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

27 RSCM Thermometry, Thermal structure, Tectonics, Alpi Apuane, Northern Apennines
28

29 **Highlight:**

30 - first RSCM data for the northern Apennines

31 - peak temperature in the Alpi Apuane metamorphic core and surroundings region

32 - new definition of the thermal structure and nappe architecture of the inner northern Apennines
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37 **ABSTRACT**
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40 In this study, Raman spectroscopy on carbonaceous material (RSCM) is applied, for the first time,
41 in the northern Apennines with particular focus on the Alpi Apuane (NW Tuscany, Italy) and
42 surrounding areas in order to constrain peak metamorphic temperatures and their variability in the
43 different continent-derived units of the nappe stack.

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

49 The collected data allowed us to constrain the relationships between the nappe architecture and
50 thermal structure as well as those between deformation structures (early and late folds and low
51 angle normal detachments) and the thermal architecture of the Alpi Apuane metamorphic core
52 providing new constraints for the thermo-mechanical evolution and exhumation history of the inner
53 northern Apennine and its geodynamic setting. In particular our data support the interpretation of
54 the Alpi Apuane as a cold metamorphic core complex in which the preserved paleothermal structure
55 and most of the exhumation is unrelated with crustal thinning presently ongoing in the area.

72
73 **INTRODUCTION**
74

75 The thermal structure and the field metamorphic gradient in mountain belts may be first order
76 variables directly related with the tectonic setting and the crustal-scale architecture of the orogens
77 (between others Chopin et al., 1991; Goscombe et al., 2005, Brown, 2009, Vitale Brovarone et al
78 2013, Agard and Vitale Brovarone, 2013 and references). Data on the thermal structure of
79 metamorphic units combined with those constraining kinematic history delineates the extent to
80 which heat and mass are transferred from mid to upper crust (Selverstone, 1988; Jolivet et al., 1998;
81 Ring et al., 1999; Chen et al., 2011; Cottle et al. 2011). Therefore, the understanding of the thermal
82 structure of the internal parts of the mountain belt and its evolution represent a key element to
83 unravel the tectonic frame and kinematics of the development of the orogenic system, allowing a
84 better definition of past geological boundary conditions as inputs for large-scale thermokinematic
85 and geodynamics simulations (Beyssac et al., 2007; Simoes et al., 2007; Avouac et al., 2012).

86 In the inner northern Apennines thermal characters and evolution of the main units of the nappe
87 stack were defined through the classical methods of clay mineralogy, vitrinite reflectance, fluid
88 inclusions and illite cristallinity for the shallowest units of the nappe stack (Cerrina et al., 1980;
89 Carter et al., 1998; Carosi et al., 2005; Reutter et al., 1978; Reutter et al., 1980; Ellero et al., 2001;
90 Montomoli et al., 2001; Montomoli et al., 2002; Botti al., 2004; Dellisanti et al. 2010, Caricchi et
91 al., 2014; Ventura et al., 2001), while in the lowermost metamorphic units Al-silicates, chloritoid-
92 chlorite thermometry, calcite-dolomite, stable isotope geothermometers, and conodonts color were
93 used (Franceschelli et al., 1990; Franceschelli et al., 1997; Franceschelli and Memmi, 1999; Molli
94 et al., 2000a,b; Molli et al., 2002; Cortecci and Orlandi, 1975; Cortecci et al., 1994; Costagliola et
95 al., 2002; Consani, 2002). More recently, thermodynamical modeling was also applied in the
96 Paleozoic basement terms of the Tuscan metamorphic units (Lo Po' and Braga, 2014; Lo Po' et al.,
97 2017).

98 Due to the patchy distribution of suitable rock types in the different units and within the nappe
99 stack, however, we still lack a precise definition of the regional thermal structure and of the
100 paleothermal field gradients.

101 As a consequence the overall tectonic setting shaping the present day nappe-architecture is still a
102 matter of debate, with crustal contractional and crustal extensional models supported by different
103 groups of authors (Carmignani and Kligfield, 1990; Boccaletti et al., 1993; Carosi et al., 2003;
104 Decandia et al., 1995; Storti, 1995; Jolivet et al., 1998; Thomson et al., 2010; Sani et al., 2014;
105 Musumeci et al., 2016). This in turn leaves open some relevant questions such as the relationships
106 between exhumation processes and crustal/litospheric thinning, which shaped the present day Moho

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

109 In this study, we applied the same geothermometer, i.e. Raman spectroscopy on carbonaceous
110 material (RSCM), to a large range of lithologies from the main units of the inner northern
111 Apennines, with special focus on the Alpi Apuane metamorphic core and nearby areas. Thanks to
112 the irreversible process of graphitization of carbonaceous material (CM), this geothermometer can
113 provide peak temperature (T) estimates for CM-bearing metasedimentary rocks independently from
114 their mineralogical assemblage, and is therefore applicable to a wider range of rock types in the
115 considered units compared to previous studies.

116 Our data allow us to constraining the field thermal structure and the exhumation-related
117 paleogradients and therefore to improving our understanding of the orogenic processes recorded in
118 the inner northern Apennines. Moreover, our data document the thermal architecture and
119 metamorphic signature of a mid-shallow orogenic wedge and its relationships with the regional
120 structures, the nappe and thrust stack styles and their internal deformation.

121

122

123

REGIONAL GEOLOGY

124

125 The northern Apennines (Fig.1) are characterized by a pile of thrust-sheets and fold nappes derived
126 from the distal part of the Adria continental margin (the Tuscan Domain) presently lying below the
127 remnants of a former intraoceanic accretionary wedge represented by the Ligurian and sub-Ligurian
128 units relicts of the former Mesozoic western alpine Tethys ocean (Elter, 1975; Bortolotti et al.
129 2001, Bernoulli, 2001; Liotta, 2002; Molli, 2008 and ref.). The recent to active tectonic framework
130 of the northern Apennines is characterized by crustal-scale extension in the inner-western
131 (Tyrrhenian) side of the orogen and shortening in its external (Po Plain and Adriatic) eastern side
132 (e.g. Elter et al., 1975; Barchi et al., 1998; Doglioni et al., 1998; Fellin et al., 2002; Bennett et al.,
133 2012; Boccaletti et al., 2010; Eva et al., 2014; Faccenna et al., 2014; Molli et al., 2015; Le Breton et
134 al., 2017).

