geosciences

*Article*

# Reconsidering the Variscan Basement of Southern Tuscany (Inner Northern Apennines)

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**Abstract:** The Pre-Mesozoic units exposed in the inner Northern Apennines mostly consist of Pennsylvanian-Permian successions unconformably deposited on a continental crust consolidated at the end of the Variscan orogenic cycle (Silurian-Carboniferous). In the inner Northern Apennines, exposures of this continental crust, Cambrian?-Devonian in age, have been described in Northern Tuscany, Elba Island (Tuscan Archipelago) and, partly, in scattered and isolated outcrops of southern Tuscany. This paper reappraises the most significant succession (i.e., Risanguigno Formation) exposed in southern Tuscany and considered by most authors as part of the Variscan Basement. New stratigraphic and structural studies, coupled with analyses of the organic matter content, allow us to refine the age of the Risanguigno Fm and its geological setting and evolution. Based on the low diversification of palynoflora, the content of sporomorphs, the structural setting and the new field study, this formation is dated as late Tournaisian to Visean (Middle Mississippian) and is not affected by pre-Alpine deformation. This conclusion, together with the already existing data, clearly indicate that no exposures of rocks involved in the Variscan orogenesis occur in southern Tuscany.

**Keywords:** Northern Apennines; Risanguigno Formation; Carboniferous; southern Tuscany; Monticiano-Roccastrada Unit; Tuscan Palaeozoic; palynology

**Citation:** Capezzuoli, E.; Spina, A.; Brogi, A.; Liotta, D.; Bagnoli, G.; Zucchi, M.; Molli, G.; Regoli, R. Reconsidering the Variscan Basement of Southern Tuscany (Inner Northern Apennines). *Geosciences* **2021**, *11*, 84. https://doi.org/10.3390/geosciences11020084

Academic Editors: Jesus Martinez-Frias and Rodolfo Carosi
Received: 5 January 2021
Accepted: 7 February 2021
Published: 12 February 2021



## 1. Introduction

Stratigraphic reconstructions of the deep successions involved in orogens later affected by post-collisional extensional tectonics are always tempting, since these are normally metamorphosed and involved in polyphase deformation, are laterally segmented and, consequently, are exposed in scattered outcrops. This is even crucial for the metamorphosed, deep successions of the Northern Apennines [1], which experienced the Variscan sedimentary and tectonic evolution (Devonian-Carboniferous), then the Alpine cycle (Triassic-Oligocene), and ultimately the extensional process leading to the opening of the Tyrrhenian Basin (Miocene-Quaternary). Nowadays, the so-called Tuscan Crystalline Basement (Cambrian?-Devonian [2]) is discontinuously exposed, and the scarcity of fossils remains inhibits precise age determination [3–5]. Thus, in absence of fossil records, the Tuscan Basement is traditionally related to the well-known and better exposed Palaeozoic succession of southeastern Sardinia, where the Alpine deformation is relatively minor [6–9].

To strengthen this approach, several studies of the pre-Alpine metamorphic rocks of the Tuscan Archipelago and Apuan Alps have incorporated palaeontological, stratigraphic and tectonic data [2,9,10–14]. On the other hand, a few studies have focused on southern Tuscany, where contrasting interpretations on datings and palaeogeographic reconstructions have been proposed [15–20]. More recently, radiometric (Ar/Ar, U/Th [21–23]) and palynological studies [24,25] have served to motivate a review of the entire Tuscan Palaeozoic successions based on bio/chronological markers. These studies contribute more precise age datings and provide new evolutionary scenarios in the context of two distinct Palaeozoic cycles (Mississippian-early Permian and middle-late Permian) [5,26]. Accordingly, we re-consider the Risanguigno Formation, which is regarded as part of the Tuscan Crystalline Basement and constitutes the oldest outcrops in southern Tuscany. In this view, this isolated and scarcely studied formation strongly influenced the reconstruction of the entire Pre-Alpine Apenninic succession. Therefore, the aim of this paper is to document and illustrate a newly discovered palynofloral content and, consequently, to provide the precise age of the Risanguigno Fm, together with its structural setting. This will lead to determination of Variscan formations in this key sector of Northern Apennines from a stratigraphic and palaeogeographic perspective.

## 2. Geological Outline of the Palaeozoic Units of Tuscany

The inner Northern Apennines (Figure 1) resulted from the convergence (Cretaceous-Eocene) and collision (Oligocene-early Miocene) between the European Corsica-Sardinia massif and the Adria microplate of the Africa pertinence. This process produced the stacking of tectonic units deriving from oceanic and continental palaeogeographic domains [27,28].

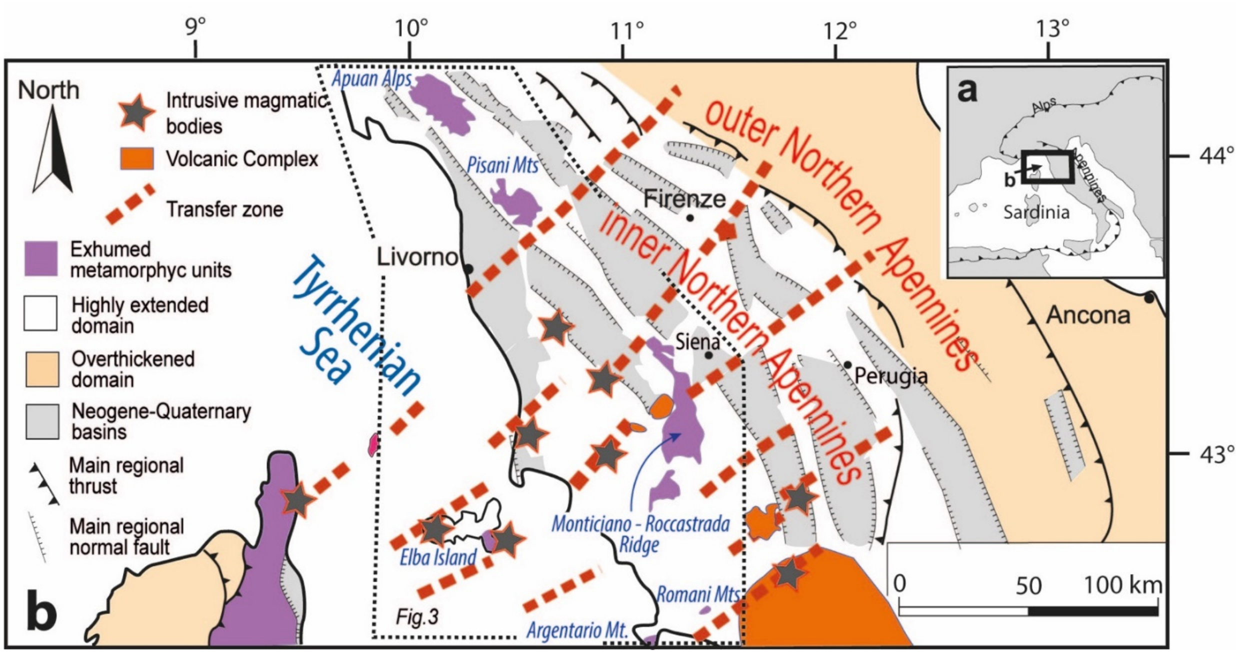


**Figure 1.** Structural sketch map of (**a**) the Northern Apennines and (**b**) Northern Tyrrhenian Sea.

In southern Tuscany these are, from top to bottom (Figure 2): (a) the Ligurian and Sub-Ligurian Units, consisting of remnants of Jurassic oceanic and transitional crust and their related Cretaceous–Oligocene sedimentary cover; (b) the Tuscan Units including the Triassic-early Miocene sedimentary (Tuscan Nappe) and Palaeozoic-Triassic metamorphic succession. According to [29,30], this metamorphic succession can be broadly subdivided in (i) a late Cambrian?-Mississippian basement (affected by deformation during the Variscan orogenesis) and (ii) a Late Pennsylvanian to Triassic sedimentary cover, deposited during the Variscan post-collisional events.

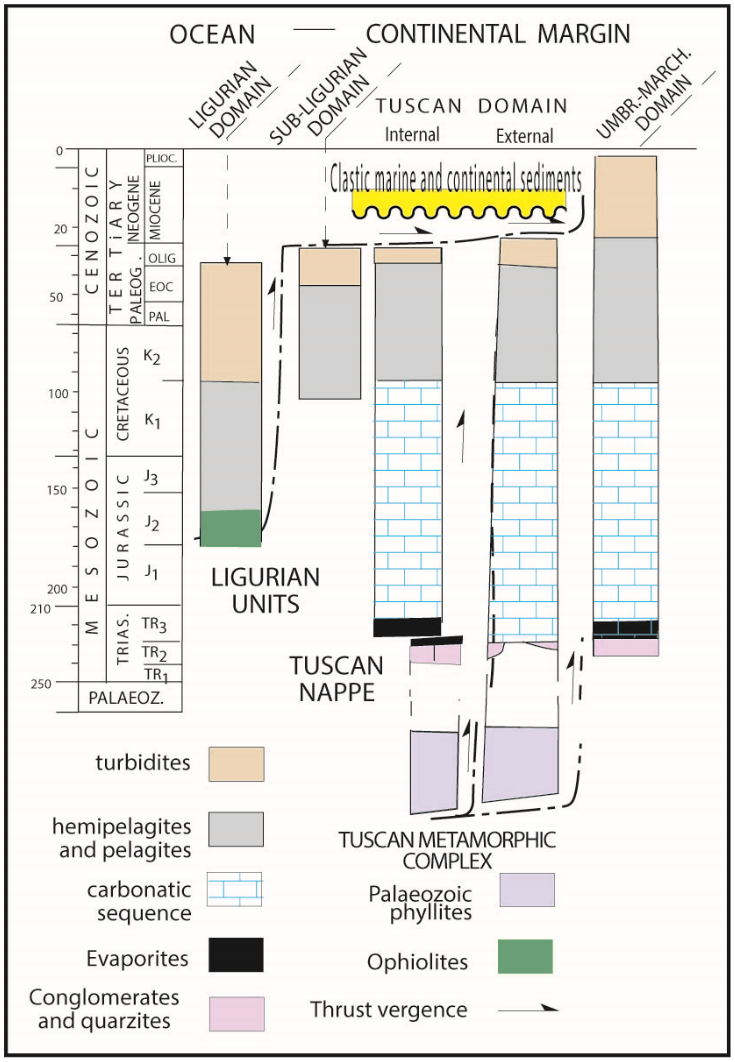


**Figure 2.** Tectono-stratigraphic columns illustrating the main features of the paleogeographic domains of the inner Northern Apennines (redrawn from [27,31]).

