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The Carboniferous-mid Permian successions of the Northern Apennines: new data from the Pisani Mts. inlier (Tuscany, Italy)

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ABSTRACT

This paper updates and partially modifies the knowledge of the geological-palaeoenvironmental and geodynamic framework of the Tuscan segment of the Variscan Chain during Permian times. Particularly, it adds new data on the contact between the upper Carboniferous-lower Permian San Lorenzo schist (SLs) and the mid-Permian Asciano breccia and conglomerate (Abc) clastic formations in the Pisani Mts. metamorphic inlier which represents one of the key outcrops for the study of the upper Paleozoic sequences in the Northern Apennines. Their sharp unconformable contact is well documented in the literature at map and outcrop scale and was ascribed to the Saalian phase of the Variscan orogeny that would have occurred in correspondence of a climatic change from equatorial to semi-arid tropical conditions. New geological investigations on the SLs and Abc led to the finding of a continuous stratigraphic section in the Pian della Conserva locality (northwestern Pisani Mts.) where the organic matter-rich SLs conformably passes upwards to the reddish immature, mainly coarse-grained deposits of Abc represents a decametric transition zone. The section was studied in detail from a lithological-sedimentological point of view and sampled for petrographic, mineralogic and chemical studies. The data show that the passage from SLs to Abc represents a main change from an equatorial, wet fluvial-lacustrine environment to a well-drained, alluvial fan system in a monsoon-like climate. This event can be related to the reactivation of the previous late Carboniferous-early Permian shear zones during mid-Permian times. Such reactivation produced morpho-tectonic highs subjected to a rapid erosion and the formation of unconformities, whereas the presence of a few residual fluvial plain areas, characterized by dysoxic conditions, is documented by the gradual passage between SLs and Abc in the Pian della Conserva section. In addition, the presence of a metavolcanoclastic or metaepiclastic layer was also recognized in the uppermost part of the SLs and it represents the first evidence of a late Carboniferous-early Permian volcanic event in the Northern Apennines.

Key words: *Pisani Mts., late Paleozoic stratigraphy, petrography, geochemistry, palaeogeography, Tuscany.*

INTRODUCTION

The Pisani Mts. is one of the most important inliers of the Northern Apennines chain (Rau & Tongiorgi, 1974). It is located along the so-called Mid Tuscan Ridge that is a regional scale structural alignment of tectonic windows allowing the exposure of the deepest metamorphic tectonic units of the Northern Apennines chain, i.e. the Tuscan Metamorphic Units that include Paleozoic and Triassic to lower Miocene formations (Vai & Martini, 2001; Pandeli *et alii* , 2004a) (Fig. 1). In the Pisani Mts. inlier the Paleozoic rocks are represented by the Buti banded phyllite and quartzite Formation (?late Ordovician), San Lorenzo schist Formation (SLs, late Carboniferous-early Permian) and Asciano breccia and conglomerate Formation (Abc, ?mid Permian) (Rau & Tongiorgi, 1974; Bagnoli *et alii,* 1979; Pandeli *et alii,* 1994, 2004a, 2008; Landi Degl'Innocenti *et alii,* 2008). These formations are separated from each other by map-scale unconformities (Fig. 2) and lie below the ?upper Ladinian/Carnian Verrucano Group that represents the syn-rift deposits at the base of the Alpine sedimentary cycle.

The sharp and erosional stratigraphic contact between SLs and Abc has been previously interpreted by some authors (Rau & Tongiorgi, 1974, 1976; Bagnoli *et alii,* 1979; Tongiorgi & Bagnoli, 1981; Pandeli *et alii*, 1994). As the unconformity surface related to the main extensional rejuvenation event of the Variscan landscape in Europe that occurred in mid-Permian times (i.e. the Saalian Event in Menning *et alii*, 2000; Wilson *et alii*, 2004). Alternatively it could be linked to the transpression that affected the European Variscan chain during Carboniferous-Permian times along local or regional megashear zones (e.g. North Pyrenaic fault in Arthaud & Matte, 1977; Ziegler, 1984; Vai, 1991; Rau, 1993; Deroin & Bonin, 2003; East Variscan Shear Zone in Padovano *et alii*, 2011, 2012) producing pull-apart basins (see McCann *et alii*, 2006). Part of the upper Carboniferous-Permian sedimentary cycles in Tuscany has been interpreted as being genetically connected with the formation of regional pull-apart basins (RAU, 1990, 1993; Pandeli, 2002; Cassinis *et alii,* 2007, 2012). In order to improve the knowledge of the late Palaeozoic stratigraphic, tectonic and palaeoenvironmental evolution of Tuscany, particularly in correspondence of the Saalian event, we carried out lithostratigraphic- sedimentological, petrographical (textural and semi-quantitative modal analyses), mineralogical (whole rock and clay minerals analysis by X-ray diffraction) and geochemical studies (main elements analysis by X-ray fluorescence) on the SLs-Abc boundary outcropping along the road to the Monte della Conserva, in the northwestern Pisani Mts. (location in Figs. 3 and 4). This paper presents the results of these studies and their implications upon the knowledge of late Paleozoic successions in Tuscany.

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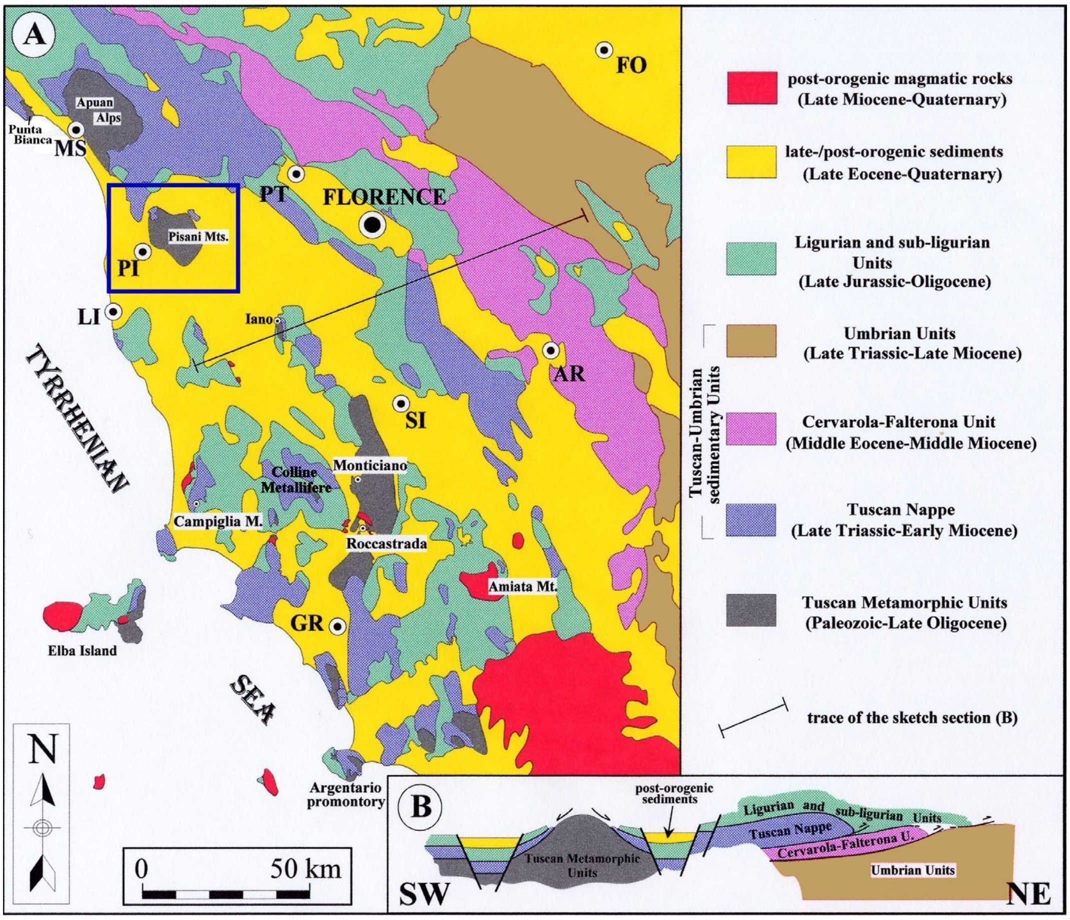

Fig. 1 - Geological sketch map (A) and section (B) of the Northern Apennines. The location of the Pisani Mts. inlier is shown by the squared area (modified from Pandeli *et alii*, 2004a).

THE TUSCAN CARBONIFEROUS-PERMIAN SUCCESSIONS

Late Paleozoic successions occur in many inliers of the Tuscan Metamorphic Unit (Pisani Mts., Iano, Monticiano-Roccastrada Ridge, etc., Figs. 1 and 5), but locally they are missing (e.g. Apuan Alps) because of stratigraphic gaps occurred before the middle-late Triassic, Alpine syn-rift sedimentation (i.e. Verrucano Group, Pandeli, 2002; Pandeli *et alii*, 2004a). The oldest Carboniferous-Permian formation is the Moscovian S. Antonio limestone Fm. (Costantini *et alii*, 1988; Lazzarotto *et alii*, 2003; Aldinucci *et alii*, 2008a) cropping out in the Monticiano-Roccastrada Ridge (SE of Monticiano) that was interpreted as deposited on a carbonate shelf present at the top of the inner active margin of the Variscan orogenic system (Costantini *et alii*, 1988; Pandeli *et alii*, 1994, 2004a) or on the foreland edge (Cocozza *et alii*, 1987). The Variscan belt was built during the main syn-metamorphic Sudetic phase (330-340 Ma, D1 event in Cruciani *et alii*, 2015) and lately modified by the Asturian dextral wrench tectonics (320-315 Ma, D2 event in Cruciani *et alii*, 2015) that began to dissect the Variscan chain. The unconformity at the top of the S.Antonio Limestone Fm. is probably connected to the final activity of the D2 transpressive phase. After that, a series of extensional or transtensional basins originated in which the first late Paleozoic i.e. ?upper Kasimovian/Gzhelian to Sakmarian/?Artinskian sedimentary cycle deposited (Rau, 1993; Cassinis et alii, 2018). Its organic matter-rich and mostly siliciclastic sediments can be related to different environments: from continental (SLs in the Pisani Mts.) to coastal-neritic (Iano schist and sandstone Formation at Iano; Spirifer shale Formation in the Monticiano-Roccastrada Ridge) in an equatorial climate (Rau & Tongiorgi, 1974; Bagnoli et al., 1979; Tongiorgi & Bagnoli, 1981; Costantini et alii, 1988; Pandeli et al., 1994, 2008; Lazzarotto *et alii*, 2003; Aldinucci *et alii*, 2008a; Landi Degl'Innocenti *et alii*, 2008;).

In the mid-Permian, the sharp appearance of little-mature, often coarse-grained red beds (e.g. Abc in the Pisani Mts.; Torri Breccia and conglomerate Formation at Iano) at the top of the Sakmarian/?Artinskian sediments marks the beginning of a second sedimentary cycle that is generally connected with the rejuvenation of the Variscan landscape due to the extensional Saalian tectonic phase (Rau & Tongiorgi, 1974; Bagnoli *et alii*, 1979; Tongiorgi & Bagnoli, 1981; Pandeli *et alii*, 1994). Moreover, a calc-alkaline magmatic event is locally testified by acidic metavolcanics in the upper part of the cycle (Iano porphyritic schist Formation, Costantini *et alii*, 1998; Pandeli, 1988, 2002) and by associated high-grade hydrothermal mineralizations (tourmalinolite clasts in the Triassic Verrucano: Rau & Tongiorgi, 1974; Cavarretta *et alii*, 1989; Fornovolasco tourmalinite on the Apuan Alps: Pandeli *et alii*, 2004b; Vezzoni *et alii*, 2018).