135 In the NW of Tuscany, the Alpi Apuane form the largest tectonic window in the inner northern
136 Apennines and expose the deepest crustal units of the belt (Tuscan Metamorphic Units) (Fig.1).
137 Three major stratigraphic and tectono-metamorphic Adria-derived continental units are traditionally
138 distinguished in the region, the Tuscan Nappe, the Massa unit and the Apuane unit (Fig.2). The
139 Tuscan Nappe consists of Mesozoic carbonates and Tertiary deep water and turbiditic sequence
140 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 overlying 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-contractual 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

243 done on polished thin sections cut perpendicularly to the main fabrics and CM was systematically
244 analyzed below a transparent adjacent mineral, generally quartz. Between 10–20 spectra were
245 recorded for each sample in the extended scanning mode (1000–2000 cm^{-1}) with acquisition times
246 from 30 to 60 s. Spectra were then processed using the software Peakfit (following Beyssac et al.,
247 2002). Based on the obtained spectra, T from samples characterized by lower-T metamorphism (i.e.
248 ~ 200 b T b 350 °C) were estimated using the correlation proposed by Lahfid et al. (2010). At
249 higher-T (i.e. ~ 350 b T b 650 °C), the T was calculated using the calibration of Beyssac et al.
250 (2002), with a calibration-attached accuracy of ± 50 °C due to uncertainties on petrologic data used
251 for the calibration. Relative uncertainties on T are, however, much smaller, around 10–15 °C
252 (Beyssac et al., 2004).

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

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

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268

269 **RSCM TEMPERATURE RECORD IN THE ALPI APUANE AND SURROUNDINGS**

270

271 Our dataset consists of 74 analyzed samples (Table 1) selected among 120 collected in various
272 stratigraphic and structural positions within the different tectonic units. The samples were collected
273 along a regional SW-NE oriented section across the inner (western) northern Apennines (Fig. 1).
274 The uppermost continental unit of the nappe pile was sampled west of the Alpi Apuane in the La
275 Spezia area (Fig. 1,2), where the stratigraphic sequence of the Tuscan Nappe is exposed as part of a
276 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 ± 26 °C) for the Tuscan Nappe; 306-
317 537 °C (mean 397 ± 64 °C, n=63) for for the Apuane and 454-509 °C (485 ± 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 ~ 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 ± 66 °C) and the lowest ($306-511$ °C, mean 368 ± 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, Turrite valley alignment) is basically the same as those defined in the south-eastern
337 segment (south of the Seravezza-Monte Corchia, Turrite valley alignment), around ~ 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 ~ 500 m from the basal contact of the
344 Massa unit (Figs. 5,9). The T decrease eastward and structurally downward to ~ 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-Al₂O₃-SiO₂-H₂O (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 ~ 260 °C for the Tuscan Nappe, ~ 485 °C for the Massa unit and ~ 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 ~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 ~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 “Stazzemesse
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

551 plate units (401 ± 65 °C mean of all our data set of RSCM T).

552 From the kinematic point of view the “window fault” cuts down-section the footwall regional
553 structures along a South-West to North-East transport direction (Molli, 2012) as shown in map and
554 cross section in Figs. 4,5,9. The low angle detachment fault is therefore in contact with the
555 uppermost structures of the western Alpi Apuane (Massa unit, Carrara Syncline, Vinca-Forno
556 Anticline) and with progressively deeper and lower regional structures (Orto di Donna Syncline,
557 Tambura Anticline and easternmost Apuane).

558 This structural cut-down section corresponds to a paleothermal architecture which shows across the
559 “window fault” and along the transport direction an eastward decrease in the T gap between
560 hangingwall and footwall from $\Delta T > 200$ °C in the west to $\Delta T < 50$ °C in the east (Fig.9). This is
561 mainly due to the cross-cut relationship and kinematic interaction between the window fault and the
562 footwall antiformal stack of the metamorphic core as figured in the conceptual model of Figure
563 11e,f.

564 Furthermore, using the thermochronological data in Fellin et al. (2007), we may date some steps of
565 the proposed kinematic history with the end of distributed deformation in the footwall metamorphic
566 core and its antiformal stack development occurred before 11 Ma (by Zr FT age constrains
567 Temperature of 240 °C), whereas the end of the activity of the “window fault” occurred at a crustal
568 depth as low as ~ 180 °C in a time interval between 7 to 4–5 Ma. After that time crustal extension
569 ending in the present day tectonic setting, superficial and deep crustal morphostructure was
570 accomodated at shallow crustal levels by high angle normal faults (Fig., 4,5,9) cross-cutting the
571 former synmetamorphic structures as well as the “window fault” (Molli et al., 2016 and references
572 therein).

573

574

CONCLUSIONS

575

576 RSCM T estimates have proven an efficient mean to put extensive T constraints on the thermal
577 structure of coherent units and on tectonic contacts even within very narrow T ranges (Beysac et
578 al., 2002; Angiboust et al., 2011, Chen et al., 2011; Vitale Brovarone et al., 2013, 2014; Bellanger
579 et al., 2014).

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

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

590 Our RSCM data support this view and remark how the paleothermal architecture of the Alpi
591 Apuane metamorphic core better fits a tectonic scenario of syn-orogenic contractional exhumation
592 associated with a cool paleothermal gradient, which allowed the preservation of inverted
593 metamorphism across the Alpi Apuane metamorphic core and its overall paleothermal architecture.

594 Our major conclusions put new constraints for the thermo-mechanical evolution and exhumation
595 history of the northern Apennine in its inner (western) side; moreover, they may be of general and
596 widespread interest for other orogens, showing anchimetamorphic to metamorphic mid to shallow
597 crustal terrains and metamorphic cores. Our data clear illustrate how the thermal and metamorphic
598 signature may have different characters and different field gradients at tens of kilometer scale
599 calling for a careful analysis of thermal data in correlation with the associated structural architecture
600 for a firm interpretation of the tectonic frame at the orogen-scale.

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FIGURE CAPTION

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

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

Table 1. Selected samples for RSCM thermometry. GPS coordinates in WGS84 system, number of spectra (n), mean R2ratio (Beysac 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 (Beysac 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.

Fig03 Examples of spectra RSCM

Fig04 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 and Franceschelli in Carmignani et al., 1987.

Fig05 Cross-sections across the Alpi Apuane with RSCM temperatures

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

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

Fig08 Stratigraphy and RSCM temperatures in the Apuane unit.

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

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

Fig.11. Evolutionary model of Apenninic wedge during crustal underplating of the Tuscan continental units: 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. Assuming a constant thermal gradient of 20 °C/Km as defined in the upper 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.