The Palaeozoic basement is made up of quartzites and phyllite with acidic to intermediate metavolcanic rock (porphyroid). At their top, black shale, radiolarite (lydian stone) and metacarbonate deposits (dolostone, calcschist) have been detected [4,10,32–34]. This succession, attributed to the Cambrian?-Devonian, on the basis of scattered fossils [4] and U/Th radiometric dating [21–23], is classically related to the central-southern Sardinia succession [35] and is considered to be involved in the Variscan orogeny during the early Carboniferous [12]. In the Inner Northern Apennines, Palaeozoic rocks involved in the Variscan deformation extensively crop out in the La Spezia-Apuan Alps-Mt. Pisani area, while smaller exposures are located in the Tuscan Archipelago (Elba island) and southern Tuscany (Figure 3). It is noteworthy that some deep wells in northern Tuscany (Pontremoli) and in the geothermal area of southern Tuscany are believed to have intersected deformed Variscan rocks [2,8,9,12,14,36–40].

The "post-Variscan" Palaeozoic-Triassic sedimentary succession (referable to the Phyllite-Quartzitic Group of [41]) is mostly exposed in the Monticiano-Roccastrada Unit (Figures 3 and 4), along the Middle Tuscan Ridge, in three different main tectonic units, as defined by [19]: Iano Sub-Unit 1; Monte Quoio-Montagnola Senese Sub-Unit 2; Monte Leoni-Farma Sub-Unit 3—Figure 4. Only minor outcrops are present elsewhere, and locally drilled by boreholes [1,9,10,37,42–46].

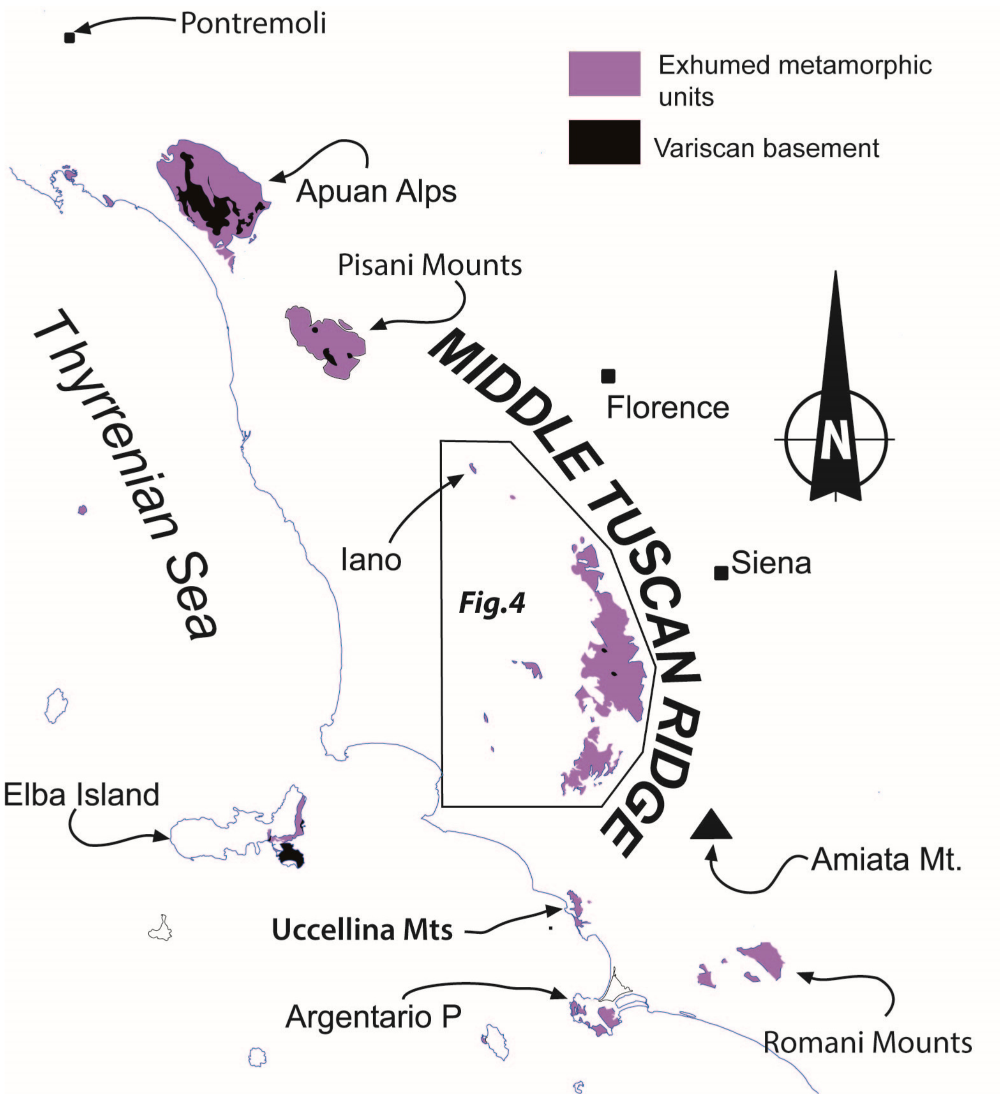


**Figure 3.** Distribution of metamorphic units in Tuscany, including Variscan deposits (in black).

This succession is formed by phyllite, metasandstone, metaconglomerate with local carbonate levels attributed to Mississippian-late Permian on the basis of the fossil [16,18,44,47–49], palynoflora content [24,25] and radiometric dating [23]. Its evolution is related to rifting [1], transcurrent/transtensive pull-apart basins [5,50] or to late Variscan compressional events [9,19].

The uppermost part of the succession is represented by the typical Triassic continental quartz-dominated clastic sedimentation belonging to the Verrucano Group [51–53].

During the Apennines collisional stages, the above-mentioned Palaeozoic-Triassic successions were involved in duplex structures, up to HP-LT conditions (P ≥ 1.1 GPa and T ~ 350–400 °C) and retrograde green schist metamorphic conditions [54–61]. Their exhumation was favoured by the development of Miocene extensional detachments [26,62], which produced extensional horses (i.e., megaboudins [63]) and the lateral segmentation of the previously stacked tectonic units.

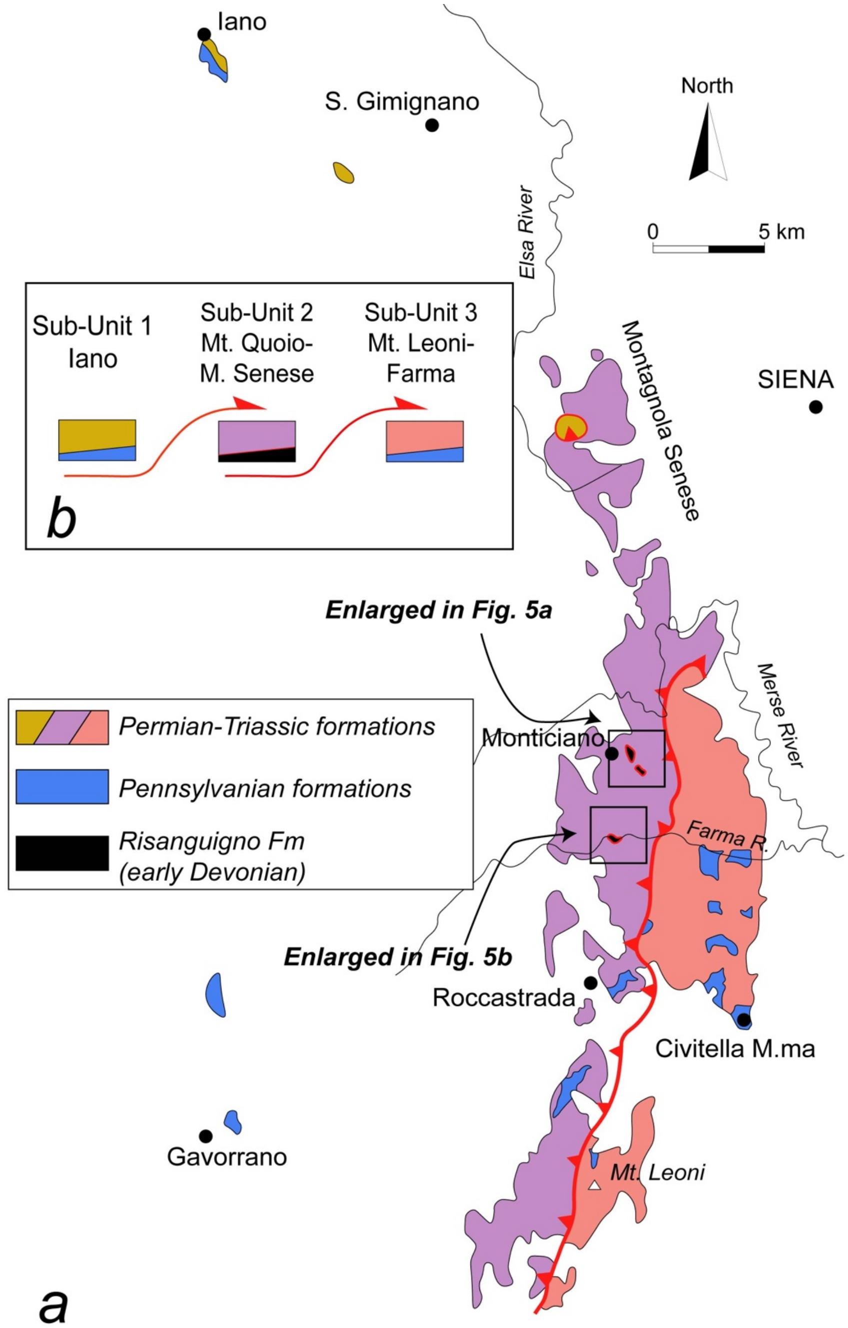


**Figure 4.** (**a**) Schematic sketch of the Middle Tuscan Ridge with geographic distribution of the three structural Sub-Units; (**b**) Simplified stratigraphy and tectonic relation among the three Sub-Units (redrawn from [64]).