During the late Permian, a third composite sedimentary cycle occurred in different parts of Tuscany. In particular, the erosion of the volcanic reliefs, probably due also to the effects of a last tectonic pulse (i.e. the Palatine tectonic event in Bagnoli *et alii*, 1979; Tongiorgi & Bagnoli, 1981), produced new red beds successions in inner Tuscany, at Iano (Fregione Siltstone Formation, see Costantini *et alii*,

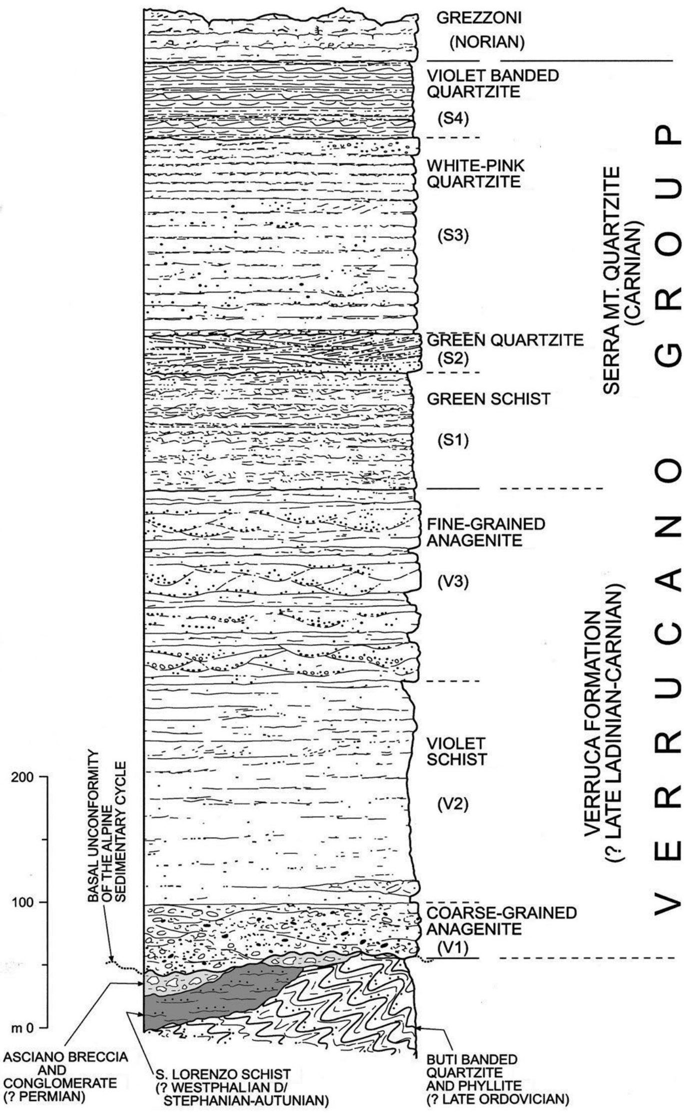

Fig. 2 - Stratigraphic column of the Paleozoic to Norian formations of the Pisani Mts. inlier (modified from Rau & Tongiorgi, 1974)

1998; Pandeli, 1998) and in the Colline Metallifere area (Castelnuovo red sandstone Formation in the drillings of the Larderello geothermal field: Bagnoli *et alii*, 1979; Pandeli *et alii*, 1991). Instead, mainly marine, organic matter rich siliciclastic sequences were deposited to the S and SE of Tuscany during Guadalupian-Lopingian times (e.g. Poggio al Carpino sandstone, Farma, Carpineta, Poggio alle Pigne and Fosso Pianaccia conglomerate formations along the Monticiano-Roccastrada Ridge; Rio Marina Formation on the Elba Island; Monte Argentario sandstone Formation in the Argentario promontory in Cirilli *et alii*, 2002; Lazzarotto *et alii*, 2003; Aldinucci *et alii*, 2008a,b; Spina *et alii*, 2019). In addition, the deep geothermal drillings of the Mt. Amiata geothermal field (Pandeli *et alii*, 1988; Elter & Pandeli, 1991) showed, below the Triassic Verrucano, a Farma Fm.-like succession (Formation A) geometrically passing downwards to alternating organic matter-rich metasiliciclastics and thick crystalline calcareous-dolomitic bodies (Formation C) including fusulinids of mid-late Permian (Roadian for Pandeli & Pasini, 1990).

GEOLOGICAL BACKGROUND OF THE PISANI MTS.

The Pisani Mts. Inlier is made of two tectonically superimposed tectonic sub-units, namely the Serra Mt. sub-Unit and the overlying S.Maria del Giudice sub-Unit (Fig. 3), that rest below the very low-grade metamorphic Tuscan Nappe (Rau & Tongiorgi, 1974; Carosi *et alii*, 1997; Montomoli *et alii*, 2001). Moreover, the Pisani Mts. tectonic window is laterally bounded by high-angle normal faults related to the Late Miocene-Quaternary, post-orogenic extensional events (Martini & Sagri, 1993). As in other Tuscan metamorphic inliers (e.g. Apuan Alps, Monticiano-Roccastrada Ridge), the Pisani Mts. successions consist of a Paleozoic “basement” and of the stratigraphically overlying Triassic to Oligocene formations of the Alpine sedimentary cycle (Rau & Tongiorgi, 1974). In particular, the Paleozoic rocks are represented by the Buti banded phyllite and quartzite Formation (attributed to the Upper Ordovician by Pandeli *et alii*, 1994, 2004a), the fossiliferous SLs (late Carboniferous-early Permian) and the unfossiliferous Abc (mid-Permian, according to Pandeli *et alii*, 1994 and Pandeli, 2002) (Fig. 2) that are separated by erosional unconformities. In addition, a main stratigraphic gap divides them from the overlying quartzose continental Triassic Verrucano Group that marks the beginning of the Alpine sedimentary cycle (Rau & Tongiorgi, 1974, 1976; Bagnoli *et alii*, 1979; Pandeli *et alii*, 1994) (Figs. 2 and 4). The S.Maria del Giudice Unit is characterized by the presence of relatively wide outcrops of SLs and Abc, whereas their exposures are a few or generally missing above the pre-Carboniferous Buti banded phyllite and quartzite Fm. in the Serra Mt.Unit (Rau & Tongiorgi, 1974; Pandeli *et alii*, 2004a).

Late Paleozoic formations corresponding to the SLs and Abc also occur beneath the Verrucano Group succession in the Iano inlier (i.e. Iano schist and sandstone and Torri breccia and conglomerate Formations, respectivelly, in Costantini *et alii*, 1998; Pandeli, 1998) to the south of the Pisani Mts. (location in Fig. 1). There the erosional contact between the two Paleozoic formations is well-documented by the same authors. Previous papers (De Stefani, 1901, Trevisan, 1955; Rau & Tongiorgi, 1974, 1976; Landi Degl’Innocenti *et alii,* 2008) suggested that the essentially grey to black metasiliciclastics of ?Kasimovian/Gzhelian to Sakmarian/?Artinskian SLs were deposited in a mostly fluvio-lacustrine environment, characterized by reducing conditions, in a peri-equatorial climate as demonstrated by its sedimentological features and an abundant fossil floristic assemblage. In addition, the discovery of neritic faunistic associations in the middle-lower part of the formation points to temporary marine ingressions (Pandeli *et alii,* 2008). The unconformably overlying Abc (see angular unconformity at a map scale in Rau & Tongiorgi, 1974) is represented by dominant purplish, little-mature ruditic rocks characterized by typical angular clasts deriving from the Paleozoic formations. These poorly sorted, unfossiliferous sediments have been associated with fluvial-fan deposits in a semi-arid, inter-tropical environment (Rau & Tongiorgi, 1974, 1976). The different lithological and sedimentological features of SLs and Abc, together with their erosional unconformable contact, allowed the same authors to identify this stratigraphic gap as due to the Saalian event of the Variscan Orogeny (Rau & Tongiorgi, 1974, 1976;

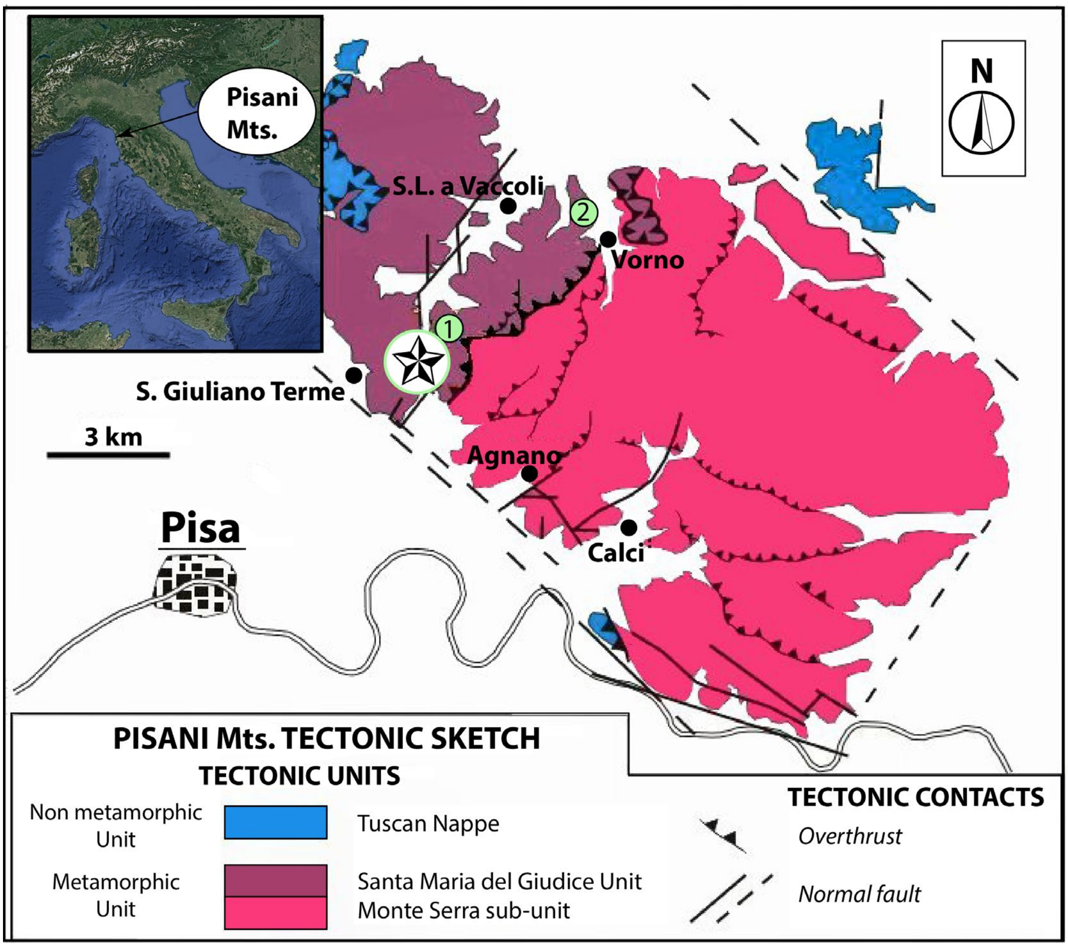

Fig. 3 - Geological structural sketch of the Pisani Mts. The encircled star is the location of the Pian della Conserva section; the full green circles are the locations of the Il Molinaccio (1) and the Mt.Castellaccio-Il Poderetto sections (2) (modified from Rau & Tongiorgi, 1974).

Bagnoli *et alii,* 1979; Pandeli *et alii,* 1994; Pandeli, 2002) such that they proposed a middle-upper Permian age for the Abc.

All the Paleozoic to Oligocene rocks of the Tuscan Metamorphic Units suffered the polyphased Alpine tectono-metamorphism (Barrovian to high pressure-low temperature metamorphism according to Franceschelli *et alii,* 2004; Brunet *et alii,* 2000; Giorgetti *et alii,* 1998; Jolivet *et alii,* 1998; Theye *et alii,* 1997; Leoni *et alii*, 2009; Brogi & Giorgetti, 2012) during syn- (Late Oligocene, 27 Ma 40Ar/39Ar radiometric age on the Apuan Alps in Kligfield *et alii,* 1986) and late-collisional (Serravallian, 14-12 Ma 40Ar/39Ar radiometric age in Kligfield *et alii,* 1986) events. In particular, the rocks of the Pisani Mts. inlier recorded three folding events (D1, D2 and D3) the first two of which are syn-metamorphic (Carosi *et alii,* 1997, 2004; Pandeli *et alii,* 2004a; Franceschelli *et alii,* 1986, 2004; Leoni *et alii,* 2009)(Figs. 4 and 6):

1) a D_1 event is identified by NE-vergent F1 isoclinal folds with a pervasive and continuous-type axial plane cleavage (S_1);
2) a coaxial D_2 folding phase produced close to tight folds with associated crenulation cleavage (S_2) and NE and W to SW vergences in restricted areas (Carosi *et alii,* 1997);
3) a D_3 event was defined by a open to close folding and spaced cleavage or zonal crenulations (S_3).