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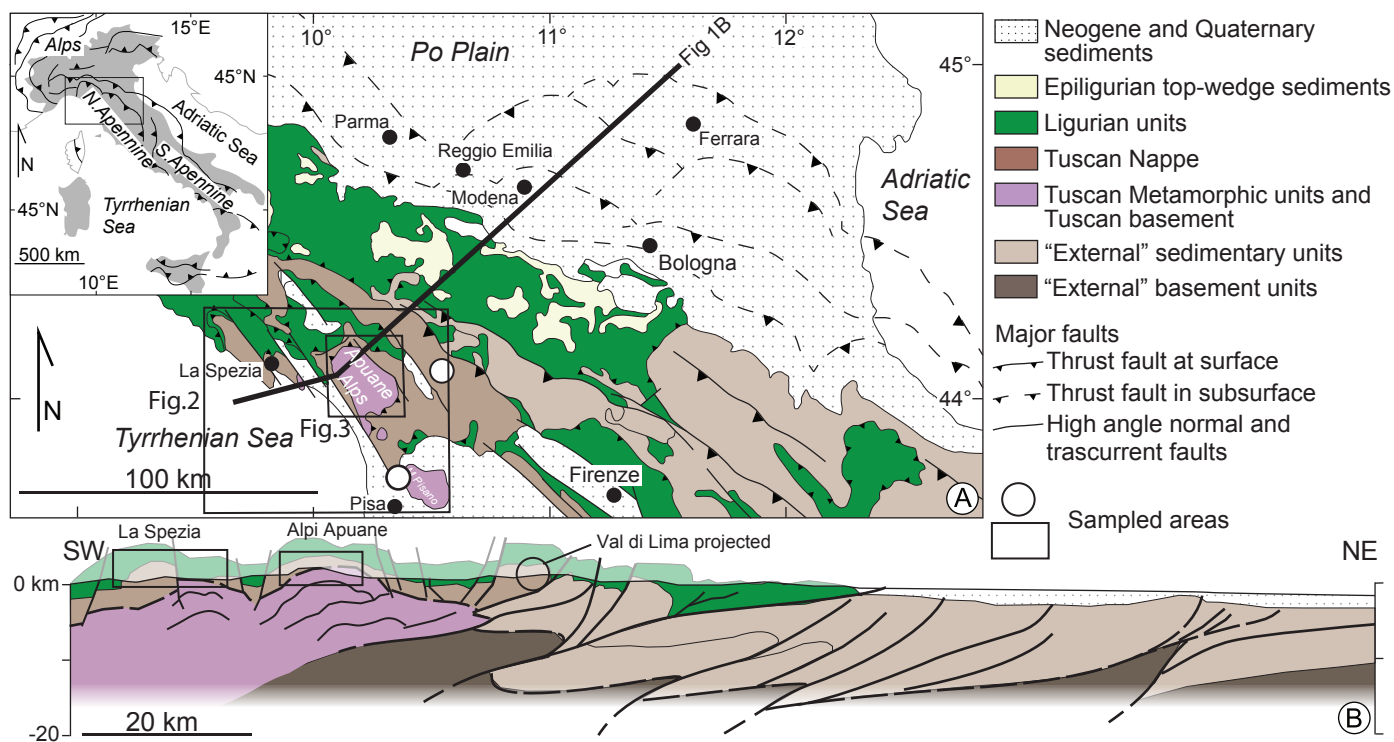


