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

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**Keywords:**

RSCM Thermometry, Thermal structure, Tectonics, Alpi Apuane, Northern Apennines

**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  $\sim 530$ - $320$  °C were found in the Alpi Apuane, whereas in the nearby metamorphic core of the M.Pisani and P.Bianca lower peak temperatures of  $305$ - $315$  °C and  $350$  °C, respectively, were found. The Tuscan Nappe in La Spezia area (west of Alpi Apuane) show temperatures in the range of  $295$ - $246$  °C whereas the same unit in the Lima Valley (east of the Alpi Apuane) temperatures lower than  $230$  °C were recorded.

The collected data allowed us to constrain the relationships between the nappe architecture and thermal structure as well as those between deformation structures (early and late folds and low angle normal detachments) and the thermal architecture of the Alpi Apuane metamorphic core providing new constraints 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 most of the exhumation is unrelated with crustal thinning presently ongoing in the area.

## INTRODUCTION

The thermal structure and the field metamorphic gradient in mountain belts may be first order variables directly related with the tectonic setting and the crustal-scale architecture of the orogens (between others Chopin et al., 1991; Goscombe et al., 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 (Selverstone, 1988; Jolivet et al., 1998; Ring et al., 1999; Chen et al., 2011; Cottle et al. 2011). Therefore, the understanding of the thermal structure of the internal parts of the mountain belt and its evolution represent a key element to unravel the tectonic frame and kinematics of the development of the orogenic system, allowing a better definition of past geological boundary conditions as inputs for large-scale thermokinematic and geodynamics simulations (Beyssac et al., 2007; Simoes et al., 2007; Avouac et al., 2012).

In the inner northern Apennines thermal characters and evolution of the main units of the nappe stack were defined through the classical methods of clay mineralogy, vitrinite reflectance, fluid inclusions and illite cristallinity for the shallowest units of the nappe stack (Cerrina et al., 1980; Carter et al., 1998; Carosi et al., 2005; Reutter et al., 1978; Reutter et al., 1980; 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), while in the lowermost metamorphic units Al-silicates, chloritoid-chlorite thermometry, calcite-dolomite, stable isotope geothermometers, and conodonts color were used (Franceschelli et al., 1990; 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, thermodynamical 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 supported by different groups of authors (Carmignani and Kligfield, 1990; Boccaletti et al., 1993; Carosi et al., 2003; Decandia et al., 1995; Storti, 1995; Jolivet et al., 1998; Thomson et al., 2010; Sani et al., 2014; Musumeci et al., 2016). This in turn leaves open some relevant questions such as the relationships between exhumation processes and crustal/litospheric thinning, which shaped the present day Moho



depth and thermal anomaly, characteristic features of the inner northern Apennine in Tuscany (Di Stefano et al., 2011; Della Vedova et al., 2001; Spada et al., 2013 and references).

In this study, we applied the same geothermometer, i.e. Raman spectroscopy on carbonaceous material (RSCM), to 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 carbonaceous material (CM), this geothermometer can provide peak temperature (T) estimates for CM-bearing metasedimentary rocks independently from their mineralogical assemblage, and is therefore applicable to a wider range of rock types in the considered units compared to previous studies.

Our data allow us to constraining the field thermal structure and the exhumation-related paleogradients and therefore to 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.

## 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) presently lying 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; Bortolotti et al. 2001, Bernoulli, 2001; Liotta, 2002; Molli, 2008 and ref.). 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 (Po Plain and Adriatic) eastern side (e.g. Elter et al., 1975; Barchi et al., 1998; Doglioni et al., 1998; Fellin et al., 2002; Bennett et al., 2012; Boccaletti et al., 2010; Eva et al., 2014; Faccenna et al., 2014; Molli et al., 2015; Le Breton et al., 2017).

In the NW of Tuscany, the Alpi Apuane form 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 Adria-derived continental units are traditionally distinguished in the region, the Tuscan Nappe, the Massa unit and the Apuane unit (Fig.2). The Tuscan Nappe consists of Mesozoic carbonates and Tertiary deep water and turbiditic sequence mainly detached from their original basement along the décollement level of the Norian anidrites

141 and dolostones to be compared with the Anidriti di Burano (Ciarapica and Passeri, 2002 and  
 142 references therein). These anydrites and dolostones are transformed almost everywhere (with some  
 143 relevant exceptions) into cataclastic breccias called Calcare Cavernoso or “cellular” limestone  
 144 (Baldacci et al., 1967; Gandin et al., 2000). The post-Norian sequence continues with Rhaetian to  
 145 Hettangian shallow water limestones (Rhaetavicula Contorta and Calcare Massiccio), Lower Liassic  
 146 to Cretaceous pelagic limestones, radiolarites and shales (Calcare selcifero, Marne a Posidonomya,  
 147 Diaspri, Maiolica), grading to hemipelagic deposits of the Scaglia (Cretaceous-Oligocene), to end  
 148 with the siliciclastic foredeep turbidites of the Macigno (Late Oligocene-Early Miocene). The entire  
 149 sequence, has a thickness between 2000 and 4000 m (Fazzuoli et al., 1986; Ciarapica and Passeri,  
 150 2002; Molli and Meccheri, 2012);

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

166 The Massa unit is exposed in the westernmost part of the Alpi Apuane tectonic window and  
 167 includes a litho-stratigraphic sequence formed by a Paleozoic basement similar to that of the  
 168 Apuane unit and a characteristic and distinctive Upper Permian–Upper Triassic metasedimentary  
 169 succession, including a Mid Triassic continental (conglomerates and pelites) to marine (carbonate  
 170 platform derived deposits) succession associated with intraplate alkaline basalts (Martini et al.,  
 171 1985). Lithostratigraphic terms younger than late Mid Triassic are not described in the literature,  
 172 although (see below) they may be locally found as tectonic lenses and small scale remnants within a  
 173 cataclastic fault zone below the contact with the overlaying Tuscan Nappe (Molli et al., 2002; Conti  
 174 et al., 2004). Traditional literature (Baldacci et al., 1967; Elter, 1975) based on the similarities in

175 stratigraphic contents of the pre-Late Triassic sequences considered the metamorphic exposures of  
 176 Punta Bianca and M.Pisano the same of the Massa unit although different peak metamorphic  
 177 conditions were recorded in the recent papers (Storti, 1995; Carosi et al., 2014; Leoni and Pertusati,  
 178 2003; Molli, 2008 and references therein).

179 The deformation structures of the Tuscan metamorphic units of the Alpi Apuane and surroundings  
 180 metamorphic cores may be referred to two main tectono-metamorphic regional events (D1 and D2  
 181 phases of Carmignani and Kligfield, 1990), which are regarded (Molli et al., 2000, 2002) as  
 182 recording progressive deformation of the distal Adriatic continental margin during continental  
 183 subduction and the syn- to post-contractional exhumation (Carmignani et al., 1990; Jolivet et al.,  
 184 1998; Carmignani et al., 2001; Molli, 2008). The two main regional events D1 and D2 were related  
 185 to different fold generations or folding phases as illustrated by Molli and Meccheri (2012) in the  
 186 Alpi Apuane. The same deformation patterns may be also recognized in the Punta Bianca and  
 187 M.Pisano metamorphic cores (Storti, 1996; Montomoli, 2002; Carosi et al., 2007; Molli, 2008;  
 188 Balestrieri et al., 2011).

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

194 During D2, the previously formed structures were reworked by different generations of folds and  
 195 high-strain zones, related to exhumation of the metamorphic units within the inner portion of the  
 196 northern Apenninic wedge (Molli, 2008). During the early stage of D2, folds with subhorizontal  
 197 axial plane crenulation formed, whereas later deformation was associated with semibrittle and  
 198 brittle structures, represented by kink and open folds, and low-angle normal faults (Molli and  
 199 Meccheri, 2000; Molli et al., 2010). The final stages of deformation are recorded by systems of  
 200 high-angle normal to oblique-normal and transcurrent faults related with the recent to active  
 201 deformation regime affecting the area (Corti et al., 2006; Bennett et al., 2012; Molli et al., 2015  
 202 a,b). Available pressure (P), T and geochronological data for the Alpi Apuane metamorphism are  
 203 summarized in Molli et al. (2000, 2002); Fellin et al. (2007 and references therein); Carosi et al.  
 204 (2007, 2013).

205 In the metamorphic units of the Alpi Apuane, peak conditions are roughly related to T between 450  
 206 and 350 °C and P of 0,8-0,4 GPa (Molli et al., 2002 and references therein). In particular, kyanite +  
 207 chloritoid + phengitic muscovite characterize the assemblages in metapelites of the Massa unit where  
 208 peak conditions in the range of 0,6-0,8 GPa and 420- 500°C (Franceschelli et al., 1986; Jolivet et

209 al., 1998; Franceschelli & Memmi, 1999; Molli et al., 2000b) were defined. Instead, pyrophyllite +  
 210 chloritoid + chlorite + phengitic muscovite in metapelites may be found in the Apuane unit, with  
 211 peak metamorphic conditions estimated in the range of 0.4-0.6 GPa and 350-450 °C (Franceschelli  
 212 et al., 1986; Di Pisa et al., 1987; Jolivet et al., 1998; Molli et al., 2000b).

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

217 In contrast to the Tuscan metamorphic units, the Tuscan nappe was accreted at a shallow crustal  
 218 level within the northern Apennines wedge beginning in early Miocene (Cerrina Feroni et al., 2004;  
 219 Molli, 2008). Burial occurred under a sequence of thrust sheets now preserved in the overlying sub-  
 220 Ligurian and Ligurian units (Figs. 1,2). Early thrusting is documented by top-to-the east small scale  
 221 shear zones and an early generation of east vergent tight to isoclinal folds within incompetent  
 222 stratigraphic layers (Gianmarino & Giglia, 1990; Carter, 1992; Molli et al., 2011). The early formed  
 223 structures in the Tuscan nappe were subsequently overprinted by small to large (kilometer-scale)  
 224 refolding associated with sub-horizontal crenulation cleavage observable in pelitic rock units, low-  
 225 angle normal faults and later upright folds (Carmignani et al., 1995; Storti, 1995; Carosi et al.,  
 226 2003). Metamorphism to anchizone grade (Cerrina Feroni et al., 1983; Carosi et al., 2003; Molli et  
 227 al., 2011) during burial and deformation has been tectono-stratigraphically constrained to a  
 228 maximum depth of 7 km for the Macigno sandstones (Reutter et al., 1978; Montomoli et al., 2001;  
 229 Montomoli, 2002; Fellin et al., 2007).

