fig. 2) and is associated with a regionally NE-oriented stretching lineation interpreted as recording the main transport direction of the inner Northern Apennines (Carmignani et al., 1978; Molli, 2008; Molli and Meccheri, 2012).

During deformation D2, the previously formed structures were reworked by different generations of folds and high-strain zones, related to exhumation of the metamorphic units within the inner portion of the Northern Apenninic wedge (Molli, 2008). Characteristic structures of D2 event, are the late folds with subhorizontal axial plane crenulation, later deformed by semibrittle and brittle structures, represented by kink and open folds, and low-angle normal faults (Molli and Meccheri, 2000; Molli et al., 2010). The final stages of deformation are recorded by systemes of high-angle normal to oblique-normal and trascurrent faults related with the recent to active deformation regime affecting the area (Corti et al., 2006; Bennett et al., 2012; Molli et al., 2016).

In the metamorphic units of the Alpi Apuane, peak conditions are roughly related to T between 450 and 350 °C and P of 0,8-0.4 GPa (Molli et al., 2002 and references therein). In particular, kyanite + chloritoid + phengitic muscovite chracterize the mineral assemblages in metapelites of the Massa unit, with peak conditions estimated in the range of 0,6-0,8 GPa and 420- 500°C (Franceschelli et al., 1986; Jolivet et al., 1998; Franceschelli and Memmi, 1999; Molli et al., 2000b). Instead, pyrophyllite + chloritoid + chlorite + phengitic muscovite in metapelites are found in the Apuane unit, with peak metamorphic conditions estimated in the range of 0.4-0.6 GPa and 350-450 °C (Franceschelli et al., 1986; Jolivet et al., 1998; Molli et al., 2000b).

The early deformation D1 in the metamophic units of the Alpi Apuane occurred during early Miocene at 27–20 Ma (Kligfield et al., 1986), whereas the syn-metamorphic D2 structures developed at T higher than 250 °C, predated 11 Ma according to zircon fission-track ages of Fellin et al. (2007).

In contrast to the Tuscan metamorphic units, the Tuscan nappe was accreted at a shallow crustal level within the Northern Apennines wedge beginning from early Miocene (Cerrina Feroni et al., 1983; Molli, 2008). Burial occurred under a sequence of thrust sheets now preserved in the overlying sub-Ligurian and Ligurian units (Figs. 1, 2). Early thrusting is documented by top-to-the east small scale shear zones and an early generation of east vergent tight to isoclinal folds within incompetent stratigraphic layers (Gianmarino and Giglia, 1990; Carter and Dworkin 1990; Molli et al., 2011). The early structures in the Tuscan nappe were subsequently overprinted by small to large (kilometer-scale) refolding associated with sub-horizontal crenulation cleavage observable in pelitic rock units, low-angle normal faults and later upright folds (Carmignani et al., 1994; Storti, 1995; Carosi et al., 2003). Metamorphism to anchizone grade (Cerrina Feroni et al., 1983; Carosi et al., 2003; Molli et al., 2011) during burial and deformation is constrained by tectono-stratigraphic features to a maximum depth of 7 km for the Macigno sandstones (Reutter et al., 1978; Montomoli et al., 2001; Montomoli, 2002; Fellin et al., 2007).

3. Raman Spectroscopy of Carbonaceous Material

Raman spectra were obtained using a Renishaw InVIA Reflex microspectrometer (IMPMC Paris). We used a 514 nm Laser Physics argon laser with circular polarization. The laser was focused on the sample by a Leica microscope with a 100× objective (NA = 0.85), and the laser power at the sample surface was set around 1 mW. The Rayleigh diffusion was eliminated by edge filters, and to achieve nearly confocal configuration the entrance slit was closed down to 15 µm. The signal was finally dispersed using a 1800 gr/mm grating and analyzed by a Peltier cooled RENCAM CCD detector. Before each session, the spectrometer was calibrated with a silicon standard. Because Raman spectroscopy of CM can be affected by several analytical mismatches, we closely followed the analytical and fitting procedures described by Beyssac et al. (2002, 2003). Measurements were done on polished thin sections cut perpendicularly to the main fabrics and CM was systematically analyzed below a transparent adjacent mineral, generally quartz. Between 10–20 spectra were recorded for each sample in the extended scanning mode (1000–2000 cm− 1) with acquisition times from 30 to 60 s. Spectra were then processed using the software Peakfit (following Beyssac et al., 2002). Based on the obtained spectra, T from samples characterized by lower-T metamorphism (i.e. ~200 ≤ T ≥ 350 °C) were estimated.

Both low-grade (<350°C) and high-grade (>350 °C) were considered. In the former case, RSCM T was estimated using the correlation proposed by Lahfid et al. (2010) for the T range of ~200 ≤ T ≥ 350 °C. In the latter case, the T was calculated using the calibration of Beyssac et al. (2002) for a T range of ~350 ≤ T ≥ 650 °C. Both calibrations have an attached accuracy of ±50 °C due to uncertainties on petrologic data used for the calibration. Relative uncertainties on T are, however, much smaller, around 10–15 °C (Beyssac et al., 2004).

For each sample, several spectra were acquired to assess the potential within-sample structural heterogeneity, with the exception of a few samples containing very little CM amount (Table 1). The latter samples have therefore higher uncertainty compared to the others, and were not considered for tectonic interpretations even though the obtained T is in the range of the neighbouring ones. In a few samples, isolated spectra of crystalline graphite (no defect bands) were interpreted as detrital CM incorporated in the sedimentary rocks prior to metamorphism, and not considered for thermometric estimates. Some structural heterogeneity was found in the samples, with a maximum standard error (standard deviation devided by $\sqrt{n}$) < 8 for most samples (Table 1).

The Raman spectra obtained from the selected samples set show a large between-sample variation in structural organization ranging from poorly organized CM (lower-T) to well cristallized graphite (higher-T) (Table 1). The collected data allow distinguishing samples characterized by T gaps in the order of about 20 °C (Fig. 3), as already observed for this method along continuous metamorphic gradients in Alpine settings (Beyssac et al., 2004; Gabalda et al., 2009; Vitale Brovarone et al., 2014)

4. RSCM Temperature record in the Alpi Apuane and sourroundings

Seventyfour samples were selected for RSCM analysis among 120 collected in various stratigraphic and structural positions within the different tectonic units (Table 1). The samples were collected along a regional SW-NE oriented section across the inner Northern Apennines (Fig. 1). The uppermost continental unit of the nappe pile was sampled west of the Alpi Apuane in the La Spezia area (Fig. 1,2), where the stratigraphic sequence of the Tuscan Nappe is exposed in different localities, from Portovenere (southern tip of western promontory of La Spezia) northward to the 5 Terre area as part of a regional-scale fold called La Spezia fold (e.g. Gianmarino and Giglia, 1991; Carter, 1992; Carosi et al., 2002; Molli et al., 2011 and references therein), in the eastern promontory of La Spezia (between Lerici and Punta Bianca) (Storti, 1995; Clemenzi et al., 2015 and references), north and east of the Alpi Apuane in the Lunigiana and Lima Valley (Molli et al., 2015; Clemenzi et al., 2014 and references).

A more systematic sampling was performed across the Alpi Apuane in order to enlighten the thermal structure of the metamorphic core that was poorly documented so far (Figs. 2,4 and Table 1). Some samples of the metamorphic units were also collected in the eastern promontory of La Spezia as well as southeastward of the Alpi Apuane in the Monte Pisano (Fig. 2).

The stratigraphic units sampled in our study are mainly from the Mesozoic to Tertiary cover sequence and in particular from siliciclastic sandstones of Macigno fm. (Late Oligocene-Early Miocene in age) and impure Triassic limestones for the Tuscan Nappe. The metamorphic equivalents (metasandstones, slates, schists, calcschists and impure marbles) were sampled in the Apuane and Massa units, together with some samples from the Paleozoic basement units (mainly phyllites and schists) (Fig. 2). The samples collected in the eastern promontory of La Spezia come from the Triassic impure limestone at the base of the Tuscan Nappe and from the underlying pre-Mesozoic terms (black phyllites supposed to be Permian age) of the metamorphic Punta Bianca unit i.e. respectively in the hanging-wall and footwall of the former major thrust reworked as a low angle normal fault (Storti, 1995; Carosi et al., 1998, Clemenzi et al., 2015). Moreover, the two analyzed samples in the Santa Maria del Giudice unit are part of the Monte Pisano metamorphic core (Rau and Tongiorgi, 1974; Carosi et al., 1993; Montomoli, 2002; Leoni et al., 2009) and are derived from its Tertiary cover sequence (Pseudomacigno Fm.).

Results are presented in maps and projected along the SW-NE structure-orthogonal regional and local cross sections (Figs. 4, 5, 6). For the sake of comparison, results of previous studies including illite-crystallinity (Cerrina Feroni et al., 1983; Carosi et al., 2003; Leoni et al. 2003) and Calcite/Dolomite thermometer (quoted references) are also shown (Fig. 2, 4).

The sampling strategy allowed constraining RSCM T within the classically defined continent-derived units of the inner Northern Apennines (Elter, 1975; Carmignani et al., 1978; Carmignani and Kligfield, 1990; Carmignani et al., 2001 between the others) which are in the current view (see above) subdivided into three major slices referred, from top to bottom, to as Tuscan nappe, Massa and Apuane (also called “Authochtonous”) units (Fig. 1). In the La Spezia area, the Punta Bianca metamorphic occurences are associated with a pristine lithostratigraphic assemblage similar to that of the Massa unit but affected by a lower grade peak metamorphic imprint (Storti, 1996; Leoni and Pertusati, 2003; Lo Po’ et al., 2017), whereas the Monte Pisano metamorphic core is similarly considered part of the Massa unit for the presence of widespread continental “Verrucano” deposits (Rau and Tongiorgi, 1974; Carosi et al., 2004; Balestrieri et al. 2011).

The overall data sets, summarized in Fig. 7 and Table 1, show significant difference in mean peak T among the major tectonic units so far defined. RSCM peak T are in the range of 246-284 °C (mean 260 ± 26 °C) for the Tuscan Nappe; 306-537 °C (mean 397 ± 64 °C, n=63) for for the Apuane and 454-509 °C (485 ± 28 °C, n=3) for the Massa unit.

In the Tuscan Nappe exposed in the La Spezia area (Figs. 1,2), a simple relationship between stratigraphic positions of the samples and peak T appears (Fig. 6). The youngest terms of the succession represented by the Macigno fm. show a mean T of 253 °C, whereas in the lowermost measured Triassic term of the Calcari a Rhaetavicula Contorta fm. (Rhaetian in age) a mean T of 289 °C was obtained.