*Variscan Basement in Southern Tuscany: the Risanguigno Formation*

In this framework, the Risanguigno Fm represents the only cropping out unit in southern Tuscany assigned to the Palaeozoic basement. It is part of Sub-Unit 2 (Monte Quoio-Montagnola Senese) of the Monticiano-Roccastrada Unit (Figure 4).

Such a formation was initially defined in the type locality of the Risanguigno Creek by [4]. These main exposures were previously described by [47,65], although interpreted as part of another formation (Boccheggiano Fm). Subsequently, [20,66,67] related other outcrops exposed in the surroundings (Farma River, Figures 4 and 5) to the Risanguigno Fm, furthermore recognized in a few boreholes [68].

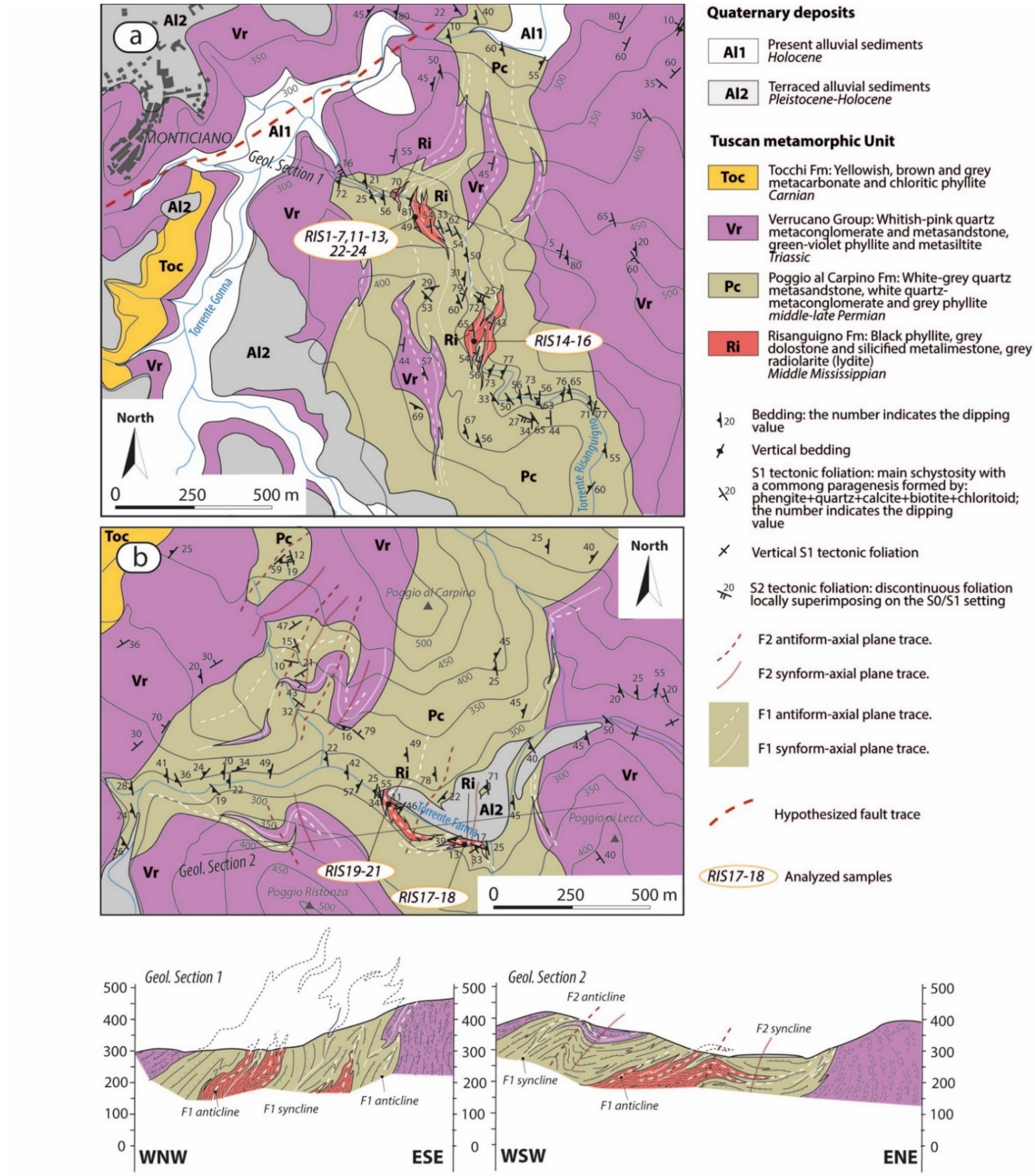


**Figure 5.** New geological maps of the study areas and related geological cross sections: (**a**) Risanguigno Creek; (**b**) Farma River (previous maps from [20,64,65]). See Figure 4 for their location.

The base of the formation is never exposed, although [20] postulated the presence of a basal stratigraphic unconformity separating the Risanguigno Fm from the underlying Variscan deformed units.

At the top, the Risanguigno Fm is in contact with the Poggio al Carpino Fm [64], a middle-late Permian [19,25,69] clast- to matrix-supported polymictic conglomerate, often alternated with grey quartzose sandstone and subordinate dark grey phyllite [70]. The contact between the Risanguigno and Poggio al Carpino formations is described as an angular unconformity by [18], in contrast with [20], indicating that the Poggio al Carpino Fm stratigraphically overlies the lower unit.

From a sedimentary point of view [2,18,19], the Risanguigno Fm is composed by black-grey graphitic to bituminous phyllite intercalated with cm- to dm-thick alternations of: (i) grey-greenish to black quartzose, granolepidoblastic metasandstone and siltstone with iron-rich carbonate matrix and detritic mica, (ii) cm-thick microcrystalline, granoblastic dolostone rich in detritic quartz and white mica, (iii) silicified grey metalimestone, and (iv) thinly bedded, grey-greenish to black chert and radiolarian lydite. A chert subsequence, up to 4.5 m thick and intercalated with fine-grained clastics, was also recognized in close outcrops by [66], and later correlated with the small chert sequence present also in the Risanguigno type locality [20]. Anhydrite in the silicified limestone is reported by [17,65], while this is not described by [68]. Local post-tectonic chloritoid needles are reported in the metasandstones and metasiltstones by [2].

Rocks are strongly deformed, making the stratigraphic reconstruction difficult. By this, and due to the fact that the basal contact is not exposed, the thickness of the Risanguigno Fm is unknown and only inferred in 40 m, at least [20].

Regarding the fossiliferous content, [4,71] reported a conodont fauna, characterized by *Ozarkodina denckmanni*, *Panderodus unicostatus* and *Icriodus* sp. This fauna was recovered from the dolostone levels in the type locality at the altitude of 304 m along the Risanguigno Creek.

Regarding the chert-subsequence, [4,68] accounted for the presence of recrystallized radiolaria, often well preserved although flattened during deformation.

The formation, originally attributed to a generic Carboniferous by [47,65], was ascribed to the Early Devonian on the basis of the conodont fauna [4]. Alternatively, [66] suggested a Tournaisian-Visean age based on the radiolaria observed in the chert subsequence, while [17,20] related these siliceous portions to late Devonian-early Carboniferous (late Emsian to Visean?) on the basis of the lithological correlation with similar deposits in the circum-Mediterranean area.

Similarly, the interpretation of the depositional environment is matter of debate. Ref. [4] proposed a shallow marine origin, while [17] favoured a moderately deep water basin origin, owing to the presence of the siliceous portions. In contrast, [71] suggested an epicontinental shelf characterized by recurrent anoxic conditions, while [20] accounted for a highly condensed sequence deposited in a starved, low energetic, distal and relatively deep marine environment.

From a tectonic point of view, the Risanguigno Fm is described as intensely deformed and marked by a metamorphic grade higher than the one affecting the overlying formation, i.e., the Poggio al Carpino Fm [4]. In this view, according to [9,37], the Risanguigno Fm evidences relics of a pre-Alpine deformation, interpreted as a Variscan syn-metamorphic tectonic foliation relatable to the Sudetic event.

## 3. Materials and Methods

A detailed field survey was carried out in key areas where the Risanguigno Fm is exposed. The fieldwork was dedicated to field mapping and data collection for describing the deformation affecting the Risanguigno Fm and the overlying units. During the survey, 21 samples of black phyllite, metasiltstone and metacarbonate (16 samples from the Risanguigno Creek and 5 samples from the Farma River (Table 1) were collected for petrographic, microfacies and biostratigraphic studies. Palynological samples (c. 20 g each for phyllite and metasiltstone lithologies and 100 g each for metacarbonate samples) were treated by standard palynological acid maceration (with 37% HCl, 50% HF, boiling HCl 10%), density separation of the organic matter (using a $ZnCl_2$ solution) and filtration of the organic-rich residue at 10 μm. As a result of the high degree of thermal alteration, the organic residue was treated with Schultz solution and filtered with 10 μm sieve.