At regional scale, the D_1 folding is related to the Oligocene collisional stage, and the D_2 folding to the following uplift of the metamorphic tectonic stack due to "…syn-collisional extensional tectonics in an active orogenic wedge or to a post-collisional extensional collapse of the whole chain" (Carosi *et alii,* 1997, 2004; Pandeli *et alii,* 2004a).

Some thrusts, with top-to-the NNE or SE (e.g. the main "Asciano-Vorno Line" that superposes the Santa Maria del Giudice Unit above the Serra Mt. Unit) or with top-to-the SW kinematics (in the Serra Mt. Unit), are also recognizable (e.g. in Figs. 3 and 4)(Giannini & Nardi, 1965; Rau & Tongiorgi, 1974).

In the Pisani Mts., D1 peak temperature conditions of the Verrucano metasediments were estimated by Leoni *et alii* (2009) at nearly 380-400 °C with pressure values ranging between 0.3 and 0.5 GPa (Franceschelli *et alii,* 1986, 2004), even if higher pressure values (up to 0.6–0.7 GPa) have also been defined through fluid inclusion studies (Montomoli, 2002). Instead, the following D2 event can be related to the brittle-ductile rheological transition at a regional scale (260-350 °C and 0.3-0.4 GPa in Franceschelli *et alii,* 2004).

THE PIAN DELLA CONSERVA SECTION

This section is exposed, generally at the scale of 10-15 m in width, between Monte Pian della Conserva and the Linari area (south of S.Maria del Giudice-S.Pantaleone in

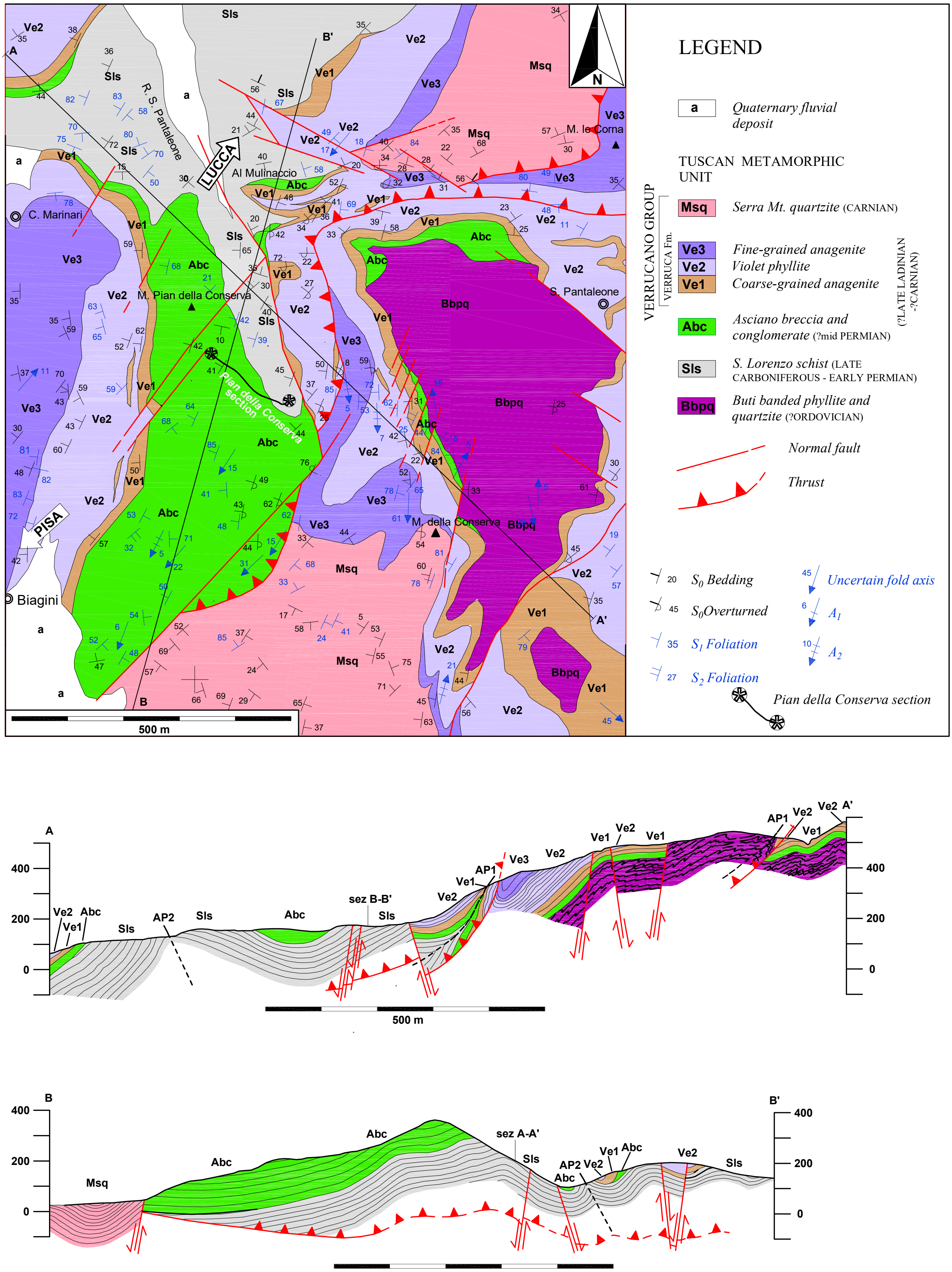

Fig. 4 - Geological sketch and sections of the Pian della Conserva area and surroundings with the location of the studied stratigraphic section (modified from Rau & Tongiorgi, 1974 and from Carosi & Pertusati, 2006).

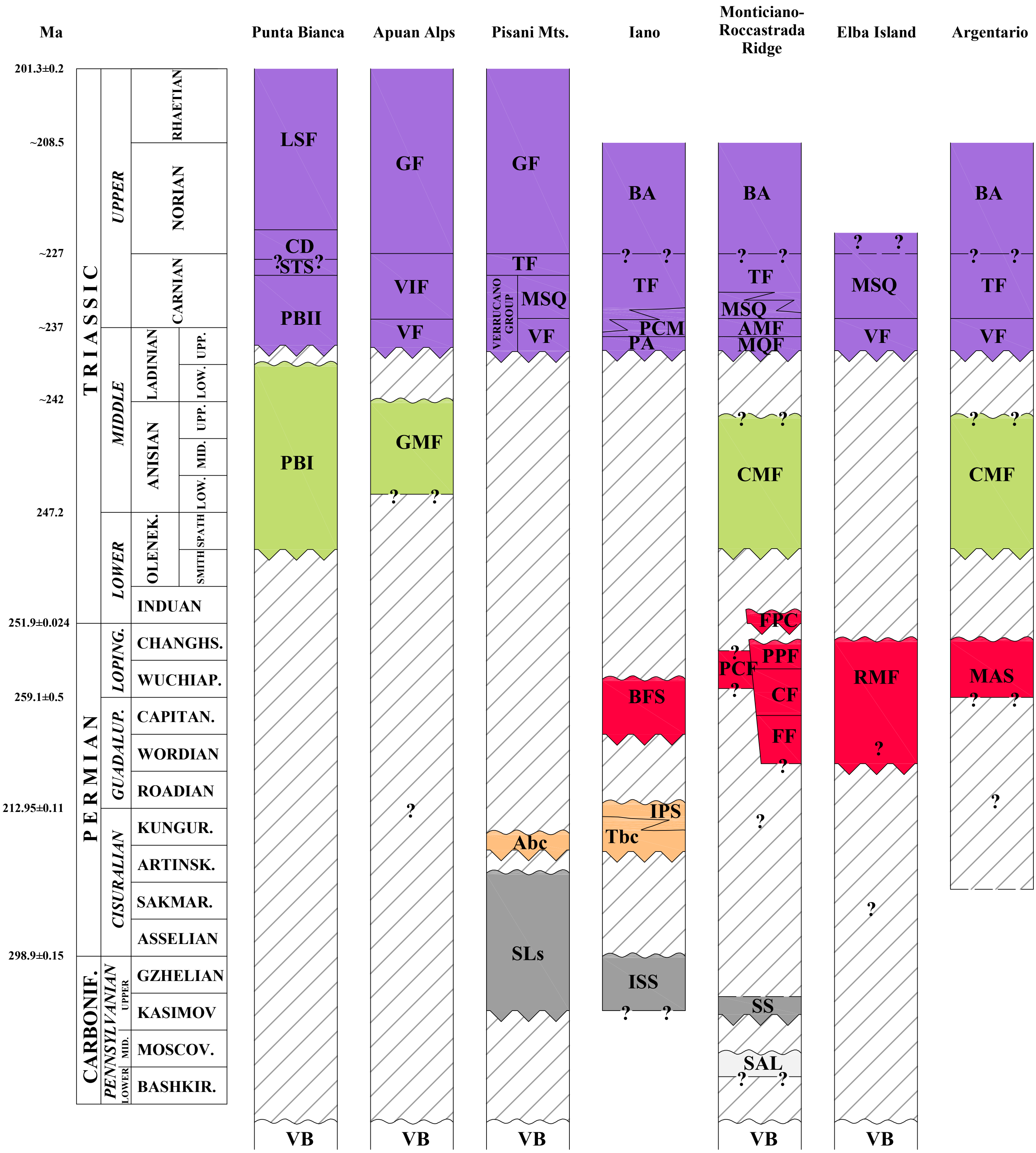

Fig. 5 - Stratigraphic correlation scheme of the late Carboniferous-Permian and Triassic formations in the Northern Apennines (data from Pandeli, 2002; Lazzarotto *et alii*, 2003; Aldinucci *et alii*, 2008a; Spina *et alii*, 2019). VB=Variscan basement; PBI=Punta Bianca I cycle; PBII=Punta Bianca II cycle (i.e. Verrucano Group); STS=S.Terenzo schist; CD=Coregna dolostone; LSF=La Spezia Formation; GMF=Grezzone Metallifero Formation; VF=Verruca Fm.; VIF=Vinca Formation; GF=Grezzoni Formation; SLs=S.Lorenzo schist; Abc=Asciano breccia and conglomerate; Verrucano Group:VF=Verruca Formation and MSQ=Monte Serra quartzite; TF=Tocchi Formation; ISS=Iano schist and sandstone; Tbc=Torri breccia and conglomerate; IPS=Iano porphyritic schist; BFS=Borro del Fregione siltstone; PA=Pietrina anagenite; AMF=Anageniti minute Formation; BA=Burano anhydrites; SAL=S.Antonio limestone; SS=Spirifer schists; PCF=Poggio al Carpino Formation; CF=Carpineta Formation; FF=Farma Formation; PPF=Poggio alle Pigne Formation; FPC=Fosso Pianaccia conglomerate; CMF=Civitella Marittima Formation; MQF=Monte Quoio Formation; RMF=Rio Marina Formation; MAS=Monte Argentario sandstone. Numerical ages (Ma) for all systems are taken from Cohen *et alii*, 2013.

the Guappero Valley) along and on the upslope side of the dirt road to the Monte della Conserva (Figs. 3 and 4). In particular, it is located at 3,5 km from Passo di Dante and its WGS84 geographic coordinates are N 43° 45'.815, E 10° 28'.466 (base of the section) and N 43° 45'.860, E 10° 28'.358 (top of the section).

Even if other stratigraphic sections of the contact between the SLs and Abc are exposed in other parts of the S.Maria del Giudice Unit (e.g the S.Pantaleone Valley-Il Molinaccio section, to the ESE of S.Maria del Giudice and the M.Castellaccio-Il Poderetto section close to Vorno, locations in Fig 3), the Pian della Conserva section decribed here remains a good section where the stratigraphic transition between the two formation is clearly visible over a length exceeding 130 m (Figs. 3, 4, 6 and 7).

