Sedimentary and tectonic burial evolution of the Northern Apennines in the Modena-Bologna area: constraints from combined stratigraphic, structural, organic matter and clay mineral data of Neogene thrust-top basins

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Abstract

Vitrinite reflectance and mineralogical data from 55 samples collected from the Mt. Cervarola Sandstones and the Granaglione Sandstones (thrust-top basin Cervarola Successions) testify the severe thermal maturity of the present-day outcropping successions. This is due to the deep tectonic burial the successions underwent during Miocene chain building. Lower levels of thermal maturity are recorded in the Mt. Cervarola Sandstones. They form a thick upper thrust sheet (Ro\% ranging between 1.0 and 1.2\%; I\% in I/S mixed layers ranging between 80 and 85\%). Higher levels of thermal maturity characterise the structurally lower thrust sheets, made up mainly of Granaglione Sandstones (Ro\% ranging between 1.2 and 1.5\%; and I\% in I/S mixed layers between 85 and 90\%). Maturity generally decreases from hinterland to foreland. Integration of Ro\% and I\% in I/S data with published low-temperature indicators allowed to reconstruct a maximum tectonic burial ranging between ~3.5 on the upper thrust sheet and ~5 km on the lower ones. Burial was mainly due to the early emplacement of the Ligurian Unit and the Modino Unit on top of the studied units and to later piggy-back thrusting of the Mt. Cervarola Sandstones onto the Granaglione Sandstones.

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1. Introduction

The Apennine fold and thrust belt of peninsular Italy forms part of the Africa-verging mountain system in the Alpine-Mediterranean region. This area evolved within the framework of convergent motion between the African and European plates since the late Cretaceous [1], and caused thrust accretion across the Adriatic continental margin [2] and Tyrrenhian back-arc extension [3]. In the Northern Apennines, structural units were mainly accreted with a main NE sense of transport (Fig. 1 and 2) and experienced diachronous and differential vertical motions, due to subsidence, tectonic loading, and exhumation related to the chain building. The amounts and causes of these movements are still a matter of debate [4-11]. In this framework, a great deal of work concerned the reconstruction of the geometry and tectonic evolution of the Ligurian Nappe, which represents the uppermost structural unit of the thrust stack, now partially or totally eroded [9, 12-16]. The Ligurian Nappe is characterised by Cretaceous-Eocene sedimentary successions deposited in the...
Fig. 1 Geological sketch map of the Northern Apennines, compiled after Boccaletti [69] and Plesi et al. [50]. Indicative trace of the regional cross-section of Fig. 2 is shown. Box shows location of Fig. 3.

Tethyan oceanic domain [17, 18]. The Epiigurian Succession is composed of Middle Eocene to Middle Miocene siliciclastic deposits representing the infilling of piggy-back basins [19]. As a matter of fact, different results were obtained for the thickness variation of the Ligurian Nappe throughout the Northern Apennines [4-6, 9, 14-15].

Apart from large outcrops of metamorphic rocks well exposed in Tuscany, most of the rocks of the Northern Apennines reached only diagenetic conditions. The study of the thermal maturity acquired by the latter can provide a powerful contribution to this debate, especially in areas affected by a complex evolution of compressive deformation and exhumation [4-6, 16]. Furthermore, the Modena-Bologna segment of the Northern Apennines represents a key area where to test the validity of this methodological approach for at least two main reasons.

First, most of the structural units that make up the Northern Apennines thrust wedge crop out in this key area (Fig. 3 and 4). From the upper to the lower one, they are:

- the undifferentiated Ligurian Units (Val Baganza Ophiolitic Unit and Monghidoro Unit);
- the Modino Unit, namely the Ventasso sub-Unit [20, 21];
- a series of thrust sheets that segmented a pre-existing tectonic stack formed by the thrust-top Cervarola Successions, at the bottom, and the Ventasso sub-Unit, at the top. These show a high degree of thermal maturity [4, 5] and exhumation [9] defined, until now, on the base of scattered organic matter and fission-track analyses.

Secondly, the Cervarola Successions that form the lowermost Unit are very well exposed. Thus, they offer the opportunity to define their stratigraphic evolution and to analyse in detail their thermal maturity by means of coupled analytical methodologies such as organic matter optical study and clay mineralogy X-ray diffraction.

Organic matter (OM) and clay minerals are highly sensitive to the changing conditions that occur during both burial diagenesis and tectonic loading of sedimentary rocks [22, 23]. Therefore they are used to define the burial and thermal evolution of sedimentary successions in relation to their depositional and tectonic history.

In detail, OM maturity increases with increasing time of burial and temperature [24-26] and the optical indicator of vitrinite reflectance (Ro%) [27] is the most widely used quantitative parameter to measure OM maturity levels in hydrocarbon exploration. This is due to the evidence that reactions, which control the transformation of vitrinite, are not reversible with exhumation and/or decreasing temperatures. Thus, they provide data on the maximum burial depths, but not on exhumation paths.

Clay minerals as well are mainly sensitive to temperature, and the use of illite/smectite (I/S) mixed layers as a “geothermometer” is generally accepted [28-30]. In fact, changes in the proportion of illite or smectite, layer expandability, and I/S ordering (as interpreted from X-ray powder diffraction profiles) are empirically related to temperature changes due to burial [31, 32]. Nevertheless other factors may control the illite enrichment of I/S mixed layers [33-36].

Consequently, if applied alone, both geothermometers have some limitations, as described in the literature [22, 37, 38]. Further difficulties are represented by the complexity of reconstructing burial and thermal histories, especially in fold-and-thrust belts where tectonic processes are superimposed to the depositional evolution [39]. Reliable results in these cases can, therefore, be attained through the integration of Ro% and I/S mixed layers data to calibrate thermal modelling of sedimentary successions.

Furthermore, integration with apatite fission-track (FT) data, that provide complementary information on the thermal history of sedimentary rocks between temperatures of 60°C and 110°C, may help to constrain modelling of the exhumation stages [9, 40].