In the eastern Promontory of La Spezia in the same stratigraphic unit i.e. the Calcari a Rhaetavicula Contorta (Rhaetian in age), a mean T of ~ 284 °C well confirmed the T obtained in the same stratigraphic unit in the western promontory.

Samples from the Tuscan Nappe in the Lima Valley (Baldacci et al., 1967; Fazzuoli et al. 1994; Botti et al., 2009; Clemenzi et al., 2014) east of the Alpi Apuane show instead lower mean temperature of 227 °C obtained for Jurassic and Cretaceous pelites and marls (Table 1, Fig. 6).

In the Alpi Apuane, although the highest T were measured in samples of the Paleozoic basement (364-537 °C, mean 445 ± 66°C, n=9) and the lowest in the youngest stratigraphic terms of the cover sequence (PseudoMacigno fm.) (306-511 °C, mean 368 ± 50°C, n=22), no simple relationships between stratigraphy and T appear at the scale of the whole metamorphic core (Figs. 4,5,8).

The mean T in the north-western part of the metamorphic complex (north of the Seravezza-Monte Corchia, Turrite valley alignment) is basically the same as those defined in the south-eastern segment (south of the Seravezza-Monte Corchia, Turrite valley alignment), around ~380 °C. The T data plotted on composite vertical cross-sections (Figs. 5,9) show, however, a well defined, yet different thermal structure and overall thermal architecture between the northern and southern Alpi Apuane.

The north-western part of the Alpi Apuane, as previously defined, (cross-sections A,B,C,D,E,F,G) shows an inverted field metamorphic gradient. Within the Apuane unit, higher T (483-507 °C, mean 465 °C) are found to the west, within a structural distance of ~500 m from the basal contact of the Massa unit (Figs. 5,9). The T decrease eastward and structurally downward to ~ 345 °C in the Orto di Donna sincline and in the Arni-Boana structural culmination, i.e. in the geometrically deepest parts of the Alpi Apuane metamorphic core (Kligfield et al., 1981; Carmignani and Kligfield, 1990; Carmignani et al., 2001; Molli and Vaselli, 2006).
The south-eastern parts of the Alpi Apuane (cross-sections H,I,L,M) are instead characterized by a normal-type metamorphic field gradient with overall upward decreasing T from 510 °C to 320 °C in a vertical structural distance of 3000 m.
Samples with the highest RSCM T are found in the south-eastern part of the Alpi Apuane, an area known in the local geological literature as "Zona dello Stazzemese" or "Stazzemese Shear Zone" (Stazzema is village included in it). The area is characterized and recognized for a long time for its distinctive structural style (see Massa 2007 for an historical ovierview) with kilometer scale recumbent D2 isoclinal folds with highly sheared and mylonitized limbs (see Carmignani et al. 1996, Conti et al., 2009; Cinquini, 2014). Samples characterized by the highest RSCM T are intimately related to mineralized bodies (Pb-Zn±Au Hg, Fe-Cu and Barite-Iron Oxide-Pyrite deposits), characteristic of this area with respect to the whole Alpi Apuane and studied and exploited since the mid of last century (Carmignani et al., 1972; Carmignani et al., 1976; Orberger, 1985; Costagliola et al., 1990; Dini et al., 1995; Costagliola et al., 1998; Biagioni et al., 2016). This was observed in samples of different age (Palaeozic, Mesozoic and Cenozoic). Other samples from the Stazzemese Shear Zone but far away from these ore bodies show lower RSCM T. The RSCM T for these samples exceed of about 180-200 °C the values obtained for the enclosing host rocks. As an example, in the Fornovolasco area (the easternmost extension of the "Zona dello Stazzemese"), Tertiary metasandstones (Pseudomacigno Fm.) show RSCM T >500°C (sample 70) if close to mineralized levels (Trimpello ore bodies), whereas the same rock type far from mineralized bodies shows T <360 °C (samples 68,69,71) (Fig. 5 and Table1). This feature suggests that the origin higher T recorded by CM is related to the hydrothermal activity responsible for the ore mineralization.

5. Comparison with previous data

Our new RSCM data find good agreement with previous available data, in particular those derived from calcite/dolomite (Ca/Do) geothermometer/analysis (Fig.4) (Di Pisa et al., 1985; Molli et al., 2000; Oesterling et al., 2007). Although different in absolute value, the RSCM and Ca/Do data well document the presence of inverted metamorphism in the north-west part of the Alpi Apuane, with higher T in the westernmost and uppermost structural positions, decreasing eastward and downward within the structural building.

To the West (where the T are highest), Ca/Do shows lower values with respect to RSCM, whereas this is not always the case or is the opposite in the central and easternmost part of the Apuane (Fig.4).

The comparison between Ca/Do and RSCM cannot be drawn for the lack of data in the south-eastern part of the Alpi Apuane ("Zona dello Stazzemese") where suitable rock-types for Ca/Do analyses are less common and therefore not deeply investigated in the literature. In this area, however, studies based on various techniques including stable isotope compositions and geothermometry, fluid inclusions and phase relationships between sulfosalts in ore bodies give host rock T around 350-400 °C and T for mineralizing fluids and ore bodies higher than 450 °C (Cortecci et al., 1989; Cortecci et al., 1994; Costagliola et al., 1997; Costagliola et al., 1998; Biagioni et al., 2013, 2016) which are similar to our RSCM results.

For the Massa unit, owing to intense wheatering and oxidation, only 3 out of 25 samples from Verrucano continental metasediments were analyzed. Our mean RSCM T is in agreement with the estimates based on Fe-Mg exchanges in coexisting chloritoid and chlorite (450-500 °C; Franceschelli and Memmi, 1999). Similar T ranges were also constrained by the stability field of the kyanite+quartz pair and chlorite+chloritoid+quartz assemblages in the FeO-Al_2O3-SiO_2-H_2O (Franceschelli et al., 1998). Using similar methods chloritoid±chlorite Mg±Fe-exchange thermometer a peak temperature of 455 °C was found by Molli et al. (2000). Ca-Do data in the Mid-Triassic marble of the Massa unit also give a similar T in the range of 430-520 °C (Cardaci, 1987).

6. Summary and discussion

The RSCM data presented in this study allowed us to better constrain the relationships between the nappe architecture and the thermal structure in the Alpi Apuane and their surroundings. This highlighting new subjects for a better and more complete understanding of the thermo-mechanical evolution and exhumation history of the inner Northern Apennines in the general frame of the evolution of the Apennines orogen. Hereafter the results and the first order points of our contribution are summarized and discussed.

6.1 *Peak temperature and tectonic units*

A first point to be remarked is the difference in the mean peak T among the structurally/stratigraphically defined tectonic units (Fig. 7). The classically accepted subdivision (Elter, 1975, Carmignani and Kligfield, 1990; Decandia et al., 1996, Vai and Martini, 2001) into three major continental units forming the backbone of the inner Northern Apennines – from top to bottom: the Tuscan nappe, the Massa and the Apuane units – appears to be fully supported by the new measured RSCM T (Fig.7) which show a mean peak T of ~ 260 °C for the Tuscan Nappe, ~ 485 °C for the Massa unit and ~ 385 °C for the Apuane unit.

Moreover, our data allow defining new tectonic units that were not clearly identified and considered in the previous models. In such group of units may be included the Punta Bianca Unit in the west and the Monte Pisano Unit in the south. Moreover, in the southern-eastern Alpi Apuane the Panie may be inserted within this group, since they are here characterized by a RSCM T of 320 °C, an intermediate value between those of the Apuane Unit and those of the Tuscan Nappe. Other evidence of missing units, inside the Alpi Apuane, may be searched for between the Massa unit and the overlying Tuscan Nappe (Fig.5 cross section E), where remnants of a post mid-Triassic cover (cherty metalimestones, marbles, phyllites) with a peak RSCM T of ~350 °C were sampled (sample 16). Those remnants are also observable as structural relicts exposed as hectometer to pluridecameter thick slices and lenses (see Molli et al., 2000) and widely recognizable as clasts (meter, decimeter to centimeter in scale) within the carbonate tectonic breccia at the base of the Tuscan Nappe in the southern Alpi Apuane (Conti et al., 2009; CARG F.260; Cinquini and Molli, 2015). These data and occurences may be interpreted as related to the former existence of a metasedimentary unit ("X unit", "missing section" in Fellin et al. 2007) originally including the post Mid-Triassic cover sequence now only scatterly observable on top of the Massa Unit.

The rank of individual tectonic unit for the Panie (Maxwell, 1956; Nardi, 1961; Giglia 1967; Carmignani et al., 2001) as well as the importance of the "X unit" to fill the gap between the base of the Tuscan Nappe and the top of the Massa unit during the syn-peak metamorphism nappe stacking are in line with what anticipated and discussed in the frame of the tectonic history of the metamorphic units by Molli et al., (2000); Molli et al., (2002); Fellin et al. (2007). Thanks to the newly defined RSCM data, and considering the mean T as an estimate for the "whole unit" thermal peak, we may emphasize that the classical subdivision into three major Tuscan units across the Alpi Apuane and surrounding introduced in literature since Elter (1975) as related to the original thrust stacking, is due instead to tectonic excision during exhumation. In other words, the present day tectonic units have to be considered as remnants of a former thicker, more complete and now only partially preserved contractional nappe stack (Coli, 1989; Van den Berg, 1989; Carmignani et al., 1990; Carmignani et al. 1995; Jolivet et al., 1998; Molli et al., 2002).

6.2 Metamorphic field gradients and thermal architecture

For the Tuscan Nappe, the dataset in the La Spezia area (Fig.2, 6) indicates a base (Triassic Rhaetian limestone) to top (Oligocene-early Miocene Macigno sandstone) difference of ~40 °C which occurs within a structural distance of 2000 m. Thus, assuming that the peak T are: (i) coheval in age and (ii) related with the pre-folding thermal architecture of the unit within the orogenic prism, a peak T normal-type field gradient of 20 °C/Km may be defined (Fig.10).

At regional scale, the collected data from the Tuscan Nappe suggest for its westernmost exposure (La Spezia area) a mean RSCM T of 271° C and a lower mean T of 227°C in the easternmost position in the Lima Valley, east of the Alpi Apuane (Fig.1,2,10). This west to east decrease of peak T, in line with previously recorded illite crystallinite and organic matter data (Reutter et al., 1978, 1983; Cerrina Feroni et al., 1983), may be referred to an original thickness of the orogenic wedge stack above the Tuscan Nappe. Moreover, assuming that the field gradient defined in the La Spezia area was constant at regional scale, this results in a variation of the wedge thickness above the Tuscan Nappe of ~2 Km from west (La Spezia) to east (Val di Lima) (Fig.10).