Structural features

This section is located in the basal part of the S.Maria del Giudice Unit, close to the main overthrust surface that allows the superposition of it over the Serra Mt. Unit (Figs. 3 and 4). In particular the Pian della Conserva section is located on the western, WNW-NW-dipping normal limb of a main hectometric-kilometric, E-vergent D_1 isoclinal anticline, which involves also the Triassic Verrucano siliciclastic sequences (Fig. 4). This structure is deformed by D_2 close, symmetric to asymmetric folds that are characterized by a westward vergence. The A_1 axes strike about N-S, whereas the A_2 have a NE-SW to N-S direction (Fig. 4). Local open to gentle D3 folds can be also recognized. The relationships between F_1 and F_2 are defined at the outcrop scale by the interference of S_2 with S_1 (Fig. 6). S_1 (=sericite+quartz±chlorite+opaque minerals as organic pigments or Fe oxides and hydroxides) is a very pervasive, continuous-type schistosity that is generally parallel to the bedding (S_0) (Figs. 7 and 8). It is locally cut at mid-high angle by the later, zonal to discrete, millimetric- to centimetric-spaced S_2 cleavage (=Fe oxides and hydroxides±sericite) (Fig. 6). S_1 is not so much transpositive on the sedimentary structures, even if rotations and flattenings of the clasts along S_1// S_0 are present, similarly to what occurs in most of the outcrops of the late Paleozoic and of the Verrucano successions (e.g. Rau & Tongiorgi, 1974; Tongiorgi *et alii*, 1977; Costantini *et alii*, 1998; Pandeli *et alii*, 2004a). For this reason the original features of the successions are basically preserved.

The main brittle structures in the studied area are the west-dipping, likely late-D1 Asciano-Vorno thrust and the later, mainly NE-SW-trending high-angle normal faults that affected the whole metamorphic inlier (Fig. 4).

Lithologic-sedimentologic data

The section was measured in detail over 126 m and includes the upper part of the SLs and the lower part of the Abc (Figs. 4, 6, 7 and 8). The data (lithology and thickness of the beds, textural features, type of the basal contact of the beds, colours and their geometry at the outcrop scale) are summarized in the column of Fig. 7, where a total of 103 sedimentary bodies were distinguished. In the case of thin bedded lithotypes, they have been grouped in a single body due to difficulties of the recognition of each bed. The

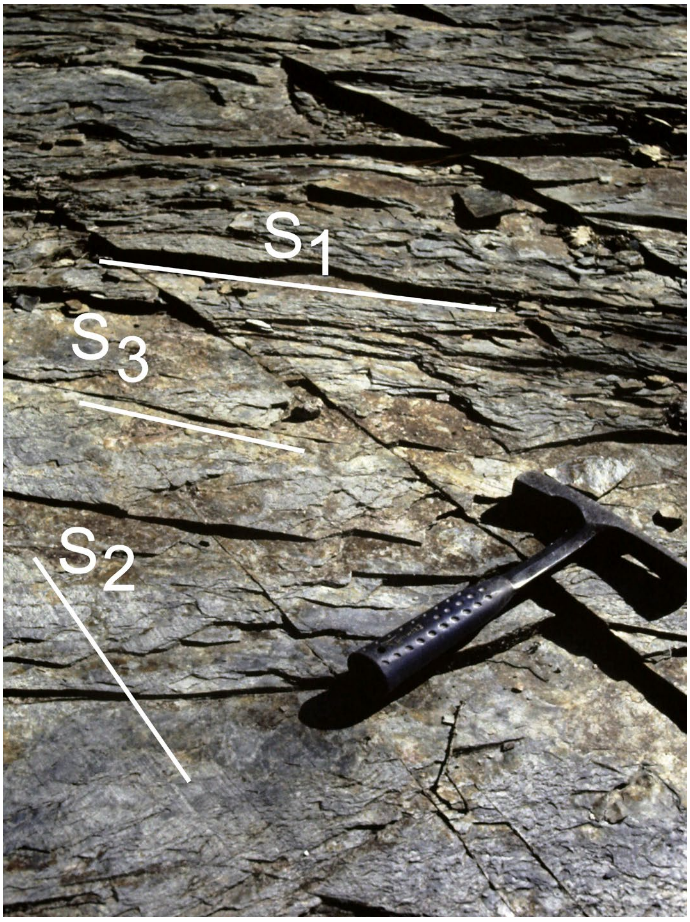

Fig. 6 - Structural elements at the mesoscale (S_1, S_2 and S_3 cleavages) in an outcrop of phyllite and metasiltstone of the SLs.

description of the section follows from the stratigraphic base of the section, in the SLs, to the top, in the Abc.

Upper part of the SLs – The section includes only the top 48 m of the SLs due to a high-angle normal fault that separates it from the Verrucano rocks outcropping to the east.

The SLs is mostly made of alternating phyllites and metasiltstones that are typically dark grey to black in color (Fig. 6) with rare decimetric-thick grey-greenish phyllitic layers and grey, mid- to fine-grained metasandstone intercalations. A peculiar part of the SLs section is that between 15m and 23m, which includes from the base: 1) a decimetric metavolcanoclastic/metaepiclastic layer (body 15, sample 10) (see later for the petrographic features) that appears as a massive, grey to yellowish, fine grained metasandstone; 2) two centimetric/decimetric levels of violet phyllite (in the body 16); 3) a 15 cm-thick metaruditic bed consisting of trough-bedded, quartzitic and matrix-supported metamicroconglomerate (body 19) and a coarse-grained metasandstone characterized by a grey phyllitic matrix with scattered clasts (body 21). Then phyllites and metasiltstones with rare decimetric metasandstone bed follow up to 34 m from the base.

The uppermost part of the SLs (about 34 m to 46 m from the base) looks different because it contains relatively common metaruditic and metaarenitic intercalations

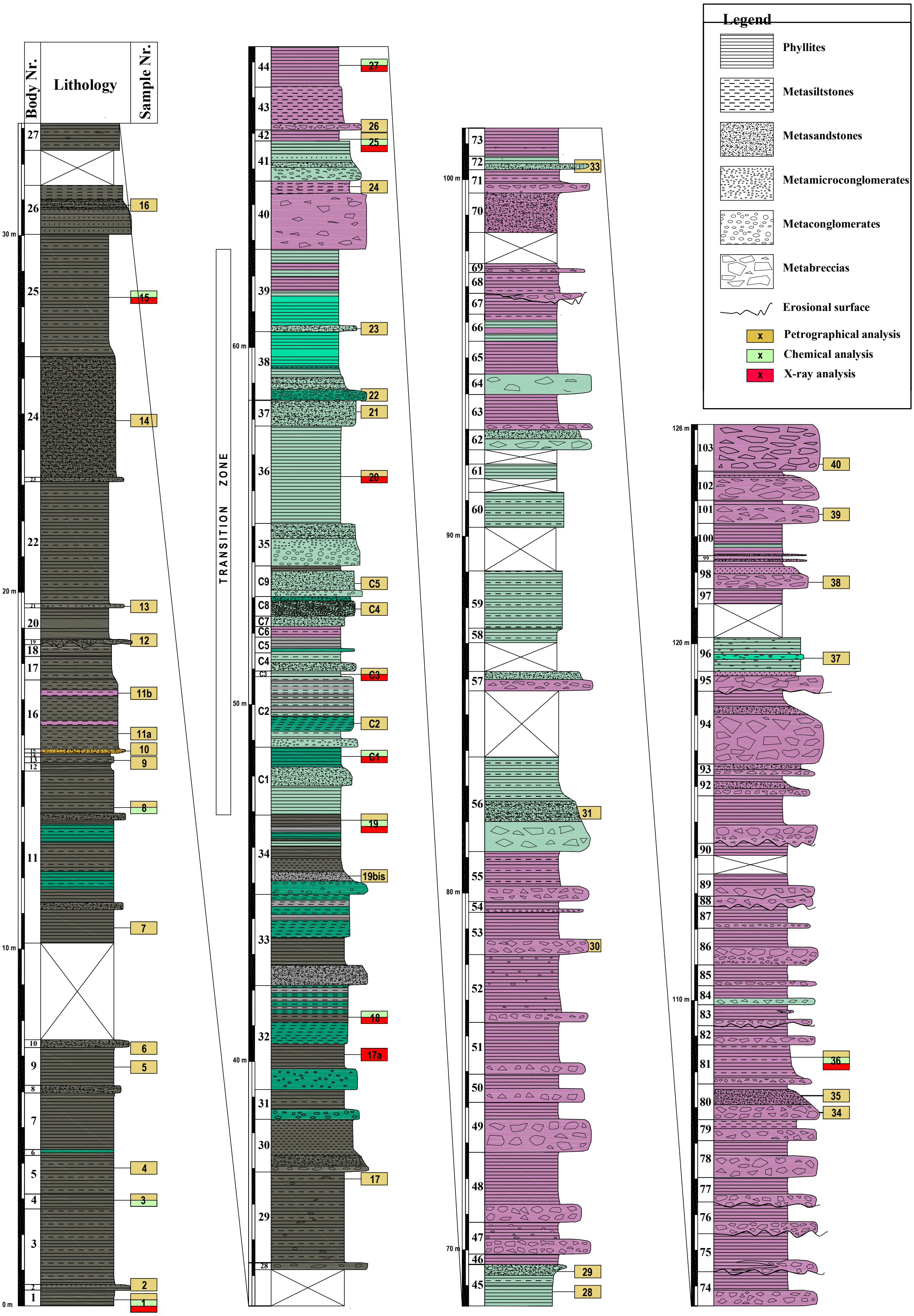

Fig. 7 - Detailed stratigraphic column of the studied section along the road to Monte della Conserva area. The colours for each lithological group are similar to those of the outcrops.

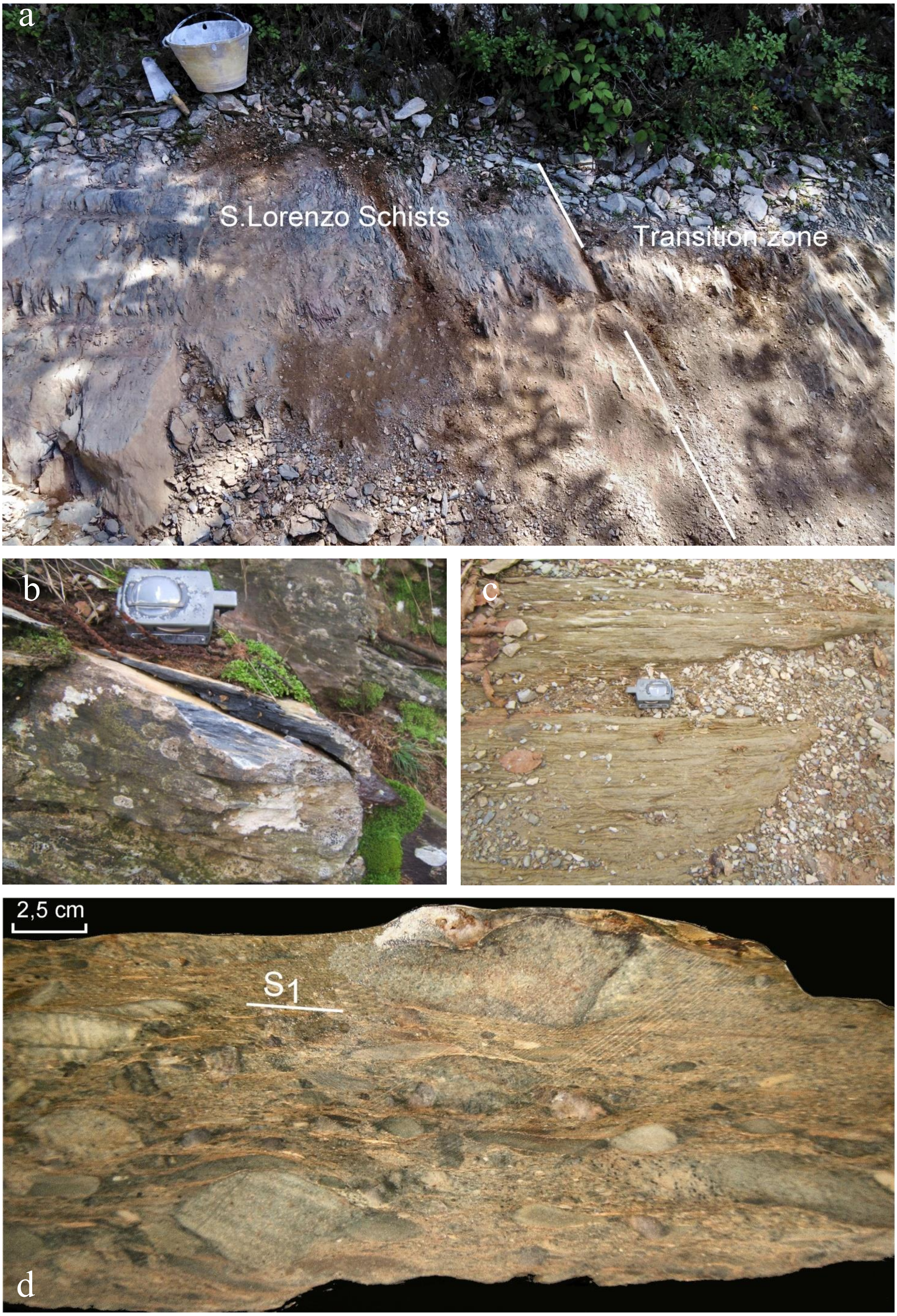

Fig. 8 - Pictures of outcrops along the Pian della Conserva section: a) outcrop of the contact between the SLs and the transitional zone; b) alternating metasandstones with black metapelite intercalations in the upper part of the SLss; c) green phyllitic horizon within the transition zone (body C1 in Fig. 7); d) cut of a green metaconglomerate sample of the transition zone (body 35 of Fig. 7), note that the internal foliation of some clasts is cut by the S1 Alpine schistosity.