Fig.1 Molli et al JSG 2017

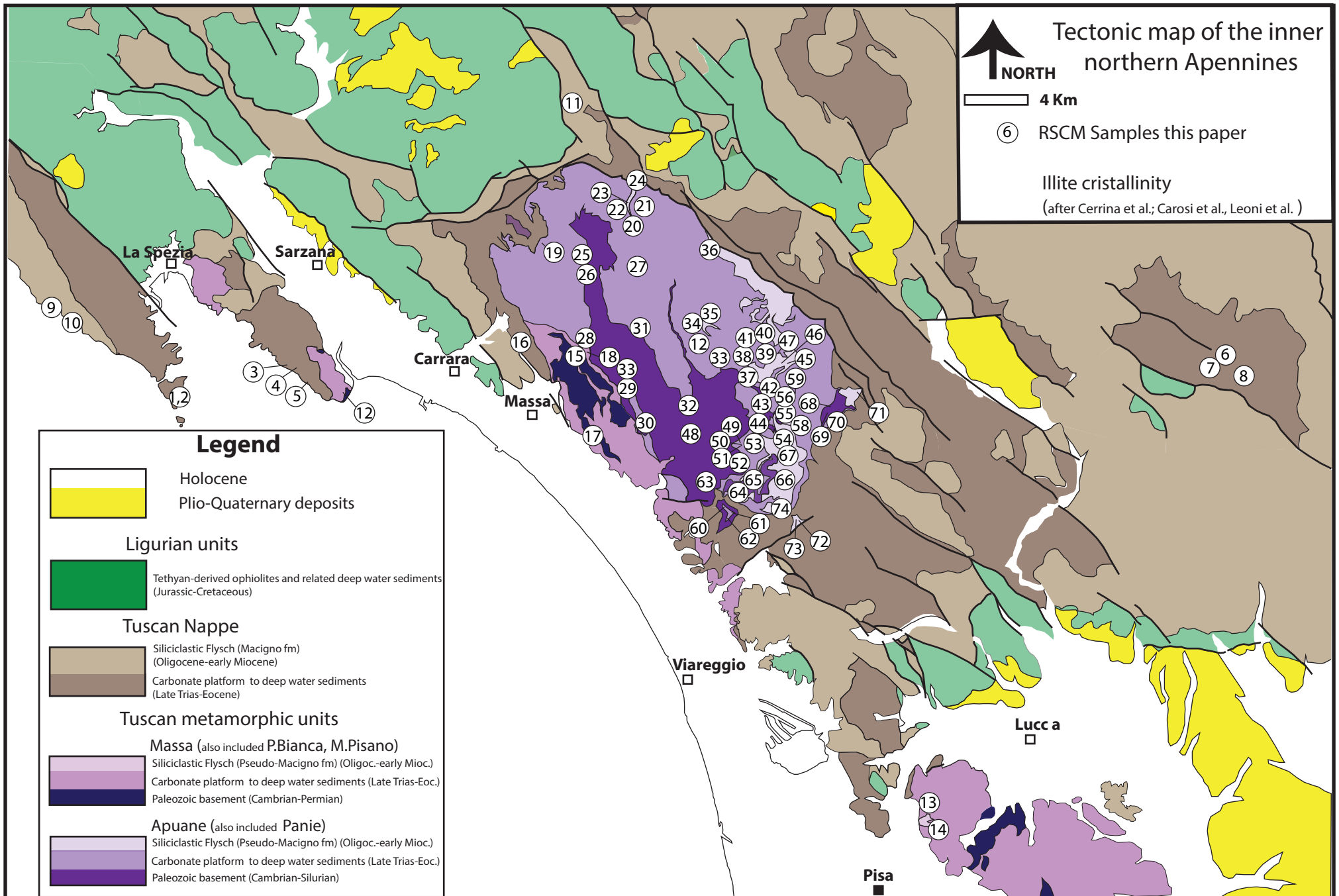
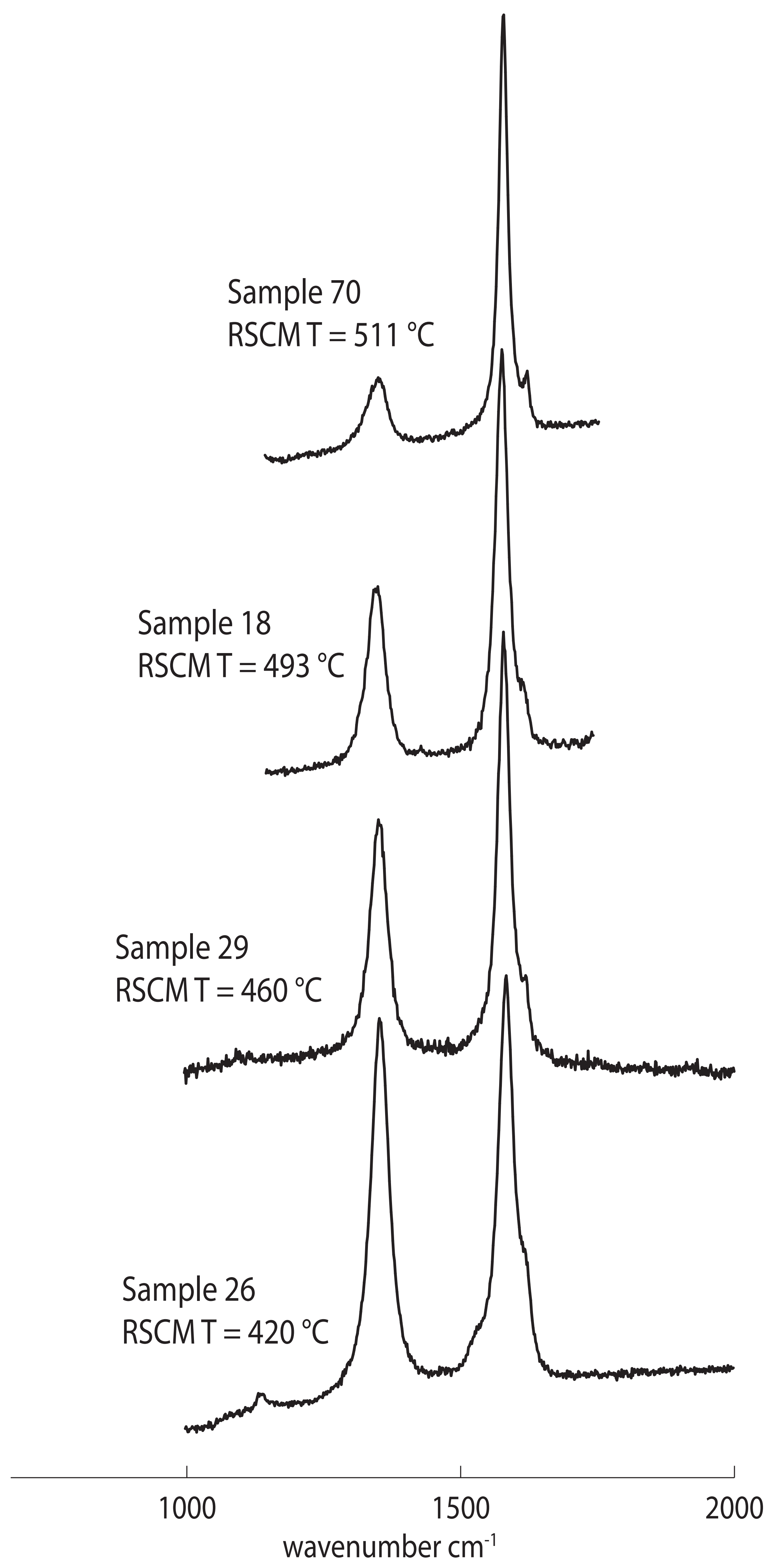
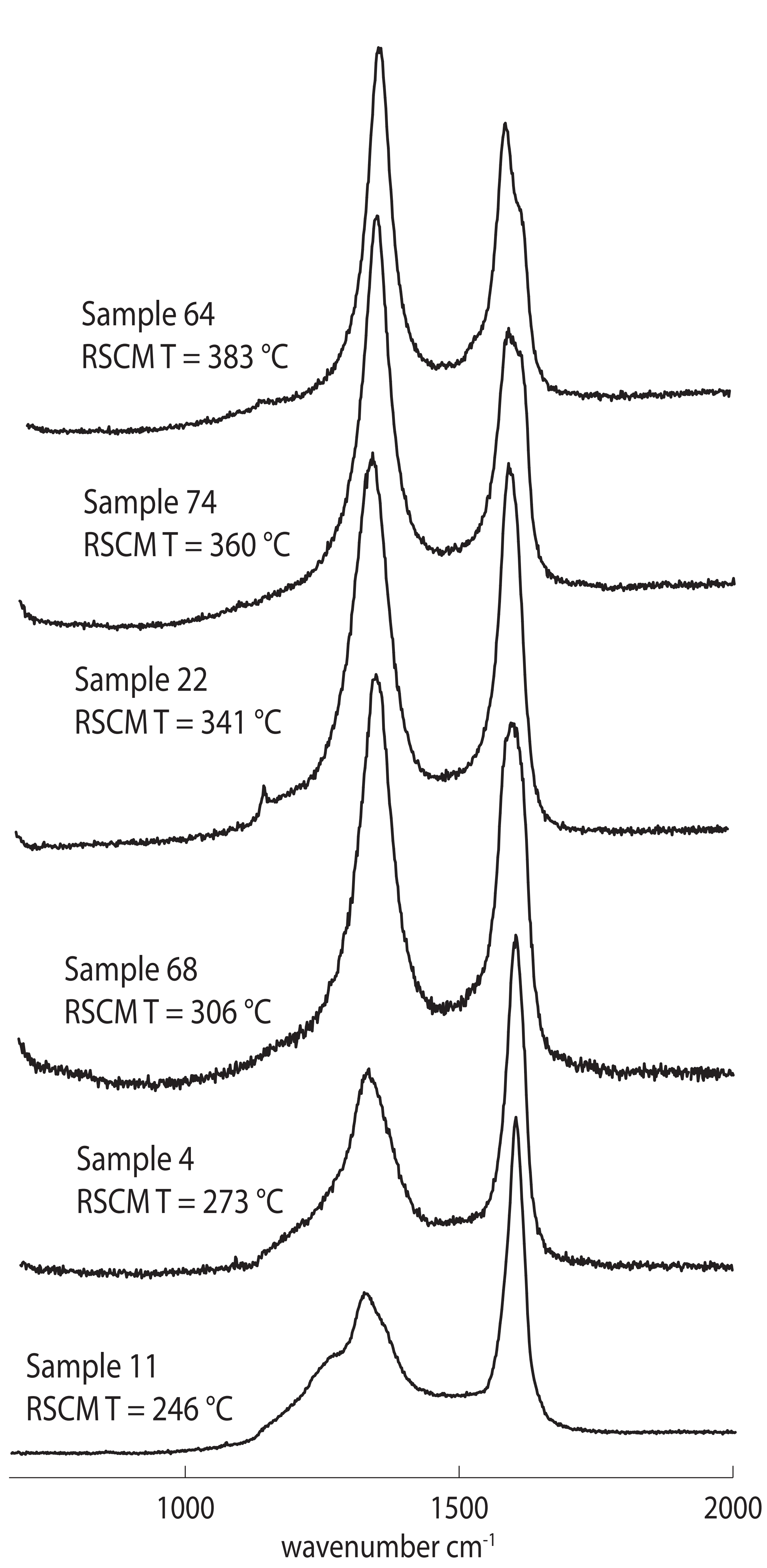