For the Alpi Apuane, taking into account the whole data set in the Apuane unit, a difference in T between the pre-Mesozoic samples and the Mesozoic to Tertiary ones may be underlined (Figs. 4, 5, 8, 9). The pre-Mesozoic basement rocks show a mean peak RSCM T of 445 °C whereas a mean of 386°C is found in the metasedimentary Mesozoic to Tertiary cover.

These data may be explained considering the higher peak T in the basement rock as a relict metamorphism of the Variscan age (Conti et al., 1993, Pandeli et al., 2003) or as a relict of a Late Variscan (Permian) thermal event in line with recently acquired data (Vezzoni et al., 2017; Pieruccioni et al., 2017).

Nevertheless, since similar higher T (Fig.8) were also found in samples with Mesozoic to Tertiary protoliths, an alternative hypothesis may also be taken into account. In this alternative frame, an Apenninic-age heating possibly related to a fluid flow infiltration in the basement rocks (and locally in the Mesozoic cover) during its detachment from the underlying subducted middle to lower crust may be envisaged (Fig. 10d). The higher peak T found in association with mineralized horizons in the southern Alpi Apuane ("Zona dello Stazzemese" or "Stazzemese Shear Zone" Figs. 9, 10) may thus be interpreted as an evidence of Apenninic-age infiltration and hot fluid flow along high-strain localized zones of deformation, which were reworked during exhumation.

Finally, the distribution of peak T at the scale of the whole Alpi Apuane (Fig.9) indicates a different and systematic arrangement with respect to the overall architecture of the structures in the north-west as opposed to the south-easternmost part. The north-west part of the Alpi Apuane (Figs. 5,9) is characterized by a SW to NE decrease of peak temperature from 495 °C in the west to 357 °C in the central and 336 °C in the eastermost position. A difference of 125° C is observed with a structural distance of ~8 Km, thus an inverted field metamorphism with a T gradient of ~20 °/Km could be defined.

Furthermore, the distribution of the peak temperatures and the resulting thermal architecture are different in the south-east part of the Alpi Apuane (Fig. 9) where an apparent normal-type gradient is observed with transition from temperatures higher than 500 °C to less than 300 °C (projected base of the Tuscan Nappe) in less than 1,5 Km (e.g. cross-section L) with an apparent field gradient in excess of 90 °C / Km.

This clearly points out the complexity of the thermal vs. structural architecture in the Alpi Apuane which well fits an overall "contractional" model of antiformal stacking (i.e. an orogenic wedge dominated by material advenction) in the northern part and an opposite "extensional" core complex model with condensed isograds (i.e. an orogenic wedge dominated by temperature advenction) for its southernmost part.

This variability in the thermal structure between the two sectors of the Alpi Apuane, however, may be only apparent since the exposed geometrically deepest and cooler levels of the eastern Alpi Apuane are not exposed in the central-southeasternmost segment of the dome in relationship with its 3D structure, see below (Fig.9).

6.3 Regional structures of the Alpi Apuane, kinematic and paleothermal evolution

6.3.1 Internal deformation of the Alpi Apuane metamorphic core

The regional structure of the Alpi Apuane metamorphic core is that of an asymmetric antiform dome-like structure defined by the attitude of the main foliation D1 dipping west along the western side of the dome and to the east along the eastern side (Carmignani and Giglia, 1979; Kligfield et al., 1979; Kligfield et al., 1981; Carmignani and Kligfield, 1990; Carmignani et al., 1995; Molli and Vaselli, 2007; Molli and Meccheri, 2012). This regional scale antiform (Figs. 4,5,9) shows internal complexities due to the presence of two minor culminations, respectively centered in the south west and north east part of the dome (Figs. 4,9). The paleoisotherms defined by our RSCM data are deformed by the later (i.e. post-D1) dome-shaped regional structures of the core, resulting in an apparently inverted type field gradient in the north-west, where the main phase (D1) isoclinal regional fold structures (Bergiola Anticline in the Massa unit, Carrara Syncline, Vinca-Forno anticline and Orto di Donna syncline, Figs. 4,5) and related axial planar folition D1 are west-dipping, and in a normal type field gradient in the east and southeast part of the Alpi Apuane, where the main phase (D1) isoclinal regional fold structures, e.g. the M.Corchia syncline (southern prolongation of the Orto di Donna-Altissimo syncline), and related axial planar foliation D1 are east- or south/east-dipping.

These relationships betwen the paleothermal architecture and regional deformation features within the Alpi Apuane and surroundings area may be inserted in the conceptual model suggested in Figure 10, which takes into account all available structural and geo-thermochronological data together with presented RSCM results.

The proposed evolutionary model envisages: i) crustal underplating of the Tuscan continental units (Fig. 10a,b) with an early stage of underthrusting and stacking below the Ligurian/subligurian lid (former Ligurian Tethys-derived accretionary wedge). Assuming a constant thermal gradient of 20 °C/Km as defined in the upper continental unit (Tuscan Nappe), a T > 400 °C was reached at crustal depth major than 20 Km, thus fitting available petrological data (Franceschelli et al., 1986; Molli et al, 2000) and our RSCM data. The Massa unit, originally derived from the westernmost position, records higher T (and P) peaks, with respect to the Apuane unit (see also Jolivet et al., 1998; Molli et al., 2000a,b); ii) a successive duplexing stage (Fig. 10c,d) may be responsible for the formation of the internal stacking and regional fold development including the overthrusting of the Massa (higher grade) unit above the Apuane unit (lower grade). During this deformation stage (late D1 in Molli et al., 2000), and following the thermo-kinematic model proposed by Dunlop et al. (1997) and Bollinger et al. (2004) a folding of previous paleoisotherms is suggested to produce the paleothermal and structural features in the western side of the Alpi Apuane across the contact between the Massa and the Apuane units and downward (Figs. 4,5).

During the crustal duplexing and antiformal stacking (Fig. 10d,e,f) a possible pathway for hot fluids coming from middle to lower crust may be suggested along some major tectonic contact and along the decollement level at the base of detached Paleozoic terms. This hot fluid channelling associated with ore mineralization was localized with the ongoing deformation and after the refolding of previous D1 structures in the eastern limb of the regional antiformal stack within the "Stazzemese Shear Zone" (Figs. 9,10e,f).

The successive stages of deformation in the Alpi Apuane metamorphic core recorded the switching in the deformation mode from crustal thickening to crustal thinning in the wake of eastward migration of contraction/extensional fronts which characterize the Northern Apennines development (Elter et al., 1975; Patacca et al., 1990; Carmignani, Kligfield, 1990; Carmignani et al., 1995; Doglioni, 1991; Pialli et al., 1998; Liotta and Ranalli, 1999; Le Breton et al., 2017 and references therein). During the vertical shortening of the previously developed antiformal stack the "Stazzemese Shear Zone" as well as the later flat lying regional D2 foliation and structures were formed (Fig.10g, h).

6.3.2 The Alpi Apuane metamorphic core and its boundary faults

As previously illustrated, the Alpi Apuane metamorphic core forms a regional scale northwest-southeast trending elliptical dome, which is separated by the overlying Tuscan Nappe by meter to hundreds of meters thick levels of carbonatic breccias and cataclasites which have been considered since Trevisan (1965) as derived from the former basal layer of the Tuscan Nappe, i.e. by an original alternation of dolomites and evaporites of Triassic age ("Calcare Cavernoso" Auct.). Carmignani and Kligfield (1990) first interpreted this breccia-layer ("window fault" in Hodgkins and Stewart, 1994; Casale, 2012) as the detachment horizon that separates low-grade to unmetamorphic upper-plate units (our RSCM T < 300 °C) from the underlying metamorphic lower plate units (401±65 °C mean of all our data set of RSCM T).

From the kinematic point of view the "window fault" cuts down-section the footwall regional structures along a south-west to north-east transport direction (Molli, 2012) as shown in map and cross section in Figs. 4,5,9. The low angle detachment fault is therefore in contact with the uppermost structures of the western Alpi Apuane (Massa unit, Carrara Syncline, Vinca-Forno Anticline) and with progressively deeper and lower regional structures (Orto di Donna Syncline, Tambura Anticline and easternmost Apuane).

This structural cut-down section corresponds to a paleothermal architecture which shows, across the "window fault" and along the transport direction, an eastward decrease in the T gap between hangingwall and footwall from ΔT > 200 °C in the west to ΔT < 50 °C in the east (Fig.9). This is mainly due to the cross-cut relationship and kinematic interaction between the window fault and the footwall antiformal stack of the metamorphic core as figured in the conceptual model of Figure 10e,h. Note that the window fault mainly formed by breccias and cataclasites derived from the basal layers of the Tuscan Nappe locally includes (for instance in the southern Alpi Apuane) crushed and brittely deformed relicts of X/"missing unit" originally on top of the Massa and Apuane units.

Furthermore, using the thermochronological data in Fellin et al. (2007), we may date some steps of the proposed kinematic history with the end of distributed deformation in the footwall metamorphic core, the antiformal stack development and the later Stazzemese Shear zone and D2 folding as occured before 11 Ma, a time at which the Alpi Apuane metamorphic core reached a temperature of c. 250 ° C as constrained by Zr FT age (Fellin et al., 2007). Localized brittle deformation along low angle normal faults and the end of the activity of the "window fault" occurred at a crustal depth as low as ~ 180 °C in a time interval between 7 to 4–5 Ma based on data collected along the western and in the eastern side of the Alpi Apuane by Fellin et al. (2007). After that time crustal extension was accommodated by the high angle (mainly) normal faults which shaped the present day tectonic setting, the regional morphostructure and the deep crustal structure (Fig., 4,5,9, 10i,l). The high angle faults cross-cut the former synmetamophic structures as well as the "window fault" (Molli et al., 2016 and references therein).

7. Conclusions

RSCM T estimates have proven an efficient mean to put extensive T constraints on the thermal structure of coherent units and on tectonic contacts even within very narrow T ranges (Beyssac et al., 2002; Rahl et al., 2005; Chen et al., 2011; Vitale Brovarone et al., 2013, 2014; Bellanger et al., 2014; Scharf et al., 2013; Wiederkehr et al., 2011).