Fig. 8 (continued) - e) alternating green and violet phyllites in the upper part of the transition zone (body 39 of Fig. 7); f) polymictic breccia beds (B) with a violet phyllitic intercalation (P) in the upper part of the Abc; g) coarser-grained clasts (see arrow) at the top of an Abc bed (body 86 in Fig. 7)and h) clasts characterized by pre-Alpine (pre-S1) foliation (see arrow) in an Abc bed (body 78 in Fig. 7).

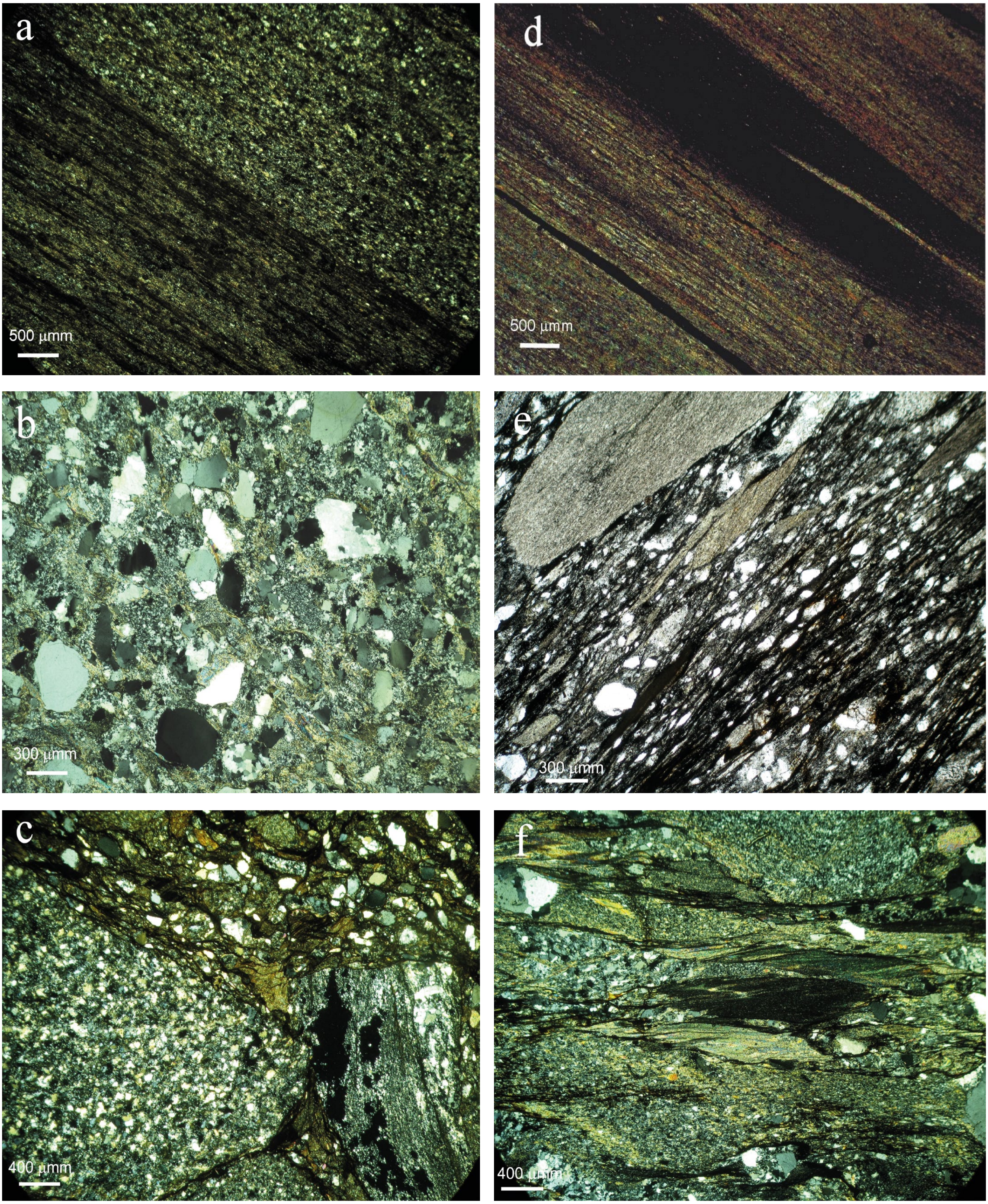

Fig. 9 - Photomicrographs of the clastic lithotypes within SLs and Abc. SLs: a) organic matter-rich phyllites within the SLs; || nicols, sample n.8; b) coarse-grained quartzose sandstone; + nicols, sample 6; c) polymictic Qtz-rich microconglomerates including graphite-rich phyllithic intraformational clasts; + nicols, sample n. 12. Abc: d) hematite-rich purplish phyllites within the Abc; || nicols, sample n. 25; e) coarse-grained polymictic sandstone within the Abc; || nicols, sample n. 34; f) polymictic breccias within the Abc, with phyllitic (see an organic matter lithic from SLs in the center of the picture) and minor quartzitic clasts; + nicols, sample 38.

within the metapelitic lithotypes (Figs. 8a and b) that are represented by decimetric to metric alternations of grey and minor grey-greenish phyllites and metasiltstones. Six massive, grey and greenish metaconglomeratic beds were distinguished; they contain sub-angular to sub-rounded, max 3 cm sized quartzitic clasts that are enclosed in a grey to greenish phyllitic matrix. The gradual vertical passage to the overlying transition zone (Fig. 8a) is characterized by an about one meter-thick alternation of grey, grey-greenish and light green phyllites and metasiltstones (body 34 in Fig. 7).

SLs-Abc transition zone – It is 17 m–thick (from body C1 to 39) and consists of dominant green to light green phyllites (Fig. 8c) and metasiltstones including greenish to grey-greenish, fine- to coarse-grained metarenite and metarudite beds. These latter are fine to coarse-grained, matrix to clast-supported metamicroconglomerates and metaconglomerates (Fig. 8d) with clasts max 5cm in size. These lithotypes appear massive or sometimes graded, passing upwards into metasandstones. Their bases are plane at the outcrop scale. Intercalations of grey and violet phyllites locally occur too in the middle and upper part of the transition zone (see bodies C6 and 39, in Fig. 7 and Fig. 8e).

Lower part of the Abc - The beginning of the Abc is indicated by the first polymictic, violet-purplish metabreccia bed (body 40 in Fig. 7) and overlying clast-bearing violet metasiltstone at 63 m from the base of the section. Above it, the basal part of the Abc (up to body 45, at about 70m from the base of the section) is characterized by prevailing violet metapelites and minor metarudites. It includes also a greenish metamicrobreccia grading upward into metasandstone/metapelite (body 41) and a reverse-graded, greenish metaconglomerate (top of body 45).

The following 12 meters of the section (up to body 55) is typically made up of violet-purple, decimeter- to meter-thick, metabreccia bodies and prevalent metapelites, locally including scattered angular pebbles. The metarudite bodies are massive, clast- to phyllitic matrix-supported and contain clasts up to 2 cm in size.

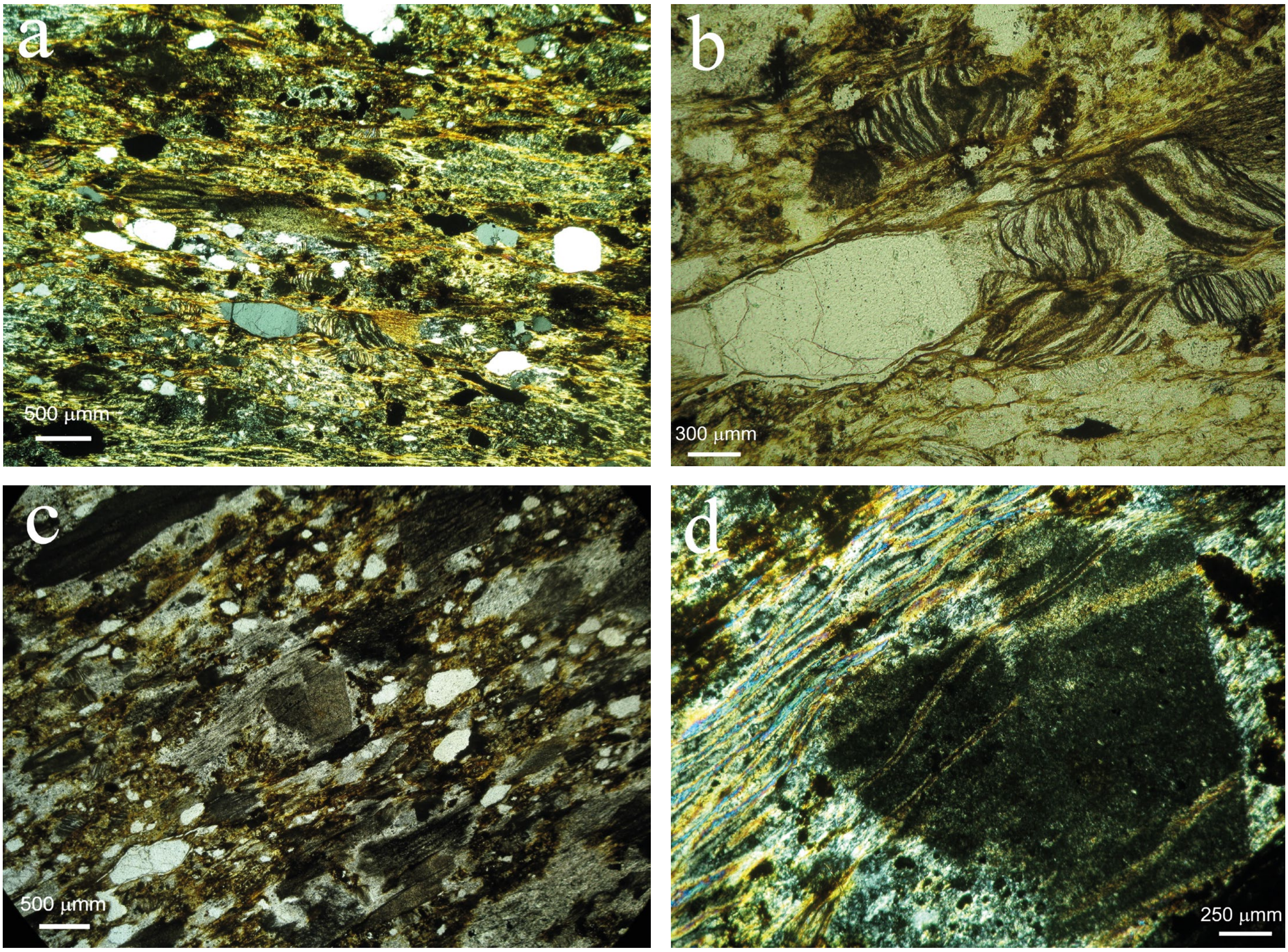

Fig. 10 - Photomicrographs of the metavolcanoclastic/epiclastic layer in the SLs (sample n. 10): a) metavolcanoclastite with abundant magmatic Qtz porphyroclasts and stretched vuggy pumice clasts, + nicols; b) magnification of Fig. 10a, || nicols; c) metavolcanoclastite with magmatic Qtz porphyroclasts and fragments of Ser phyllite (after altered glassy shards), || nicols; d) magnification of Fig. 10c: phyllite clast including altered porphyroclasts substituted by abundant Rt needles aggregates, + nicols .