230

231

## 232 **RAMAN SPECTROSCOPY OF CARBONACEOUS MATERIAL**

233

234 Raman spectra were obtained using a Renishaw InVIA Reflex microspectrometer (IMPMC Paris).  
 235 We used a 514 nm Laser Physics argon laser in circular polarization. The laser was focused on the  
 236 sample by a DMLM Leica microscope with a 100× objective (NA = 0.85), and the laser power at  
 237 the sample surface was set around 1 mW. The Rayleigh diffusion was eliminated by edge filters,  
 238 and to achieve nearly confocal configuration the entrance slit was closed down to 15 µm. The signal  
 239 was finally dispersed using a 1800 gr/mm grating and analyzed by a Peltier cooled RENCAM CCD  
 240 detector. Before each session, the spectrometer was calibrated with a silicon standard. Because  
 241 Raman spectroscopy of CM can be affected by several analytical mismatches, we closely followed  
 242 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  $\text{cm}^{-1}$ ) 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.  $\sim 200$  b T b  $350^\circ\text{C}$ ) were estimated using the correlation proposed by Lahfid et al. (2010). At higher-T (i.e.  $\sim 350$  b T b  $650^\circ\text{C}$ ), the T was calculated using the calibration of Beyssac et al. (2002), with a calibration-attached accuracy of  $\pm 50^\circ\text{C}$  due to uncertainties on petrologic data used for the calibration. Relative uncertainties on T are, however, much smaller, around  $10\text{--}15^\circ\text{C}$  (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 divided 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 crystallized graphite (higher-T) (Table 1). The collected data allow distinguishing samples characterized by T gaps in the order of about  $20^\circ\text{C}$  (Fig. 3), as already observed for this method along continuous metamorphic gradients in Alpine settings (Vitale Brovarone et al., 2014)

## RSCM TEMPERATURE RECORD IN THE ALPI APUANE AND SURROUNDINGS

Our dataset consists of 74 analyzed samples (Table 1) selected among 120 collected in various stratigraphic and structural positions within the different tectonic units. The samples were collected along a regional SW-NE oriented section across the inner (western) 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 as part of a regional-scale fold called La Spezia fold (e.g. Gianmarino and Giglia, 1991; Carter, 1992; Carosi et

277 al., 2002; Molli et al., 2011 and references therein), in the eastern promontory of La Spezia  
 278 (between Lerici and P.Bianca) (Storti, 1996; Clemenzi et al., 2015 and references), north and east of  
 279 the Alpi Apuane in the Lunigiana and Lima Valley (Molli et al., 2015; Clemenzi et al., 2014 and  
 280 references).

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

285 The stratigraphic units sampled in our study are mainly from the Mesozoic to Tertiary cover  
 286 sequence and in particular from siliciclastic sandstones of Macigno fm. (Late Oligocene-Early  
 287 Miocene in age) and impure Triassic limestones for the Tuscan Nappe. The metamorphic  
 288 equivalents (metasandstones, slates, schists, calcschists and impure marbles) were sampled in the  
 289 Apuane and Massa units altogether with some samples from the Paleozoic basement units (mainly  
 290 phyllites and schists) (Fig. 2). The samples collected in the eastern promontory of La Spezia come  
 291 from the Triassic impure limestone at the base of the Tuscan Nappe and from the underlying pre-  
 292 Mesozoic terms (black phyllites supposed to be Permian age) of the metamorphic Punta Bianca unit  
 293 i.e. respectively in the hanging-wall and footwall of the former major thrust reworked as a low  
 294 angle normal fault (Storti, 1996; Carosi et al., 1998, Clemenzi et al., 2015). Moreover, the two  
 295 analyzed samples in the S.Maria del Giudice unit are part of the Monte Pisano metamorphic core  
 296 (Rau and Tongiorgi, 1974; Carosi et al., 1993; Montomoli, 2002; Leoni et al., 2009) and are derived  
 297 from its Tertiary cover sequence (Pseudomacigno Fm.).

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

302

303 The sampling strategy allowed constraining the RSCM T within the classically defined continent-  
 304 derived units of the inner northern Apennines (Elter, 1975; Carmignani et al., 1978; Carmignani and  
 305 Kligfield, 1990; Carmignani et al., 2001 between the others) which are in the current view (see  
 306 above) subdivided into three major slices referred, from top to bottom, to as Tuscan nappe, Massa  
 307 and Apuane (also called “Autochthonous”) units (Fig. 1). In the La Spezia area, the Punta Bianca  
 308 metamorphic occurrences are associated with a pristine lithostratigraphic assemblage similar to that  
 309 of the Massa unit but affected by a lower grade peak metamorphic imprint (Ciarapica and Passeri,  
 310 1985; Storti, 1996; Leoni and Pertusati, 2003; Lo Po’ et al., 2017), whereas the Monte Pisano

311 metamorphic core is similarly considered part of the Massa unit for the presence of widespread  
312 continental “Verrucano” deposits (Rau and Tongiorgi, 1974; Carosi et al. 2011).

313

314 The overall data sets, summarized in Fig. 7 and Table 1, show significant difference in mean peak T  
315 among the major tectonic units so far defined.

316 The RSCM peak T are in the range of 246-284 °C (mean  $260 \pm 26$  °C ) for the Tuscan Nappe; 306-  
317 537 °C (mean  $397 \pm 64$  °C, n=63) for for the Apuane and 454-509 °C ( $485 \pm 28$  °C, n=3) for the  
318 Massa unit.

319 In the Tuscan Nappe exposed in the La Spezia area (Figs. 1,2), a simple relationship between  
320 stratigraphic positions of the samples and peak T appears (Fig. 6). The youngest terms of the  
321 succession represented by the Macigno fm. show a mean T of 253 °C, whereas in the lowermost  
322 measured Triassic term of the Calcari a Rhaetavicula Contorta fm. (Rhaetian in age) a mean T of  
323 289 °C was obtained.

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

327 Samples from the Tuscan Nappe in the Lima Valley (Baldacci et al., 1967; Fazzuoli et al. 1992;  
328 Botti et al., 2009; Clemenzi et al., 2014) east of the Alpi Apuane show instead lower mean  
329 temperature of 227 °C obtained for Jurassic and Cretaceous pelites and marls (Table 1, Fig. 6).

330

331 In the Alpi Apuane, although the highest T were measured in samples of the Paleozoic basement  
332 ( $364-537$  °C, mean  $445 \pm 66$  °C) and the lowest ( $306-511$  °C, mean  $368 \pm 50$  °C) in the youngest  
333 stratigraphic terms of the cover sequence (PseudoMacigno fm.), no simple relationships between  
334 stratigraphy and T appear at the scale of the whole metamorphic core (Figs. 4,5,8).

335 The mean T in the north-west part of the metamorphic complex (north of the Seravezza-Monte  
336 Corchia, Turríte valley alignment) is basically the same as those defined in the south-eastern  
337 segment (south of the Seravezza-Monte Corchia, Turríte valley alignment), around  $\sim 380$  °C. The T  
338 data plotted on composite vertical cross-sections (Figs. 5,9) show, however, a clearly well-defined,  
339 yet different thermal structure and overall thermal architecture between the northern and southern  
340 Alpi Apuane.

341 The north-west part of the Alpi Apuane, as previously defined, (cross-sections A,B,C,D,E,F,G)  
342 shows an inverted field metamorphic gradient. Within the Apuane unit higher T ( $483-507$  °C, mean  
343  $465$  °C) are found in the west, within a structural distance of  $\sim 500$  m from the basal contact of the  
344 Massa unit (Figs. 5,9). The T decrease eastward and structurally downward to  $\sim 345$  °C in the Orto

345 di Donna sincline and in the Arni-Boana structural culmination, i.e. in the geometrically deepest  
 346 parts of the Alpi Apuane metamorphic core (Kligfield et al., 1981; Carmignani and Kligfield, 1990;  
 347 Carmignani et al., 2001; Molli and Vaselli, 2007).

348 The south-eastern parts of the Alpi Apuane (cross-sections H,I,L,M) are instead characterized by a  
 349 normal-type metamorphic field gradient with overall upward decreasing T from 510 °C to 320 °C in  
 350 a vertical structural distance of 3000 m.

351 Samples with the highest RSCM T are founded in the south-eastern part of the Alpi Apuane, an area  
 352 known in the local geological literature as “Zona dello Stazzemese” or “Stazzemese Shear Zone”  
 353 (Stazzema is village included in it). The area is characterized and recognized for a long time for its  
 354 distinctive structural style (see Massa 2007 for an historical overview) with kilometer scale  
 355 recumbent D2 isoclinal folds with highly sheared and mylonitized limbs (see Carmignani et al.  
 356 1996, Conti et al., 2009; Cinquini, 2014). The area is also peculiar with respect to the whole Alpi  
 357 Apuane for the presence of characteristic mineralizations of Pb-Zn±Au Hg, Fe-Cu and Barite-Iron  
 358 Oxide-Pyrite deposits studied and employed since the mid of last century (Carmignani et al., 1972;  
 359 Carmignani et al., 1976; Orberger, 1985; Costagliola et al., 1990; Dini et al., 1995; Costagliola et  
 360 al., 1998; Biagioni et al., 2016).

361 Significantly, the highest RSCM T are found in different protoliths (Palaeozoic, Mesozoic-Cenozoic  
 362 in ages) in close relationships with mineralized. The RSCM T for these samples exceed of about  
 363 180-200 °C the values obtained for the enclosing host rocks. As an example, in the Fornovolasco  
 364 area (the easternmost extension of the “Zona dello Stazzemese”), Tertiary metasandstones  
 365 (Pseudomacigno Fm.) show RSCM T >500°C (sample 70) if close to mineralized levels (Trimpello  
 366 ore bodies), whereas the same rock type far from mineralized bodies shows T <360 °C (samples  
 367 68,69,71) (Fig. 5 and Table1).