Our data in the Alpi Apuane metamorphic core well illustrate how RSCM T distribution are related/controlled in different ways by regional and local deformation structures and in turn that the observed style of deformation and type of structures are controlled/related with local paleotemperatures.

Since the seminal paper of Carmignani and Kligfield (1990), the Alpi Apuane have been world-wide recognized as a metamorphic core complex (Withney et al., 2013), recording mid-crustal distributed post-orogenic "ductile" extensional deformation. This view, however, has been questioned by different authors who have suggested that extensional denudation of the Alpi Apuane was instead related with underplating and thickening of the internal Northern Apennines (among others Cello and Mazzoli, 1996; Jolivet et al., 1998, Fellin et al., 2007).

Beside localized fluid-mediated thermal effects (see Section 4), our RSCM data document that the paleothermal architecture of the Alpi Apuane metamorphic core better fits a tectonic scenario of syn-orogenic contractional exhumation associated with a cool paleothermal gradient, which allowed the preservation of inverted metamorphism across the Alpi Apuane metamorphic core and its overall paleothermal architecture.

Nevertheless, post-antiformal stack structures (regional flat-lying D2 foliation and the Stazzemese Shear zone) may be related to the switching and transition from crustal thickening to crustal thinning, when the metamorphic core was already at mid crustal depth (c.15 Km and temperature of ≤350°C). Our major conclusions put new contraints for the thermo-mechanical evolution and exhumation history of the Northern Apennine in its inner (western) side; moreover, they may be of general and widespread interest for other orogens, showing anchimetamorphic to metamorphic mid to shallow crustal terrains and metamorphic cores. Our data clearly illustrate how the thermal and metamorphic signature may have different characters and different field gradients at tens of kilometer scale, calling for a careful analysis of thermal data in correlation with the associated structural architecture for a firm interpretation of the tectonic frame at the orogen-scale.

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Figures caption

Fig.01. Geological setting of the Northern Apennines and regional cross sections (mod. by Molli, 2008) with indicated the studied areas.

Fig.02. Tectonic map of the inner Northern Apennines with locations of analyzed samples. In the figure are also reported previous Temperature data sets and related references. For illite cristallinity data grey and black values are related respectively to the Scaglia fm. (Late Cretaceous-Oligocene) and Calcari a Rhaetavicula Contorta Fm. (Late Trias).

Fig.03 Examples of spectra RSCM of selected analyzed samples. To be noticed as significant differences in the spectra correspond to slight differences in peak temperatures.

Fig.04 Geological map of the Alpi Apuane with measured RSCM temperatures and other data available from literatures: (1) Ca/Do from in Molli et al. 2000; (2) Di Pisa et al. 1985.

Fig.05 Cross-sections across the Alpi Apuane with RSCM temperatures

Fig.06. a) Cross section of La Spezia area and measured RSCM temperatures; b) Stratigraphy and RSCM temperatures in the Tuscan Nappe.

Fig.07 RSCM temperatures in the different tectonic units of the Alpi Apuane and nearby metamorphic core of Punta Bianca and Monte Pisano. The vertical position of the samples correspond to the distance from the reference surface represented by the basal contact of Tuscan Nappe (see scal bar in meters).

Fig.08 Stratigraphy and RSCM temperatures in the Apuane unit.

Fig.09. Paleothermal and structural architecture of the Alpi Apuane metamorphic core complex. a) structural architecture of the Alpi Apuane metamorphic core; b) window-scale paleothermal architecture; c) paleothermal architecture in cross-sections view.

Fig.10. Evolutionary model for the Alpi Apuane within the different stages of Apenninic wedge growth from crustal thickening to crustal thinning stages (* Kligfield et al., 1986; ** Giglia, Radicati di Brozolo, 1974; *** Fellin et al., 2007 and references): a) early stage of nappe stacking below the Ligurian/subligurian lid (former accretionary wedge); b) the same as in a) with in red dashed lines the 400°, 350° and 300 °C paleoisotherms; c,d) successive duplexing stage with formation of internal stacking and overthrusting of Massa (higher grade) above the Apuane unit (lower grade). During this deformation path, a folding of previous paleoisotherms is envisiged to produce the thermal features described at pages 10-11 (see cross sections E,F,I of Figs. 4,5 and Fig.9). In blue the possible path way of hot fluids coming from subducted middle to lower crust which may be associated with ore bodies, reworked within the Stazzemese Shear zone during

following deformation stages; e) antiformal stacking phase with development of: 1) finite geometry of regional deformation structures (dome shape of main foliation and related regional D1 structures) and 2) the finite thermal structure with the regional folding of previous isotherms (f); g), h) switching from crustal thickening to crustal thinning with development of D2 structures related to a vertical shortening accounting for a minimum of 20% of distributed ductile thinning (see Molli and Vaselli, 2007), as well as the "Stazzemese Shear Zone", which is the possible deeper expression of a linked extensional detachment system including the brittle "window fault". The activity of the "window fault" continued up to crustal depth corresponding to an ambient temperature of 180 °C (see thermochronological data in Fellin et al., 2007; i) and l) final stages of exhumation (4-5 Km of vertical displacement) of the Alpi Apuane metamorphic core in a crustal thinning stage starting from 7-5 Ma (Ap Ft Fellin et al., 2007 and references) and continuing up to now (Bennett et al., 2012; Molli et al., 2016). During this stage, deformation is accommodated by high angle normal to transtensive faults cross cutting the "window fault" as well as the syn-metamorphic templates. In l) isotherms are drawn according to thermal data and modeling in Verdoya et al., 2005; Pauselli et al., 2006; Faccenda et al., 2009.

Table 1. Selected samples for RSCM thermometry. GPS coordinates in WGS84 system, number of spectra (n), mean R2ratio (Beyssac et al., 2002a) or RA1 ratio (Lahfid et al., 2010) for n spectra with corresponding standard deviation (sdv), and calculated temperature with standard error (SE). Standard error is the standard deviation divided by $\sqrt{n}$. The absolute error on temperature is ±50 C (Beyssac et al., 2002a). *low-T samples processed with RA1 ratio. ** Samples for which the degree of graphitization of CM might reflect hydrothermal processes rather than regional metamorphism.

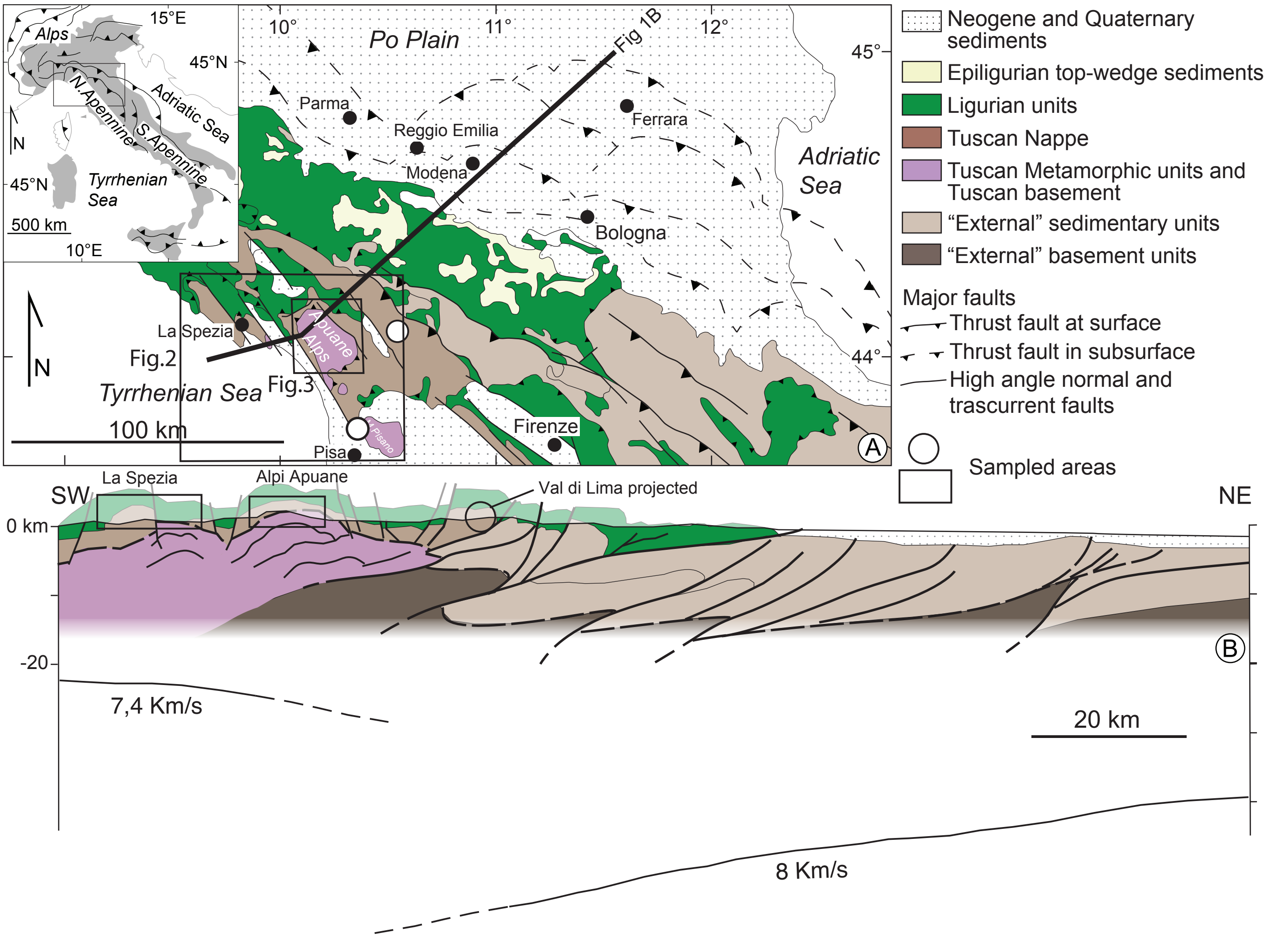

Fig.01 Molli et al., JSG

Fig.01. Geological setting of the northern Apennines and regional cross sections (mod. by Molli, 2008) with indicated the studied areas.