In synthesis, the aims of this contribution are: 1) to present new stratigraphic data of the Cervarola Successions and their lateral variations and discuss the paleogeographic setting of the Modena-Bologna Apennines with special regard to the Aquitanian-Langhian time interval; 2) to present and discuss new Ro and mineralogical data from the Northern Apennines.
Fig. 3 Geological sketch map of the Northern Apennines comprised between Scoltenna R. and Silla R. valleys with sample location (see also Fig. 5 for stratigraphic distribution).
Fig. 4. Geological cross sections through the study area. Traces are shown in Fig. 3. Poles to bedding collected from different thrust sheets are shown in the box. Data from Corno alle Scale thrust sheet refer to poles to bedding measured in the syncline (A) and the anticline (B).
sector comprising Mt. Cervarola and Corno alle Scale, affected by complex Miocene compressive evolution; 3) to compare and integrate new results with existing apatite FT and Ro data; 4) to provide values of maximum tectonic and/or sedimentary burial in the study area; 5) to suggest a possible geological model for the observed distribution of data with respect to thrust emplacement.

2. The Cervarola Successions

2.1. Stratigraphy

The Aquitanian-Langhian thrust-belt building process strictly controlled the sedimentation of the Cervarola Successions that widely crop out in the Northern Apennines [41-43] (Fig. 1). They consist of an Aquitanian-Burdigalian [41, 42] basal portion made up, in the Piacenza-Reggio Emilia-Modena Apennines, of the Civago Marl and Serpiano Fm. and, in the Bologna Apennines, of the Civago Marl, Serpiano Fm., Torrente Carigiola Fm. and Stagno Fm. [42, 43]. The Burdigalian Mt. Cervarola Sandstones offlap the first succession, whereas the Langhian Granaglione Sandstones unconformably overlie the second one. The basal portion of both successions was partly deposited on an already deformed substratum consisting of the Mt. Modino Unit, which previously overthrust the internal part of the Tuscan Nappe [44-48]. Hence, the Cervarola Successions are interpreted as deposed, at least partially, in a piggy-back basin [49-50].

The Cervarola Successions cropping out in the study area (Modena-Bologna Apennines, Fig. 1 and 3) are described in two stratigraphic schematic logs (Fig. 5).

Fig. 5a represents the Cervarola Succession cropping out between the Scoltenna R. and Dardagna R. valleys (Fig. 3) and consists only of the Mt. Cervarola Sandstones, organised in five members. From the bottom:

- The Amorotti-Dardagna Member is characterised by thick turbiditic beds (up to 16 m thick) with a medium and coarse-grained arenitic base (F5-F6-F8 Facies of Mutti) [51]; the top of each bed is generally represented by the F9a Facies, in which the siltitic Tc Bouma division prevails. The marly-pelitic Td Bouma division consists of an F9a Facies, in which the siltitic Tc Bouma division prevails. The marly-pelitic Td Bouma division is very thin and sometimes absent. Fine-thin bed (F9a Facies) layers, slumping layers and pebbly sandstones (F2 Facies) alternate with the thick beds; the fine-thin bed layers have a thickness varying from 30 cm up to some meters. The pebbly sandstones include millimetric and centimetric pebbles with different composition (metamorphic, plutonic and calcareous rocks). Several fining-thinning upward facies sequences, lobe and lobe-fringe sandstones, can be recognized in the arenaceous-pelitic succession. This member is attributed to the Forlaciari & Rìo [52] Burdigalian MNN3a Biozone [41].

- The Torrente Fellicarolo Member consists of a basin plain deposit, represented by a thick succession of thin-medium turbidites (F9a Facies), interbedded with metric and decametric megaturbidites characterised by a coarse-medium graded arenitic base (F6-F8 Facies) or by a fine arenitic-siltitic one (Tc Bouma division); they always show a thick marly interval (Tc-d Bouma divisions) at the top. The lateral continuity of these megaturbidites allows the correlation of the same portion of the stratigraphic succession over distances of several kilometers. From the bottom up, the easily identifiable megaturbidites at the field scale are the Poggiofloraro Bed, the couple Elisa-Sandra Beds, the Fellicarolo 1, Fellicarolo 2 and Fellicarolo 3 Beds [41, 42, 53]. From the Dardagna Valley to the Croce Arcana Pass a thick slumping deposit marks the boundary between the Dardagna-Amorotti and Fellicarolo Members. The marly lithofacies represents the stratigraphic top of the Fellicarolo Member. This member is attributed to Burdigalian MNN3a-MNN3b Biozones [42].

- Three lithofacies form the Rio Carnale Member. The lower lithofacies consists of a thickening and coarsening upward turbiditic succession: at the bottom there are thin-medium siltitic-marly turbidites (F9a Facies), whereas turbiditic beds with a medium and coarse-grained arenitic base (F5-F6-F8) and thin marly-pelitic Td Bouma division represent the top of this lithofacies. An association of the pebbly-sandstone (F2 Facies) and slumping deposits, 40 m thick, represents the middle lithofacies. A succession of thin and fine turbiditic strata (F9a facies and rarely F8-F9a Facies associations) forms the upper lithofacies. This lithofacies represents a turbiditic body confined within a depression lying at the top of the middle lithofacies. The age of the Rio Carnale Member is Burdigalian (MNN3b Biozone) [42].

- The sandstones lobe of the Rio Becco Member, about 150 m thick, unconformably overlies the Rio Carnale Member. It is characterised by thick turbiditic beds with a conglomeratic or coarse-medium graded arenitic base (F2-F4-F5-F6-F8 Facies). The top of each bed consists of an F9a Facies, in which the siltitic Tc Bouma division prevails. The marly-pelitic Td Bouma division is very thin and sometimes absent. Three fine-thin bed layers (F9a Facies) and slumping-beds alternate with the thick beds. The Rio Becco Member is of Burdigalian age (MNN3b Biozone) [42].

- The thinning and fining upward succession of Rio Lezza Member, about 150 m thick, is made up of thin and fine-grained turbiditic beds (F9a Facies) with alternating yellowish beds rich in carbonatic components, two decametric volcanoclastic layers and slumping deposits near the top. Similar coarse-grained beds (F5 and/or F8 Facies) are present near the bottom. Stratigraphic and sedimentological features indicate a progressive deactivation of the turbiditic currents and the return to the initial sedimentary conditions of low sedimentation rates (such as in the Serpiano Fm., see later). This condition suggests a strong topographic
Fig. 5 Synthetic stratigraphic logs of the Mt. Cervarola Sandstones (a) and Granaglione Sandstones (b) with sample location. Calcareous nannofossils Biozones from Fornaciari and Rio [52] and Fornaciari et al. [70]. Lithostratigraphic units from Botti [42].
control due to the ongoing tectonic deformation of the basin, whose sedimentation ended when the allochthonous units (Ligurian and Modino Units) thrust over this succession. The Rio Lezza Member dates back to the Burdigalian (MNN3b Biozone) [42].