## 368 369 **COMPARISON WITH PREVIOUS DATA**

370  
 371 Our new RSCM data find good agreement with previous available data, in particular those derived  
 372 from calcite/dolomite (Ca/Do) geothermometer/analysis (Fig.4) (Di Pisa et al., 1985; Molli et al.,  
 373 2000; Oesterling et al., 2007). Although different in absolute value, the RSCM and Ca/Do data well  
 374 document the presence of inverted metamorphism in the North/West part of the Alpi Apuane, with  
 375 higher T in the westernmost and uppermost structural positions which decrease eastward and  
 376 downward within the structural building.

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



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

388 For the Massa unit we were able to find only 3 suitable samples among more than 25 analyzed since  
 389 they were almost totally oxidized coming mainly from Verrucano continental metasediments. Our  
 390 mean RSCM T is, however, in agreement with the estimates based on Fe-Mg exchanges in  
 391 coexisting chloritoid and chlorite (450-500 °C; Franceschelli and Memmi, 1999). Similar T ranges  
 392 were also constrained by the stability field of the kyanite+quartz pair and chlorite+chloritoid+quartz  
 393 assemblages in the FeO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O (Franceschelli et al., 1998).

394 Using similar methods (chloritoid±chlorite Mg±Fe-exchange thermometer a peak temperature of  
 395 455 °C was found by Molli et al. (2000).

396 Ca-Do data in the Mid-Triassic marble of the Massa unit also give a similar T in the range of 430-  
 397 520 °C (Cardaci, 1987).

398

399

## 400 SUMMARY AND DISCUSSION

401

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

408

### 409 Peak temperature and tectonic units

410 A first point to be remarked is the difference in the mean peak T among the  
 411 structurally/stratigraphically defined tectonic units (Fig. 7).

412 The classically accepted subdivision (Elter, 1975, Carmignani and Kligfield, 1990; Decandia et al.,  
 413 1996, Vai and Martini, 2001) into three major continental units forming the backbone of the inner  
 414 northern Apennines – from top to bottom: the Tuscan nappe, the Massa and the Apuane units –

415 appears to be fully supported by the new measured RSCM T (Fig.7) which show a mean peak T of  
 416  $\sim 260$  °C for the Tuscan Nappe,  $\sim 485$  °C for the Massa unit and  $\sim 385$  °C for the Apuane unit.  
 417 Moreover, our data suggest that the nappe stack was originally formed by units overlooked in  
 418 current literature. In such group of units may be included the Punta Bianca Unit in the West, and  
 419 the Monte Pisano Unit in the South. Moreover, in the southern-eastern Alpi Apuane the Panie may  
 420 be inserted within this group, since they are here characterized by a RSCM T of 320 °C, an  
 421 intermediate value between those of the Apuane Unit and those of the Tuscan Nappe. Other  
 422 evidence of missing units, inside the Alpi Apuane, may be searched for between the Massa unit and  
 423 the overlying Tuscan Nappe (Fig.5 cross section E), where remnants of a post mid-Triassic cover  
 424 (cherty metalimestones, marbles, phyllites) with a peak RSCM T of  $\sim 350$  °C were sampled (sample  
 425 16). Those remnants are also observable as structural relicts exposed as hectometer to  
 426 pluridecameter thick slices and lenses (see Molli et al., 2000) and widely recognizable as clasts  
 427 (meter, decimeter to centimeter in scale) within the carbonatic tectonic breccia at the base of the  
 428 Tuscan Nappe in the southern Alpi Apuane (Conti et al., 2009; CARG F.260; Cinquini and Molli,  
 429 2015). These data and occurrences may be interpreted as related to the former existence of a  
 430 metasedimentary unit (“X unit”, “missing section” in Fellin et al. 2007) originally including the  
 431 post Mid-Triassic cover sequence now only scatterly observable on top of the Massa Unit.  
 432 The rank of individual tectonic unit for the Panie (see discussion in Nardi, 1967, Giglia 1967) as  
 433 well as the importance of the “X unit” to fill the gap between the base of the Tuscan Nappe and the  
 434 top of the Massa unit during the syn-peak metamorphism nappe stacking are in line with what  
 435 anticipated and discussed in the frame of the tectonic history of the metamorphic units by Molli et  
 436 al., (2000); Molli et al., (2002); Fellin et al. (2007). Thanks to the newly defined RSCM data and  
 437 considering the mean T as an estimate of the “whole unit” thermal peak, we may emphasize that the  
 438 classical subdivision into three major Tuscan units across the Alpi Apuane and surrounding  
 439 introduced in literature since Elter (1975) as related to the original thrust stacking is due instead to  
 440 tectonic excision during exhumation, i.e present day tectonic units have to be considered as  
 441 remnants of a former thicker, more complete and now only partially preserved contractional nappe  
 442 stack (Coli, 1989; Van den Berg, 1989; Carmignani et al., 1990; Carmignani et al. 1995; Jolivet et  
 443 al., 1998; Molli et al., 2002).  
 444

#### 445 **Metamorphic field gradients and thermal architecture**

446 For the Tuscan Nappe, the dataset in the La Spezia area (Fig.2,6) indicates a base (Triassic Rhaetian  
 447 limestone) to top (Oligocene-early Miocene Macigno sandstone) difference of  $\sim 40$  °C which occurs  
 448 within a structural distance of 2000 m. Thus, assuming that the peak T are: (i) coheval in age and

449 (ii) related with the pre-folding thermal architecture of the unit within the orogenic prism, a peak T  
450 normal-type field gradient of 20 °C/Km may be defined (Fig.11).

451 At regional scale, the collected data from the Tuscan Nappe suggest for its westernmost exposure  
452 (La Spezia area) a mean RSCM T of 271° C and a lower mean T of 227°C in the easternmost  
453 position in the Lima Valley, east of the Alpi Apuane (Fig.1,2). This West to East decrease of peak  
454 T, in line with previously recorded illite crystallinity and organic matter data (Reutter et al., 1978;  
455 Cerrina Feroni et al., 1983), may be referred to an original different thickness of the orogenic wedge  
456 stack above the Tuscan Nappe. Moreover, assuming that the field gradient defined in the La Spezia  
457 area was constant at regional scale, this results in a variation of the wedge thickness above the  
458 Tuscan Nappe of ~2 Km from west (La Spezia) to east (Val di Lima) (Fig.11).

459  
460 For the Alpi Apuane, taking into account the whole data set in the Apuane unit, a difference in  
461 temperatures between the pre-Mesozoic samples and the Mesozoic to Tertiary ones may be  
462 underlined (Figs. 4,5,8,9).

463 The pre-Mesozoic basement rocks show a mean peak RSCM T of 445 °C whereas a mean of 386°C  
464 is found in the metasedimentary Mesozoic to Tertiary cover.

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

469 Nevertheless, since similar higher T (Fig.8) were also found in samples with Mesozoic to Tertiary  
470 protoliths, an alternative hypothesis may also be taken into account.

471 In this alternative frame, an Apenninic-age heating possibly related to a fluid flow infiltration in the  
472 basement rocks (and locally in the Mesozoic cover) during its detachment from the underlying  
473 subducted middle to lower crust may be envisaged (Fig. 11). The higher peak T found in  
474 association with mineralized horizons in the southern Alpi Apuane may thus be interpreted as an  
475 evidence of Apenninic-age infiltration and hot fluid flow along high-strain localized zones of  
476 deformation, which were reworked during exhumation ("Zona dello Stazzemese" or Stazzemese  
477 Shear Zone. Figs. 9, 11).

478  
479 Finally, the distribution of peak T at the scale of the whole Alpi Apuane (Fig.9) indicates a different  
480 and systematic arrangement with respect to the overall architecture of the structures in the north-  
481 west as opposed to the south-easternmost part.

482 The North-West part of the Alpi Apuane (Figs. 5,9) is characterized by a SW to NE decrease of

483 peak temperature from 495 °C in the west to 357 °C in the central and 336 °C in the easternmost  
 484 position. A difference of 125° C is observed with a structural distance of ~8 Km, thus an inverted  
 485 field metamorphism with a T gradient of ~20 °/Km could be defined.

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

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

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

500

## 501 **Regional structures of the Alpi Apuane, kinematics and paleothermal evolution**

### 502 **- Internal deformation of the Alpi Apuane metamorphic core**

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

517 East- or South/East-dipping.

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

522 The proposed evolutionary model envisages: i) crustal underplating of the Tuscan continental units  
 523 (Fig. 10a,b) with an early stage of underthrusting and stacking below the Ligurian/subligurian lid  
 524 (former Ligurian Tethys-derived accretionary wedge). Assuming a constant thermal gradient of 20  
 525 °C/Km as defined in the upper continental unit (Tuscan Nappe), a  $T > 400$  °C was reached at crustal  
 526 depth major than 20 Km, thus fitting available petrological data (Franceschelli et al., 1985; Molli et  
 527 al, 2000) and our RSCM data. The Massa unit, originally derived from the westernmost position,  
 528 records higher Temperature (and Pressure) peaks, with respect to the Apuane unit (see also Jolivet  
 529 et al., 1998; Molli et al., 2000a,b); ii) a successive duplexing stage (Fig. 10c,d) may be responsible  
 530 for the formation of the internal stacking and regional fold development including the overthrusting  
 531 of the Massa (higher grade) unit above the Apuane unit (lower grade). During this deformation  
 532 stage (late D1 in Molli et al., 2000), and following the thermo-kinematic model proposed by  
 533 Dunlop et al. (1998) and Bollinger et al. (2004) a folding of previous paleoisotherms is suggested to  
 534 produce the paleothermal and structural features in the western side of the Alpi Apuane across the  
 535 contact between the Massa and the Apuane units and downward (Figs. 4,5).

536 During the crustal duplexing and antiformal stacking (Fig. 11d,e,f) a possible pathway for hot fluids  
 537 coming from middle to lower crust may be suggested along some major tectonic contact and along  
 538 the decollement level at the base of detached Paleozoic terms. This hot fluid channelling associated  
 539 with ore mineralization was localized with the ongoing deformation and after the refolding of  
 540 previous D1 structures in the eastern limb of the regional antiformal stack within “Stazzemese  
 541 Shear Zone” (Figs. 9,10e,f).