**Table 1.** Analysed samples, with related geographical coordinates, lithology and content (quotes in meter above sea level —m a.s.l.).

| Sample | Locality | Quote | Latitude | Longitude | Lithology | Analysis | Content |
|---|---|---|---|---|---|---|---|
| RIS 1 | Risanguigno Creek | 304 m a.s.l. | 43°8′3.85″ N | 11°11′38.13″ E | Black phyllite | Palynology | productive |
| RIS 2 | Risanguigno Creek | 304 m a.s.l. | 43°8′4.03″ N | 11°11′37.84″ E | Fine metasandstone | Palynology | barren |
| RIS 3 | Risanguigno Creek | 304 m a.s.l. | 43°8′4.34″ N | 11°11′33.84″ E | Black phyllite | Palynology | productive |
| RIS 4 | Risanguigno Creek | 304 m a.s.l. | 43°8′4.43″ N | 11°11′33.74″ E | Black phyllite | Palynology | productive |
| RIS 5 | Risanguigno Creek | 304 m a.s.l. | 43°8′8.01″ N | 11°11′32.15″ E | Black phyllite and lidyte | Palynology | productive |
| RIS 6 | Risanguigno Creek | 304 m a.s.l. | 43°8′7.95″ N | 11°11′32.12″ E | Black phyllite and lidyte | Palynology | productive |
| RIS 7 | Risanguigno Creek | 304 m a.s.l. | 43°8′7.98″ N | 11°11′32.11″ E | Black phyllite | Palynology | productive |
| RIS 11 | Risanguigno Creek | 304 m a.s.l. | 43°8′3.77″ N | 11°11′40.46″ E | Black phyllite | Palynology | barren |
| RIS 12 | Risanguigno Creek | 304 m a.s.l. | 43°8′4.72″ N | 11°11′34.02″ E | Dolostone | Palynology | barren |
| RIS 13 | Risanguigno Creek | 304 m a.s.l. | 43°8′7.76″ N | 11°11′31.90″ E | Dolostone | Palynology | barren |
| RIS 14 | Risanguigno Creek | 324 m a.s.l. | 43°7′46.76″ N | 11°11′43.98″ E | Black phyllite | Palynology | barren |
| RIS 15 | Risanguigno Creek | 324 m a.s.l. | 43°7′47.91″ N | 11°11′43.53″ E | Black phyllite | Palynology | productive |
| RIS 16 | Risanguigno Creek | 324 m a.s.l. | 43°7′47.95″ N | 11°11′43.44″ E | Black phyllite | Palynology | productive |
| RIS 17 | Farma River | 265 m a.s.l. | 43°5′15.41″ N | 11°11′23.57″ E | Metasiltstone | Palynology | productive |
| RIS 18 | Farma River | 265 m a.s.l. | 43°5′15.32″ N | 11°11′24.59″ E | Black phyllite | Palynology | productive |
| RIS 19 | Farma River | 270 m a.s.l. | 43°5′20.19″ N | 11°11′13.15″ E | Black phyllite | Palynology | barren |
| RIS 20 | Farma River | 270 m a.s.l. | 43°5′20.13″ N | 11°11′13.22″ E | Metacarbonate | Palynology | barren |
| RIS 21 | Farma River | 270 m a.s.l. | 43°5′20.10″ N | 11°11′13.28″ E | Metacarbonate | Palynology/Conodonts | barren |
| RIS 22 | Risanguigno Creek | 304 m a.s.l. | 43°8′4.22″ N | 11°11′33.97″ E | Dolostone | Palynology/Conodonts | barren |
| RIS 23 | Risanguigno Creek | 304 m a.s.l. | 43°8′4.28″ N | 11°11′33.79″ E | Dolostone | Palynology/Conodonts | barren |
| RIS 24 | Risanguigno Creek | 304 m a.s.l. | 43°8′4.18″ N | 11°11′35.98″ E | Dolostone | Palynology/Conodonts | barren |

Light microscope observations were performed on palynological slides using a Leica DM1000 microscope (Leica, Wetzlar, Germany) using the differential interference contrast technique in transmitted light. Images were captured using the camera on the digital microscope and successively corrected for contrast and brightness using the open-source

Gimp software. The palynological slides are stored at the Sedimentary Organic Matter Laboratory of the Department of Physics and Geology, University of Perugia, Italy. Metacarbonate samples were collected from dolostone levels for the analyses of conodont content and processed by standard procedures using 10% acetic acid. The residue was washed through a 71 μm sieve.

## 4. Results

The results are summarized in different sections, according to the main issues of lithology, fossil content, and deformation.

### *4.1. Lithological Characteristics*

The outcrops exposed in the Risanguigno Creek and Farma River were revisited (Figure5).

In the Risanguigno Creek, the formation crops out in two small windows (quote 304 m and quote 324 m a.s.l.) in correspondence of the riverbed (Figure 5a). A small supplementary outcrop, never described before, was discovered along the riverbed at quote 300 m. The Risanguigno Fm is mostly dominated by black to grey phyllite, locally intercalated by cm-thick level and lenses of metasandstone and metasiltstone (Figure 6a,b). Only in the outcrop of quote 304 m is phyllite intercalated with cm-thick beds and lenses of microcrystalline dolostone and silicified grey metacarbonate (Figure 6c). These are geometrically positioned below a small succession (max 2 m thick) displaying alternation of phyllite and chert beds/lydite in thinly bedded laminae (Figure 6d). The transition from the Risanguigno Fm to the overlying grey quartzose metasandstone and metaconglomerate formation (Poggio al Carpino Fm) is marked by a sharp angular unconformity (Figure 6e).

Along the Farma River, outcrops are located close at the Ferriera locality, on the right bank of the riverbed at quote 270 m and 265 m a.s.l. (Figure 5b). Black bituminous phyllite, locally smelly and rich in millimetric-sized crystals of pyrite, is the dominant lithotype. Conversely, metasandstone and metasiltstone, as also dolostone and metacarbonate, are less diffuse. The 4.5-m-thick chert sequence evidenced by [66] constitutes the main lithological variation and morphological prominence (Figure 6f,g). Similarly to the Risanguigno Creek, here, also, the chert beds are positioned at the top of the succession, immediately below the Poggio al Carpino Fm.

In both valleys, the complete stratigraphic reconstruction is prevented by an intense folding (see the next paragraph).

### *4.2. Fossiliferous Content*

Twenty-one samples were obtained from almost all the analysed outcrops. In the Risanguigno Creek, three samples were from quote 324 (RIS14, 15, 16) and thirteen from quote 304 (RIS1, 2, 3, 4, 5, 6, 7, 11, 12, 13, 22, 23, 24). In the Farma River, two samples were from quote 265 (RIS17,18) and three from quote 270 (RIS19, 20, 21). All of them were analysed for their palynological content. Four samples were analysed for conodont content (Table 1).

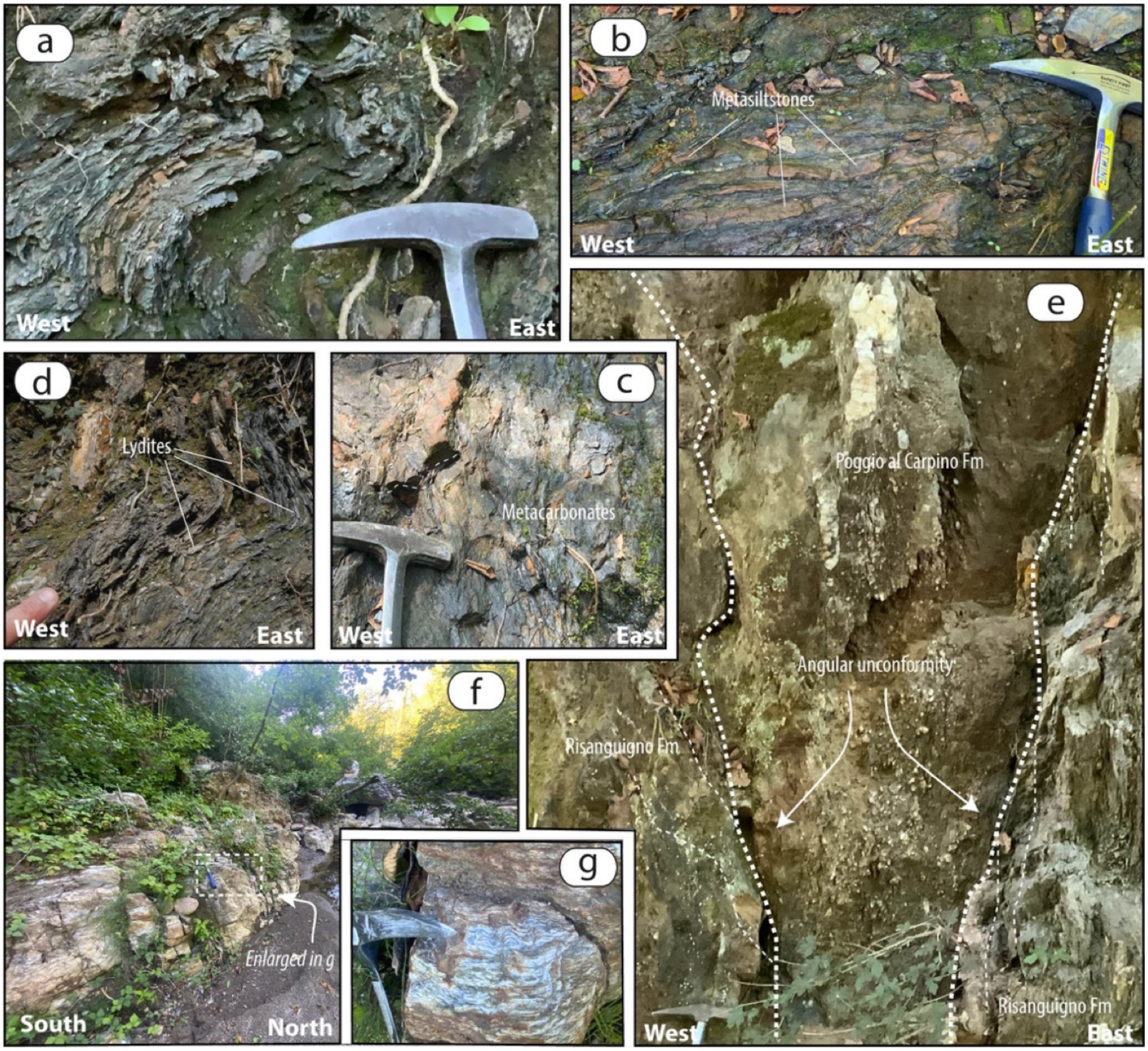


**Figure 6.** Lithological characteristics of the Risanguigno Fm: (**a**) view of the dominant black phyllite; (**b**) thin intercalations of metasiltstone lenses; (**c**) examples of metacarbonate beds; (**d**) example of thin laminae and beds of lydite; (**e**) upper contact of the Risanguigno Fm with the Poggio al Carpino Fm with evidence of the angular unconformity; (**f**) chert sequence cropping out along the Farma River; (**g**) detail of thinly laminated chert sequence.