Fig. 5b represents the Cervarola Succession outcropping between the Silla R. and Reno R. Valleys (Fig. 3). In this area it consists, from the bottom, of:

- The Aquitanian (MNN1d Biozone) Civago Marls. They are characterised by dark grey marls, siltitic-marls, and marly diluted turbidites (Facies F9a) showing chert-rich horizons that represent important stratigraphic markers at regional scale. These are also present in the Vicchio Marls (Aquitanian-Serravallian Tuscan piggy-back deposits) and in the Bisciario Fm. (Umbrian foredeep deposits). The Civago Marls are interpreted as a slope deposit in which the epipelagic deposition is interrupted by sporadic detrital events indicating the beginning of the Serpiano Fm. turbiditic sedimentation.

- The Aquitanian (MNN1d Biozone) [42] Serpiano Fm., about 200 m thick. It is made up of thin or medium siltitic-pelitic turbidites (siltite/mudstone ratio generally = 1) with alternating sporadic dark shale and silica-rich horizons. In the upper portion lens-shaped coarse-grained beds are present. Stratigraphic and sedimentological features point out that the sedimentary environment changed; in fact this formation represents a marginal basin turbiditic sedimentation marking a by-pass area (probably between the slope and the basin plain). The gravity flows deposited the coarser clasts in depressions of variable size as a result of speed and efficiency reduction.

- The Aquitanian (MNN1d Biozone) [42] Torrente Carigiola Fm., about 900 m thick. It is composed of two members. The lower one consists of thin or medium siltitic-pelitic turbidites (F9a Facies), which form the background sedimentation, alternating with arenaceous-pelitic turbidites thickly to thinly bedded with a medium-grained arenitic bottom (F6-F7-F8 Facies) and a siltitic-marly top (F9a Facies). The distribution of slumps and chert-rich horizons is scattered. The distinctive feature of this member is the occurrence of mega-beds up to 30 m thick. They show a poorly sorted, microconglomeratic, and very coarse-grained arenitic bottom (F5-F6-F8 facies) and a very thick siltitic-marly top (F9a Facies). The sandstone/mudstone ratio of these mega-beds is close to 1.

The upper 50 m thick member, consists of very thin siltitic-marly and pelitic turbiditic beds (Tc-d and Td-e Bouma divisions). Several thin slumping deposits and calcareous-marly beds with a yellowish weathering colour alternate with the typical succession. Three lens-shaped arenaceous-marly beds (F8-F9a Facies) occur in the upper part of this member.

The Torrente Carigiola Fm. represents a well-developed turbiditic depositional system, in which lobe, lobe-fringe facies and associated siliciclastic mega-beds prevail. The upper pelitic facies, interpreted as a turbiditic overflowing deposit, represents the system’s deactivation. Both tectonic activity and eustatic variations might be the factors controlling this deactivation.

- The Aquitanian-Burdigalian (MNN2 Biozone) [42] Stagno Fm., about 600-700 m thick. It is composed of two members showing well-developed fining- and thinning-upward sequences. The lower member consists of arenaceous-pelitic turbidites with typical F7 (medium-grained arenitic traction carpets), F8 (medium to fine-grained arenite, massive and well sorted division), and F9a facies associations (siltic-marly interval corresponding to the Tc and Td Bouma divisions). Moreover, it is characterised by a sandstone/mudstone ratio greater than 1 and amalgamation structures. In the upper part of this member, thin-fine turbidites layers (F9a Facies) and several pebbly sandstones are locally distributed.

The upper pelitic-arenaceous member is made up of siltitic-marly turbidites (F9a Facies) forming thin to medium beds. Locally, arenaceous-pelitic turbidites (F8-F9a Facies), about 50-70 cm thick, are present with sandstone/mudstone ratio always less than 1. A distinctive feature of this member is the occurrence of several mega-beds with sandstone/mudstone ratio from 1/4 to 1/5.

East of the studied area [43] a pelitic Burdigalian (MNN3a-MNN3b Zones) third member is present at the top of the Stagno Fm. It consists of very thin beds of hardened marly siltstone and silty marlstone, which testify the deactivation of the Stagno depositional system.

The Stagno Fm. testifies a turbiditic system consisting of lobe and lobe-fringe facies associations.

- The Langhian Granaglione Sandstones (MNN4b-MNN5a Biozone) [42, 43, 54]. These lie unconformably over the Stagno Fm. The Granaglione Sandstones, about 600 m thick, show thickening- and coarsening-upward sequences. Thin siltitic-marly turbidites (F9a Facies) prevail in the lower part of this formation, whereas thickly to very thickly bedded, medium-grained turbidite bed-sets are common in the upper part.

2.2. Tectono-sedimentary evolution

The reconstructed evolution of the sedimentary basin containing the Cervarola Successions is shown in Fig. 6 [41-42].

Since Aquitanian p.p. - Burdigaglian p.p. times (Fig. 6a), the basin topography turned out to be rather irregular because of thrust propagation within the Tuscan Units (Tuscan Nappe and Modino Unit) that started being translated outwards. At this time, the Cervarola basin was filled by the Civago Marls along the slope, the Serpiano Fm. along the internal margin and the Torrente Carigiola and Stagno Fms. in the deepest zone.

In Burdigalian p.p. times (MNN3a-MNN3b Zones) (Fig. 6b), further thrust propagation split the basin into two
Fig. 6 Reconstructed tectonic evolution of the Cervarola sedimentary basin during Aquitanian-Quaternary times: A) Aquitanian p.p.-Burdigalian; B) Burdigalian; C) Langhian; D) Langhian-Tortonian, roman numbers indicate early thrust faults, arab numbers indicate late thrust faults; E) Present-day. Distances are not to scale.
portions. In the outer area, the marly sedimentation of the Stagno Fm. occurred only in the deepest zones, whereas, in the inner sectors, the Mt. Cervarola Sandstones deposited on top of the Civago Marls and Serpiano Fm., as a result of increased subsidence. The progressive migration of the allochthonous units (Ligurian Units and Ventasso Sub-Unit) from West to East broke the Mt. Cervarola Sandstones sedimentation off. The sedimentation stopped in the MNN3a biozone in the inner zones (Reggio Emilia-Modena Appennines) and in the MNN3b, in more external areas (Scoltella R. valley).