#### 542 - The Alpi Apuane metamorphic core and its boundary faults

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

plate units ( $401 \pm 65$  °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  $\Delta T > 200$  °C in the west to  $\Delta T < 50$  °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 11e,f.

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 and its antiformal stack development occurred before 11 Ma (by Zr FT age constrains Temperature of 240 °C), whereas the end of the activity of the “window fault” occurred at a crustal depth as low as  $\sim 180$  °C in a time interval between 7 to 4–5 Ma. After that time crustal extension ending in the present day tectonic setting, superficial and deep crustal morphostructure was accommodated at shallow crustal levels by high angle normal faults (Fig., 4,5,9) cross-cutting the former synmetamorphic structures as well as the “window fault” (Molli et al., 2016 and references therein).

## 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; Angiboust et al., 2011, Chen et al., 2011; Vitale Brovarone et al., 2013, 2014; Bellanger et al., 2014).

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 disputed 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).

Our RSCM data support this view and remark how 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.

Our major conclusions put new constraints 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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922



## FIGURE CAPTION

923

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925

926 Fig01. Geological setting of the Northern Apennine and regional cross sections (mod. by Molli,  
927 2008) with indicated the studied areas.

928 Fig02. Tectonic map of the inner northern Apennines with locations of analyzed samples. In the  
929 figure are also reported previous Temperatures estimates and references.

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

936 Fig03 Examples of spectra RSCM

937 Fig04 Geological map of the Alpi Apuane with measured RSCM temperatures and other data  
938 available from literatures: (1) Ca/Do from in Molli et al. 2000; (2) Di Pisa et al. 1985 and  
939 Franceschelli in Carmignani et al., 1987.

940 Fig05 Cross-sections across the Alpi Apuane with RSCM temperatures

941 Fig06. a) Cross section of La Spezia area and measured RSCM temperatures; b) Stratigraphy and  
942 RSCM temperatures in the Tuscan Nappe.

943 Fig07 RSCM temperatures in the different tectonic units of the Alpi Apuane and nearby  
944 metamorphic core of Punta Bianca and Monte Pisano.

945 Fig08 Stratigraphy and RSCM temperatures in the Apuane unit.

946 Fig.09. Paleothermal and structural architecture of the Alpi Apuane metamorphic core.

947 Fig.10. Microscopic view of Tuscan carbonates in the different tectonic units with related RSCM  
948 Tmax and Ca/Do from Molli et al. (2000). All samples have the same protolith of the “Calcere  
949 Massiccio” Jurassic in age. a) Tuscan Nappe limestone; b) metalimestone from Panie Unit; c,d)  
950 Carrara marbles from Apuane unit (c,d respectively from western and eastern side of the Alpi  
951 Apuane).

952 Fig.11. Evolutionary model of Apenninic wedge during crustal underplating of the Tuscan  
953 continental units: a) early stage of nappe stacking below the Ligurian/subligurian lid (former  
954 accretionary wedge); b) the same as in a) with in red dashed lines the 400°, 350° and 300 °C  
955 paleoisotherms. Assuming a constant thermal gradient of 20 °C/Km as defined in the upper  
956 continental unit (Tuscan Nappe) a temperature higher of 400 °C is reached at depth major than 20

957 Km, fitting the petrological data available (Franceschelli et al., 1985; Molli et al, 2000) and our  
958 RSCM data. Note that the Massa unit originally derived from the westernmost position recorded  
959 higher Temperature (and Pressure) peaks, with respect of the Apuane unit (see also Molli et al.,  
960 2000); c,d) successive duplexing stage with formation of internal stacking and overthrusting of  
961 Massa (high grade) above the Apuane unit (lower grade). During this deformation path, which  
962 basically follow the thermo-kinematic model proposed by Bollinger et al. 2004, a folding of  
963 previous paleoisotherms is envisaged to produce the thermal features described at page 10 (see cross  
964 sections E,F,I of Figs. 4,5). In d) are also indicated the possible path way of hot fluids coming from  
965 subducted middle to lower crust which may be associated with ore bodies, reworked within the  
966 Stazzemese Shear zone during following exhumation stage; e) antiformal stacking phase with  
967 development of: 1) finite geometry of regional deformation structures (dome shape of main  
968 foliation and related regional D1 structures); 2) “Stazzemese Shear Zone” possible deeper  
969 expression of extensional detachment system witness by the brittle structure of the “window fault”  
970 (see Molli and Vaselli, 2007); d) finite thermal structure result of the regional folding of previous  
971 isotherms by the antiformal stack- related dome.  
972