#### 4.2.1. Palynological Content

Ten samples out of 21 were productive, even yielding strongly degraded palynofloral assemblages (Table 1). Degradation was mainly due to intense in situ pyritization affecting the exine of miospores. A low metamorphic grade with a temperature of about 350–400 °C [56] was recognized. Nonetheless, different organic microfossils were recognized, adding new data for the age determination of the Risanguigno Fm. The palynological assemblage mainly consists of ornamented forms as *Auroraspora balteola*, *Claytonispora distincta*, *Retialetes radforthii*, *Vallatisporites? hystricosus*, *Perotrilites magnus*, *Spelaeotriletes balteatus*, *S. pretiosus* and *Grandispora* sp. Different tetrads of indeterminate apiculate spores also occur (Figure 7).

#### 4.2.2. Conodont Content

All processed samples were barren in terms of conodont content.

### *4.3. Deformation*

The Risanguigno Fm, together with the overlying units (Permian Poggio al Carpino Fm and Triassic Verrucano Group) exposed in the Risanguigno Creek and Farma River (Figure 5), are commonly involved in polyphase folding characterized by superposed $F_1$ and $F_2$ folds, with NS and NS-NNE axial trends, respectively.

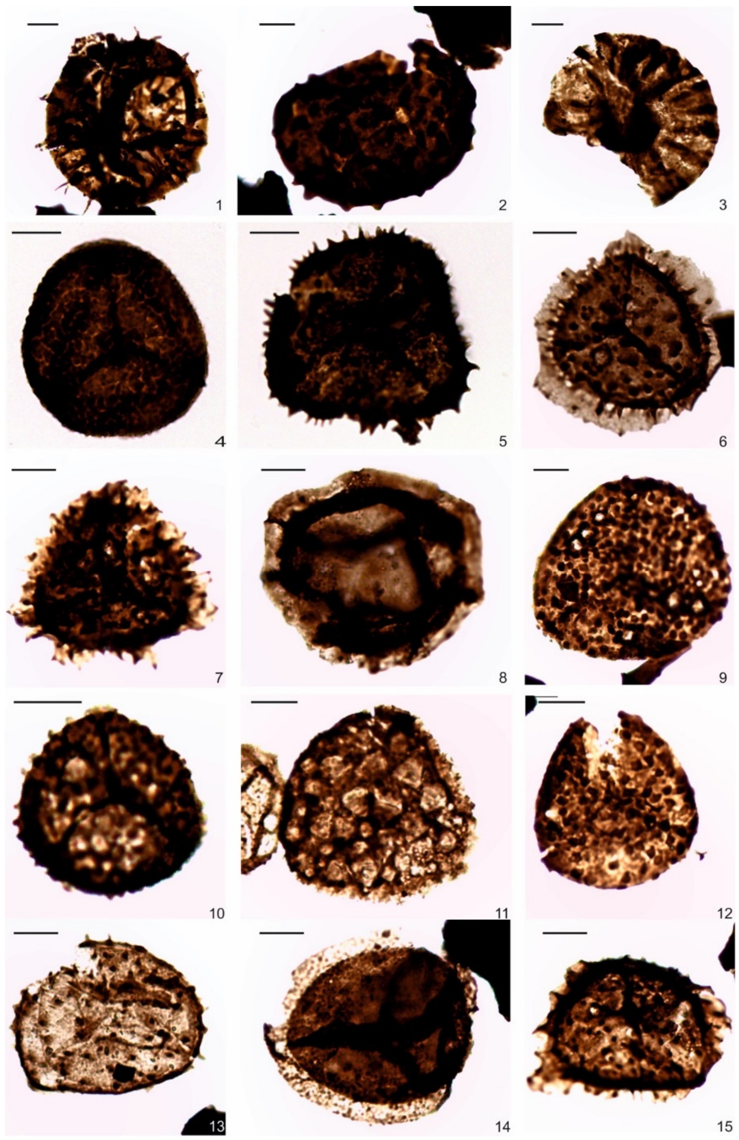


**Figure 7.** Miospores from Risanguigno Formation. Scale bar indicates 10 μm. (**1**) *Claytonispora distincta* Playford and Melo 2012 (slide: RIS 3). (**2**) *Pustulatisporites* sp. (slide: RIS 3). (**3**) *Retialetes radforthii* Staplin 1960 (slide: RIS 15). (**4**,**15**) Indeterminate miospore (slide: RIS 15). (**5**) Tetrad of indeterminate apiculate spores (slide: RIS 3). (**6**,**7**). *Vallatisporites? hystricosus* (Winslow) Byvscheva 1985 (slide: RIS 15). (**8**) *Auroraspora balteola* Sullivan 1964 (slide: RIS 3); (**9**) *Spelaeotriletes balteatus* (Playford) Higgs 1975 (slide: RIS 15). (**10**,**11**) Indeterminate spore with a heavily pyritized exine. (slide: RIS 15). (**12**) *Spelaeotriletes pretiosus* (Playford) Neves and Belt 1970 (slide: RIS 18). (**13**) *Grandispora* sp. (slide: RIS 15). (**14**) *Perotrilites magnus* Hughes and Playford 1961 (slide: RIS 15).

Both folding events are referrable to the Alpine evolution. F1 folds are the prominent structures and involve the entire succession, defining the main shape and geometries of the exposures (Figures 8 and 9). F1 folds range from map-scale to outcrop-scale and have hectometre- to decimetre sizes (Figure 8). These consist of tight and isoclinal recumbent folds, with axial planes steeply dipping toward west. F1 hinge lines mostly dip gently toward S-SE (Figure 8), although in some rare cases they dip toward N-NW (Figure 9).