Since Langhian times (Fig. 6c), the Granaglione Sandstones and the Marnoso-Arenacea Fm. deposited on the basal Cervarola succession and the Umbrian substratum, respectively [55]. This was probably due to a renewed subsidence in the most external zones possibly triggered by both isostatic re-equilibrium and progressive flexure of the adjacent Umbrian domain. Thus, the Granaglione Sandstones filled a piggy-back basin, open towards the adjacent foreland together with the previously emplaced Ventasso sub-Unit.

2.3. Thrust geometry and sequence

Moving from West to East, five thrust sheets (Fig. 3 and 4) developed:

- the Corno alle Scale thrust sheet, which forms a NW-SE overthrown hanging-wall anticline of Mt. Cervarola Sandstones, with scattered preserved remnants of the Ventasso sub-Unit at the top. The calculated shortening is of about 7-8 kilometres, based on recently constructed cross sections [42];
- the Mt. La Nuda and Rocca Corneta thrust sheets, both striking NW-SE, mainly made up of Granaglione Sandstones. They are comprised between the Corno alle Scale (at the hanging-wall) and the Mt. Grande (at the footwall) thrust sheets;
- the Mt. Grande thrust sheet, striking NW-SE to E-W, mainly made up of Granaglione Sandstones and their basal succession. It lies directly at the footwall of either the Corno alle Scale thrust sheet or the Mt. La Nuda one;
- the Mt. Pizzo thrust sheet, striking NW-SE to WNW-ESE, mainly made up of Granaglione Sandstones and their basal succession. It entirely crops out at the footwall of the Mt. Grande thrust sheet;
- the Pennola thrust sheet, mainly made up of the Ventasso sub-Unit and the Granaglione Sandstones, cropping out at the footwall of the Mt. Pizzo thrust sheet.

The youngest compressive deformation is constrained by the age of the Marnoso-Arenacea Fm. (developed in MNN5a Biozone) that represents the footwall of the Pennola thrust sheet which crops out near Lizzano in Belvedere.

Compressive post-Langhian tectonic events mainly disrupted the original relationships between the described Cervarola Successions, whose present-day geometrical setting is shown in Fig. 3 and 4.

The reconstructed timing of deformation defines a piggy-back sequence [42] including (Fig. 6d and e):

1. an early overthrusting of the Modino Unit (Ventasso sub-Unit) onto the Cervarola Successions [44, 47]. The Ventasso sub-Unit overthrust the Mt. Cervarola Sandstones in post-Burdigalian times (Biozones MNN3a-MNN3b) and the Granaglione Sandstones since Langhian times (Biozone MNN4b);
2. a late deformation phase that produced the overthrust of the Mt. Cervarola Sandstones over the Granaglione Sandstones. The latter in turn deformed from hinterland to foreland together with the previously emplaced Ventasso sub-Unit.

3. Organic matter and Clay mineralogy analyses

3.1. Samples and analytical details

A suite of 31 samples for vitrinite reflectance analysis was collected mainly in stratigraphic succession from the upper thrust sheet in the Mt. Cervarola Sandstones (18 samples distributed in a ~2,000 m thick succession) and from the four lower thrust sheets in the Granaglione Sandstones (13 samples distributed in a ~600 m thick succession) (see Fig. 3 and 5). One sample comes from the small tectonic window of Marnoso-Arenacea Fm. collected north of the village of Lizzano in Belvedere, where the Marnoso-Arenacea Fm. is overthrust by the Granaglione Sandstones (see Fig. 3). Samples were collected mainly from the Ta-Tc intervals of the Bouma division of thin-fine turbiditic beds, thick arenaceous-pelitic beds, arenaceous-pelitic megaturbidites, and arenitic F6 facies of thick arenaceous-pelitic beds (Table I). The 24 samples for mineralogy X-ray semi-quantitative analysis (on whole-rock samples and < 2 µm grain-size fractions) were collected in the same sites mainly in Tc and Td intervals of the Bouma division of thin-fine turbiditic beds and black shales (Fig. 3 and 5 and Table I).

Whole-rock samples, prepared for vitrinite reflectance analysis, were mounted on epoxy resin and polished according to standard procedures. Random reflectance (Ro%) was measured under oil immersion, with a Zeiss Axioscope microscope, in reflected monochromatic non-polarised light. An average 20 measurements were performed on vitrinite fragments for each sample (never smaller than 5 nm and only slightly fractured and/or altered). Mean reflectance and standard deviation values were calculated for all measurements.

The mineralogy of the < 2 µm (equivalent spherical diameter), 2-16 µm grain-size fractions, and whole-rock samples was determined by XRD (Scintag mod. Xc, CuKα radiation, solid state detector, spinner). After centrifugation, the suspension containing the < 2 µm and 2-16 µm grain-size fractions was decanted, pipetted, and dried at room tempera-
Table 1
Organic matter maturity and clay mineralogy data. v = sample for Ro% analysis; Ar = sample for X-Ray analysis. Acronyms for bulk composition: Q = quartz; P = plagioclase; C = calcite; K = K-feldspar; Ph = phyllosilicates; D = dolomite; Py = pyrite. Values are expressed in percentage. Acronyms for < 2 μm and 2-16 μm grain-size fractions: Mi = illite; I/S = illite/smectite mixed layers; C/S = chlorite/smectite mixed layers; Cl = chlorite.