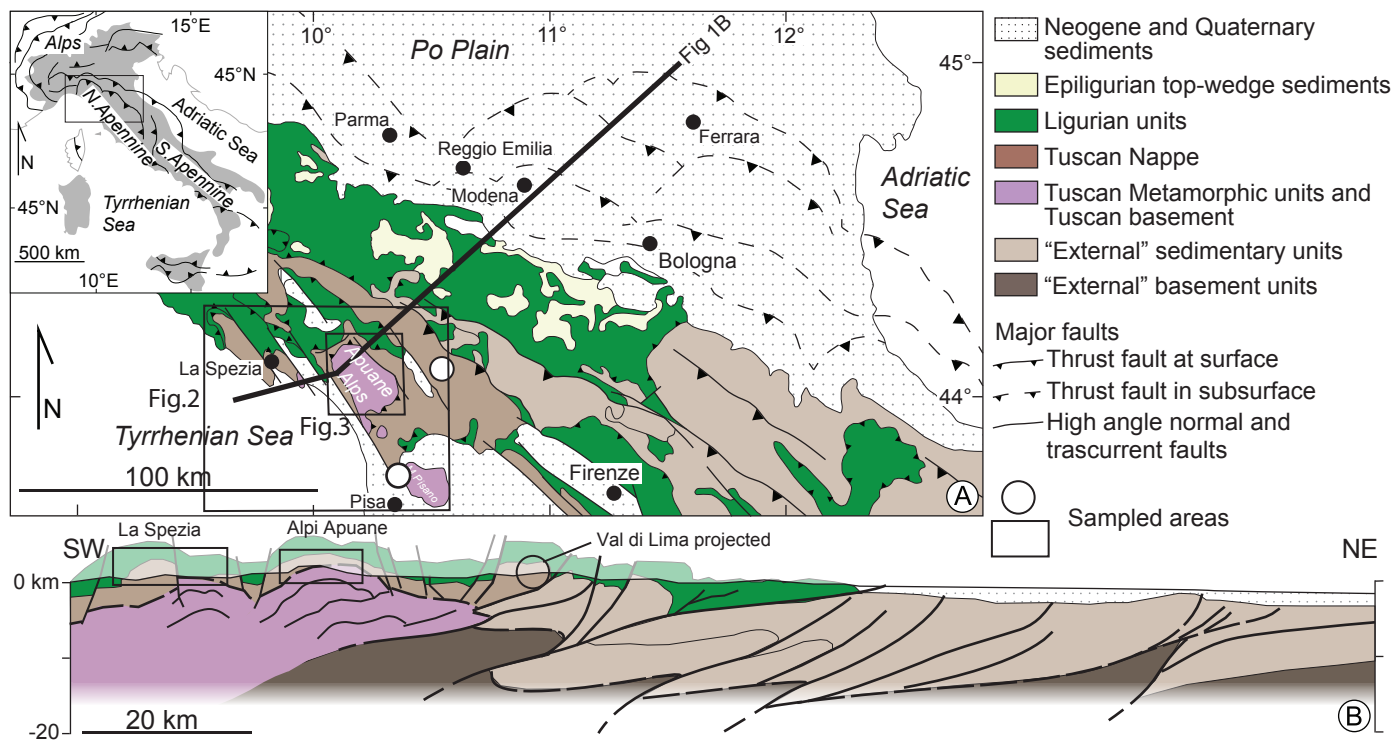


Fig.1 Molli et al JSG 2017

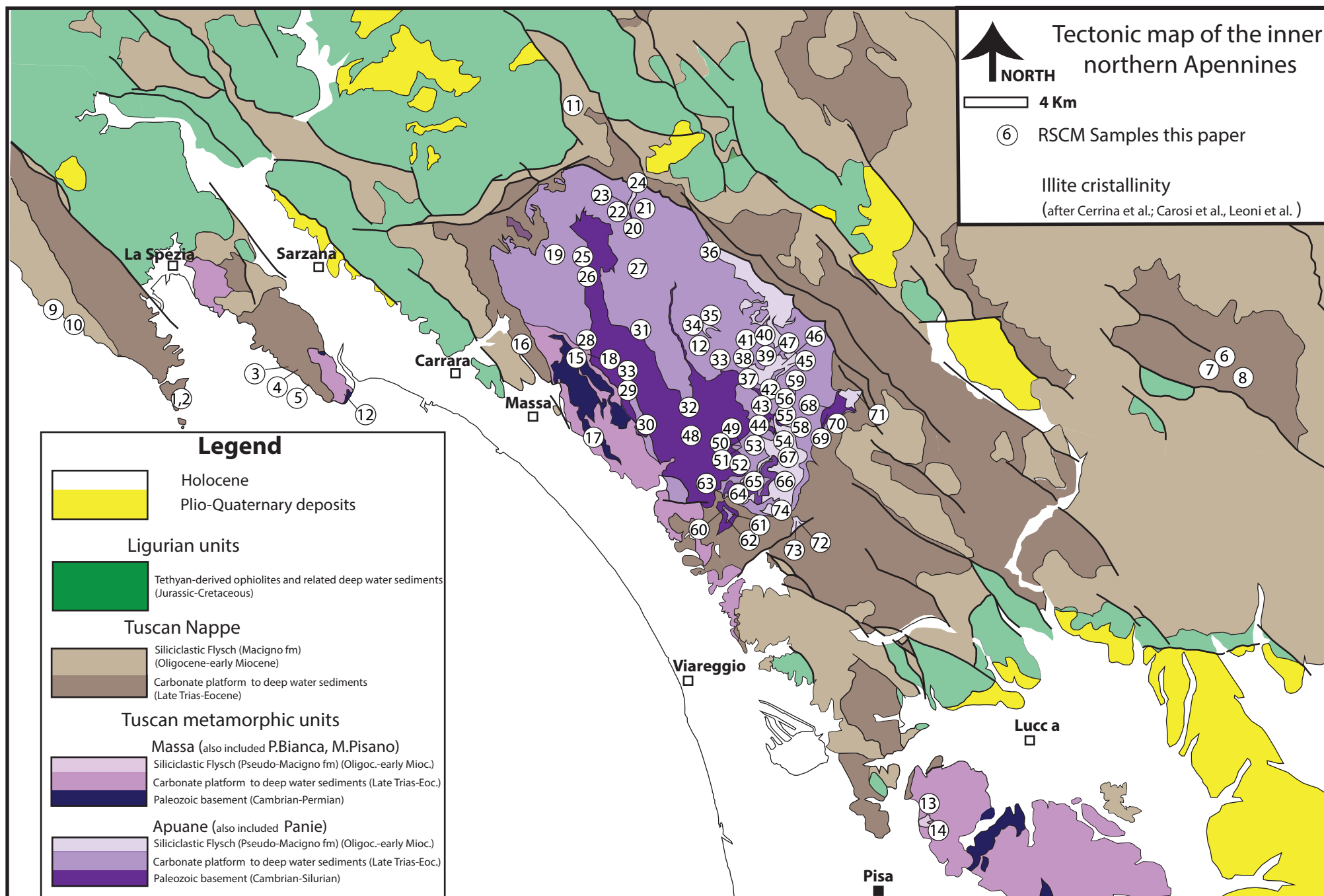
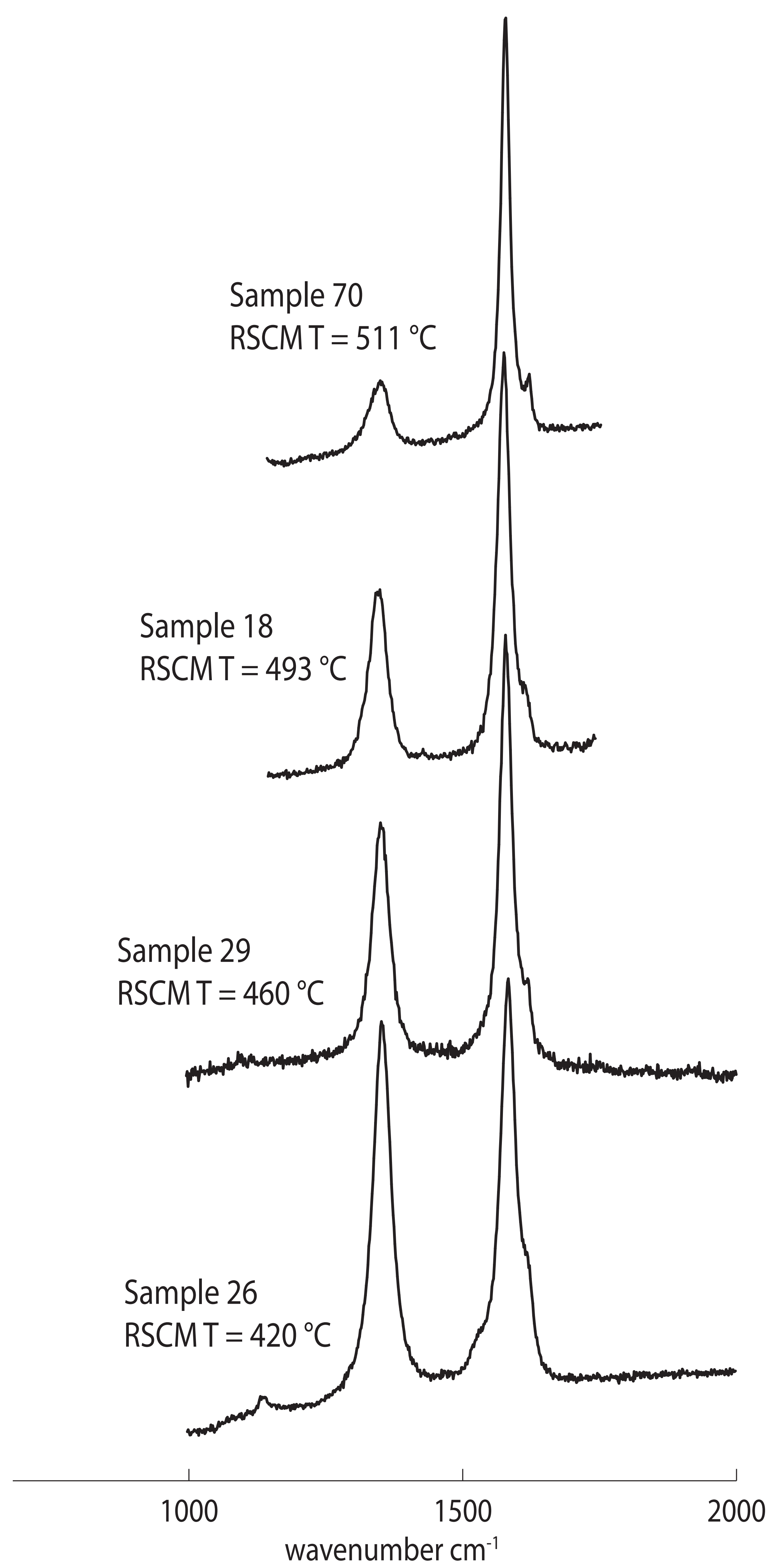
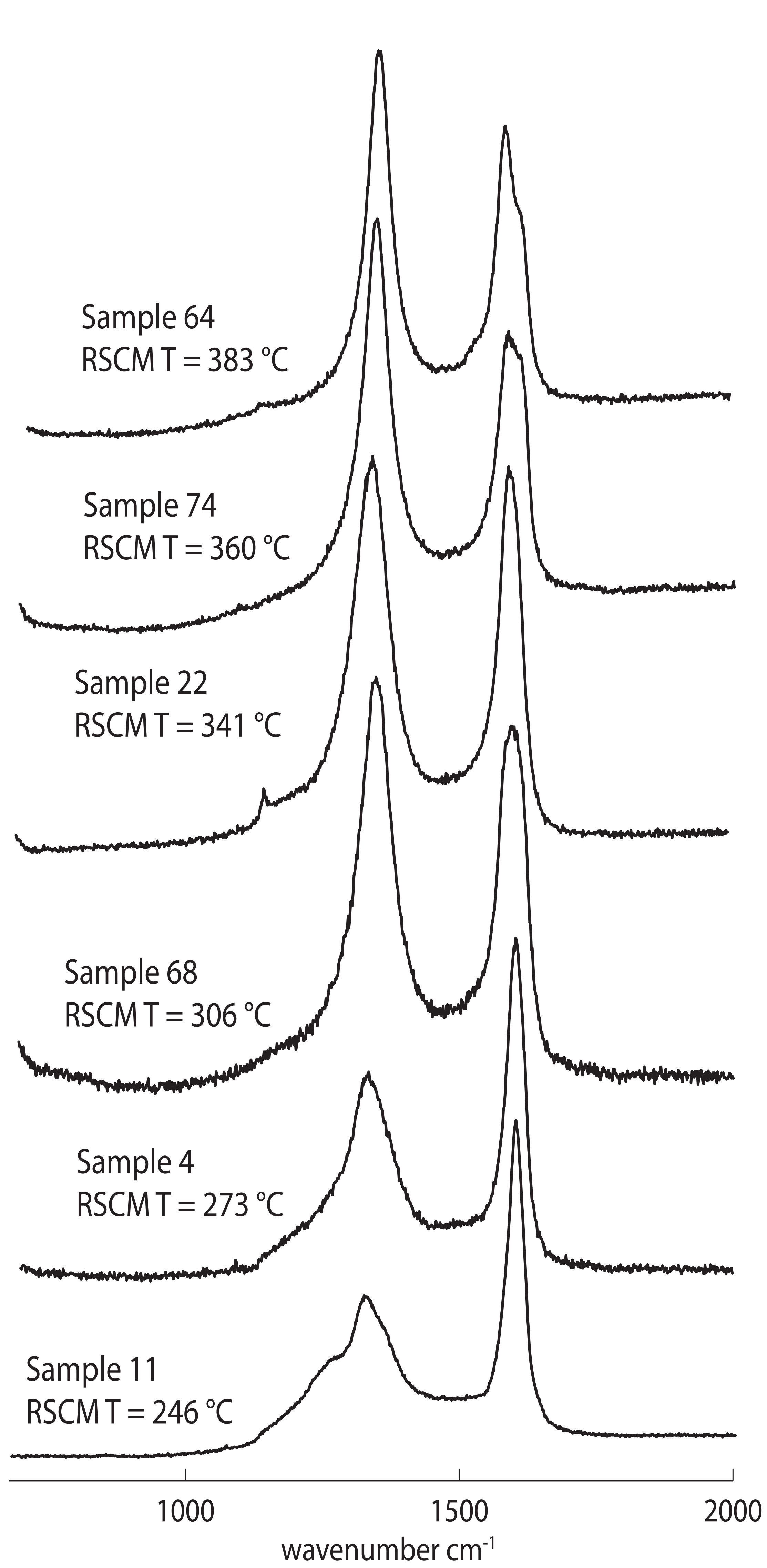