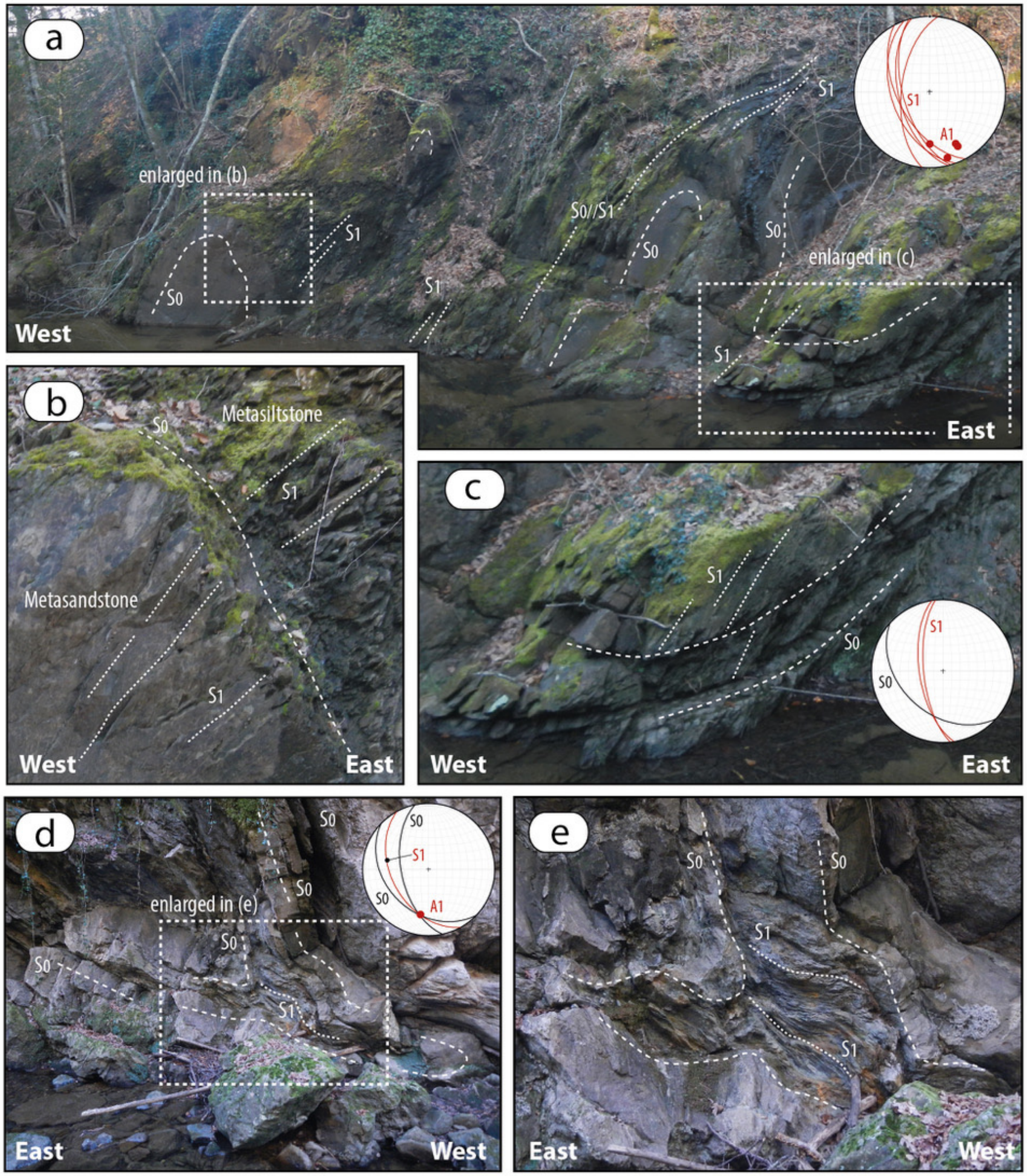


**Figure 8.** N-S trending $F_1$ folds affecting the metasandstone and metapelite succession of the Poggio al Carpino Fm exposed in the Risanguigno Creek. (**a**) F1 sub-isoclinal folds and related S1 axial planar tectonic foliation and related stereographic diagram (lower hemisphere, equiareal diagram); (**b**,**c**) enlarged sector of the $F_1$ hinge zones indicated in (**a**) and showing the $S_0/S_1$ angular relationships also shown in the stereographic diagram (lower hemisphere, equiareal diagram); (**d**,**e**) hinge zone of $F_1$ fold with a pervasive axial planar $S_1$ tectonic foliation developed within the metapelite; relationships between $S_0$ and $S_1$ are indicated in the stereographic diagram (lower hemisphere, equiareal diagram).

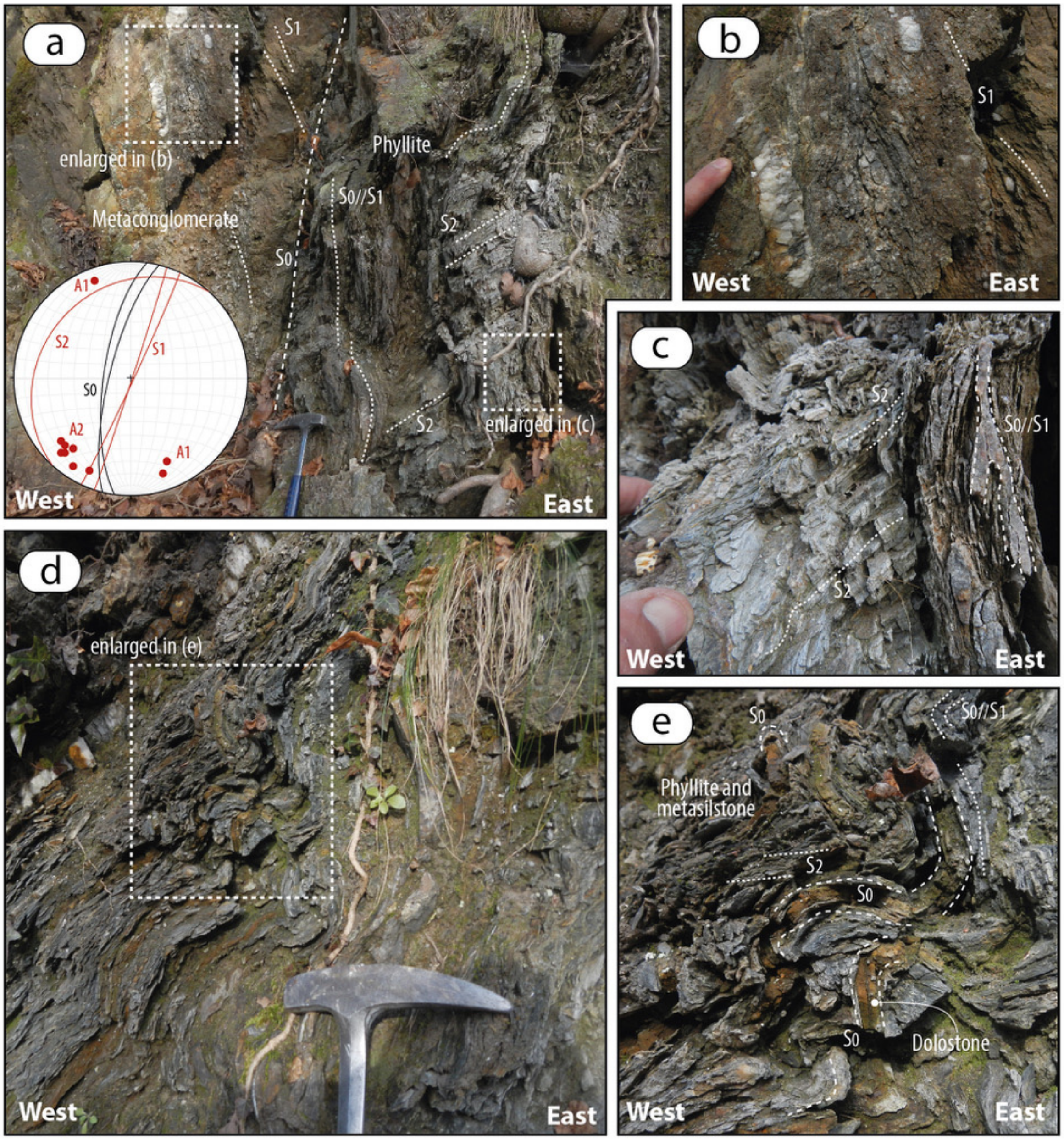


**Figure 9.** Macroscopic scale deformation pattern of the phyllite and metacarbonate belonging to the Risanguigno Fm. (**a**) detail of the contact separating the Risanguigno Fm from the Poggio al Carpino Fm and geometrical relationships between $S_0/S_1$ and $S_2$ foliations (see the text for more details) also indicated in the stereographic diagram (lower hemisphere, equi-areal diagram). (**b**) Penetrative S1 foliation crossing the metaconglomerate level belonging to the basal part of the Poggio al Carpino Fm. (**c**) Centimetre-scale isoclinal $F_1$ folds and the $S_1$ axial planar tectonic foliation crossed by the $S_2$ tectonic foliation. (**d**,**e**) $F_2$ open folds affecting the $S_0/S_1$ foliations affecting phyllite and metacarbonate levels.

In the quartz-metasandstone and metaconglomerate, $S_1$ is a rough cleavage, as highlighted by the differentiated domains when alternating quartzitic and micaceous layers are present. The $L_1$ object lineation occurs in the phyllite and metasilstone, defined by elongated quartz and mica lenses tracking the x axis of the finite strain ellipse.

At the microscopic scale, $S_1$ relates to a continuous foliation, mainly defined by elongate quartz layers, formed by flattened and dynamically recrystallized grains, alternated with mica-rich domains (Figure 10a,b). Mica domains are mainly composed of fine-grained white mica and biotite (Figure 10a–d) with locally developed chloritoid crystals, grown both along the main foliation and crossing it (Figure 10d).