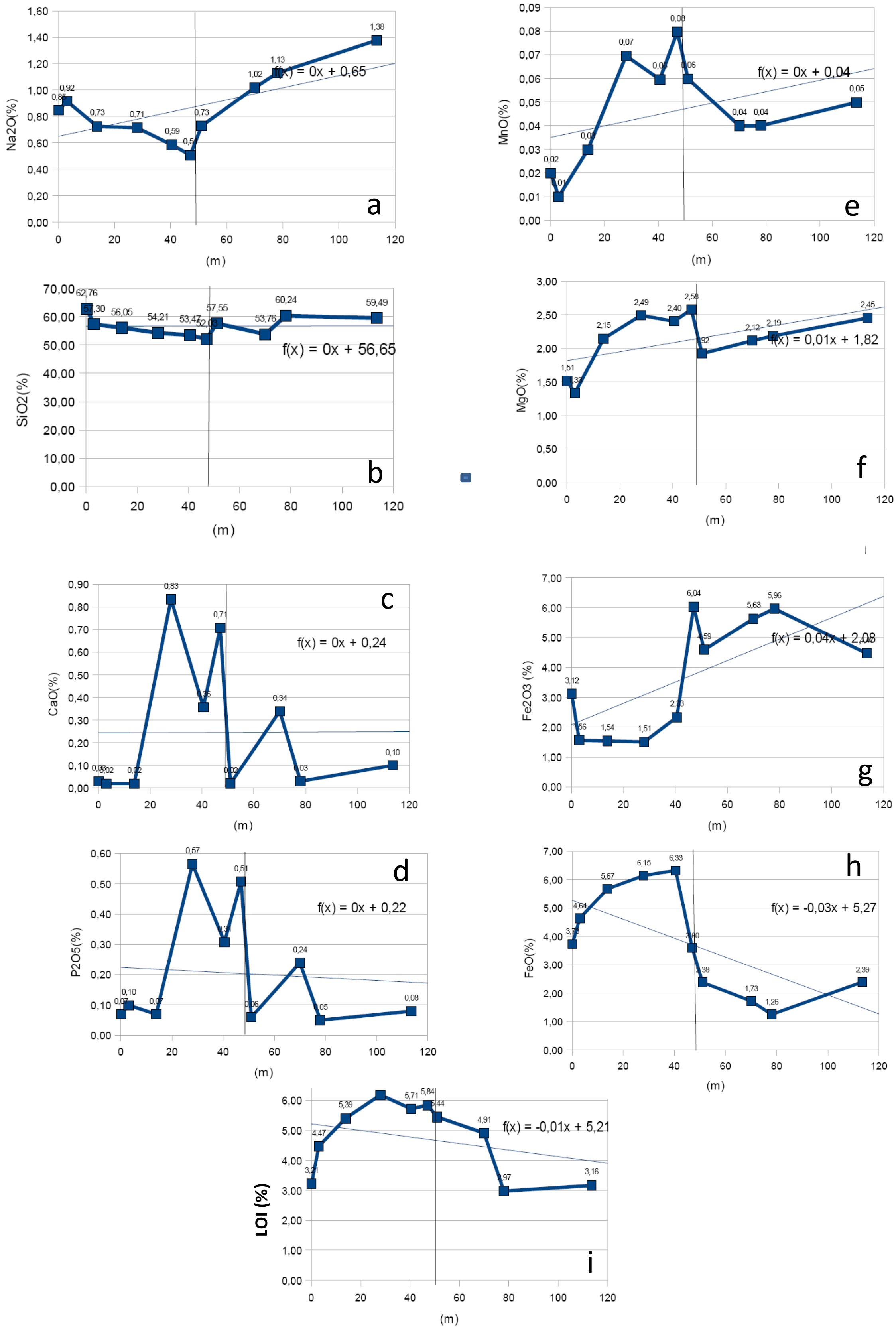

Fig. 11 - Chemical diagrams for the concentration (%) of major elements and LOI in pelitic samples collected in the SLs (1,3,8,15,18, 19), in the Abc (25,27,36) and in the transition zone (C1) (see bold numbers in Fig 8a). In the abscissa, the location of the sample (in meters) from the base of the Pian della Conserva section. The vertical line marks the contact between the SLs and the transition zone.

Greenish clastic lithotypes prevail again from body 56 to body 62. This interval is dominated by metapelites with some intercalations of max 1 m-thick massive to graded metabreccia passing vertically into metasandstone beds (e.g. body 56 in Fig. 7).

The typical matrix-supported breccia bodies, that alternate with metapelite and with minor, generally poorly sorted metasandstone (Fig. 8f), represent the final violet-purple 30 m of the section (from body 63 to body 103). Its decimetric to 2,5 m-thick metabreccia beds are generally massive or crudely graded (generally with reversed-type grading, e.g. body 86, Fig. 8 g) often showing basal erosional surfaces and local lenticular geometries at outcrop scale. Quartzitic-phyllitic clasts, characterized by a pre-S_1 foliation, are relatively frequent(Fig. 8h). The mean size of the clasts in the metarudites increase going upward to the top of the section (max 8 cm). In the uppermost 15 m, the breccia beds prevail and appear as organized in coarsening- and thickening-upwards cycles. Anyway, rare greenish metabreccia beds (body 84 in Fig. 7) and clast-bearing pelitic intercalations (body 96) continue to be locally present in Abc at the top of the section.

Petrographic and Mineralogic data

The stratigraphic locations of the analyzed samples are shown in Fig. 7. Semiquantitative modal analyses were performed on 41 thin sections of the most representative lithotypes (metapelitic, metarenitic and fine-grained metaruditic lithotypes) for the SLs, Abc and their transition zone (Fig. 7). The photomicrographs of the samples are shown in Figs. 9 and 10; the details of the petrographic analyses are in Tab. I (mineral abbreviations are from Whitney & Evans, 2010 and Ser=sericite, Op=organic matter pigment). All the three Tables cited in the text are in the Electronic Supplementary Materials.

X-ray analysis was performed on 11 metapelitic lithotypes of the studied section in order to define both the whole rocks composition and the mineralogy of the clay fraction assemblages. Mineralogical analysis of the samples was carried out at the Department of Earth Sciences (University of Florence) by X-ray diffraction (XRD), utilizing a Philips PW 1050/37 diffractometer with a Philips X'Pert PRO data acquisition and interpretation system, operating at 40 kV-20 mA, with a Cu anode, a graphite monochromator and with 2°/min goniometry speed in a scanning range between 5°-70°θ and 5°-32°θ for the clay fraction. The qualitative diffractometer analyses were performed on both the <63mm grain-size fraction of the whole samples, previously crushed and powdered, and on the <4 mm clay fraction, extracted after washing and settling according to the Stokes law (Cipriani, 1958a,b; Cipriani & Malesani, 1972). The samples of the <4 mm clay fraction were analyzed untreated, after a treatment with ethilenic glycol, and after heating either at 450° C and 600° C.

SLs

- Metapelites. They are typical dark grey to black, lepidoblastic Ser and Ser+Qtz phyllites that contain variable Op; they often include millimetric and sub-millimetric layers of Qtz-rich siltstone and very fine-grained metasandstones (Fig. 9a).

- Metarenites. These are Qtz-rich sandstones characterized by prevalent angular to sub-angular, monocrystalline Qtz grains (Fig. 9b) with ondulatory-type extintion. In some cases Qtz shows a "mortar"–type or "druse"-type and contains Chl flakes. Lithics are always subordinate to Qtz grains and made up of quartzose-micaceous metasandstone (sometimes with scarce Pl and Fe-rich Cc grains), metaquartzarenite and Mu±Qtz and Ser or Ser+Chl , often Op-rich phyllites. These latter can be considered original intraformational clasts.

- Metarudites. Also this lithotype includes abundant Qtz-rich components. In particular, sub-angular to sub-rounded Qtz clasts (generally polycrystalline with ondulatory-type extinction) prevail above the lithic fraction made up of the same rocks described for the metaarenites (Fig. 9c).

- Metavolcanoclastic layer. Sample 10 (body 15 in Fig. 7) is a volcanics-rich metarenite consisting in prevalent monocrystalline "volcanic"-type Qtz (characterized by straight extinction and local embayments) and fragments of vuggy (with Ser fillings) metapumices made up of alternating Mu+Ser and Fe-rich bands. These latter sometimes include porphyroclasts of "volcanic" Qtz (Figs. 10 a and b) and of Ser phyllite with local ghosts of altered porphyroclasts substituted by aggregates of abundant Rt needles (Figs. 10c and d). Ser and Ser+Chl , often Op-rich phyllites and quartzitic-phyllitic lithics are also present. The matrix is micaceous-quartzitic.

Transition zone

It is characterized by green, Chl-rich metasediments.

- Metapelites. They are Chl+Ser±Qtz phyllites that sometimes include Chl and Ms flakes and rare lithics of Ser phyllite.

- Metarenites. They consist of Qtz-rich metasandstones that include Ms and Chl flakes and fragments of Chl and Ser phyllites in a phyllitic (Ser+Chl)-quartzitic matrix. Sometimes Qtz contains Chl "rosette".

-Metarudites. They contain prevalent, sub-angular to sub-rounded, mono- and polycrystalline Qtz clasts above the lithic fraction made up of Pl-bearing quartzitic metasandstones, quartzitic-micaceous sandstones and siltstones, Chl phyllites, quartzarenites and Ser phyllites in a phyllitic (Ser+Chl)-quartzitic matrix locally with Hem pigment.

Abc

The colors of the Abc lithotypes are generally grey-violet to violet because of the presence of abundant Hem pigment in the pelitic components.

- Metapelites. They consist of lepidoblastic Ser and Ser+Qtz phyllites containing variable quantities of Hem pigment that sometimes is concentrated in lens and layers parallel to $S_1//S_0$ (Fig. 9d).

- Metarenites. This lithotype can be often considered as lithic-quartzose metasandstone (Fig. 9e) because of the abundance of the rocks fragments, mostly similar to those of SLs. Locally abundant clastic Chl and coarse-grained lithics of Chl±Ser phyllites and of likely intraformational, Hem-rich metapelites are also present.

- Metarudites. They show an evident textural and compositional low maturity because the clasts are represented by often abundant angular phyllitic lithics and sub-angular clasts of polycrystalline Qtz, quartzose-micaceous metasandstones or quartzarenites (Fig. 9f). The former are mostly represented by Hem-rich phyllites, but some Op-rich phyllitic clasts were also recognized (Fig. 9f). Other phyllitic-quartzitic clasts show evident pre-Alpine, Hem-rich millimetric bands; these latter are cut at their boundaries by S1 that pervasively imprints the metapelitic matrix (Figs. 8 d and h)

The whole rock X-ray analyses performed on 11 samples, collected in the phyllites and metasiltstone of SLs, of Abc and of their transition zone, reveal an almost similar main mineralogical composition with clay minerals, quartz, muscovite, anorthoclase, albite (samples 1, 15, 17a, 18, 19, 25) and hematite (samples 25, 27, 36). The clay minerals association is always represented by illite, kaolinite and chlorite, but in the samples of the transition zone (sample C1, C3 and 20) and in the overlying Abc (samples 25, 27 and 36), minor amounts of chlorite-vermiculite were defined too.

Chemical data

The original compositional features of the Paleozoic and Triassic successions in the Pisani Mts., as of most coeval sequences cropping out in the Northern Apennines, were not modified by the low-grade metamorphism (see Puxeddu *et alii*, 1984; Franceschelli *et alii*, 1987; Verrucchi *et alii*, 1994). We performed chemical analyses on a part of the samples chosen for X-ray analysis, i.e. 10 metapelite samples (samples 1, 3, 8, 15, 18,19,C1, 25, 27 and 36 in Fig 7). In particular, the analysis of the major elements (% of SiO_2, TiO_2, Al_2O_3, Fe_{tot} MnO, MgO, CaO, Na_2O, K_2O and P_2O_5) was carried out at the Department of Earth Sciences of the University of Florence through a X-ray fluorescence (XRF) on pressed powder pellets, using a Philips PW 1480 wavelength-dispersive spectrometer. Major elements have been determined using a Rh anode and corrected for the matrix effect according to the method of Franzini *et alii* (1975) (see results in Tab. II); volumetric titration (using $K_2Cr_2O_7$ as titrant) was also performed for the determination of Fe^{2+} (FeO) and the recalculation of Fe_2O_3 by difference from the Fe tot obtained by X-ray fluorescence. LOI (loss on ignition) values were defined measuring the difference of weight of the samples after placing them in an oven for about 3 hours at a temperature of about 700 ° C. This data was subsequently corrected on the basis of the analysis of Fe^{2+} obtained through volumetric titration (since during the heating the Fe^{2+} tends to oxidize, resulting in an error in the calculation of the LOI). The data are shown in Tab II. Pearson's coefficient "ρ" was also calculated for the couples of the different elements to measure their linear correlations ($-1<\rho<0$ inverse or $1>\rho>0$ direct correlation or $\rho=0$ no correlation, see Tab. III).