Fig.02 Molli et al., JSG



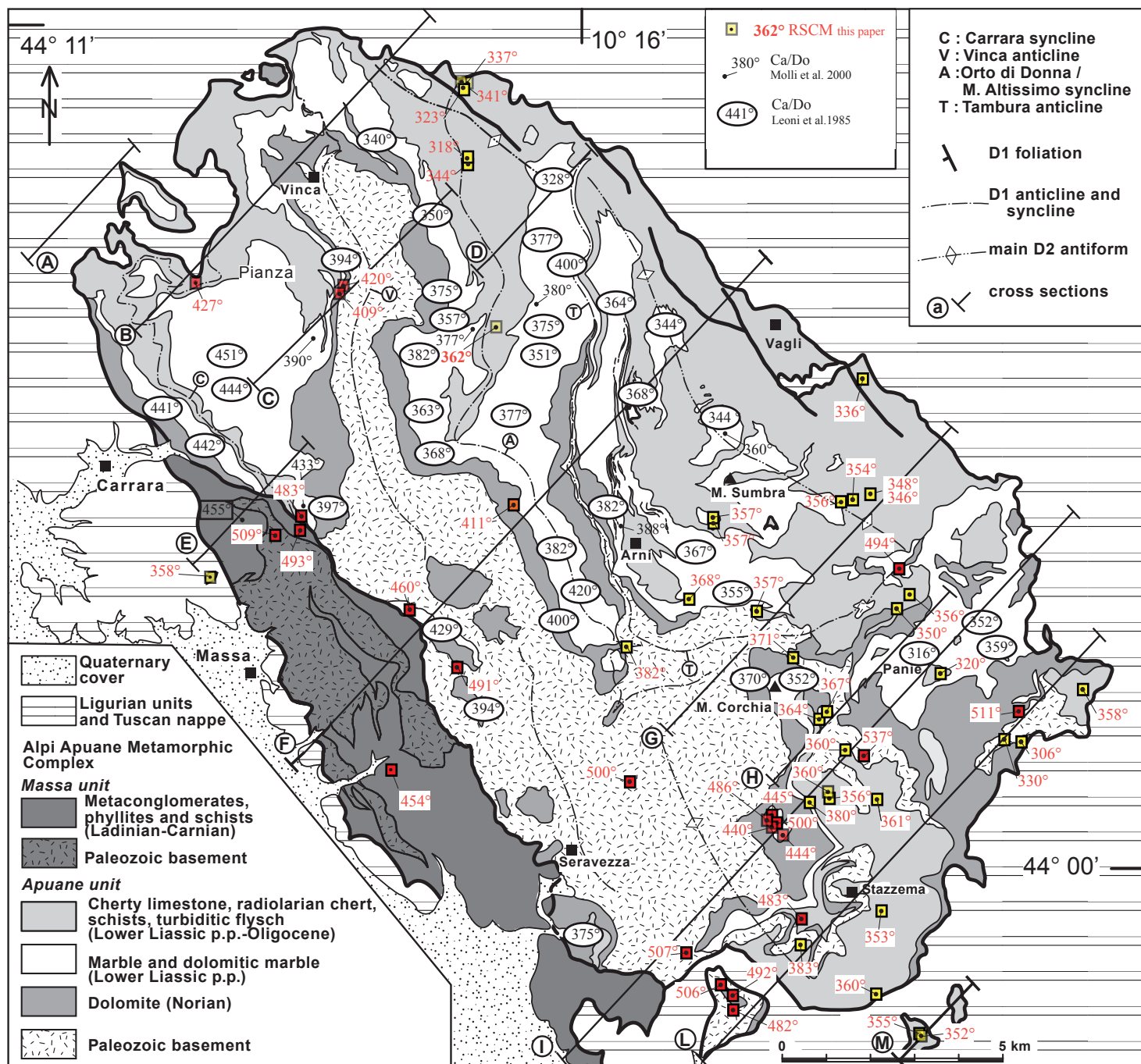


Fig.04 Molli et al. JSG



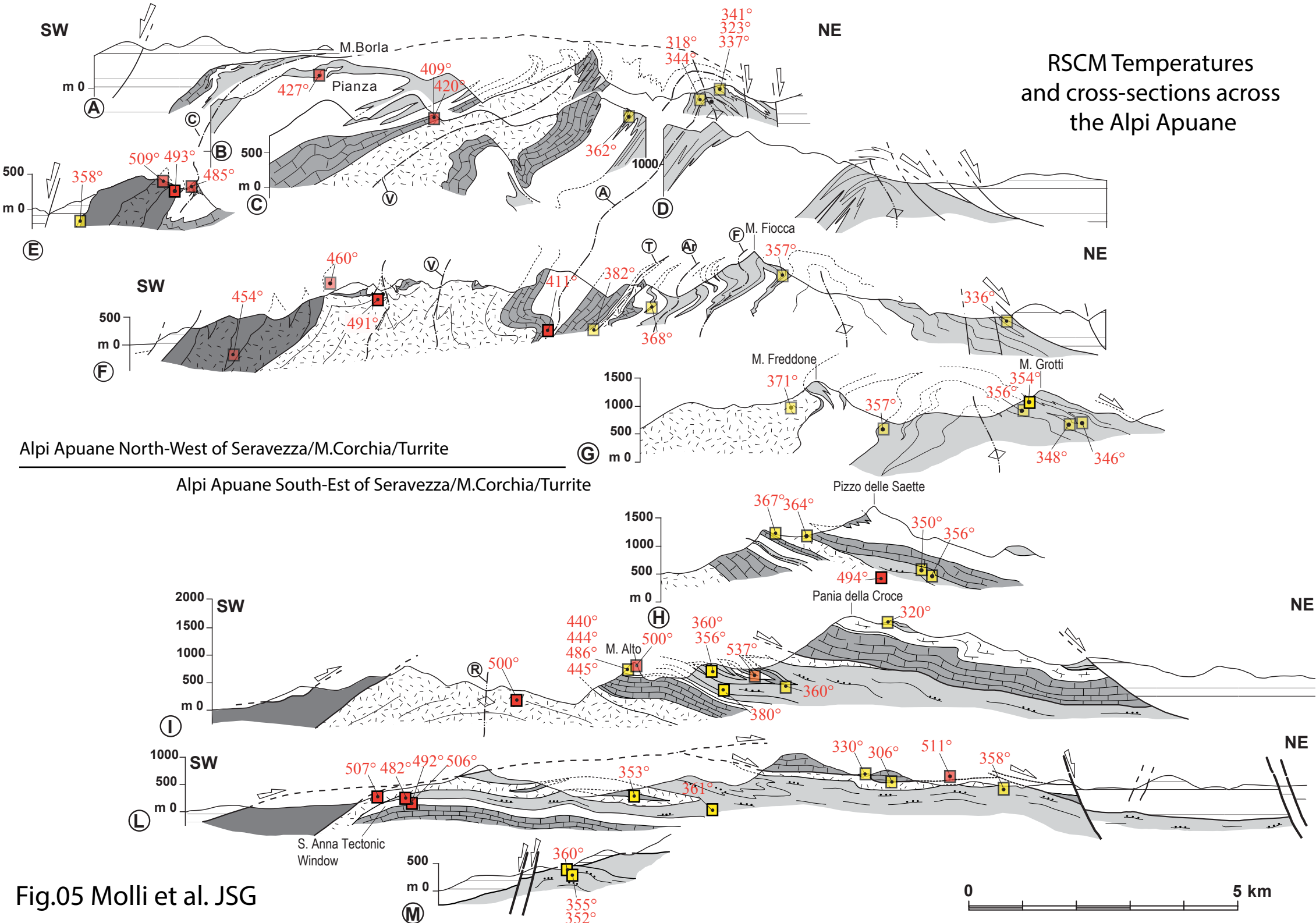


Fig.05 Molli et al. JSG

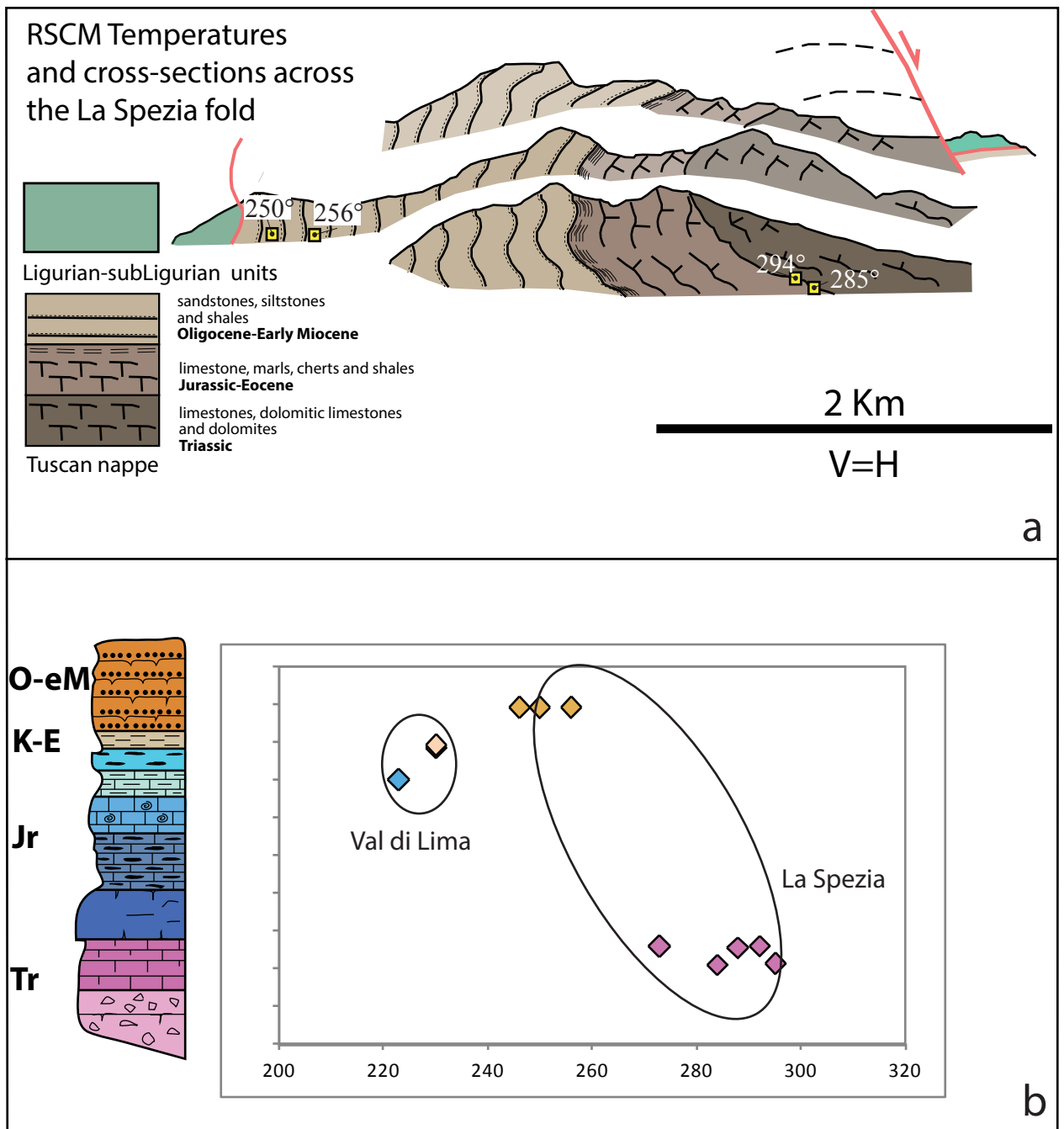


Fig. 06 Molli et al JSG



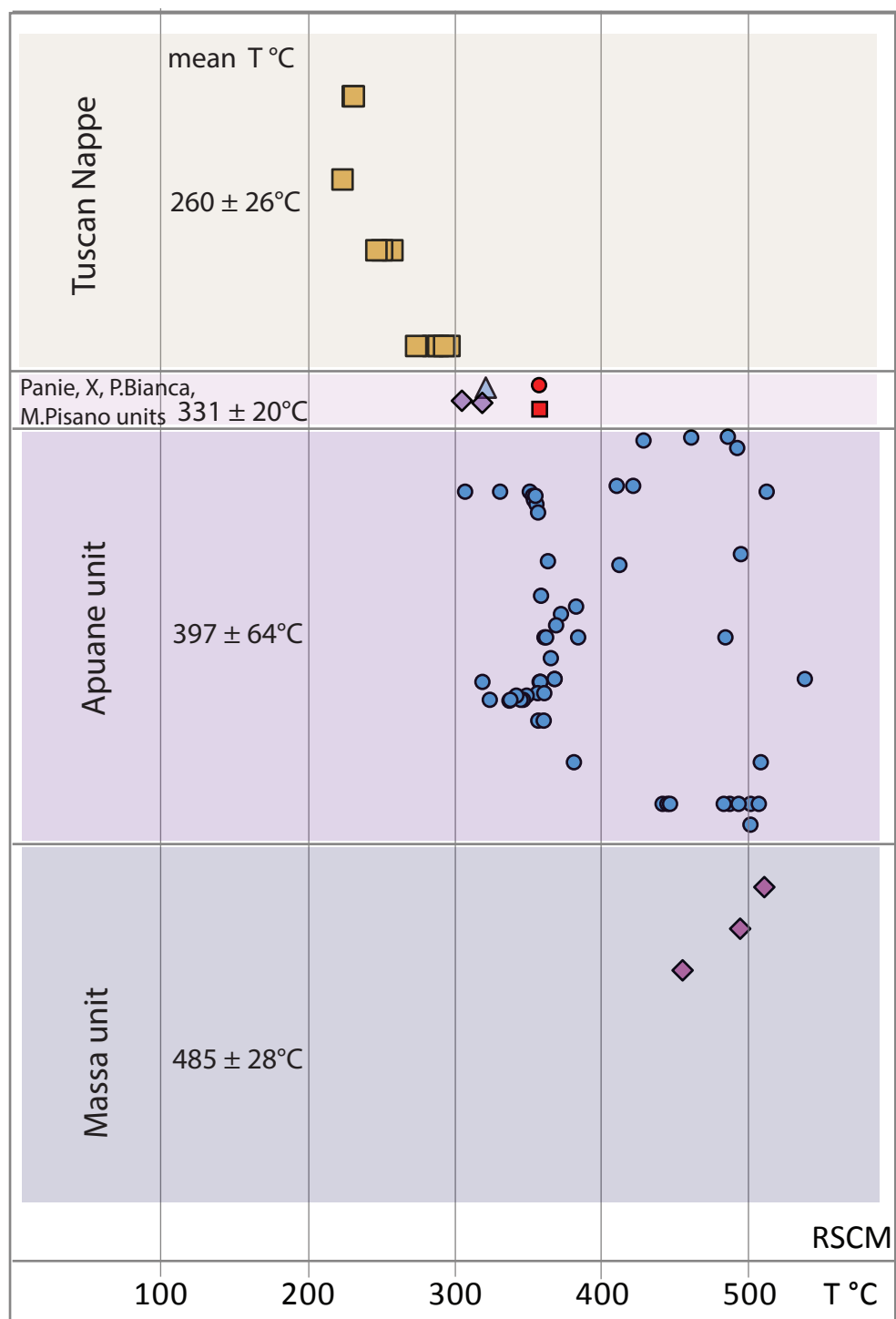


Fig07 Molli et al., JSG

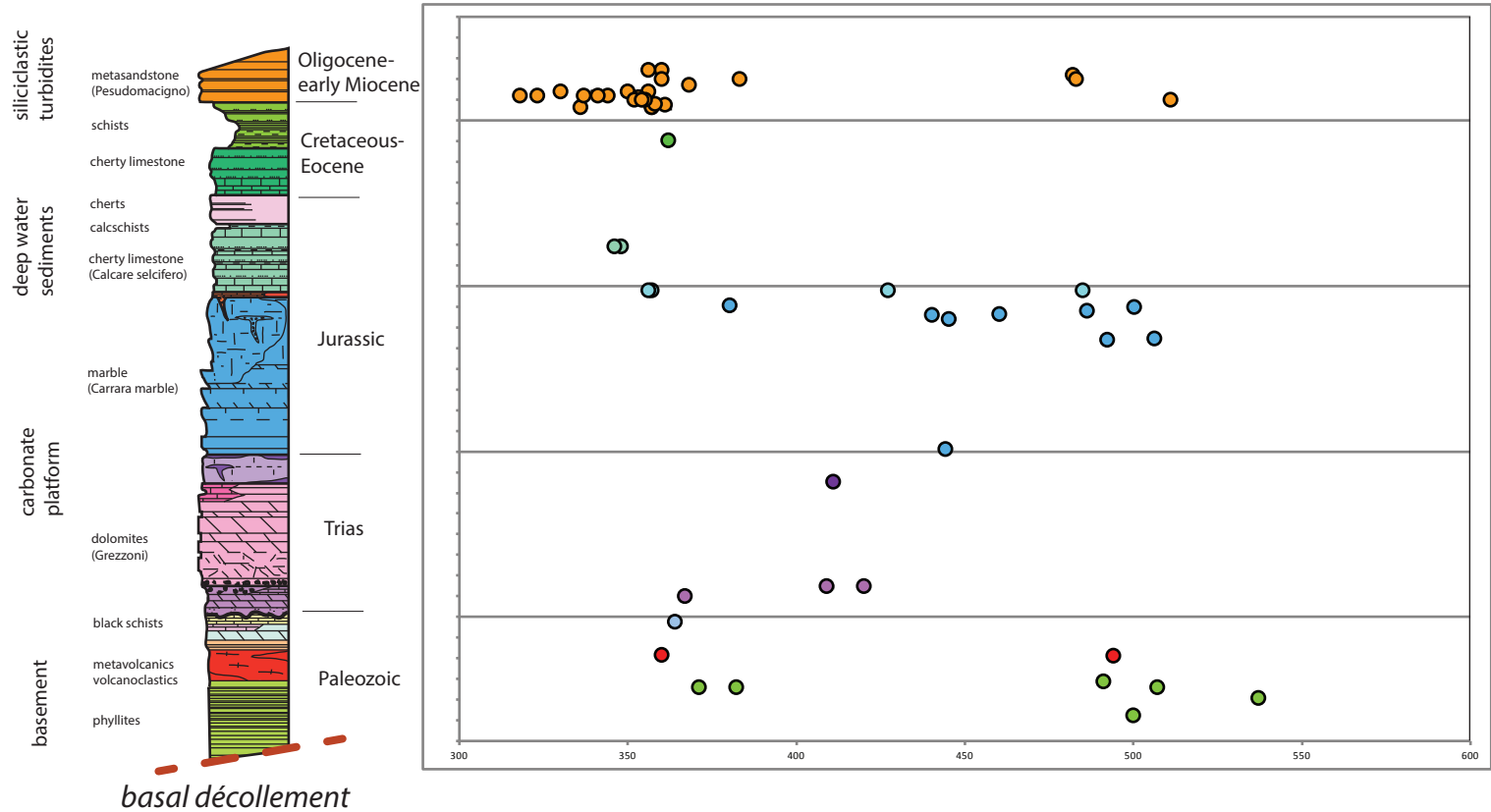


Fig08 Molli et al., JSG

# Paleothermal and structural architecture of the Alpi Apuane metamorphic core

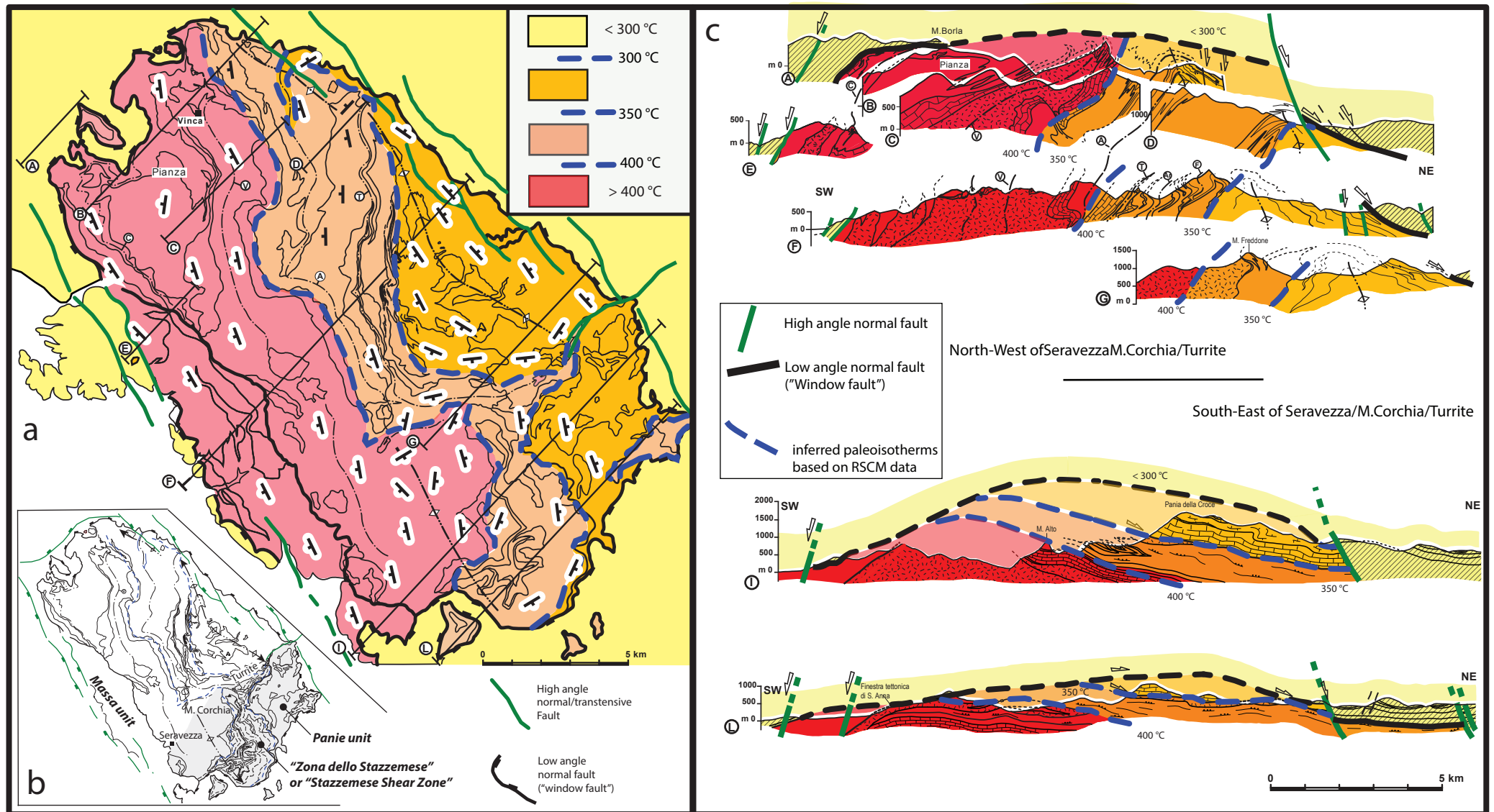


Fig. 09 Molli et al JSG

# Tectonic and paleothermal evolution of the Alpi Apuane metamorphic core

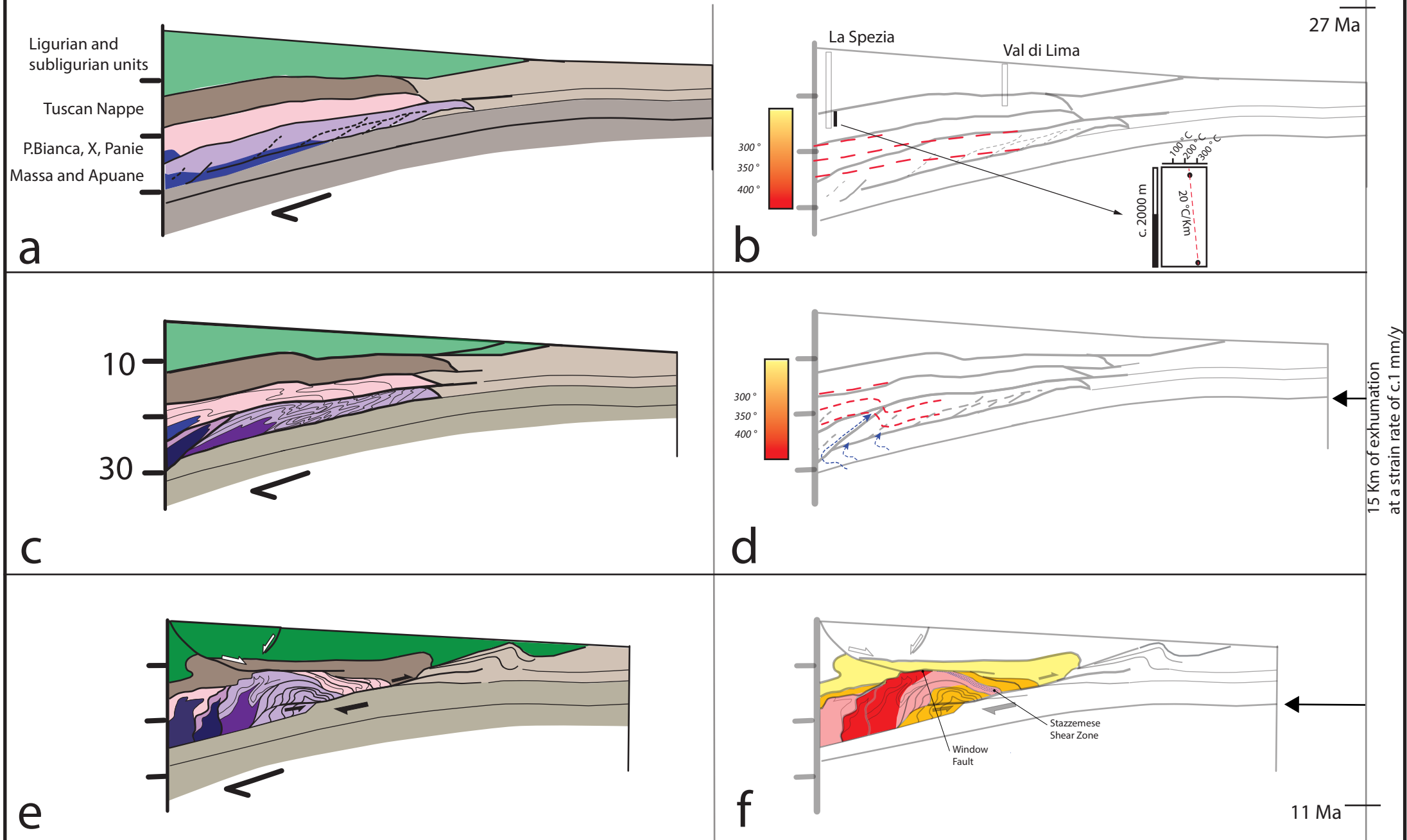


Fig.11 Molli et al JSG

Sample	Tectonic unit		coordinates		n	R2/RA1*	SD	T(°C)	SE
	Rock-type	stratigraphic age	latitude (N)	longitude (E)					
	<b>Tuscan Nappe</b>								
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			12	0,57	0,00	246	1
	<b>P.Bianca Unit</b>								
12	black schist	Permian?	44°02'13.30"	9°58'33.29"	10	0,64	0,001	358	1,00
	<b>M.Pisano Unit</b>								
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
	<b>Massa Unit plus XX Unit</b>								
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
	<b>Apuane unit</b>								