Fig.02 Molli et al., JSG



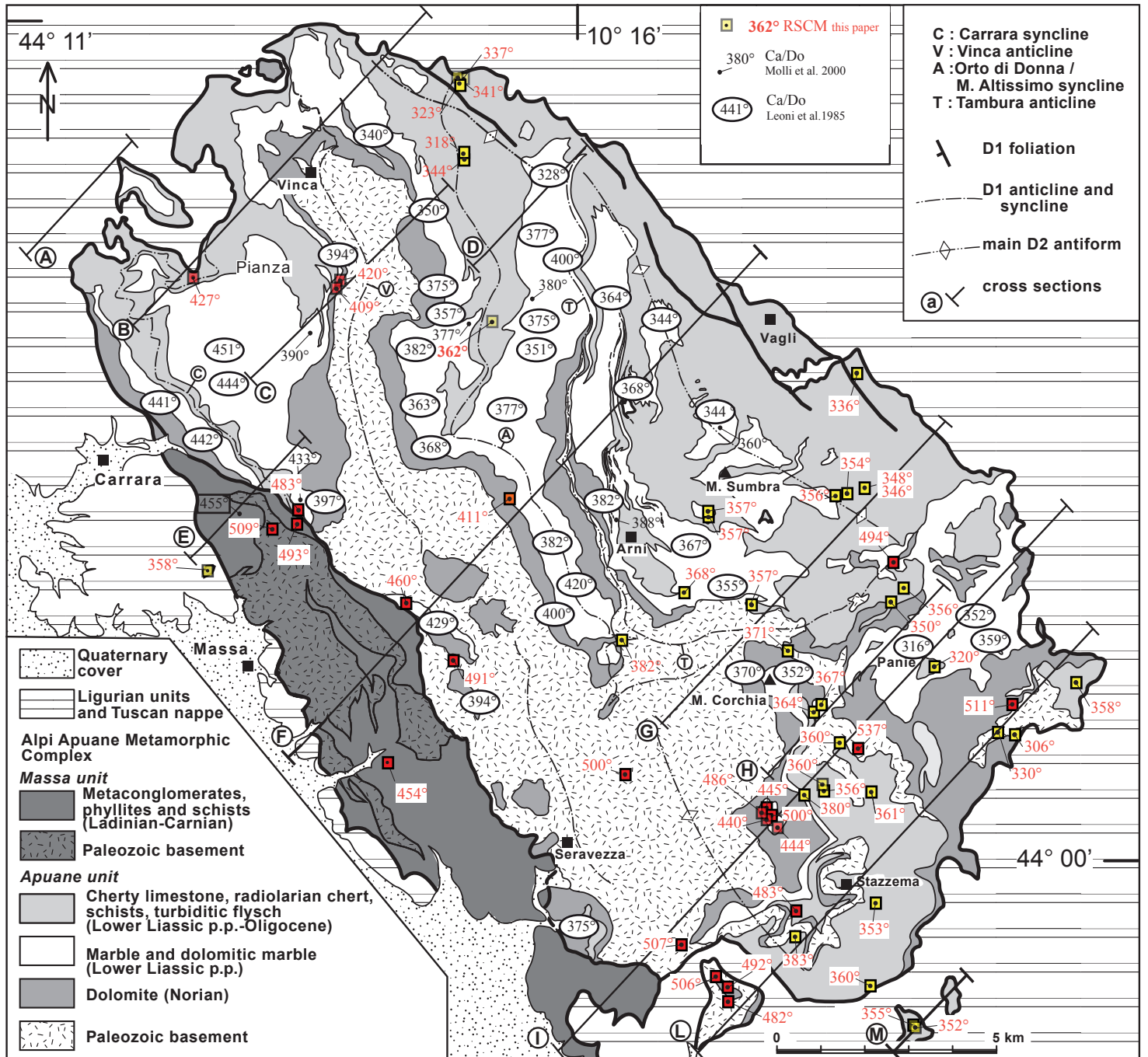
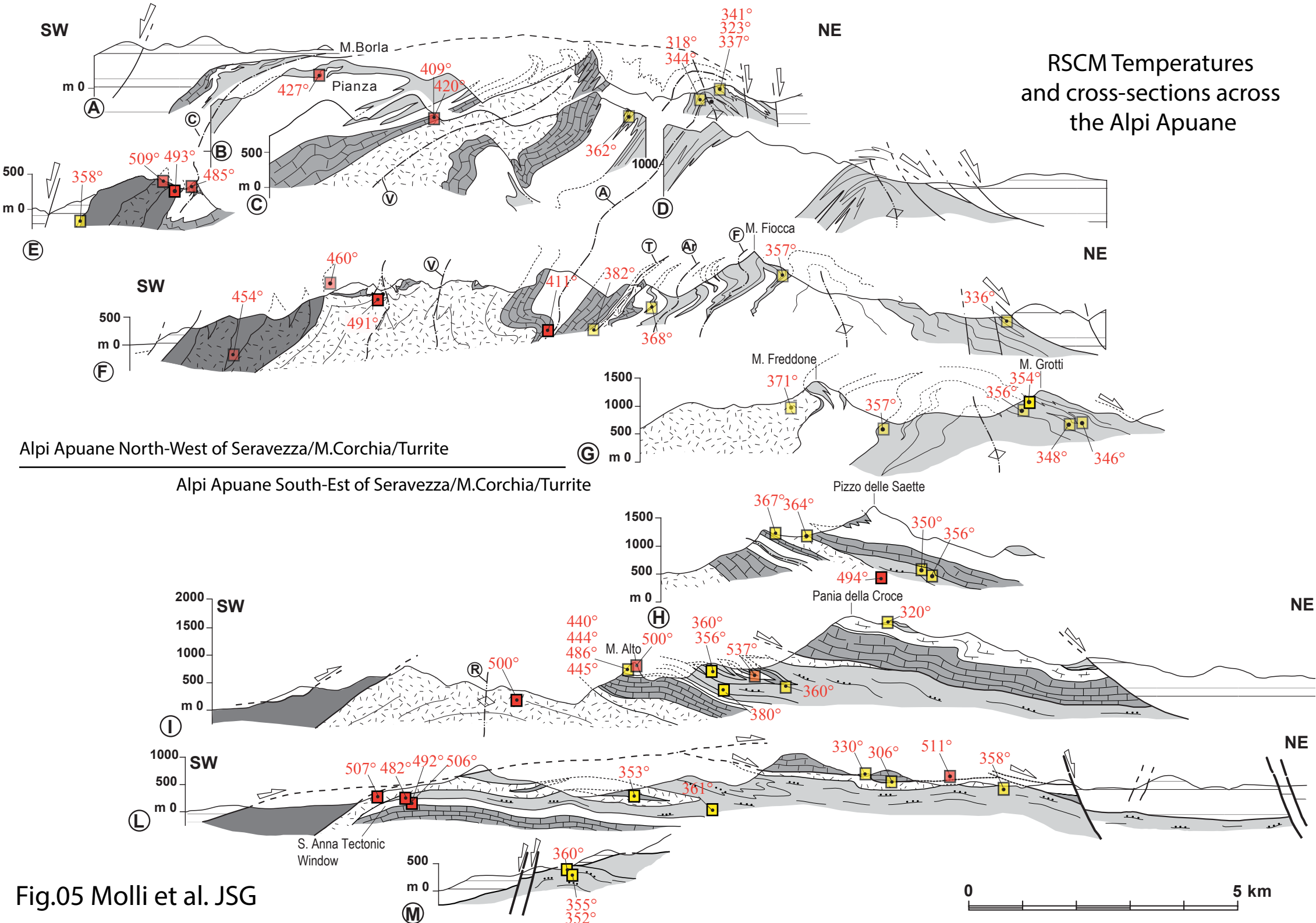