Fig.02 Molli et al., JSG

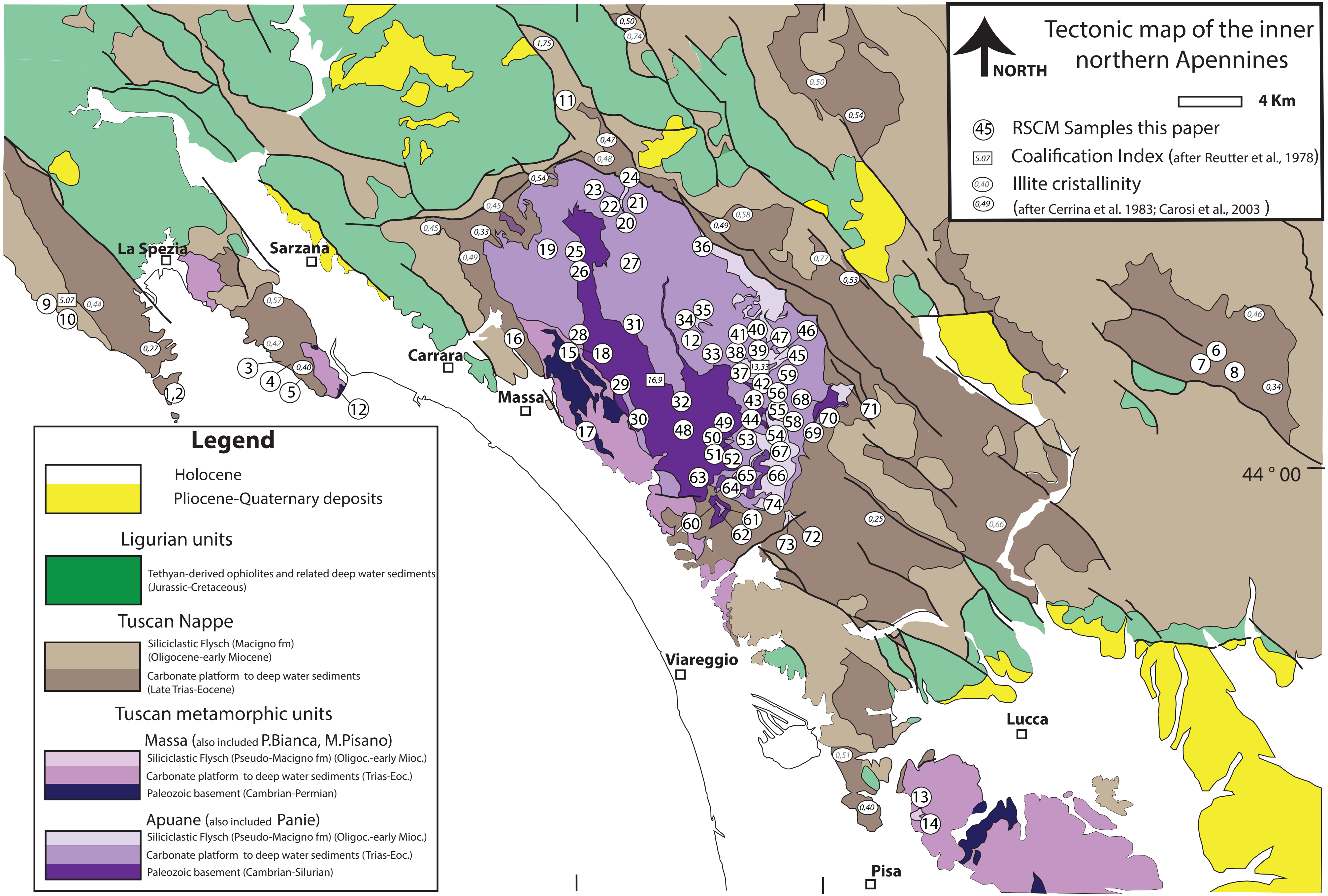

Fig.02. Tectonic map of the inner northern Apennines with locations of analyzed samples. In the figure are also reported previous Temperature data sets and related references. For illite cristallinity data grey and black values are related respectively to the Scaglia fm. (Late Cretaceous-Oligocene) and Calcari a Rhaetavicula Contorta Fm. (Late Trias).

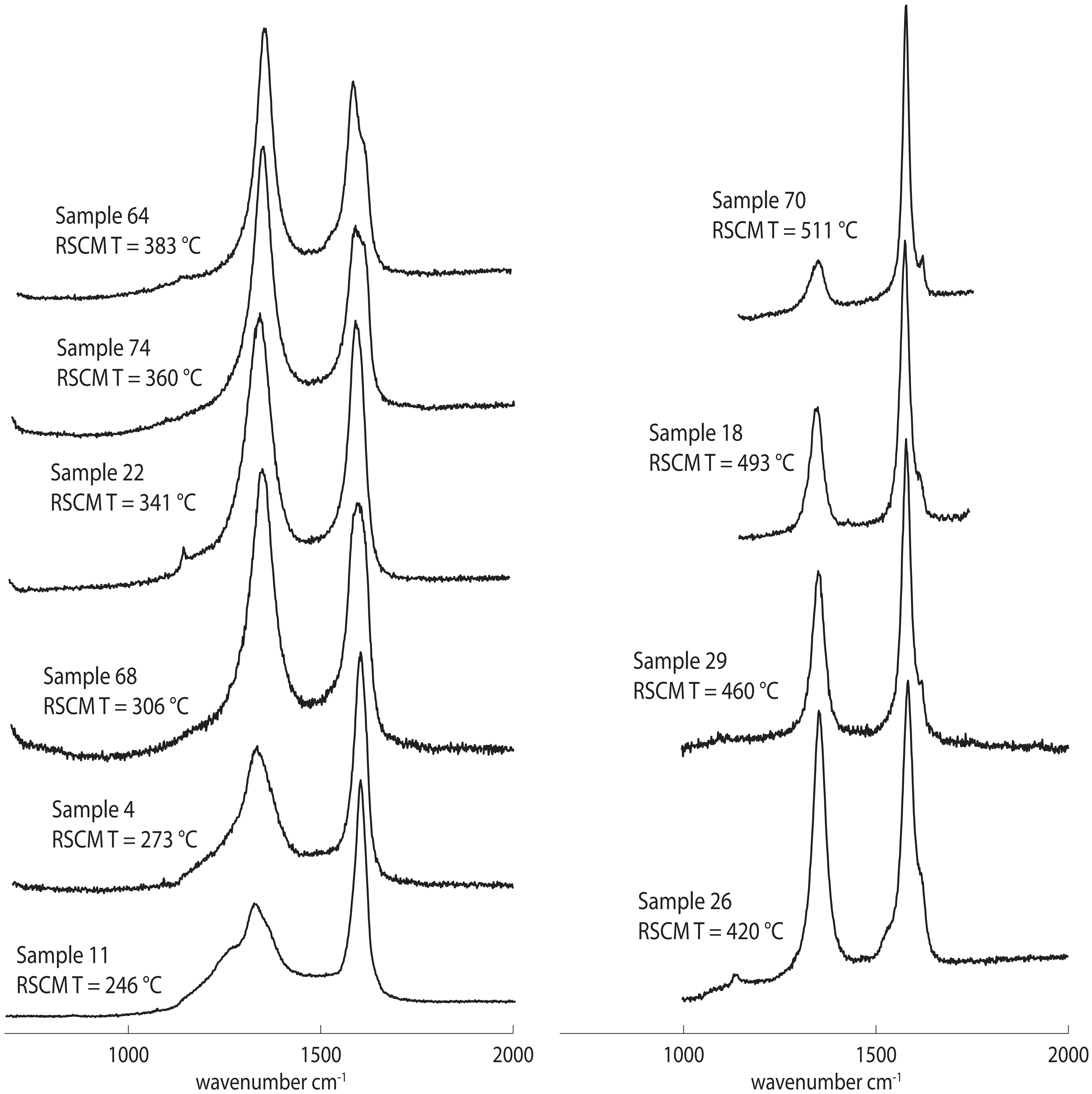

Fig.03 Examples of spectra RSCM of selected analyzed samples. To be noticed as significant differences in the spectra correspond to slight differences in peak temperatures.

Molli et al JSG

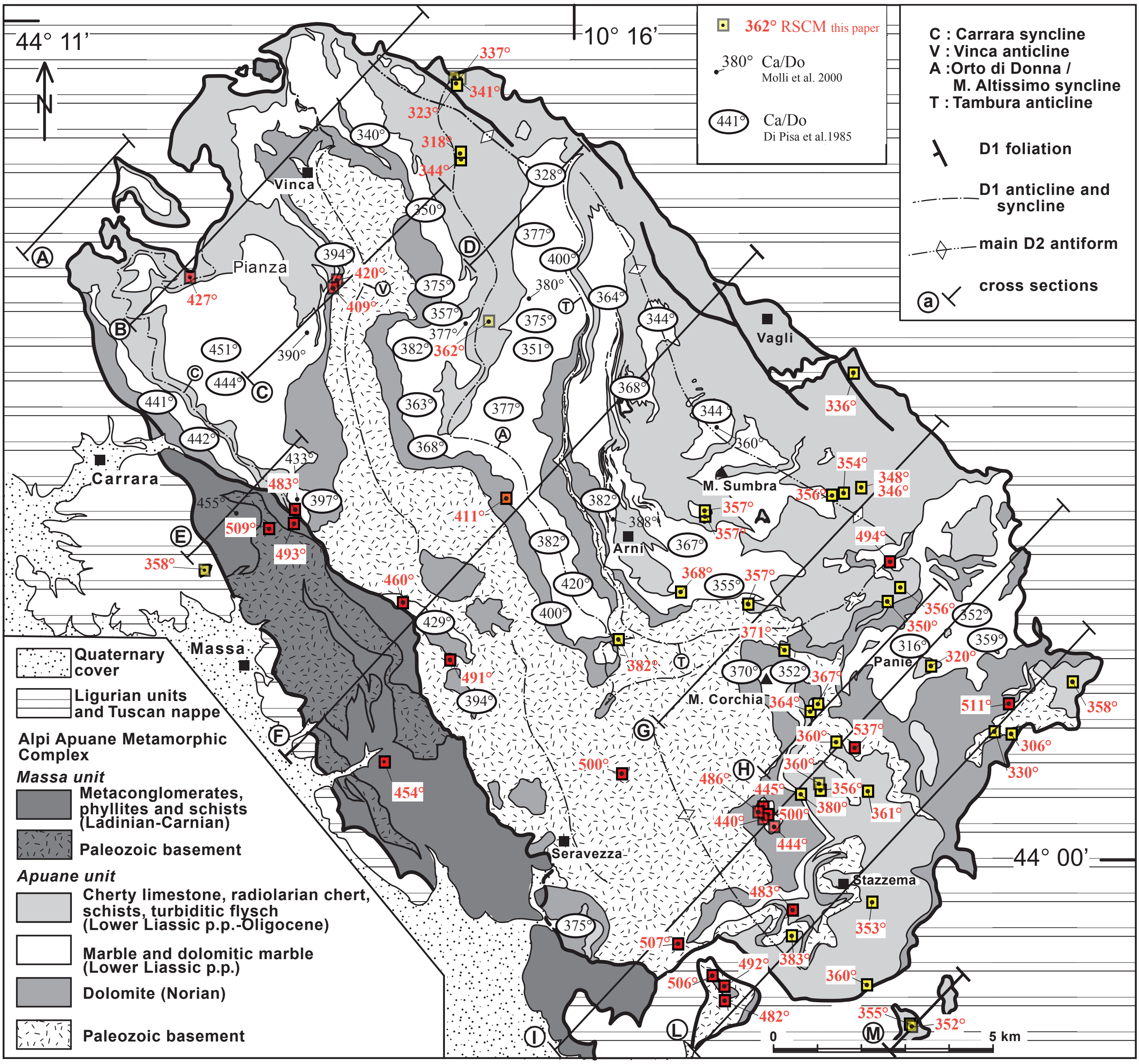

Fig.04 Molli et al. JSG

Fig.04 Geological map of the Alpi Apuane with measured RSCM temperatures and other data available from literatures: Ca/Do from in Molli et al. 2000; Di Pisa et al. 1985.