<table>
<thead>
<tr>
<th>Structural Unit</th>
<th>Vitrinite analysis samples</th>
<th>Clay mineral analysis samples</th>
<th>Coordinates</th>
<th>Lithology</th>
<th>% Ro ± s.d. (nr. measurement)</th>
<th>% I ± FS ± s.d. (2-16 μm)</th>
<th>X-ray semiquantitative analysis</th>
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<td>SC 1v</td>
<td>SC 1Ar</td>
<td>44° 14' 45&quot; N 10° 40' 27&quot; E</td>
<td>Silicic Tc Bouma division in thin-fine turbiditic bed</td>
<td>barren</td>
<td>80 ± 2.5</td>
<td>80 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<tr>
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<td>M 2Ar</td>
<td>44° 15' 46&quot; N 10° 14' 09&quot; E</td>
<td>Silicic Tc Bouma division in thick arenaceous-pelitic turbiditic bed</td>
<td>barren</td>
<td>80 ± 2.5</td>
<td>80 ± 2.5</td>
<td>Q(1)K(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<td>M 1Ar</td>
<td>44° 15' 28&quot; N 10° 42' 54&quot; E</td>
<td>Silicic Tc Bouma division in thin-fine turbiditic bed</td>
<td>1.013 ± 0.160 (8.6)</td>
<td>80 ± 2.5</td>
<td>80 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<td>STE 1Ar</td>
<td>44° 15' 15&quot; N 10° 42' 08&quot; E</td>
<td>Arenitic-Ta Bouma division (STE 1v) and silicic Tc Bouma division (STE 1Ar) in thin arenaceous-pelitic turbiditic bed</td>
<td>1.033 ± 0.123 (14)</td>
<td>80 ± 2.5</td>
<td>80 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)</td>
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<td>CV 1Ar</td>
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<td>Silicic Tc Bouma division in thin-fine turbiditic bed</td>
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<td>Q(1)K(1)P(1)Ph(1)C(1)D(1)</td>
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<td>Bell2-Past v</td>
<td>Bell2-Past Ar</td>
<td>44° 10' 10&quot; N 10° 49' 11&quot; E</td>
<td>Silicic Tc Bouma division in thin-fine turbiditic bed</td>
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<td>PC 3Ar</td>
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<td>Silicic Tc Bouma division in thick arenaceous-pelitic turbiditic bed</td>
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<td>80 ± 2.5</td>
<td>80 ± 2.5</td>
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<td>Arenitic-Ta Bouma division in thick arenaceous-pelitic turbiditic bed</td>
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<td>80 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<td>MO 1v</td>
<td>MO 1Ar</td>
<td>44° 14' 46&quot; N 10° 42' 49&quot; E</td>
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<td>1.114 ± 0.116 (18)</td>
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<td>80 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
</tr>
<tr>
<td>RU 3v</td>
<td>RU 3Ar</td>
<td>44° 11' 28&quot; N 10° 45' 22&quot; E</td>
<td>Silicic Tc Bouma division in arenaceous-pelitic megaturbiditic bed (RU 3v) and black shale (RU 3Ar)</td>
<td>barren</td>
<td>85 ± 2.5</td>
<td>85 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
</tr>
<tr>
<td>RU 2v</td>
<td>RU 2Ar</td>
<td>44° 11' 30&quot; N 10° 45' 27&quot; E</td>
<td>Arenitic-silicic Ta-c divisions in arenaceous-pelitic megaturbiditic bed (RU 2v) and black shale (RU 2Ar)</td>
<td>1.156 ± 0.123 (9)</td>
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<td>85 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<tr>
<td>RU 1v</td>
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<td>44° 11' 33&quot; N 10° 45' 32&quot; E</td>
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<td>1.068 ± 0.102 (20)</td>
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<td>85 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<td>TO 3v</td>
<td>TO 3Ar</td>
<td>44° 10' 06&quot; N 10° 50' 00&quot; E</td>
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<td>1.200 ± 0.103 (20)</td>
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<td>85 ± 2.5</td>
<td>Q(1)K(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<td>TO 2v</td>
<td>TO 2Ar</td>
<td>44° 10' 12&quot; N 10° 50' 03&quot; E</td>
<td>Arenitic-silicic Ta-c Bouma divisions in thick arenaceous-pelitic turbiditic bed</td>
<td>1.164 ± 0.124 (24)</td>
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<td>85 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
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<td>TO 1v</td>
<td>TO 1Ar</td>
<td>44° 10' 16&quot; N 10° 50' 10&quot; E</td>
<td>Arenitic-silicic Ta-c Bouma divisions in arenaceous-pelitic turbiditic bed</td>
<td>barren</td>
<td>80 ± 2.5</td>
<td>85 ± 2.5</td>
<td>Q(1)P(1)Ph(1)C(1)D(1)Py(1)</td>
</tr>
<tr>
<td>Mt. La Nuda Thrust Sheet Granaglione Sandstones Langhian</td>
<td>RAI 9v</td>
<td>RAI 9Ar</td>
<td>44° 07' 12&quot; N 10° 51' 10&quot; E</td>
<td>Arenitic Fe Mutti Facies (RAI 9v) and pelitic Td Bouma Division (RAI 9Ar) in thick arenaceous-pelitic turbiditic bed</td>
<td>1.543 ± 0.167 (28)</td>
<td>90 ± 2.5</td>
<td>90 ± 2.5</td>
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</table>