Fig.04 Molli et al. JSG

RSCM Temperatures and cross-sections across the Alpi Apuane



Alpi Apuane North-West of Seravezza/M. Corchia/Turrite

Alpi Apuane South-East of Seravezza/M. Corchia/Turrite

Fig.05 Molli et al. JSG

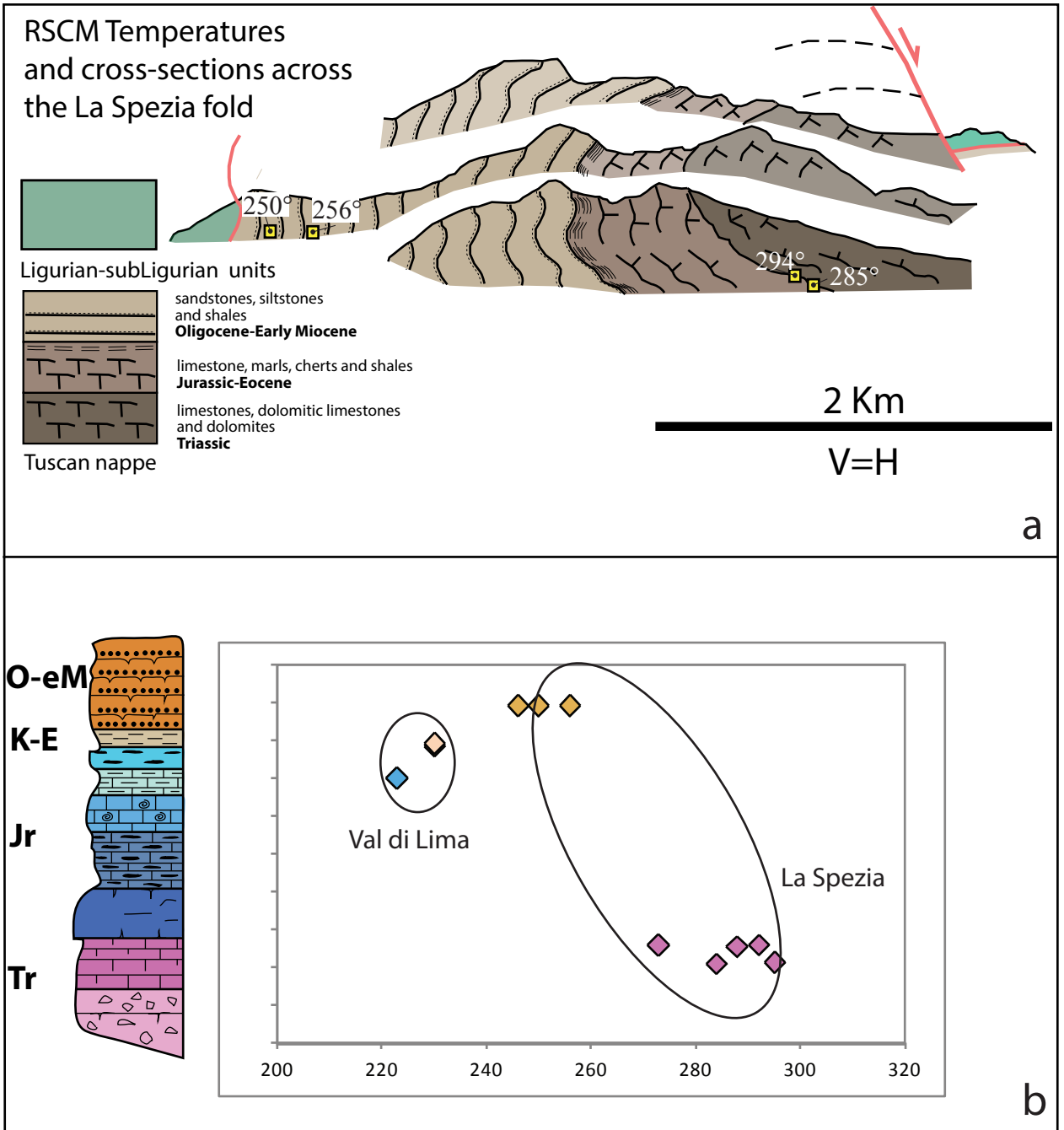


Fig. 06 Molli et al JSG

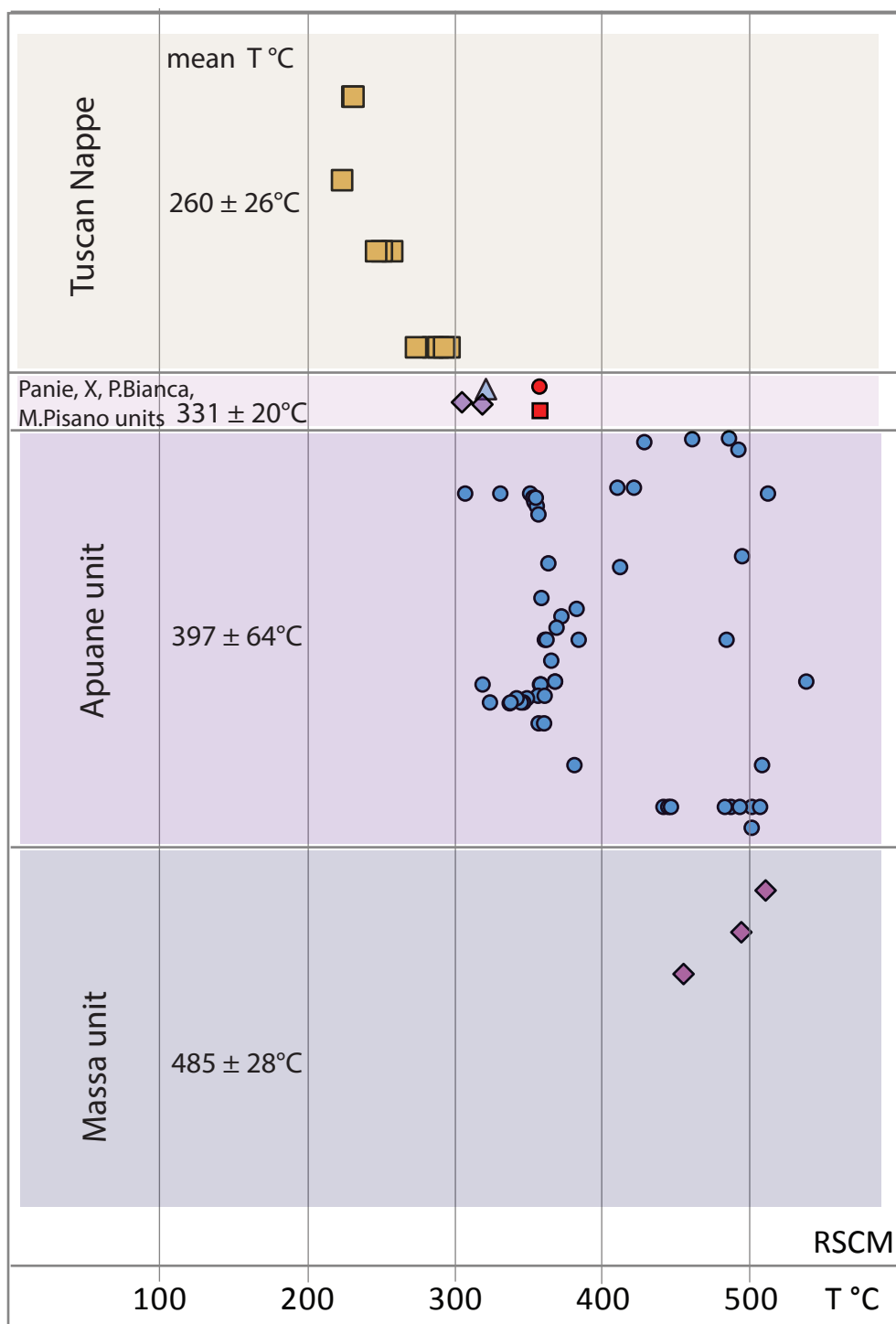