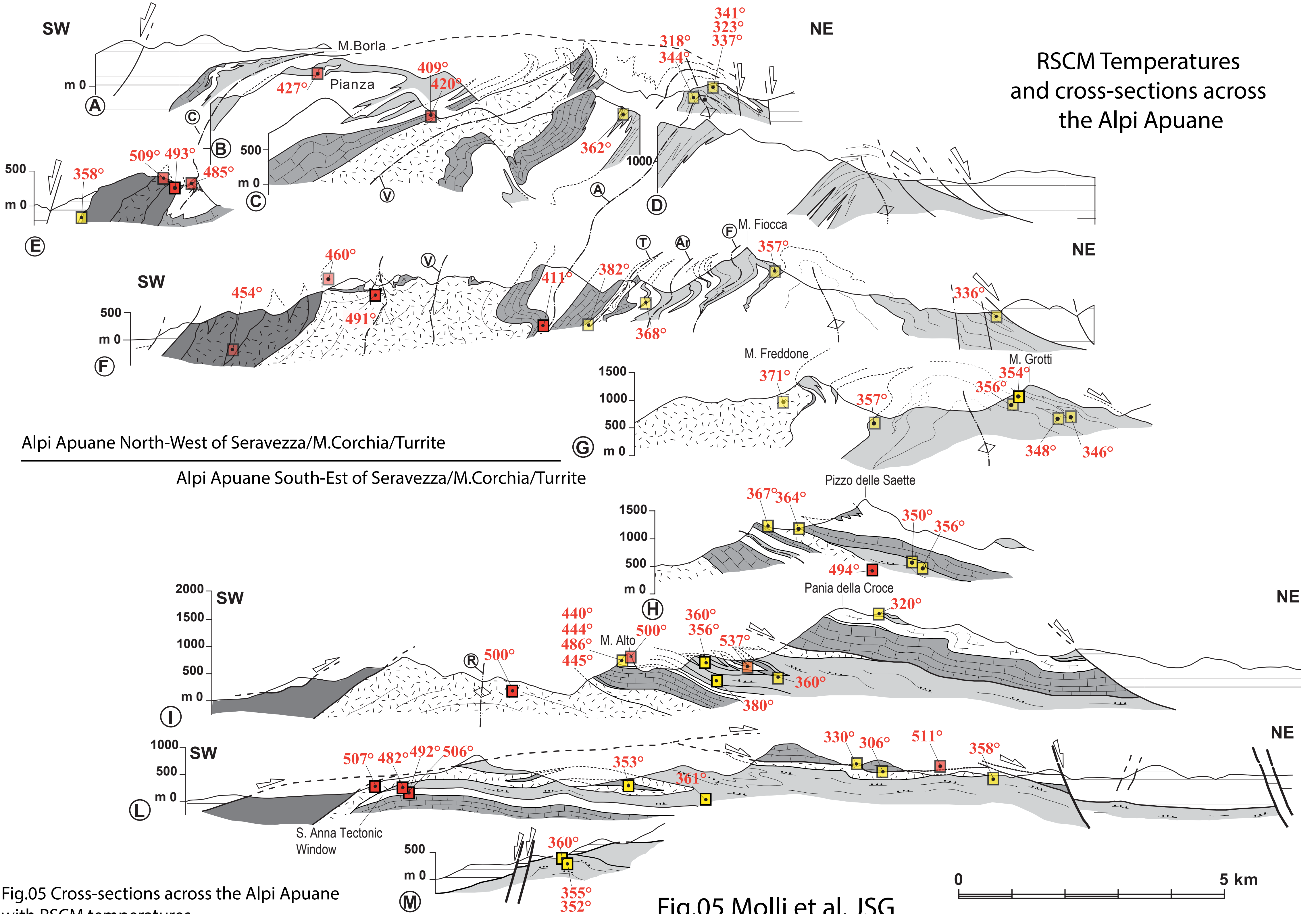

Fig.05 Cross-sections across the Alpi Apuane with RSCM temperatures

Fig.05 Molli et al. JSG

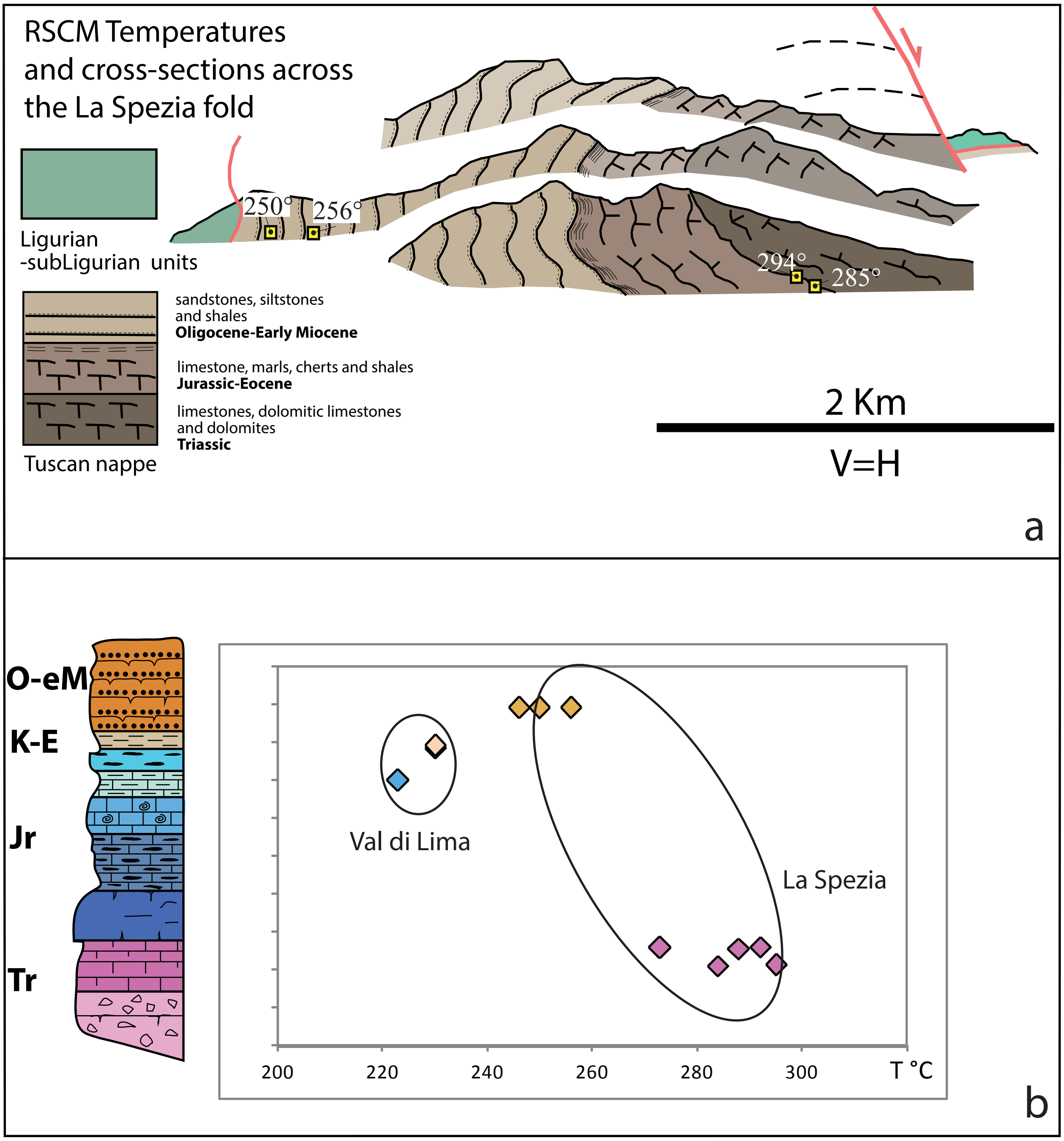

Fig. 06 Molli et al JSG

Fig.06. a) Cross section of La Spezia area and measured RSCM temperatures; b) Stratigraphy and RSCM temperatures in the Tuscan Nappe.