The data obtained for the different samples, shown in Tab. II, were plotted in eight binary diagrams in which the percentage of analysed chemical elements (Fig. 11 a,b,c,d,e,f,g,h) and LOI (Fig. 11 i) are represented on the ordinate axis and their stratigraphic location on the abscissa axis.

They generally show a significant chemical and LOI variations in the samples at the beginning of the transition zone (after sample 19 at the top of SLs, see vertical line in Fig. 11). In particular, the Na values (Fig. 11 a) show two distinct trends: from SLs sample 8 to sample 19 and in the following SLs-Abc transition (located between sample 19 and sample C1) we can see a regular decreasing trend, whereas a regularly increasing trend is evident for the Abc samples.

The overall Na trend shows a moderate direct correlation with that of Si (ρ = 0.59, while it has a clear inverse correlation with those of P_2O_5 and LOI (see Tab III). Instead Si has a moderate or strong reverse correlation with most of the other elements (except Ti with ρ=0.53) and, above all, with LOI (ρ=-0.86). The moderate positive correlation between Na and Si can be related to the presence of albite revealed in the petrographic analyses.

The graphs of the percentages of Ca (Fig. 11c) and P_2O_5 (Fig. 11d) show a basically identical trend with a strong decrease of the values in correspondence of the transition zone that is also demonstrated by a very high (ρ = 0.99) Pearson's correlation coefficient. Instead the graphs of the percentages of Mn (Fig. 11e) and Mg (Fig. 11f) show a substancial similar trajectory with a clear break at the transition horizon and a relatively high ρ (ρ =0.84). Particularly significant is the Mg graph (Fig. 11f) where a clear break of the increasing trend is present in correspondance of the transition zone. Moreover, Mn shows a high positive correlation with Ca and P_2O_5 and moderate with LOI, whereas Mg has a positive correlation index only with P_2O_5 and Ca (see Tab. III). The graphs of Fe^{3+} (Fig. 11g) and Fe^{2+} (Fig. 11h) do not have particular correlations with the graphs of the others elements (ρ<0.50, down to -0.48 in Tab. III). Anyway, a quick increase of the Fe 3+ content and a correspondent quick reduction of Fe 2+ is clearly shown in Figs 11 g and h, respectivelly in correspondence of the transition zone Al shows a peculiar behavior as it has a strong direct correlation with the K (ρ=0.89) given the presence of muscovite and moderate with the LOI (ρ=0.58).

The graph of the LOI (Fig. 11i) shows an overall increase in SLs and then a decrease passing in Abc that are clearly related to the abundance of Op in the two formations.

DISCUSSION

The data showed in the previous paragraphs allow new elements for the knowledge of the geology of the Pisani Mts. In particular they update and partially modify the sedimentary-palaeoenvironmental and geodynamic significance of the SLs-Abc succession in the framework of the Tuscan Paleozoic.

Stratigraphic-sedimentary, compositional and Palaeoenvironmental features

For the first time, an about 130 m–thick detailed stratigraphic succession, testifing to a gradual transition between the SSl and Abc, was found (transition zone in Fig. 7) and studied in detail. In all the other known sections this contact has been described as sharp and characterized by an erosional surface (e.g. angular unconformity at the map scale in Rau & Tongiorgi, 1974). The different lithological-sedimentary features of the two formations have been interpreted as an evident change of their depositional palaeoenvironment and of the climatic conditions. In particular, the textural (e.g. roundness of the clasts in the metaruditic beds) and compositional (e.g. the evident richness in lithics in the Abc metarudites) maturity of the sediments decreases and an overall coarsening-upward trend of the siliciclastic deposits is evident moving from the base to the top of the section. In both the SLs and Abc, the lithic assemblage includes metapelites, but also metasandstones (i.e. quartzose-micaceous metasandstones and metaquartzarenites). In particular, especially in the Abc, some metarenite clasts include Pl grains and Fe-rich carbonates and some of the phyllites-quartzitic lithics are characterized by pre-Alpine, Hem-rich millimetric bands. These latter are typical features of the Buti banded phyllite and quartzite that stratigraphically rests under the Carboniferous-Permian successions (cfr. Rau & Tongiorgi, 1974; Pandeli *et alii,* 1994, 2004a). This suggests that source of a part of the lithics was the pre-Carboniferous basement rocks that in the Northen Apennines is characterized by relics of the Variscan schistosity (Se in Pandeli *et alii*, 1994). The Op-rich phyllitic lithics in the SLs metarenites and metarudites can be considered as intraformational component. In the Abc, likely intraformational, Hem-rich metapelites are abundant, but Op-rich lithics continue to be present and testifie the reworking of the SLs. The lithostratigraphic data show that alternations of Op-rich phyllites and metasiltstones, often containing typical continental floristic and faunistic fossil assemblages (Rau & Tongiorgi, 1974; Landi Degl'Innocenti *et alii,* 2008), are prevalent in the lower part of the SLs. The presence of these, sometimes rhytmic, alternations is typical of sedimentary fillings of fluvial-lacustrine-marsh environments in unstable continental subsiding areas (Rau & Tongiorgi, 1974, 1976). It reveals the existence of a delicate balance in these depressed area, broken and restored by the variation of environmental and geological conditions such as the presence of vegetation, debris contribution from the slopes of the surrounding reliefs and subsidence of the basin. In fact, the development of a thick vegetation on the marshland may constitute a filter for the coarser fluvial inputs, involving the deposition of fine-grained sediments rich in organic materials. Subsequent partial sinkings of this area with minor detrital contributions allowed the disappearance of the marshlands and the establishment of a lacustrine environment with sediments characterized by a low organic matter content of the sediments. The progressive and cyclical filling of these ephemeral, lacustrine-march areas, due to the disappearance of the vegetal barriers, is instead given by the increase of mediumto coarse-grained fluvial clastic deposits especially towards the top of the formation (see also Rau & Tongiorgi, 1974).

In agreement with Landi Degl'Innocenti *et alii* (2008), we suggest that the sedimentary environment of the SLs was characterized by a complex alluvial system close to a coastal plain characterized by shallow channels and swampy to lacustrine areas. Particularly at the top of the SLS, these last areas were reached by the coarse-grained flows coming from to the neighboring fluvial channels (e.g. as crevasse splays).

The color of the beds can also be considered significant and diagnostic of the sedimentary environment. In fact, dark gray to black colors largely prevail in the lower part of the SLs in the Pian della Conserva section due to the relatively high content in organic material and to the reduction chemical potential of swamp environment conditions. Also the direct correlation between Ca and P_2O_5 in the chemical analyses can be explained mostly by the local relatively high content of organic matter in the SLs samples (mostly plants, but locally also animals as mollusks, insects and crustaceans, i.e. Estheria in the upper part of SLs see Rau & Tongiorgi, 1974) and perhaps also by the presence of Ap even if as accessory mineral. Only at about 17 m from the base, after the sedimentation of the metavulcanoclastic bed, the two violet phyllitic levels (present also in the lower Permian part of SLs in the typical Via Pari section in Rau & Tongiorgi, 1974) suggest temporary oxidizing conditions. In the upper part of SLs (about 40m from the base of the studied section) a general decrease of organic matter is testified by grey to greenish colours of the metapelitic lithotypes and a decrease of the LOI. Also the presence of relatively frequent intercalations of metasandstone and metaconglomerates testifies an evolution of the environment to an alluvial plain with small channels, flooding plains and water pools.

The alternation of green to light green, grey to violet phyllites bodies and decimetric to about 1 m-thick, green metasandstone and metaconglomerates (often organized in channel fill cycles) characterizes the following Transition Zone to Abc. This sedimentary assemblage suggest the continuation of the same fluvial environment in a dysoxic, at times oxidizing (see local violet metapelitic intercalations) environmental conditions.

The first violet-reddish breccia bed at about 63 m from the base of the section marks the beginning of the Abc in which two, about 1 m-thick green horizons are present in the first 15 meters. Then the succession is made up of a metric alternation of violet to purple, but locally also grey-greenish metabreccias or little mature metaconglomerates and metapelitic, generally silty bodies. These, commonly pelitic matrix-supported metarudites are massive and the coarser clasts at the top of the beds. Moreover they show a general increase of the mean grain size towards the top of the section. Several erosional surfaces were identified at the base of the breccia beds, as well as their lenticular geometries at the outcrop scale.

The sedimentary features of the Abc metarudites suggest a debris flow-like transport mechanism, i.e. a cohesive, mass flow due to the support of the pelitic-rich matrix. Therefore we agree with Rau & Tongiorgi (1974) that the depositional environment of the Abc can be related to alluvial fans, but, given the frequent metapelic intercalations and the reduced thickness of the metabreccia beds in this section, we suggest a distal position. In the other section of Pisani Mts. (Rau & Tongiorgi, 1974) and of Iano (Costantini *et alii,* 1998), the Abc are instead represented by dominant commonly amalgamated thick breccia beds characteristic of more inner parts of alluvial fans likely close to the reliefs. Only in the last 15 meters of the Pian della Conserva section and upward (field observation) the breccia beds are thicker, sometimes welded or with a few pelitic interbeds, and organized in negative-type cycles, that suggests a prograding trend of the alluvial fans.

The data and interpretations of this paper constrain a relatively gradual and concordant transition from the SLs to Abc in the Pian della Conserva section, whereas in other places of the Pisani Mts. (Rau & Tongiorgi, 1974) and at Iano (Costantini *et alii,* 1998) their contact is sharp and marked by erosional surfaces. We think that can be related to the palaeogeographic location of the different sections (or sedimentary areas) respect to the Permian tectonic structures. In the case of the Pian della Conserva section, it probably remained in a low morphological position (e.g. fluvial plains), recording a progressive, but relatively quick environmental and sedimentary change. Other surrounding areas were instead uplifted by the Saalian tectonics, probably as wide restraining bands, allowing the non-deposition of the transition horizon and/or the erosion of the previous successions. Anyway the quick arrival of the Abc low mature clastic inputs is linked to the Saalian rejuvenation of the Variscan landscape that allowed a partial erosion and recycling of the SLs sediments and of the underlying pre-Carboniferous basement (i.e. Buti banded phyllites and quartzites). This positive tectonic pulse, probably connected to the reactivation of the previous shear zone systems (e.g. the East Variscan Shear Zone in the Alps, Ballèvre *et alii*, 2018), produced general uplifts in the inner part of the Tuscan sector and allowed an improvement of the drainage capacity of the sedimentary system that passed to oxidizing conditions.

As to the stratigraphy of the analyzed formations, the fossiliferous SLs can be easily correlated with the correspondent successions of the upper Carboniferous-lower Permian basins of Sardinia (e.g. S. Giorgio, Seui, Perdasdefogu, Escalaplano basins in Cassinis *et alii*, 2018). The unfossiliferous Abc sediments were tentatively attributed to a Permian or to a Permian-Triassic formation by Rau & Tongiorgi (1974), Bagnoli *et alii* (1979) and Pandeli *et alii* (1994). The study of the Iano inlier (Costantini *et alii*, 1998; Pandeli, 1998) revealed that the Abc correspondent metasediments (Torri Breccia and Conglomerate Formation), lying on the late Carboniferous Iano schists and sandstones, pass latero-vertically to calc-alkaline metavolcanics (Iano porphitic schist Formation) and in its turn to overlying red, volcanics-rich siliciclastics (Fregione siltstone Formation). Therefore, the Pisani Mts.+Iano successions appear so similar to the Permian ones of the South Alpine area suggesting their correlation (Pandeli, 1998, 2002; Cassinis *et alii*, 2018). In particular, Abc can be correlated with the mid-Permian Ponte Gardena conglomerate of the Dolomites area (Bolzano province) or with the Dosso dei Galli conglomerate of the Collio Basin (Brescia province). This attribution is strengthened by the presence of overlying peculiar acidic volcanics in the above-said areas (e.g. Auccia volcanics in the Collio area and Athesian volcanics in the Dolomites: Cassinis et al., 2018). Moreover, the uppermost erosional contact of the Iano porphyritic schist with the overlying Fregione siltstone red beds that can be related to the unconformity between the mid-Permian volcanites (e.g. Athesian volcanic platform) and the overlying late Permian volcanics-rich Val Gardena sandstone-Verrucano Lombardo (Pandeli, 2002; Cassinis *et alii*, 2018).