Fig07 Molli et al., JSG

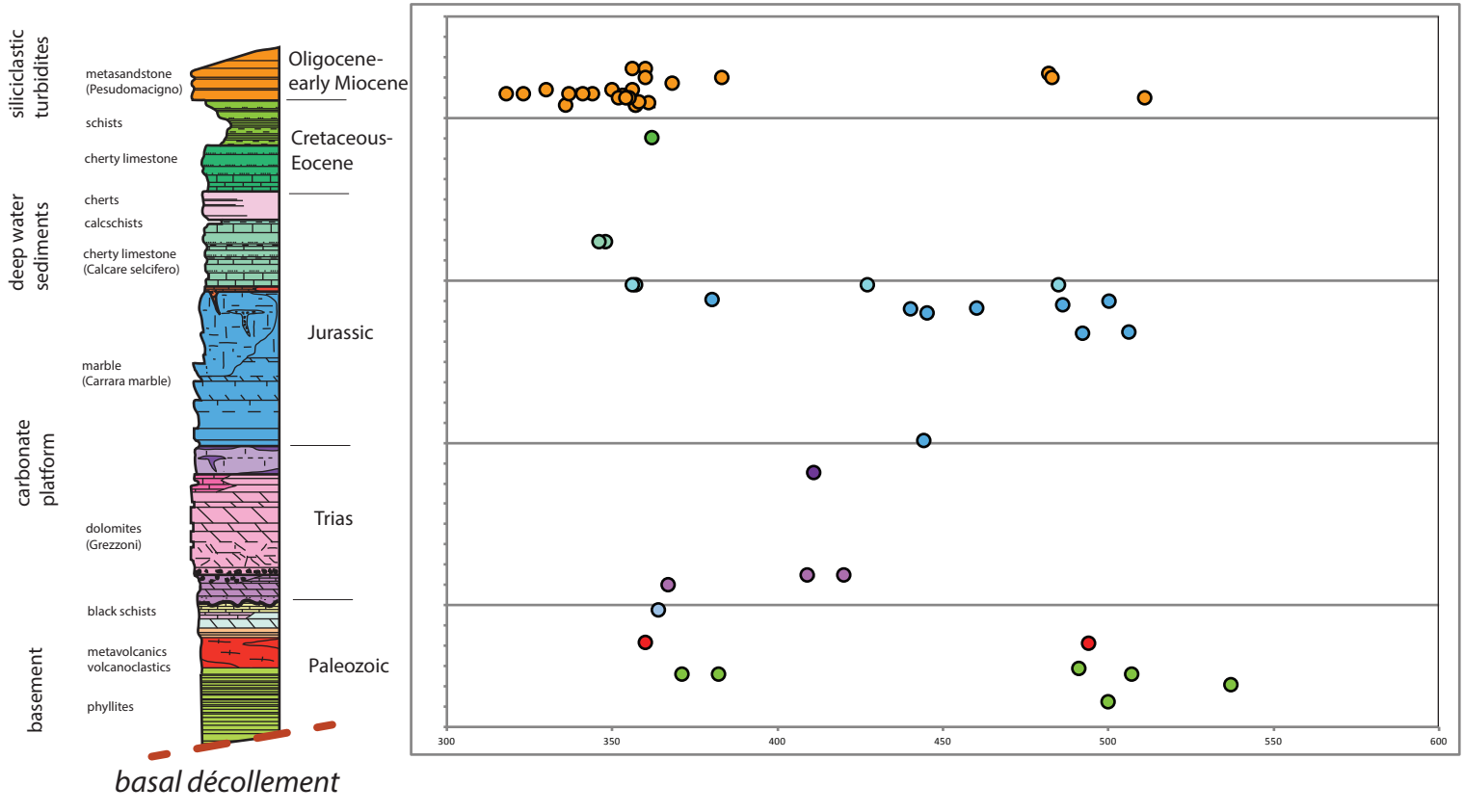


Fig08 Molli et al., JSG

Paleothermal and structural architecture of the Alpi Apuane metamorphic core

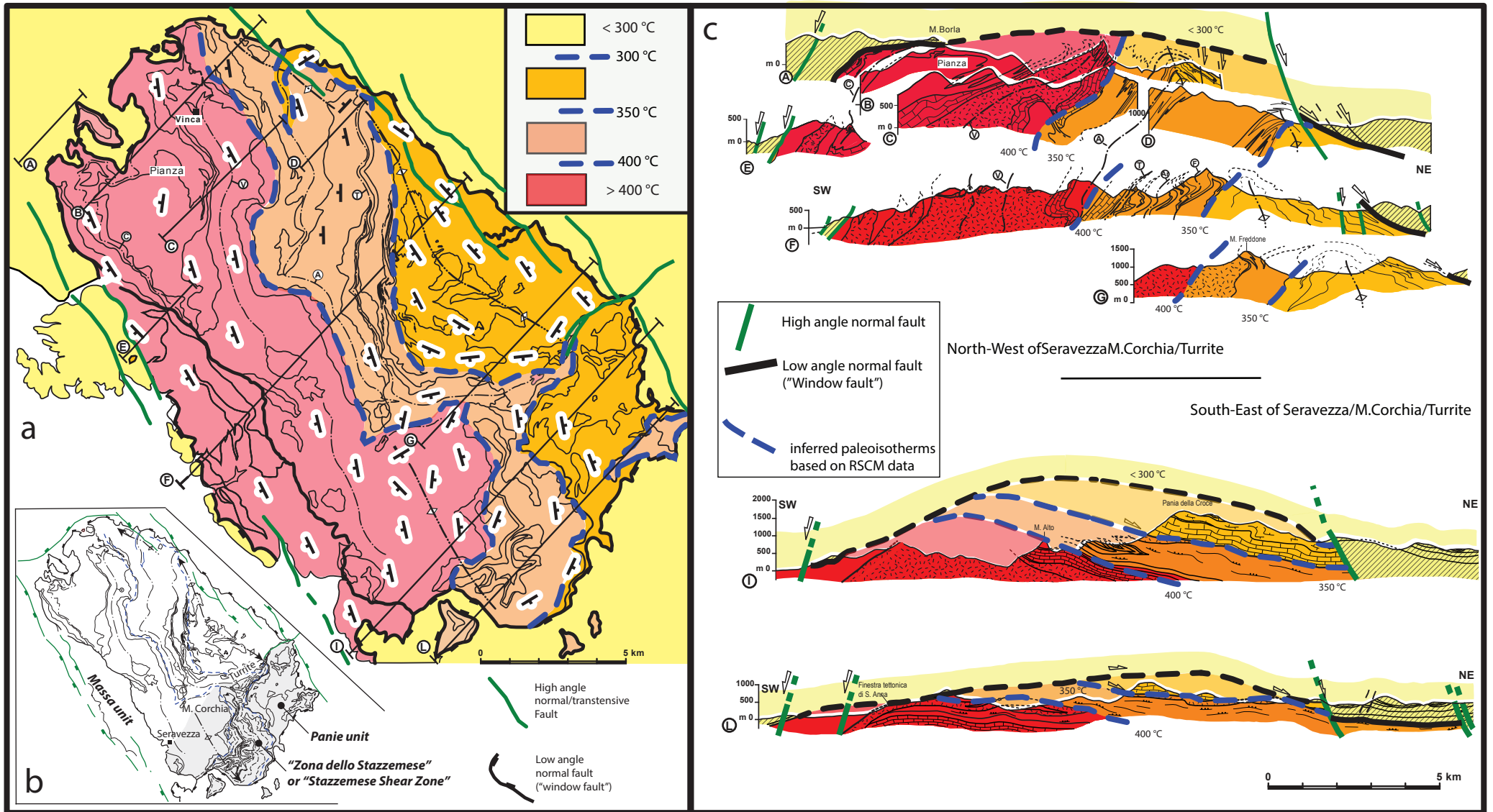


Fig. 09 Molli et al JSG

Tectonic and paleothermal evolution of the Alpi Apuane metamorphic core

