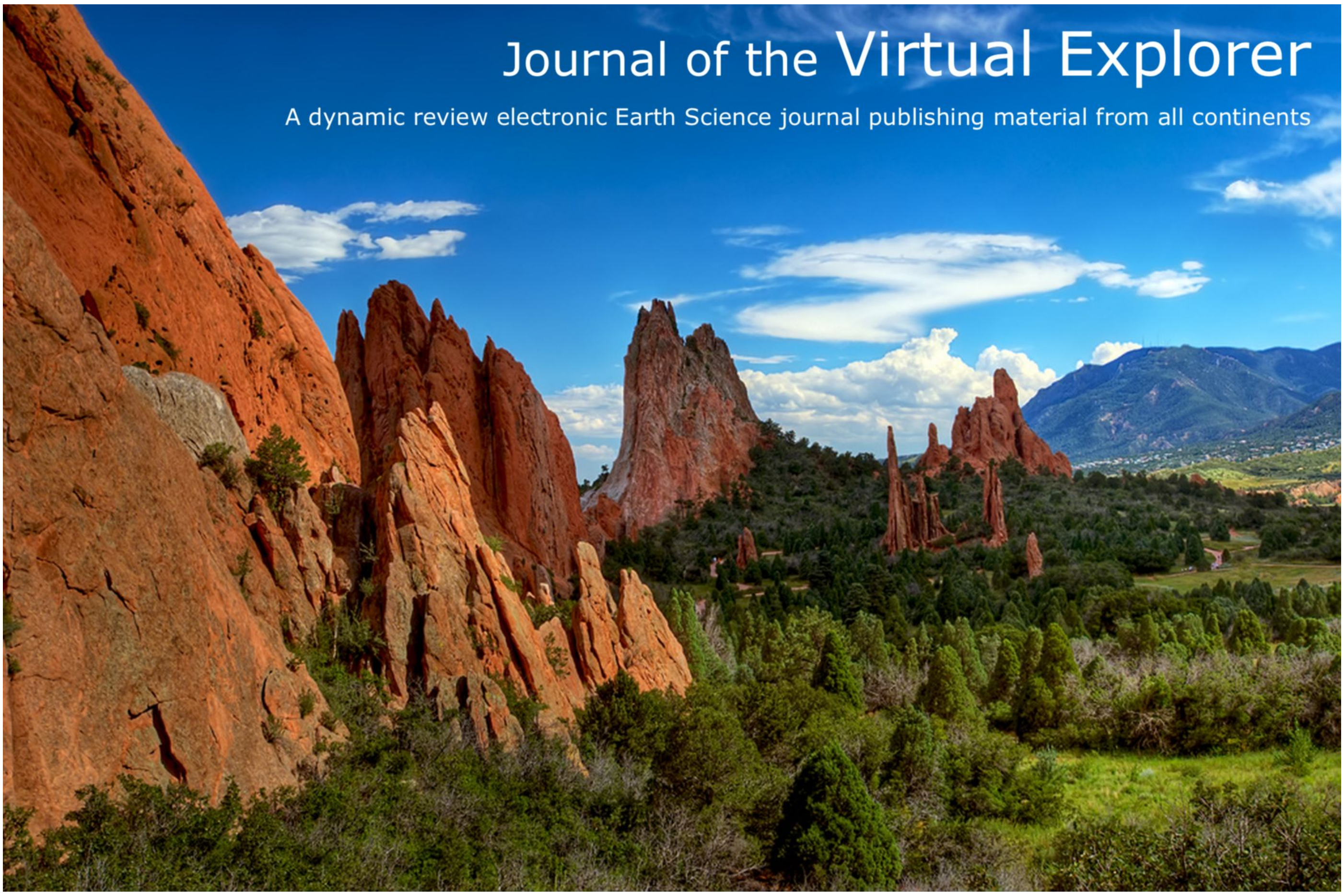

Sedimentary vs. tectonic burial and exhumation along the Apennines (Italy)

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Abstract: We review the burial-exhumation history of sedimentary units along the Apennines, focussing on paleo-thermal and thermochronological data derived from organic matter optical analyses, X-ray diffraction of clay-rich sediments, fission-track and (U-Th)/He dating.