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			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
34	calcschist	Jurassic	44°04'12.38"	10°15'48.15"	14	0,64	0,02	357	2,7
35	metasandstone (PMG)	Oligocene-Miocene	44°04'31.71"	10°16'06.59"	15	0,64	0,01	357	1,51
36	metasandstone (PMG)	Oligocene-Miocene	44°05'44.41"	10°19'26.09"	13	0.64*	0,01	336	3,4
37	phyllite	Paleoz	44°02'25.53"	10°18'06.57"	15	0,61	0,02	371	2,83
38	impure metalimestone	Jurassic	44°03'44.54"	10°17'21.58"	13	0,64	0,03	357	3,64
39	impure limestone	Jurassic	44°05'44.41"	10°19'07.76"	14	0,64	0,03	356	3,97
40	metasandstone (PMG)	Oligocene-Miocene	44°04'12.65"	10°18'50.03"	12	0,64	0,01	354	1
41	impure metalimestone	Jurassic	44°04'22.61"	10°19'51.55"	15	0,66	0,01	348	0,94
42	impure metalimestone	Jurassic	44°04'20.11"	10°19'43.84"	15	0,66	0,01	346	1,15
43	black schist	Paleoz	44°01'44.50"	10°18'23.93"	15	0,62	0,02	367	2,53
44	black schist	Paleoz	44°01'42.58"	10°18'11.36"	15	0,62	0,01	364	1,39
45	metasandstone (PMG)	Oligocene-Miocene	44°03'16.95"	10°19'33.32"	15	0,65	0,02	350	2,85
46	metasandstone (PMG)	Oligocene-Miocene	44°03'21.64"	10°19'33.30"	15	0,64	0,01	356	1,16
47	phyllite	Paleoz	44°04'20.51"	10°19'57.70"	14	0,33	0,06	494	7,88