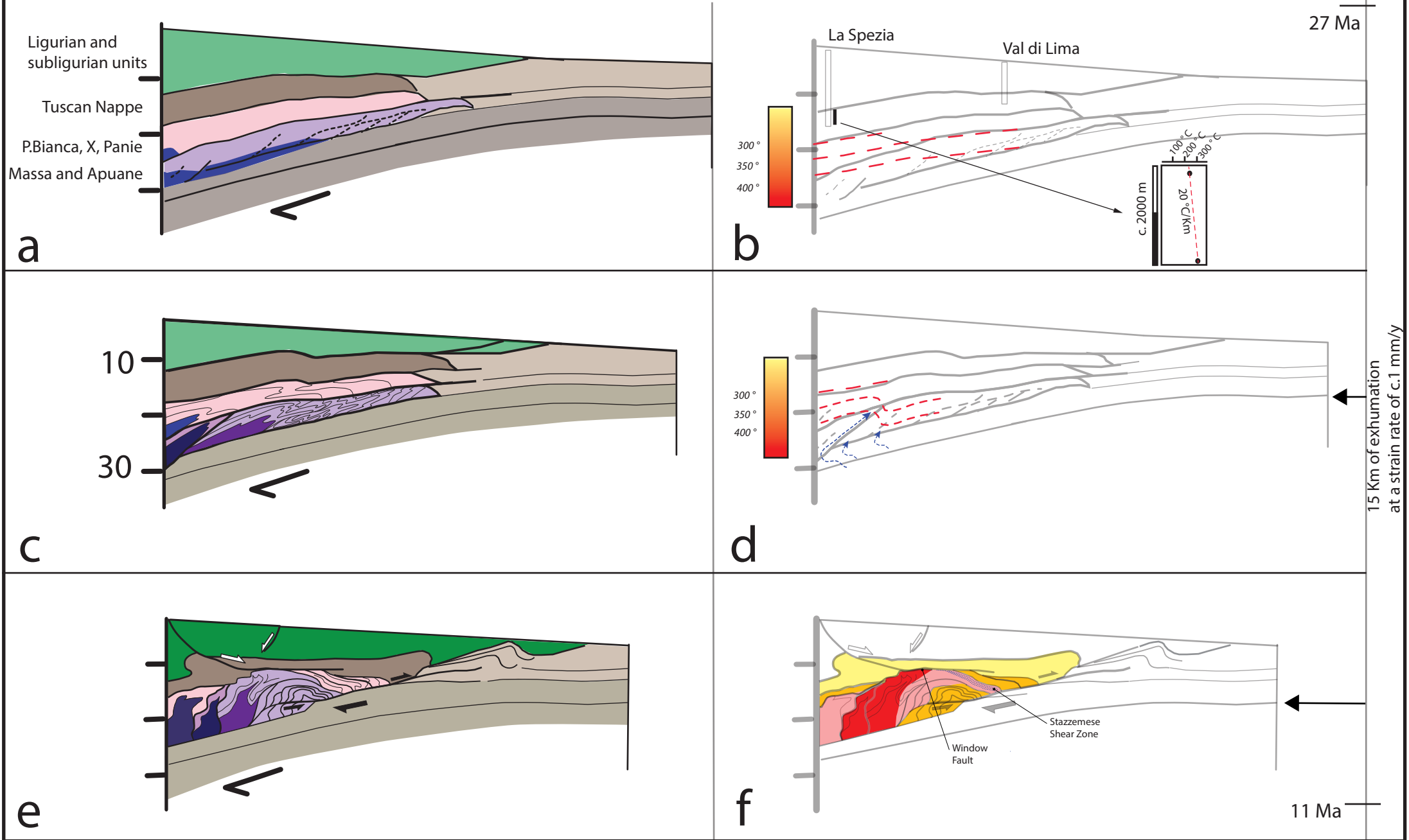


Fig.11 Molli et al JSG

Sample	Tectonic unit		coordinates		n	R2/RA1*	SD	T(°C)	SE
	Rock-type	stratigraphic age	latitude (N)	longitude (E)					
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			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			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