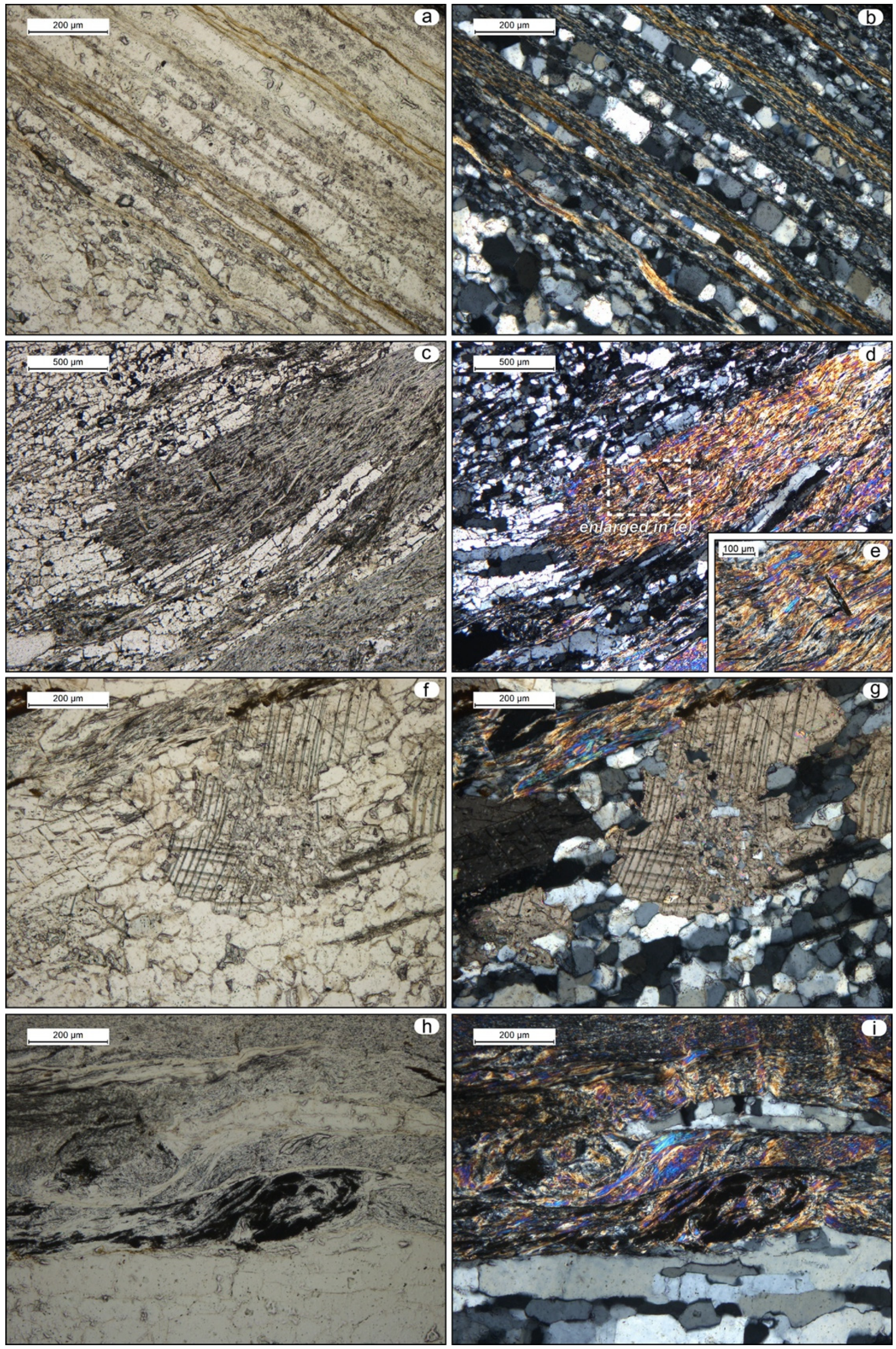


**Figure 10.** (**a**,**b**) Phyllitic quartzite (Risanguigno Fm) showing the $S_1$ foliation consisting of metamorphic layering made up of quartz and white mica + biotite levels ((**a**) plane polarized light; (**b**) crossed polars). (**c**,**d**) Microscale $F_1$ fold with associated $S_1$ foliation mainly formed by quartz + white mica + biotite + chloritoid. This latter is also represented by post-kinematic bigger crystals (see (**e**)), suggesting syn- and post-S1 development ((**c**) plane polarized light; (**d**) crossed polars). (**f**,**g**) Mineralogical association of the S1 foliation developed within carbonate rich levels, mainly composed by qtz + cc + white mica + biotite + chloritoid ((**f**) plane polarized light; (**g**) crossed po-

lars). (**h**,**i**) s-c shear zone (top-to-the right) affecting the organic matter-bearing phyllite and developed coevally with the $S_1$ foliation; the latter is affected by a later crenulation cleavage possible related to the $F_2$ folding event ((**h**) plane polarized light; (**i**) crossed polars).

Syn-kinematic calcite locally developed within the polycrystalline quartz-rich layers (Figure 10e,f). Localized mylonitic layers with mica fish structures (Figure 10 g,h) developed mainly at the boundary between quartz- and mica-dominated domains. $F_2$ folds are also recognisable both at the map and outcrop scale and display hectometre to decimetre sizes (Figures 8 and 9). $F_2$ folds deformed $F_1$ isoclinal folds and their related $S_1$ axial planar foliation. $F_1$/$F_2$ fold interferences have been reconstructed in the Farma Creek area (Figure 8), where $F_1$ folds affecting the Triassic and Palaeozoic succession have been deformed by top-to-the-East verging $F_2$ folds. $F_2$ folds consist of gentle to close folds, in some cases overturned. Axial planes are gently to moderately dipping toward West. $F_2$ hinge lines are sub-horizontal or deep gently toward SSW (Figure 9).

An axial-planar foliation ($S_2$) is associated with $F_2$ folds, well developed only in the metapelite levels (Figure 9). It ranges from spaced disjunctive to a crenulation cleavage. At the microscopic scale, the $S_2$ consists of a spaced foliation often producing zonal crenulation cleavage defined by symmetric or asymmetric microfolds.

## 5. Discussion

The newly obtained data, especially from the bio-chronological perspective, allow us to frame the Risanguigno Fm in a new scenario with fallouts in the Palaeozoic palaeogeography of Gondwana. We describe this in the following sections.

### *5.1. New Bio-Chronological Framework of the Risanguigno Fm*

The palynological assemblage shows similar compositional characteristics to those documented in the Mississippian successions of Western Europe, northern Gondwana and other areas.

*Auroraspora balteola* was documented in the mid-Visean within the *Knoxisporites triradiatus-Knoxisporites stephanephorus* (TS) Zone of Kammquartzite Formation in the Rhenohercynian Zone (Germany; [72]) and in the late Visean of England [73] in assemblage with *Spelaeotriletes pretiosus* in the Tournaisian of eastern Scotland [74]. This last taxon marks the base of the *Spelaeotriletes pretiosus-Raistrickia clavata* (PC) Zone attributed to the late Tournaisian and first described from SW Britain [75] and from Ireland [76]. Later, in the latter country, [77] also documented the PC biozone, characterized by the occurrence of *S. balteatus* and *Claytonispora distincta* within a stratigraphic interval attributed to middle-late Tournaisian on the basis of conodont fauna. In Belgium, the base of the PC biozone occurred within the upper *Siphonodella crenulata* conodont Zone (late Tournaisian, [78]). *Spelaeotriletes pretiosus* was also reported in assemblage with *S. balteatus* from other Mississippian sequences of Western Europe [79–82], North America [83–86] and China [87]. The species was also documented from similar-aged rocks in some regions of Northern Gondwana. In particular, in North Africa, [88,89] considered microfloristic assemblage marked by the occurrence of *S. pretiosus*, *S. balteatus* and *Vallatisporites vallatus* of late Tournaisian age, without excluding a younger early Visean age. In Algeria, *S. pretiosus* occurred in the middle Tournasian-lower Visean palynozones [90,91]. In Libya, a similar microflora was found in the late Tournaisian-Visean time interval (palynozones XI and XII [92]; palynozones 13 and 14 [93,94]). Analogous palynoflora also occurs in the Tournaisian-early Visean of Saudi Arabia [95,96] and the Central Iranian Basin [97]. In Southeastern Turkey, [98] tentatively correlated the *Spelaeotriletes pretiosus-Aratrisporites saharensis* assemblage, where *Vallatisporites hystricosus* also occurs, with the PC biozone of Western Europe. In Western Gondwana regions, a similar assemblage also characterizes the late middle to early late Tournaisian *Spelaeotriletes pretiosus-Colatisporites decorus* Biozone documented from Brazil [99–105]. On the other hand, in the northern Gondwana regions, *S. balteatus* was also documented in slightly younger time-intervals (e.g., Visean of Libya [89]; Visean of Morocco [106]; Visean-Bashkirian of Saudi Arabia [95,107]).

Regarding the conodont content previously reported by [4], the new investigation carried out in the same levels was not productive. This negative evidence, coupled with the contemporaneous presence of a younger-aged rich microflora, suggests that the previously reported conodonts were reasonably reworked fossils, deriving from older deposits.

Therefore, based on the stratigraphic range of the recorded microflora, we can confirm the age of Risanguigno Fm as being late Tournaisian-Visean, as already suggested by [66] on the basis of radiolarian fossil content.

### 5.2. Paleoenvironmental Insights

The Risanguigno Fm depositional environment was highly debated in previous studies and alternatively attributed to shallow [4], moderate [7,64] or relatively deep marine environments [20]. The presence of Middle Mississippian metacarbonate/dolostone and siliceous portions (lydite beds) seems consistent with carbonate-to-radiolarite platform environment, also recognized in several lower Carboniferous tectofacies (eastern Southern Alps, Karawanken Mountains, external Dinarides, southern margin of the Pannonian Basin, Aegean islands, Calabria and southern Sardinia [7,107]) of the central Mediterranean area. Accordingly, the lydite deposits do not necessarily require a deep-water environment since these can develop in different depositional areas [108,109], especially if associated with a local silica-enrichment related to volcanic activity in nearby zones [4]. In this view, it is worth remembering that the Variscan evolution was associated with a widespread magmatism during the late Carboniferous [110–112], as well as during the Mississippian [112–115]. On the other hand, the organic-rich property of the phyllite supports the deposition in a starved, oxygen-deficient environment. In fact, the finding of spores characterized by pseudosculpture induced by deposition of pyrite crystals in the wall (exine) interstices is indicative of syn-depositional pyrite, suggesting that the water/sediment interface was in a strongly reducing state [116–119]. Regarding the bathymetric definition of this anoxic environment, the interpretation remains difficult. Nonetheless, the type and morphology of the recovered microflora are indicative of a shallow-marine-to-epicontinental depositional environment: the presence of ornamented spores and tetrads suggest a proximal depositional environment since the spores were selected according to their hydrodynamic equivalence, and the tetrads did not maintain their integrity along the distal direction [120].

Consequently, we interpreted the Risanguigno Fm as being deposited during the Middle Mississippian in a shallow-marine-to-epicontinental setting, characterized by starved, anoxic condition in its lower portion and progressively evolving to carbonate-radiolarite platform. Some authors [121] have evidenced that chert sedimentation dominated during the late Devonian and Mississippian in the tropical Palaeotethys strait, and associated their development with sea-level rise.

The organic-rich deposit could also be related to oceanic anoxic events known for the late Frasnian to Late Mississippian age and influenced by global climatic and oceanographic changes. One of these corresponds to the mid-Tournaisian carbon isotope excursion (TICE) [122,123], as indicated by the largest positive δ13C excursion in the Phanerozoic. This is related to the climatic transition between the Devonian greenhouse and the late Paleozoic ice age [124]. Such TICE was interpreted as being the result of either Oxygen Carbon sequestration in foreland basin deposits (tectonic-sedimentation driver [122,125]) or oxygen minimum zone expansion (marine anoxia driver [126–129]).

### 5.3. Stratigraphic Setting

The new palynological evidence frames the Risanguigno Fm in the Mississippian, thus implying a reconsideration of the southern Tuscany Palaeozoic setting.