<table>
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<tr>
<th>Structural Unit</th>
<th>Formation</th>
<th>Stratigraphic age</th>
<th>Coordinates</th>
<th>Lithology</th>
<th>% Ro ± s.d. (nr. measurement)</th>
<th>% I in I/S ± s.d.</th>
<th>X-ray semiquantitative analysis</th>
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</thead>
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<tr>
<td>VID 1v</td>
<td></td>
<td></td>
<td>44°10’15”N 10°51’40”E</td>
<td>Arenitic-siltitic Ta-c Bouma divisions in thick arenaceous-pelitic turbiditic bed</td>
<td>1,485 ± 0,151 (52)</td>
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<td>/</td>
</tr>
<tr>
<td>RAI 8v</td>
<td>RAI 8Ar</td>
<td></td>
<td>44°07’24”N 10°51’33”E</td>
<td>Siltitic Tc Bouma division (RAI 8v) and pelitic Td Bouma division (RAI 8Ar) in thin-fine turbiditic bed</td>
<td>1,386 ± 0,089 (11)</td>
<td>85 ± 2.5</td>
<td>85 ± 2.5</td>
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<tr>
<td>Mt. Grande Thrust Sheet</td>
<td>Granaglione Sandstones</td>
<td>Langhian</td>
<td>RAI 7v</td>
<td>RAI 7Ar</td>
<td></td>
<td>44°07’28”N 10°51’49”E</td>
<td>Siltitic Tc Bouma division (RAI 7v) and pelitic Td Bouma division (RAI 7Ar) in thin-fine turbiditic bed</td>
</tr>
<tr>
<td>RAI 6v</td>
<td>RAI 6Ar</td>
<td></td>
<td>44°07’35”N 10°52’07”E</td>
<td>Siltitic Tc Bouma division (RAI 6v) and pelitic Td Bouma division (RAI 6Ar) in thin-fine turbiditic bed</td>
<td>1,465 ± 0,090 (13)</td>
<td>85 ± 2.5</td>
<td>85 ± 2.5</td>
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<tr>
<td>RAI 5v</td>
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<td></td>
<td>44°07’40”N 10°52’22”E</td>
<td>Siltitic Tc Bouma division (RAI 5v) and pelitic Td Bouma division (RAI 5Ar) in thin-fine turbiditic bed</td>
<td>barren</td>
<td>85 ± 2.5</td>
<td>85 ± 2.5</td>
</tr>
<tr>
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<td>RAI 1Ar</td>
<td></td>
<td>44°08’40”N 10°53’33”E</td>
<td>Arenitic Ta Bouma division (RAI 1v) and pelitic Td Bouma division (RAI 1Ar) in turbiditic bed</td>
<td>1,423 ± 0,125 (7)</td>
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<td>RAI 4v</td>
<td>RAI 4Ar</td>
<td></td>
<td>44°08’06”N 10°52’34”E</td>
<td>Siltitic Tc Bouma division (RAI 4v) and pelitic Td Bouma division (RAI 4Ar) in thin-fine turbiditic bed</td>
<td>1,414 ± 0,121 (5)</td>
<td>85 ± 2.5</td>
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<tr>
<td>RAI 2v</td>
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<td></td>
<td>44°08’33”N 10°53’23”E</td>
<td>Siltitic Tc Bouma division (RAI 2v) and pelitic Td Bouma division (RAI 2Ar) in thin-fine turbiditic bed</td>
<td>barren</td>
<td>80 ± 2.5</td>
<td>80 ± 2.5</td>
</tr>
<tr>
<td>RAI 3v</td>
<td>RAI 3Ar</td>
<td></td>
<td>44°08’28”N 10°53’11”E</td>
<td>Siltitic Tc Bouma division (RAI 3v) and pelitic Td Bouma division (RAI 3Ar) in thin-fine turbiditic bed</td>
<td>1,387 ± 0,111 (10)</td>
<td>85 ± 2.5</td>
<td>85 ± 2.5</td>
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<tr>
<td>Pennola Thrust Sheet</td>
<td>Granaglione Sandstones</td>
<td>Langhian</td>
<td>GRA 2v</td>
<td></td>
<td>44°09’03”N 10°54’24”E</td>
<td>Arenitic Fb Mutti Facies in thick arenaceous-pelitic turbiditic bed</td>
<td>1,351 ± 0,066 (8)</td>
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<td>GRA 1v</td>
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<td></td>
<td>44°08’52”N 10°54’08”E</td>
<td>Arenitic Fb Mutti Facies in thick arenaceous-pelitic turbiditic bed</td>
<td>barren</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Marnoso Arenacea Formation Langhian</td>
<td>Torre 1v</td>
<td></td>
<td>44°11’39”N 10°52’00”E</td>
<td>Siltitic Ta Bouma division in thin-fine turbiditic bed</td>
<td>1,222 ± 0,141 (20)</td>
<td>/</td>
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</table>
ture on glass slides to produce a thin highly oriented aggregate [58]. Whole-rock samples were scanned from 2 to 70 °2/θ at a scan speed of 1 °2/θ/min, a step size of 0.05 °2/θ and a count time of 3 s at 40 kV and 45 mA. Oriented air-dried samples were scanned from 1 to 48 °2/θ at a scan speed of 0.75 °2/θ/min, a step size of 0.05 °2/θ and a count time of 4 s at 40 kV and 45 mA. The presence of expandable clays was determined for samples treated with ethylene glycol at 25°C for 15h. Treated samples were scanned at the same conditions of air-dried aggregates with a scanning interval of 1-30 °2/θ.

3.2. Results

3.2.1. New Organic matter data

Analysed kerogene is generally abundant, homogeneous and mainly made up of well-preserved macerals. They belong to the huminite-vitrinite group, with predominance of collotelinite and telinite fragments, and subordinately to the inertinite group [27]. Pyrite either finely dispersed or in small globular aggregates is locally present along the rims of the vitrinite macerals.

On most samples two separate clusters of Ro-value were recognised. The first one, characterised by lower Ro values and a Gaussian distribution, is representative of autochthonous wood fragments, whereas the second one, less regularly distributed and with higher values, is made up of highly oxidised or recycled fragments. The latter group was not taken into account, as it does not provide meaningful information on the burial/thermal evolution of the analysed stratigraphic units. Measurements on these fragments are generally less abundant than those conducted on autochthonous OM.

In the Mt. Cervarola Sandstones of the Corno alle Scale thrust sheet, Ro% data of autochthonous fragments (see Table I) slightly decrease from the bottom to the top of the succession with mean values between 1.20 and 1.01 that show only local exceptions.

In the lower thrust sheets that are maole up of the Granaglione Sandstones, a slight reduction in organic maturity is recorded from hinterland to foreland (see Table I). The highest mean Ro value (1.54%) is recorded in the innermost thrust sheet (Mt. La Nuda thrust sheet). Decreasing values between 1.38 and 1.48% were measured in the two intermediate thrust sheets (respectively Mt. Grande and Mt. Pizzo thrust sheets). A slightly lower value derives from the most external thrust sheet (Pennola thrust sheet with 1.35%). The Marnoso-Arenacea Fm. cropping out at the footwall of the Granaglione Sandstones shows an even lower value (1.22%).

3.2.2. New mineralogical data

In the pelitic whole-rock samples (see Table I), X-ray diffraction patterns show the presence of phyllosilicates, plagioclase, quartz, calcite, dolomite, and sometimes k-feldspar and pyrite. Siltites reveal greater amounts of calcite, quartz and plagioclase than shales, which show major amounts of phyllosilicates. These differences are related to the different grain-size of the two lithologies.