Cassinis et al. (2018) consider the Torri breccias and conglomerates and the overlying metavolcanics as the uppermost part of its first main late Paleozoic sedimentary cycle (i.e. the late Carboniferous-early Permian cycle); on the contrary they separated the Abc sediments from the underlying SLs in the Pisani Mts. by a clear unconformity surface (see Fig. 4 in Cassinis et al., 2018). Our studies are in agreement with this second possibility that relates the Abc-type successions and overlying acidic volcanics to a single, main mid-Permian cycle that followed the late Carboniferous-early Permian (SLs) one, as it is defined in most of late Paleozoic successions in northern Italy (Cassinis et al., 2018).

The discovery of the volcanics-rich layer (body 15 in Fig. 7) in the SLs represents the first evidence of an acidic metavolcaniclastic or metaepiclastic intercalation in the late Carboniferous-early Permian successions of the Northern Apennines. This rock is rich in rhyolite-derived components like "magmatic" quartz, pumices and devetrified glass shards (transformed in phyllitic lithotypes by the Alpine metamorphism). Calcalkaline acidic magmatism is well-know in Sardinia both in Ordovician (e.g. "Porpyroids" Auctt. of the Nappe Zone in Carmignani *et alii*, 2001) and in late Paleozoic (Carboniferous-early Permian volcanic-sedimentary Complex in Carmignani *et alii*, 2001) times. The Porphyroids are mostly metamorphic rhyolitic to andesitic lavas with abundant feldspar phenocrysts, whereas the late Paleozoic products are generally rhyolitic to rhyodacitic ignimbrites and tuffs. The Ordovician Porphyroids are also present in the metamorphic successions of the Northern Apennines (i.e. in the Apuan inlier and in the eastern Elba Island, Puxeddu *et alii*, 1984; Principi *et alii*, 1985) where these sodic-potassic rhyolites are characterized by a strong polyphase metamorphic recrystallization, a high feldspar content and local presence of Variscan schistosity relics (Puxeddu *et alii*, 1984; Pandeli *et alii*, 1994; Pandeli *et alii*, 2004a). Instead, no evidence of late Carboniferous-early Permian volcanism has been recognized up to now in Tuscany, but only the presence of mid-Permian pumiceous, quartz-rich ignimbritic metarhyolites (i.e the Iano porphyritic schist). Anyway, given that the petrographic features of the weakly recrystallized volcanic components of SLs layer are so similar to that of the Iano porphyritic schists (cfr. Pandeli, 1998), we think that the former belongs to the late Paleozoic volcanism or to its dismantling. In this frame, the SLs metavolcanoclastic bed can be considered as a witness of an acidic magmatic event in the Carboniferous-early Permian time interval that predated the main mid-Permian one.

Palaeoclimatic evolution

According to Rau & Tongiorgi (1974, 1976) and Landi Degl'Innocenti *et alii* (2008) the Op-rich SLs are related to a lacustrine-fluvial-marshy environment in a humid, peri-equatorial climate that was probably close to the seaside (see the neritic horizon found in SLs in Pandeli *et alii*, 2008). Instead, previous papers suggested a semi-arid, inter-tropical climate for Abc (Rau & Tongiorgi, 1974; Costantini *et alii*, 1998; Pandeli, 2002; Pandeli *et alii*, 2004a) due to the red-purple colours of these sediments. In this frame, Landi Degl'Innocenti *et alii* (2008), studying the fossiliferous content of SLs, highlighted, in agreement with Rau & Tongiorgi (1974), a clear palaeofloristic and environmental change in the upper part of the formation, early Permian in age. In particular, they defined an increase of the Conifers (e.g. the typical *Walchia piniformis*) with respect to the Pteridophyte, that were dominant in the lower and central part of SLs, assuming that this change may indicate drier conditions. The comparison with the coeval lower Permian formations of the South Alpine area (Collio Formation, Pietra Simona member), containing mudcracks and rare tetrapod footprints (Conti *et alii*, 1991; Avanzini *et alii*, 2008; Santi, 2005; Ronchi, 2008), suggests a partial drying up of the climate in the Sakmarian-Artiskian time. However, Pittau *et alii* (2002, 2008) noted in the Carboniferous-Permian basins in Sardinia that the increase of conifers at the expense of Pteridophyte (ferns) could be determined by local conditions of soil drainage capacity and not necessarily by a drier climate.

Also Sheldon (2005) showed that "red beds" do not necessarily indicate an arid or sub-arid climate, but can be related rather to the conditions of drainage of the ground. In particular, he assumed that the reddish color does not necessarily documents a net drying up, but rather a higher degree of soil drainage with consequent setting of a more oxidizing environment.

Also the chemical variations in the studied metasediments point to change of environmental conditions in the two formations, i.e from a humid climate and mostly swampy areas (which allowed the accumulation of sediments rich in organic matter and of Fe^{2+}), to oxidising conditions of fluvial/alluvial fan systems.

In fact, considering the depositional environment of the Abc as an alluvial fan (Rau & Tongiorgi, 1974; 1976; Pandeli, 2002), we believe that more oxidizing conditions could be related to its greater drainage capacity compared to the periodically flooded and stagnant environment of the SLs. Given also the lack of carbonate caliche-like concretions in Abc metapelite (as in the other sections of the Pisani Mts. and of Iano), these sediments appear similar to those present in wet monsoon climates (cfr. Sheldon, 2005). Therefore we believe that the Abc alluvial fan could be envisaged as having formed in a monsoon-like wet and well drained palaeoenvironment.

Late Carboniferous to Permian tectono-sedimentary evolution of the Pisani mts.–Iano successions in the geodynamic framework of the Tuscan Paleozoic sequences

Mid-Permian times represent a very important focal point in the late Paleozoic geodynamics. In fact, dextral megashears systems dominated the tectonic activity in the late Carboniferous-early Permian of the south Variscan belt producing its fragmentation and the development of pull-apart basins (Arthaud & Matte, 1977; Ziegler, 1984; Vai, 1991; Rau, 1993; Pandeli, 2002; McCann *et alii*, 2006; Padovano *et alii*, 2011-2012; Berra & Angiolini, 2014; Cassinis *et alii*, 2018). According to Rau (1993), the early Permian part of the SLs marks the end of the Variscan cycle and the Abc can be related to different geodynamic conditions. Particularly, this mid-Permian geodynamic change ("Mid-Permian Episode" *Auctt.*) was related to the inversion of the megashears sense from dextral to sinistral by Rau (1993) and (Deroin & Bonin, 2003). Anyway, important trans-pressional phenomena occurred in the Alps area (Prost & Becq-Giraudon, 1989; Rau, 1993; Cadel *et alii.*, 1966; Cassinis *et alii.*, 2008) likely due to the reactivation of the late Carboniferous megashears (e.g. the Carboniferous to Mesozoic polyphase activity of the East Variscan Shear Zone in Ballèvre *et alii.*, 2018). This event allowed the mid-Permian Saalian unconformity and important modifications in the peneplained Variscan landscape (Rau & Tongiorgi, 1974, 1976). Instead, the first dominant Alpine extensional or another regional trans-tensional event occurred instead later during the late Permian with the opening of new syn-rift or pull-apart basins after the so-called compressional "Palatine event" that allowed the dismantling of a part of the mid-Permian volcanoes (Bagnoli *et alii*, 1979; Tongiorgi & Bagnoli, 1981; Pandeli, 2002). These basins, developed at regional (e.g. Verrucano Lombardo and Val Gardena sandstones in the South Alpine area: Cassinis *et alii*, 2018) or local scale (Castelnuovo red sandstone and Fregione siltstone Formations in Tuscany), hosted typical volcanic-rich, siliciclastic red beds. Also an evident compositional variation of the associated magmatism, from the dominant mid-Permian calcalkaline-type to the exclusive alkaline one in the late Permian-Triassic (i.e. the alkaline magmatism in Corsica-Sardinia and Provence, Carmignani *et alii*, 2001; Deroin & Bonin, 2003; Cocherie *et alii*, 2005), occurred. According to Berra & Angiolini (2014) and Cassinis *et alii* (2018), the development of these late Permian basins is coeval and probably connected to the opening of the NeoTethys to the SE of the Variscan belt.

The birth of these last basins marks the beginning of the main Alpine rifting and sedimentary cycle in the Southern Alps area (Cassinis *et alii*, 2018), whereas they indicate a more complex geodynamic evolution during late Permian-Triassic times in the Northern Apennines area (Rau, 1991, 1993; Pandeli, 2002). In fact, repeated attempts of breaking of the Gondwanaland crust through "aborted"- rift stages occurred in Tuscany, i.e. the different late Permian sedimentary cycles in Southern Tuscany, the ?lower-middle Triassic Verrucano first cycle at Punta Bianca, the probably coeval Grezzone metallifero on the Apuan Alps and the Civitella Marittima Formation outcropping from the Monticiano-Roccastrada Ridge to the Argentario Promontory (Fig. 5) (Rau, 1993; Pandeli, 2002). Therefore, it is evident that the Tuscan area was affected by frequent variations of the tectonic regime from compressional (allowing erosion and unconformities) to extensional (development of sedimentary basins). These phenomena can linked to the presence of a long-living active transcurrent lineament or to the action of shear zones or rift systems characterized by different regional strikes. Anyway these structures finally lead to the main Alpine rifting of the Tuscan sector in the Late Ladinian (i.e. Verrucano Group cycle), to the breakup stage and following spreading of the western Tethys, Ligurian-Piedmontese ocean during Middle Jurassic (Bortolotti & Principi, 2005; Principi *et alii*, 2015) that has been connected to an overall sinistral-type shearing regime (Bortolotti *et alii*, 1990).

CONCLUSIONS

This interdisciplinary study of the SLs-Abc contact in the Pian della Conserva section partially modifies the state of the knowledge of the sedimentary, palaeoenvironmental and geodynamic framework of the Tuscan segment of the Variscan Chain in Tuscany during Permian times. The lithostratigraphic data show that in the Pian della Conserva section the contact between the SLs and Abc is not defined by a sharp, erosional, likely unconformable surface as in most of the outcrops of the Pisani Mts. and Iano, but it appears rather as gradual and conformable through a transition zone.

In fact, in the uppermost part the SLs black organic matter-rich metapelites passing upward into alternating grey to green phyllites and metasiltstones with quartz-rich metasandstones and metaconglomerates points to a vertical transition from a swamp-dominated palaeoenvironment to a complex fluvial system at the top of SLs. The latter continued to be active in the greenish transition zone with dysoxic environmental conditions, before passing to the low mature, violet-purple debris-flow deposits of the Abc that are related to distal and middle parts of alluvial fans. This passage is also underlined by a significant change of the chemical trends obtained for the metapelitic lithotypes in correspondence of the transition zone.

In the literature, the variation in colour of the two formations was related to the transition from hot humid sub-equatorial (SLs) to a hot sub-arid, inter-tropical climate (Abc), suggesting a drying up conditions. Taking also into account previous palaeofloristic data of the upper part of SLs, we think that the Abc red beds could be related not to a semi-arid climate, but to a well-drained, oxidizing, possibly monsoon-like environmental conditions. The strong improvement of the drainage capacity of the Abc sedimentary environment respect to Sls can be related to the general tectonic uplift and landscape rejuvenation produced by the transpressive Saalian event. This renewed shearing activity of the previous late Carboniferous-early Permian wrench systems is documented also in some parts of the Alps (e.g. South Alpine and Helvetic Domains).

This event produced tectonic-morphological highs characterized by a quick erosion and formation of unconformities. Instead, the gradual passage from the SLs and Abc palaeoenvironments documented by the Pian della Conserva section attests to the peristence of fluvial sedimentation in residual plain areas (probably representing small inner valleys close to the rejuvenated relieves) that were reached later by the Abc alluvial fan systems.

Finally, the finding of the metavolcanoclastic or metaepiclastic layer in the uppermost part of the SLs likely constitutes the first evidence of a late Carboniferous-early Permian, calcalkaline volcanic activity in the Northern Apennines that predated the mid-Permian volcanic event occurred after the Saalian tectonic pulse.

ELECTRONIC SUPPLEMENTARY MATERIAL

This article contains electronic supplementary material (Tables I, II and III) which is available online to authorised users.

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