The Risanguigno Fm represented an issue in the lateral juxtaposition with the other southern Tuscany Palaeozoic deposits belonging to the three sub-units of the Monticiano Roccastrada Unit (i.e., Sub-Unit 1: Scisti di Iano Fm—[130,131]; Sub-Unit 3: Calcari di S.Antonio-Scisti a Spirifer formations—[16,18]—Figure 4b). The new attribution of the Risanguigno Fm to the Middle Mississippian implies a stratigraphic correlation with all these Carboniferous deposits as representing different portions of a same marine depositional environment, evolving through time.

In this view, the Risanguigno Fm is interpreted as the older cropping out deposits of the basin. This shallow marine-to-epicontinental setting was progressively evolving, in its upper part, to a Moscovian shale-carbonate deposition (Calcare di S.Antonio Fm—Scisti a Spirifer Fm; [16,18]—Figure 11) and open marine environment during Upper Pennsylvanian (Scisti di Iano Fm. [131]). A similar age (up to lower Permian) is also testified for the continental succession (Scisti di San Lorenzo Fm; [132]) exposed in the northernmost area of Tuscany (Figure 11).

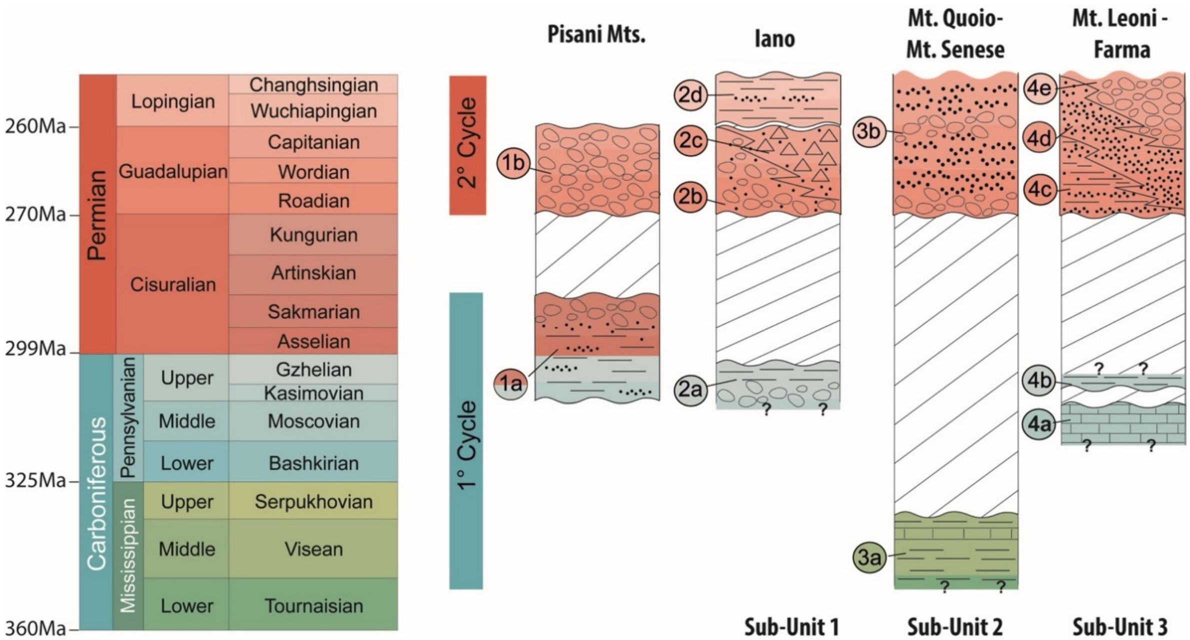


**Figure 11.** Stratigraphic chart relating the different successions of the Monticiano-Roccastrada Unit located in the Middle Tuscan Ridge (for location, see Figure 4a): Pisani Mts: 1a—Scisti di San Lorenzo Fm; 1b—Breccia di Asciano Fm; Iano (Sub-Unit 1): 2a—Scisti di Iano Fm; 2b—Breccia e Conglomerati di Torri Fm; 2c—Scisti Porfirici Fm; 2d—Fosso del Fregione Fm; Mt. Quoio-Mt. Senese (Sub-Unit 2): 3a—Risanguigno Fm; 3b—Poggio al Carpino Fm; Mt. Leoni- Farma River (Sub-Unit 3): 4a—Calcare di Sant'Antonio Fm; 4b—Scisti a Spirifer Fm; 4c—Farma Fm—Falsacqua Fm; 4d—Carpineta Fm—Quarziti di Poggio alle Pigne Fm; 4e—Le Cetine Fm.-Conglomerato di Fosso Pianacce Fm. See the main text for references.

This Carboniferous-lower Permian deposition was succeeded by a second middle-late Permian sedimentary cycle (see, e.g., [5] for a review) where the older deposits were partially dismantled and accumulated in the new one. This is also testified in the Monticiano-Roccastrada area by the occurrence of numerous clastic fragments relatable to the Risanguigno Fm [4], or by the presence of middle Carboniferous (late Visean-early Namurian: [16,47–49,133,134]) clasts, bioclasts and olistoliths embedded within the middle-late Permian Farma and Carpineta formations [70].

### 5.4. Deformation Insights

The deformation evidenced by the structural survey indicates that the Risanguigno Fm shared its tectono-metamorphic evolution with the overlying middle-late Permian

Poggio al Carpino Fm and Triassic Verrucano Group, therefore highlighting their involvement in the Alpine deformational history. Noteworthy, neither outcrop-scale nor microscopic-scale evidence suggests the involvement of the Risanguigno Fm in a pre-Alpine deformation. This implies that the depositional environment of the Risanguigno Fm remained reasonably external to the orogenesis of Variscan chain, even during the formation of foreland and/or piggy-back basins. In this view, the presence of a Variscan tectonic phase in explaining the angular unconformity separating the Risanguigno Fm with the overlying Poggio al Carpino Fm and attributed to the Sudetic [15,43] or Bretonian phase [9,18,38] is denied. Therefore, such an angular unconformity is to be considered as having developed during the Carboniferous-Permian post-collisional tectonic regime [32,45,53], giving rise to short-lived, possibly pull-apart basins, dominated by continental to shallow-marine conditions [5].

### *5.5. Paleogeographical Implications*

According to several reconstructions [1,5,135–141], during the Variscan evolution the Mississippian foredeep and piggy-back basin facies are always represented by coarse-dominated deposits (Culm facies—[141–144]) rapidly involved in the orogenesis and then progressively dismantled during exhumation and uplift. Accordingly, this foredeep basin was considered as possibly having been affected by late Variscan deformation [9,19], thus determining basins and rises, bringing to highly diverse depositional settings [20]. Coupling this latter interpretation with the results of the new structural survey (which rules out the Variscan deformation), we conclude that the Risanguigno Fm is not related to the Culm deposits. Thus, we propose the Risanguigno Fm as the oldest deposits of this sedimentary succession promoted in the "stable" Gondwana foreland that developed within fairly narrow continental or epicontinental domains. These depositional features could have favoured the low-energy, anoxic environments.

These settings evolved during the Late Pennsylvanian-Permian [32,45,64], originating graben/semigraben [1] or transcurrent/transtensive pull-apart basins [5,32,145] dominated by continental (Scisti di San Lorenzo Fm [131]) to shallow-marine conditions (Scisti di Iano Fm [130]), or local development to carbonate platform (Calcare di S. Antonio Fm [7]).

## 6. Conclusions

The new palynological-fossiliferous data for the Risanguigno Fm, coupled with its sedimentary and deformational setting, make it possible to assign it to the Middle Mississippian (late Tournasian-Visean) and to exclude its encompassment in the Variscan basement.

For this reason, it is possible now to exclude in southern Tuscany the outcrops of successions deformed during Variscan Orogenesis. Consequently, the Tuscan Crystalline Basement (Cambrian?-Devonian) is only exposed in the northern Tuscany (Apuan Alps, Pisani Mts and La Spezia area) and Tuscan Archipelago (Elba Island).

Sedimentation of Risanguigno Fm occurred in a shallow-marine-to-epicontinental setting, characterized by starved, anoxic conditions. This setting, localized in the Variscan foreland, evolved to open marine during the Pennsylvanian-Permian without any involvement in the Variscan Orogenesis.

On these bases, the Tuscan Palaeozoic-Triassic sedimentary succession (Phyllite-Quartzitic Group of [40]), classically considered as "post-Variscan" and now comprising the Middle Mississippian Risanguigno Fm, is no more to be related to the Variscan Orogenesis.

**Author Contributions:** Conceptualization, E.C., D.L., A.B. and A.S.; methodology, A.S., A.B. and E.C.; software, E.C., A.B., A.S. and M.Z.; formal analysis, A.S., G.B., A.B. and E.C.; investigation, E.C., A.B., A.S. and R.R.; writing—original draft preparation, E.C.; writing—review and editing, A.B., D.L., A.S., G.B., M.Z., G.M. and R.R.; project administration, E.C., A.S.; funding acquisition, E.C. and A.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** The Research Project of the Department of Physics and Geology (University of Perugia) 'RED-AB—REDiscovering the Apennine Basement: a multidisciplinary correlation among the Northern Apennine Upper Paleozoic–Triassic successions (CAPEZBASE2017) is acknowledged by EC and AS. E.C. thanks to the Research Project 2021 of the Department of Earth Sciences (University of Firenze) "Circolazione di fluidi nel sottosuolo e travertini: esempi in aree chiave del Settore Tirrenico dell'Appennino Settentrionale (Italia) e dell'Anatolia (Turchia)". A.S. thanks also PRIN 2017RX9XXXY.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The presented data are available on request from the corresponding author.

**Acknowledgments:** Enrico Capezzuoli and AmaliaSpina warmly thanks Mauro Aldinucci (Eni) and Geoff Clayton (University of Sheffield, UK) for the discussions on the treated subjects. The authors thanks to Ausonio Ronchi, and an anonymous reviewer for their constructive comments.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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