In the Northern Apennines, burial conditions and timing of exhumation progressively decreases eastwards from the inner towards the outer zones and through the nappes from the lowermost to the uppermost unit. Apart from large outcrops of metamorphic rocks well exposed in Tuscany, most of the rocks of the Northern Apennines reached only diagenetic conditions. In the Central Apennines paleo-thermal and thermochronological data indicate a substantial low sedimentary and tectonic burial testifying minor amounts of orogenic shortening with a prevailing thick-skinned structural style and scarce exhumation when compared to the Northern and Southern Apennines. In the Southern Apennines, thermal indicators record exhumation of sedimentary units in the axial zone of the chain from depths locally in excess of 4 km (Lagonegro Unit and Monte Alpi structure). Apatite fission-track data indicate that exhumation marks the late tectonic stages (younger than 10 Ma) of chain evolution, probably initiating with the buttressing of the allochthonous wedge against the thickening passive margin of Adria microplate. On the other hand, higher structural units (derived from Apenninic platform deformation) show variable amounts of burial along the strike of the chain (increasing from Lucania to North Calabria border). In Eastern Sicily thermal maturity decreases from hinterland to foreland as a result of less severe thermal evolution and/or tectonic loading apart from the Peloritani Mts. in the hinterland that subdued two different phases of exhumation: the first between 35-20 Ma and the second younger than 15 Ma. Accretionary prism made up of Sub-ligurian unit (namely Sicilidi) in the footwall of the Peloritani Mts. mainly exhumed in Burdigalian times (17-19 Ma) from depths of a few kilometers. Frontal thrust stack derived from late deformation of Mesozoic passive margin successions mainly exhumed in Tortonian-Pliocene times from depths of about three kilometers. Syn-orogenic siliciclastics (mainly thrust-top basins) generally show low thermal maturity testifying scarce burial apart from those at the rear of the chain (on top of the Peloritani Mts) that are thermally imprinted by out-of-sequence reactivation in Serravalian times followed by fast exhumation in extensional regime.

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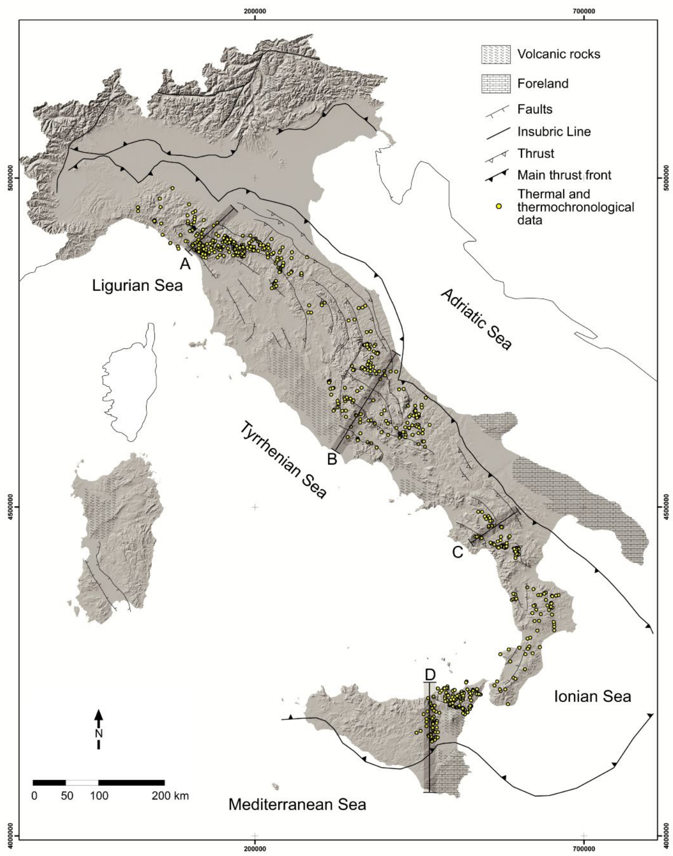
Paper is in dynamic review. Readers are invited to submit comments to the author and cc: team@virtualexplorer.com.au.