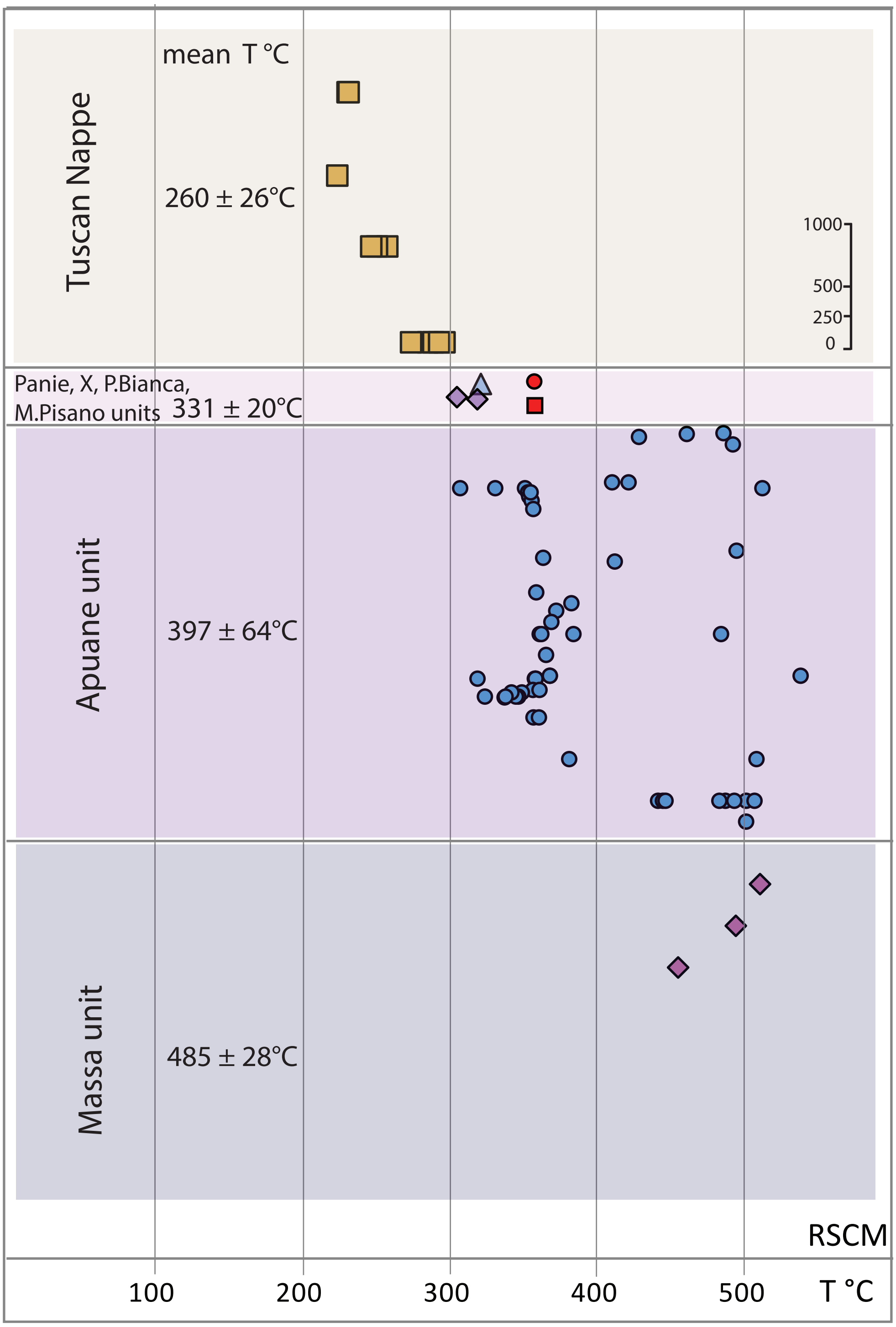

Fig07 Molli et al., JSG

Fig.07 RSCM temperatures in the different tectonic units of the Alpi Apuane and nearby metamorphic core of Punta Bianca and Monte Pisano. The vertical position of the samples correspond to the distance from the reference surface represented by the basal contact of Tuscan Nappe (see scal bar in meters).

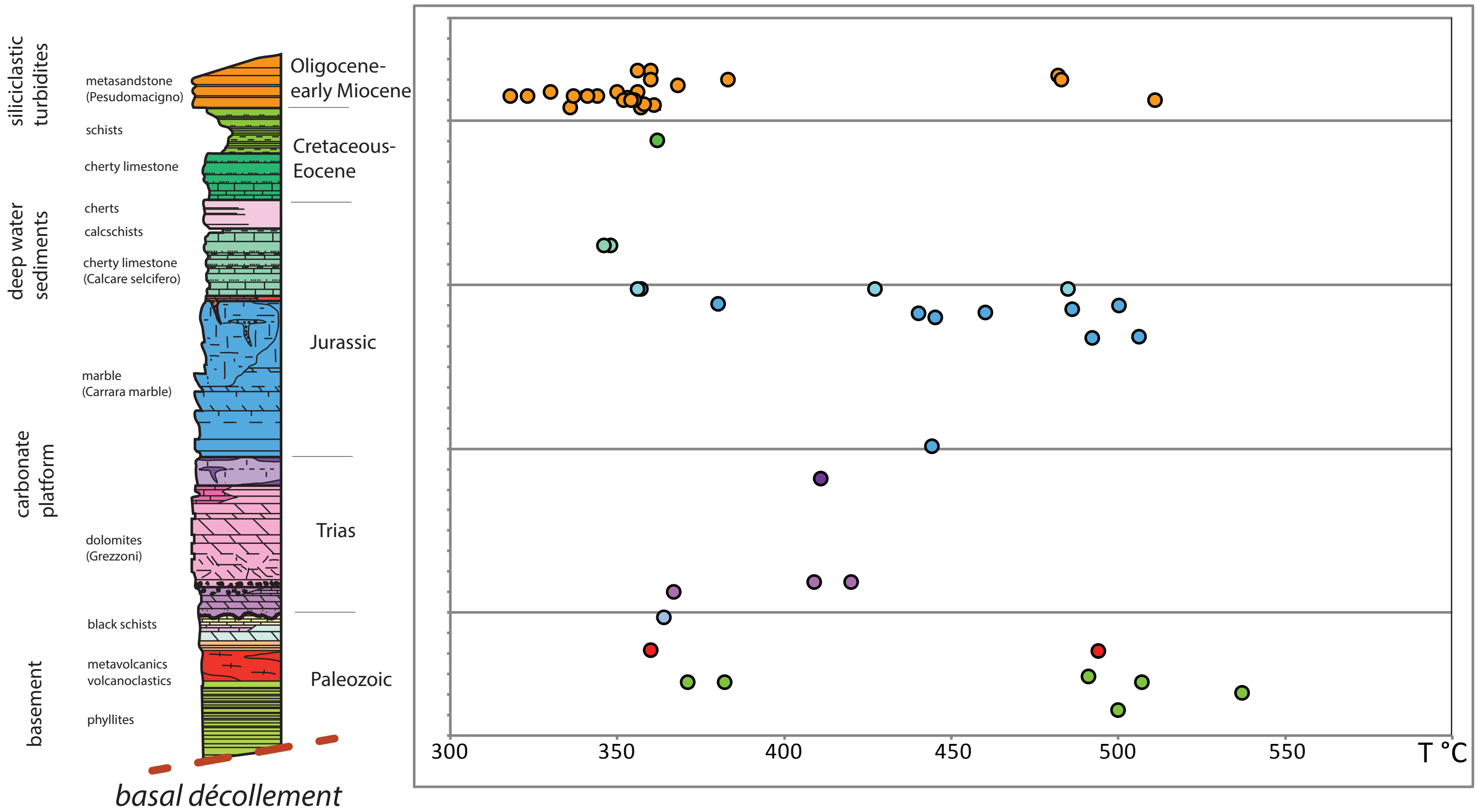

Fig08 Molli et al., JSG

Fig.08 Stratigraphy and RSCM temperatures in the Apuane unit.

Paleothermal and structural architecture of the Alpi Apuane metamorphic core

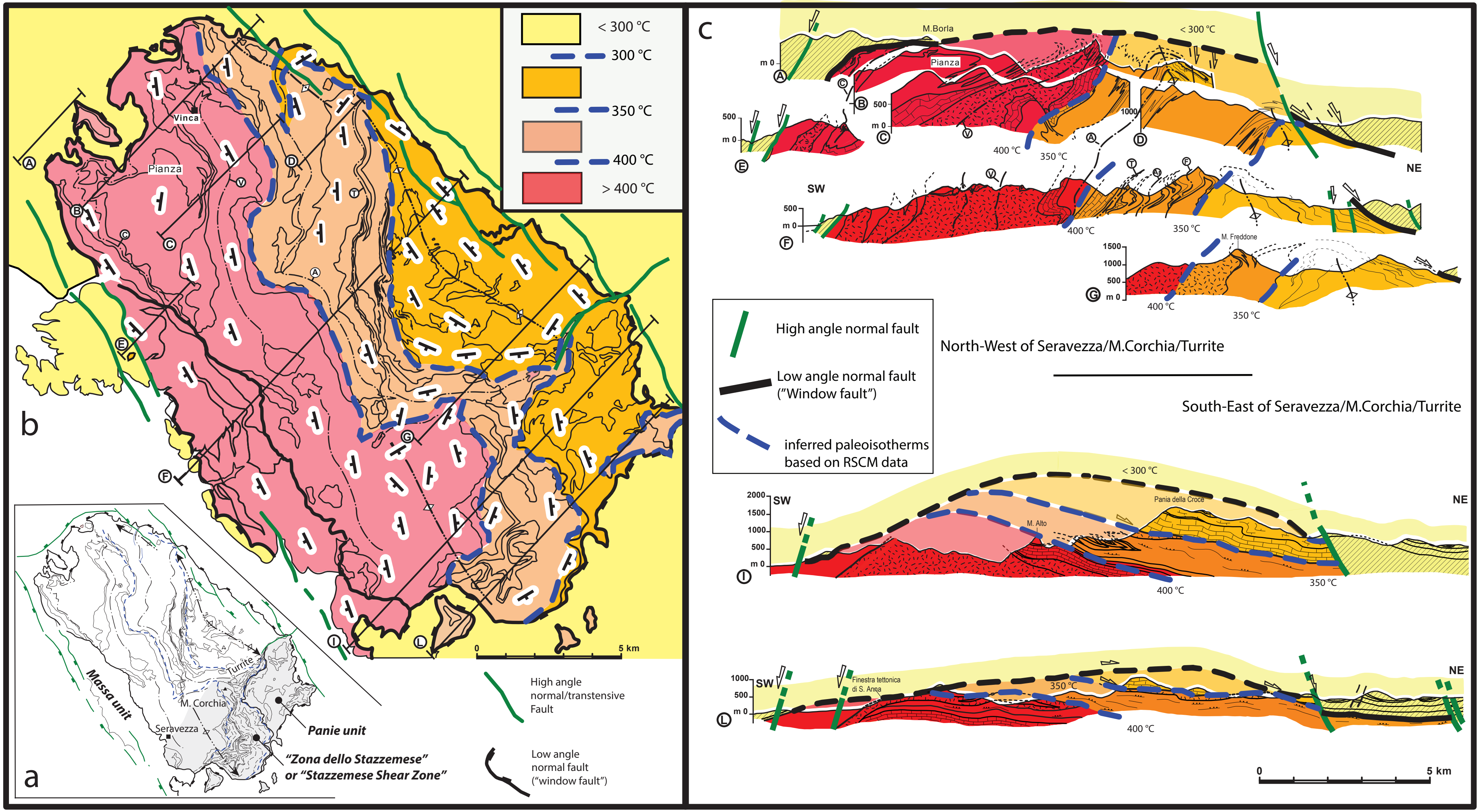

Fig. 09 Molli et al JSG

Fig.09. Paleothermal and structural architecture of the Alpi Apuane metamorphic core complex. a) structural architecture of the Alpi Apuane metamorphic core; b) window-scale paleothermal architecture; c) paleothermal architecture in cross-sections view.