48	phyllite	Paleoz	44°01'36.00"	10°25'95.01"	17	0,32	0,07	500	7,45
49	impure marble	Jurassic	44°00'22.70"	10°17'25.13"	16	0,32	0,06	500	6,86
50	impure marble	Jurassic	44°00'14.32"	10°17'30.10"	29	0,35	0,07	486	6,09
51	impure marble	Jurassic	44°00'13.18"	10°17'29.84"	11	0,45	0,04	440	6,13
52	impure marble	Late Trias	44°00'31.21"	10°17'20.65"	16	0,44	0,03	444	4,02
53	impure marble	Jurassic	44°00'28.85"	10°17'23.59"	8	0,44	0,07	445	12,06
54	metasandstone (PMG)	Oligocene-Miocene	44°00'46.44"	10°18'23.82"	15	0,59	0,03	380	3,82
55	metasandstone (PMG)	Oligocene-Miocene	44°01'17.33"	10°18'57.70"	19	0,63	0,03	360	2,81
56	metasandstone (PMG)	Oligocene-Miocene	44°01'31.86"	10°19'06.39"	20	0,64	0,01	356	1,5
57	schist	Paleozoic	44°00'40.87"	10°18'57.25"	14	0,23	0,10	537	13,38
58	metasandstone (PMG)	Oligocene-Miocene	44°01'36.50"	10°18'46.18"	13	0,63	0,04	360	5,31
59	impure metalimestone	Jurassic	44°02'13.20"	10°19'49.27"	20	0.63*	0,01	320	2,48
60	impure marble	Jurassic	43°97'58,6"	10°27'57,8"	15	0,3	0,06	506	6,6
61	impure marble	Jurassic	43°97'50,6"	10°27'62,7"	15	0,33	0,08	492	9,89
62	metasandstone (PMG)	Oligocene-Miocene	43°97'21,5"	10°28'00,7"	15	0,36	0,05	482	6,09
63	phyllite	Paleoz	43°58'51.1"	10°15'55.2"	4	0,30	0,07	507	17

[illegible]