In the < 2 µm grain-size fraction, illite is the most abundant clay mineral and prevails on chlorite, I/S and chlorite/smectite (C/S) mixed layers. Furthermore, we analysed the 2-16 µm grain-size fraction to compare the different mineralogical composition and to identify possible weathering processes. In the 2-16 µm grain-size fraction, a similar assemblage was found but it differs in percentage when compared with the finer fraction. The coarser fraction is characterized by major amounts of illite (average value 49% vs. 41%), chlorite (29% vs. 27%) and C/S mixed layers (13% vs. 12%), and lower amounts of I/S mixed layers (9% vs. 20%). No substantial mineralogical differences were recognised between the Mt. Cervarola Sandstones and the Granaglione Sandstones.

I/S mixed layers observed in the < 2 µm grain-size fraction, correspond to R > 1 > 1 structures wherein the illite content ranges between 80% and 90%. RA9 is the unique sample where the R3 structure has been identified. A slight increase with depth of the illitic layers in I/S mixed layers is testified in the upper thrust sheet (80% → 85%) and in the lower thrust sheets (80% → 85%).

Moving from the inner to the outer thrust sheet made up of the Granaglione Sandstones, a decrease of the illitic content has been recognised (from 90% to 80%).

Estimates of temperatures comprised between ~170-180°C and 210°C are reliable for the upper portion of the Mt. La Nuda thrust sheet. This temperature range is suggested by the illite content in I/S mixed layers, R1 to R3 transition [31, 38] and C/S regular mixed layers [60]. The above temperatures were sufficient to have caused recrystalization of original clay minerals, but insufficient to cause the complete reaction of illitization [29, 31].

The rest of the area suffered temperatures ranging between 100-110°C and 170-180°C [31] according to the R > 1 ordering of I/S mixed layers.

The percentage of illitic layers in I/S mixed layers in the < 2 µm grain-size fraction is a measure of smectite-to-illite transition in shale [61]. The difference of the illitic content in I/S mixed layers between < 2 µm and 2-16 µm fractions may be due to the reaction kinetics by which different size crystallites re-equilibrate during burial diagenesis (crystallites of < 2 µm size record temperature changes “more quickly” than bigger ones); it also may be due to the presence of “detrital” micas that generally enrich the coarser fraction.

For what concerns the percentage of illite in I/S mixed layers, we found no differences between the grain-size fractions analysed (Table I). This suggests that the permanence of the tectonic load for about 8-10 Myrs on the studied sections was long enough to equalize the reaction rates of the two fractions.

Mica composition is shown in Rey and Kübler’s triangle diagram (Fig. 7) [62]. Only the illite composition was identified, indicating that no detrital metamorphic supply (phengite, muscovite) affected the sedimentation.
3.2.3. Integration of the presented data with pre-existing organic matter and thermocronal data

Pre-existing data from the investigated zone and the surrounding areas derive from studies on both organic matter maturity [4-6] and apatite fission-track [9]. Within the Corno alle Scale thrust sheet, the data collected from isolated samples show a general increase: Ro% goes from 1.00 to 1.74 and FT age from ~3.3 to ~5.5 Myrs for the area around Mt. Cervarola and a region a few tens of km to the South, respectively.

For the lower thrust sheets, Reutter et al. [4] indicate a Ro value of 1.52% for the inner thrust sheet (Mt. La Nuda) within the study area. A few km to the south, moving from internal to external thrust sheets, Ro data evolve from ~2.4% to ~1.0% and mean FT age from ~4 to ~6 Myrs.

As a matter of fact, there is good agreement between pre-existing and new organic matter data within the study area. Their integration allows one to recognise an increasing trend of organic matter maturity moving from the study area toward the SE.

Furthermore, our new data allow to recognise:
- a decreasing maturity trend from older to younger sediments in the sedimentary successions never evidenced before;
- a horizontal decreasing maturity trend from West to East in the lower thrust sheets cropping out in the study area, previously detected a few kilometres to the South.

Moreover, fission tracks data have been interpreted to reflect exposure to paleotemperatures of at least ~110°C followed by rapid cooling during the Mio-Pliocene down to temperatures as low as ~60°C [9]. This is in partial agreement with I/S data that testify maximum paleotemperatures comprised between 110°C and 210°C.

4. Thermo-structural modelling and geological interpretation

4.1. Modelling constraints

Thermo-structural modelling was performed using BASIN MOD-1D SOFTWARE FOR WINDOWS [63]. This software allows reconstructing the burial and thermal evolution of sedimentary successions both in undeformed and deformed conditions from geological data (e.g., age of sedimentary successions and tectonic/erosional events, pure and mixed lithologies, thicknesses, porosity, permeability and thermal conductivity of sedimentary successions). These data derive from the integration between the database of physical features provided by the modelling software and the geological information coming from the regional literature and the new stratigraphic and structural data presented above.

Burial curves have been corrected for decompaction according to the Sclater and Christie’s method [64]. Sea level changes have been neglected, as sediments thickness, more than water column controls, thermal evolution [65]. Thermal modelling has been performed through LLNL Easy %Ro [26], adopting a geothermal gradient ranging from 15°C/km during sedimentation to 30°C/km during thrusting and exhumation phases and a surface temperature of 10°C [9] (Table II). Thrusting is considered instantaneous when compared with the duration of sedimentation, as generally suggested in theoretical models [66]. The exhumation rate is considered constant as deduced from Ventura et al. [9]. Burial curves have been calibrated with Ro% and I% in I/S, according to the geothermometer’s correlation proposed by Pollastro [38].
Thermo-structural modelling allowed the reconstruction of:
- the tectonic loading experienced by Mt. Cervarola Sandstones and caused by the emplacement of the Modino (Ventasso sub-Unit) and Ligurian Units, today partially eroded;
- the tectonic loading experienced by the Granaglione Sandstones, caused first by the emplacement of the Modino Unit (Ventasso sub-Unit) and the overlying Ligurian Unit, then by the Corno alle Scale thrust sheet;
- the Corno alle Scale thrust geometry and its past extension in the southeast sector of the study area, where erosion has exposed the Granaglione Sandstones.

4.2. Modelling results

Modelling results that better explain the thermal and burial evolution of the study area are shown in Fig. 8 and Table II.