Fig.10 Molli et al JSG

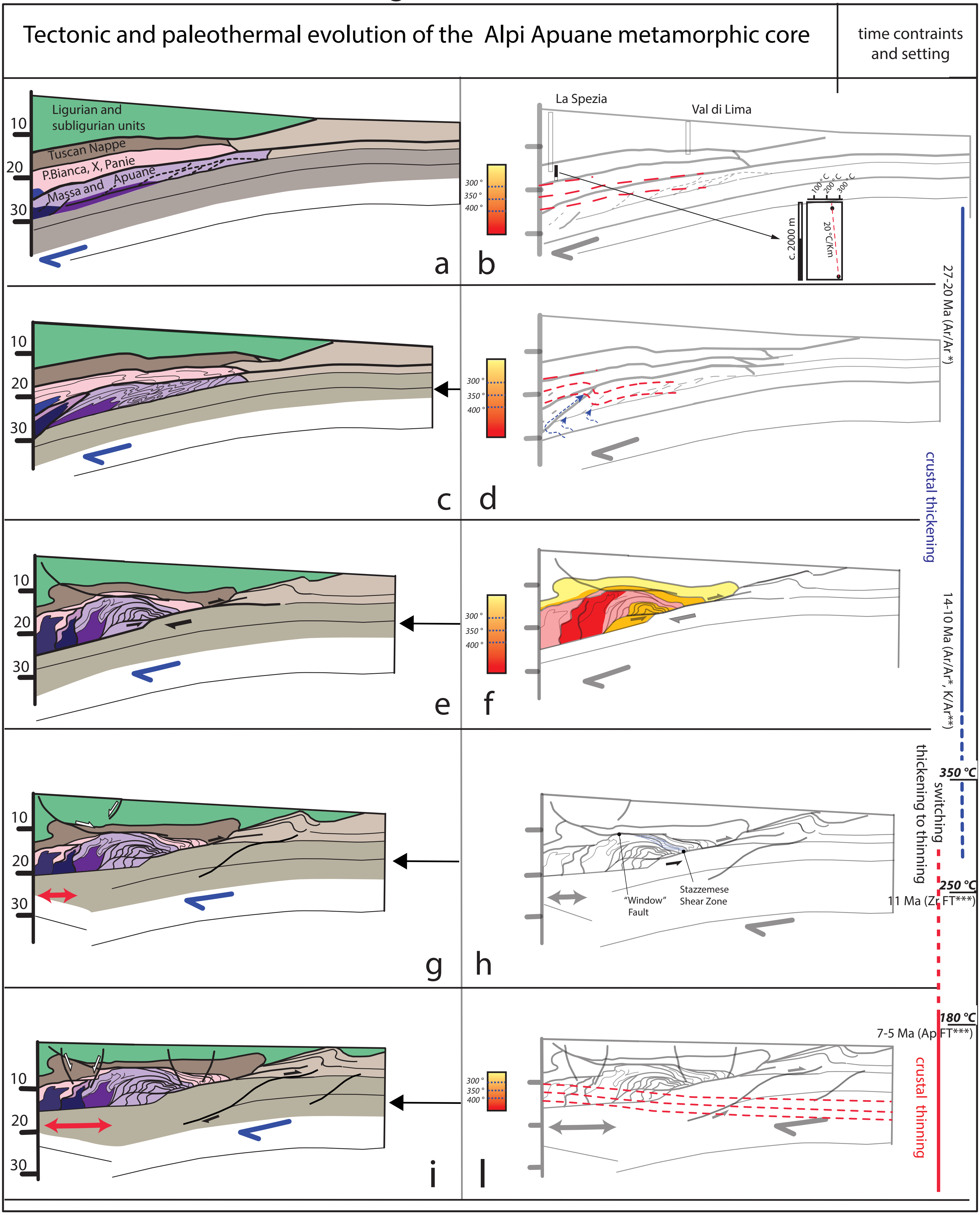

Fig.10. Evolutionary model for the Alpi Apuane within the different stages of Apenninic wedge growth from crustal thickening to crustal thinning (* Kligfield et al., 1986; ** Giglia, Radicati di Brozolo, 1974; *** Fellin et al., 2007 and references): a) early stage of nappe stacking; b) the same as in a) with in red dashed lines the 400°, 350° and 300 °C paleoisotherms. c,d) successive duplexing stage with formation of internal stacking and overthrusting of Massa (higher grade) above the Apuane unit (lower grade). During this stage, a folding of previous paleoisotherms is envisiged to produce the thermal features described at pages 10-11 (see cross sections E,F,I of Figs. 4,5 and Fig.9). In blue the possible path ways of hot fluids associated with ore bodies, reworked within the Stazzemese Shear Zone during later deformation stages; e), f) antiformal stack phase with development of: 1) finite geometry of regional D 1 deformation structures and 2) the finite thermal structure with the regional folding of previous isotherms by the structures of the antiformal stack-related dome; g), h) switching from crustal thickening to crustal thinning with development of D2 structures related to a vertical shortening as well as the "Stazzemese Shear Zone", which is the possible deeper expression of a linked extensional detachment system including the brittle "window fault". The activity of the "window fault" continued up to crustal depth corresponding to an ambient temperature of 180 °C (see thermochronological data in Fellin et al., 2007; i) and l) final stages of exhumation (4-5 Km of vertical displacement) of the Alpi Apuane metamorphic core in the crustal thinning stage continuing up to now. During this stage, deformation is accommodated by high angle normal to transtensive faults cross cutting the "window fault" as well as the syn-metamorphic templates. In l) isotherms are drawn according to thermal data and modeling in Verdoya et al., 2005; Pauselli et al., 2006; Faccenda et al., 2009.

Sample	Tectonic unit		coordinates		n	R2/RA1*	SD	T(°C)	SE
	Rock-type	stratigraphic age	latitude (N)	longitude (E)					
	Tuscan Nappe								
1	impure limestone	Trias	44°02'01.25"	9°50'49.26"	15	0.60*	0,004	284	1,49
2	impure limestone	Trias	44°02'29.79"	9°51'05.45"	15	0.61*	0,006	295	2,24
3	impure limestone	Trias	44°02'52.21"	9°56'55.08"	13	0.61*	0,01	288	4
4	impure limestone	Trias	44°02'43.99"	9°57'05.56"	12	0.59*	0,01	273	3
5	impure limestone	Trias	44°03'30.46"	9°55'44.00"	12	0,61	0,01	292	1
6	marls	Jurassic	44°02'39.81"	10°40'03.68"	11	0.55*	0,01	223	4,5
7	slate	Cretaceous	44°01'05.25"	10°42'31.67"	3	0.55*	0,001	230	1,71
8	marls	Jurassic	44°02'40.39"	10°40'05.18"	15	0.56*	0,01	230	4,64
9	sandstone (MG)	Oligocene-Miocene	44°06'02.11"	9°44'04.24"	15	0.58*	0,01	256	3,77
10	sandstone (MG)	Oligocene-Miocene	44°06'02.75"	9°44'00.92"	14	0.58*	0,02	250	6,13
11	sandstone (MG)	Oligocene-Miocene	44°10'21.06"	10°12'31.58"	12	0,57	0,00	246	1
	P.Bianca Unit								
12	black schist	Permian?	44°02'13.30"	9°58'33.29"	10	0,64	0,001	358	1,00
	M.Pisano Unit								
13	metasandstone (PMG)	Oligocene-Miocene	43°46'49.15"	10°26'03.93"	12	0,62	0,01	305	4,00
14	metasandstone (PMG)	Oligocene-Miocene	43°46'48.75"	10°26'03.00"	11	0,62	0,01	318	7,00
	Massa Unit plus XX Unit								
15	phyllite	Paleoz	44°04'16.70"	10°08'5046"	17	0,3	0,07	509	8,12
16	impure metalimestone	Jurassic	44°03'15.84"	10°07'33.32"	16	0,64	0,02	358	2,72
17	black schist	Permian?-Mid-Trias	44°01'17.23"	10°11'05.70"	20	0,42	0,04	454	4,54
18	black schist	Permian?-Mid-Trias	44°04'23.22"	10°08'59.77"	14	0,33	0,04	493	5
	Apuane unit								
19	impure metalimestone	Jurassic	44°6'52.94"	10°07'41.80"	25	0,48	0,04	427	3,64
20	metasandstone (PMG)	Oligocene-Miocene	44°8'16.54"	10°11'48.83"	13	0,73	0,03	318	3
21	metasandstone (PMG)	Oligocene-Miocene	44°8'16.42"	10°11'48.87"	13	0,67	0,04	344	5
22	metasandstone (PMG)	Oligocene-Miocene	44°9'31.65"	10°12'00.87"	14	0.65*	0,01	341	3
23	metasandstone (PMG)	Oligocene-Miocene	44°9'31.77"	10°12'00.83"	14	0.63*	0,01	323	3
24	metasandstone (PMG)	Oligocene-Miocene	44°9'32.19"	10°12'00.84"	13	0.65*	0,01	337	4
25	black schist	Permian?-Mid-Trias	44°6'34.10'	10°09'53.45"	15	0,52	0,01	409	1,29
26	black schist	Permian?-Mid-Trias	44°6'33.45"	10°09'53.23"	15	0,50	0,02	420	2,37
27	impure metalimestone	Jurassic	44°7'12.73"	10°12'42.85"	15	0,62	0,02	362	2,51
28	impure metalimestone	Jurassic	44°04'21.33"	10°09'03.79"	19	0,35	0,04	485	3,93
29	impure marble	Jurassic	44°11'37.34"	10°11'37.13"	13	0,41	0,04	460	5,62
30	phyllite	Paleoz	44°02'20.74"	10°12'04.74"	16	0,34	0,06	491	7,23
31	schist	Late Trias	44°04'30.71"	10°12'56.02"	1	0,51		411	
32	phyllite	Paleozoic	44°02'23.67"	10°14'56.62"	15	0,58	0,02	382	2,4
33	metasandstone (PMG)	Oligocene-Miocene	44°03'29.81"	10°15'39.26"	10	0,6	0,05	368	6,79