Regarding the Corno alle Scale thrust sheet, diagram A1 in Fig. 8 shows that, after a progressive burial due to siliciclastic sedimentation of Mt. Cervarola Sandstones between ~21 and ~18 Myrs (MNN3a - MNN3b) [42], the emplacement of allochthonous units (namely Ligurian and Modino Units) took place in post-Burdigalian times. This brought about a fast tectonic burial of Mt. Cervarola Sandstones and its subsequent permanence in the footwall of the regional thrust, at depths greater than 3.5 km for about 10 Myrs. In fact regional data [9, 67] indicate that the tectonic load started being removed off Corno alle Scale since Tortonian times and is nowadays totally eroded. According to this modelling, Mt. Cervarola Sandstones experienced maximum palaeo-temperatures that never exceeded 170°C during tectonic loading. The intermediate portion of the formation reached a temperature of ~110°C at ~3.6 Myrs. This is in substantial agreement with apatite fission track data from two samples collected near Mt. Cervarola [9] that give out ages of 3.1 ± 1.1 and 4.1 ± 0.5 Myrs.

Regarding the present-day lower thrust sheets, diagram B1 in Fig. 8 shows the case of the Mt. Pizzo thrust sheet. Here, the Granaglione Sandstones sedimentation took place in Langhian times (comprising MNN4b and MNNS5a Biozones) ending with the emplacement of the allochthonous units that previously had thrust the Mt. Cervarola Sandstones. Then the Granaglione Sandstones underwent the emplacement of the Corno alle Scale thrust sheet that caused a further tectonic burial. It exerted a progressively decreasing loading from hinterland to foreland comprised between 5.2 km (nowadays recorded in Mt. La Nuda thrust sheet) and 4.8 km (nowadays recorded in Mt. Grande and Mt. Pizzo thrust sheets) (Table II). This decrease could be due to the progressive tectonic thinning of the Corno alle Scale thrust sheet probably caused by a low-angle hanging-wall ramp geometry. The influence of the tectonic loading exerted by the Corno alle Scale thrust sheet becomes irrelevant on the Marnoso Arenacea Fm. cropping out in the Lizzano in Belvedere area. The progressive development of the lower thrust sheets, that generally show small amounts of shortening, does not cause an increase of the calculated tectonic loading (Fig. 4).

The Diagrams of Fig. 8 A2 and B2, derived from the described burial histories, show the present-day calculated maturity plotted against measured maturity values for the different tectonic units. Fitting between them is quite satisfactory for Ro% values, whereas I% data (related to the < 2 µm grain-size fraction and generally slightly higher than Ro% data) show a minor agreement.

Table 2

<table>
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<tr>
<th>Modelled succession/Thrust sheet</th>
<th>Geothermal gradient during sedimentation (°C/km)</th>
<th>Geothermal gradient during thrusting and exhumation (°C/km)</th>
<th>Thrusting Age (Ma)</th>
<th>Calculated maximum burial (km)</th>
<th>Calculated maximum temperature at the top/bottom of the succession (°C)</th>
<th>Onset of exhumation (Ma)</th>
<th>Calculated exhumation rate (mm/yr)</th>
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<tr>
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<td>15</td>
<td>30</td>
<td>18.4</td>
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<td>30</td>
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<td>154/164</td>
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<td>15.4</td>
<td>4.8</td>
<td>154/164</td>
<td>7.5</td>
<td>0.64</td>
</tr>
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</table>
Fig. 8 Burial and thermal history diagrams of the Mt. Cervarola Sandstones (Corno alle Scale thrust sheet, A1) and Granaglione Sandstones (Mt. Pizzo thrust sheet, B1), and derived present-day maturity vs. depth diagrams (A2 and B2). Note poor agreement between Ro% and I% in I/S (converted in Ro%) in diagram A2 and good agreement in diagram B2. See text for explanation.
5. Final Remarks

This work integrates classical stratigraphic and structural approaches in a complex area of the Modena-Bologna Apennines with the study of both organic matter maturity and clay mineralogy. This provided new constraints regarding the Neogene-Quaternary evolution of an exhumed sector of the Northern Apennines.

First of all, the tectonic burial of the Cervarola Successions represents the primary cause of their thermal maturity. This is mainly due to the emplacement of the Ligurian and Modino Units and subordinately to its internal thrust stacking in a piggy-back sequence. This latter event brought first to the emplacement of the Corno alle Scale thrust sheet, made up of Mt. Cervarola Sandstones, and then to the stacking of the more external Cervarola Successions closed at the top by the Granaglione Sandstones. Furthermore, the progressive maturity growth from the hanging-wall to the footwall of the Corno alle Scale thrust sheet with no maturity upsurge through the main tectonic contact supports the hypothesis that maximum burial heating occurred after thrust emplacement. This interpretation agrees with Ro upsurge through the main tectonic contact supports the footwall of the Corno alle Scale thrust sheet with no maturity growth from the hanging-wall to the top by the Granaglione Sandstones. Furthermore, the progressive maturity growth from the hanging-wall to the footwall of the Corno alle Scale thrust sheet with no maturity upsurge through the main tectonic contact supports the hypothesis that maximum burial heating occurred after thrust emplacement. This interpretation agrees with Ro upsurge through the main tectonic contact supports the footwall of the Corno alle Scale thrust sheet with no maturity growth from the hanging-wall to the top by the Granaglione Sandstones. Furthermore, the progressive maturity growth from the hanging-wall to the footwall of the Corno alle Scale thrust sheet with no maturity upsurge through the main tectonic contact supports the hypothesis that maximum burial heating occurred after thrust emplacement. This interpretation agrees with Ro upsurge through the main tectonic contact supports the footwall of the Corno alle Scale thrust sheet with no maturity growth from the hanging-wall to the top by the Granaglione Sandstones.

Regarding the amount of reconstructed maximum burial, even though a more external position [15], files recorded in the Palazzuolo 1 well, which was drilled in the Pliocene (Table II). This value is compatible with estimated Quaternary erosion rates derived from geomorphological studies in the Northern Apennines (0.4-0.5 mm/yr) [68] and with the long-term mean exhumation rate in the last 11 Myrs recently calculated from thermochronometric data [10].

Acknowledgments

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References