Introduction

Reconstructing paths and rates of exhumation in orogens is one of theare main goals in defining their kinematics. Traditional contributions to this topic have been provided by classical geochronological techniques when dealing with the inner portions of orogens. The advent of fission tracks studies since the early sixties allowed to dateenabled dating of the last portion of exhumation paths at shallow crustal levels thanks to low closure temperatures of zircon and apatite (respectively about 240 and 110°C). Furthermore, the improvement of knowledge about He diffusion in apatite allowed the development in the last 10 years of a new technique that provides quantitative constraints to the very final last path of exhumation down to 40°C. As a matter of fact, apatite fission track (AFT) and apatite (U–Th)/He [hereafter (AHe)] are the most widespread thermochronometers for investigating the tectonic and climate-driven interactions for durations of heating and cooling in excess of 106 years within the top few kilometers of the crust (e.g., Ehlers and Farley, 2003; Reiners and Brandon, 2006). These techniques are also widely used for investigating burial conditions in sedimentary basins in different tectonic settings and in the external portions of orogens (namely fold and thrust belts) that are, par excellence, the sites devoted to hydrocarbons genesis and accumulation, where maximum burial amounts (due to either sedimentary loading or overthusting) never exceed a few kilometers. In these settings, the reconstruction of burial and exhumation processes is a crucial issue for petroleum exploration. Low temperature thermochronology is then generally coupled with paleothermal indicators - as a combined approach can provide information on both time and extent of burial and cooling evolution. Among the existing paleothermal indicators, the most widespread is vitrinite reflectance that provides detailed resolution in diagenesis and very low grade metamorphism as it increases irreversibly with temperature and depth (Dow, 1977; Stach *et al.*, 1982). Other organic matter thermal indicators derived from fluorescence colours and thermal alteration of palinomorphs (Staplin, 1969) and pyrolisis (Tissot and Espitalié, 1975) may be used to strengthen vitrinite data. Paleo-thermal indicators from clay mineralogical assemblages, measured by X-ray diffraction, such as Kübler Index (Kübler, 1967) and illite content in mixed layer illite-smectite (I-S) may be used for reconstructing maximum burials as well (Pollastro, 1993). Although each approach has its own advantages, in general clay mineral and organic maturity indicators are complementary or at least compensate each other where they cannot be applied singularly. The integration of vitrinite reflectance and illite content in I-S may provide important pieces of information on heating rates that cannot be provided by a single indicator (Hillier *et al.*, 1995 for review; Aldega *et al.*, in press for applications).

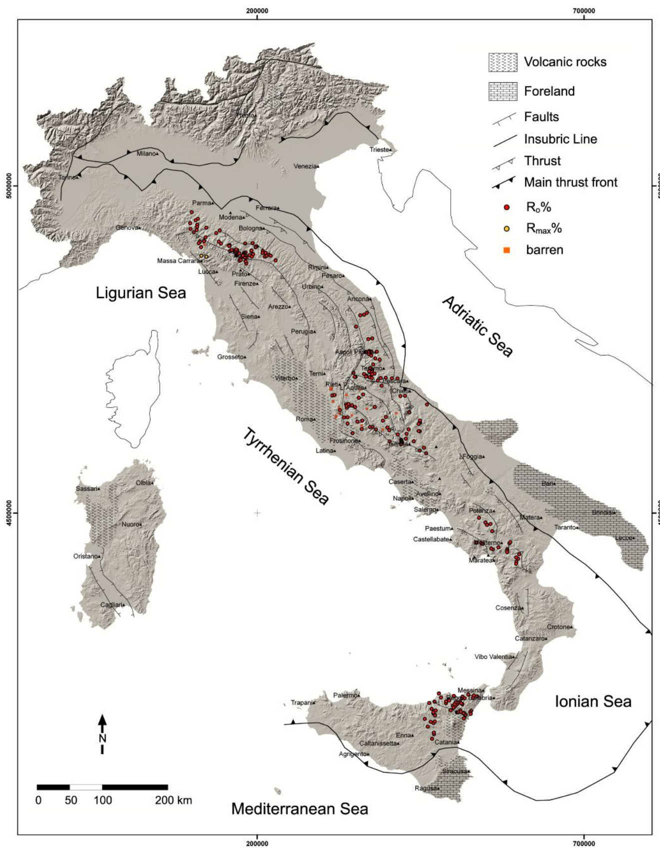
The main purpose of this paper is to provide, for the first time, an updated database of thermal and thermochonological indicators for the Italian Apennines fold-and thrust belt with special regard to sedimentary units (Figs. 1-5). It may represent a robust starting point for validating structural and geodynamic models that include modelling of the vertical movements within the orogen. This database, organized in ArcGIS platform, gathers most of the data from samples with known location and sampling coordinates, collected in the last fifteen years along four representative regional sections of the Apennines, with contributions provided in the eighties on organic thermal maturity in the Northern Apennines (Reutter, 1980; 1983; 1991). Other available mineralogical data used to detect diagenetic and low-grade metamorphic stages of different tectonic units in Northern (e.g., Leoni *et al.*, 1996; Carosi *et al.*, 1999; 2003, Dellisanti *et al.*, 2008) and Southern Apennines (Perri *et al.*, 2008) and in Sicily (Barbera *et al.*, 2009) were not added in the database for the lack of sampling coordinates.

Figure 1. Distribution of paleo-thermal and thermo-chronological along the Apennines and Sicily



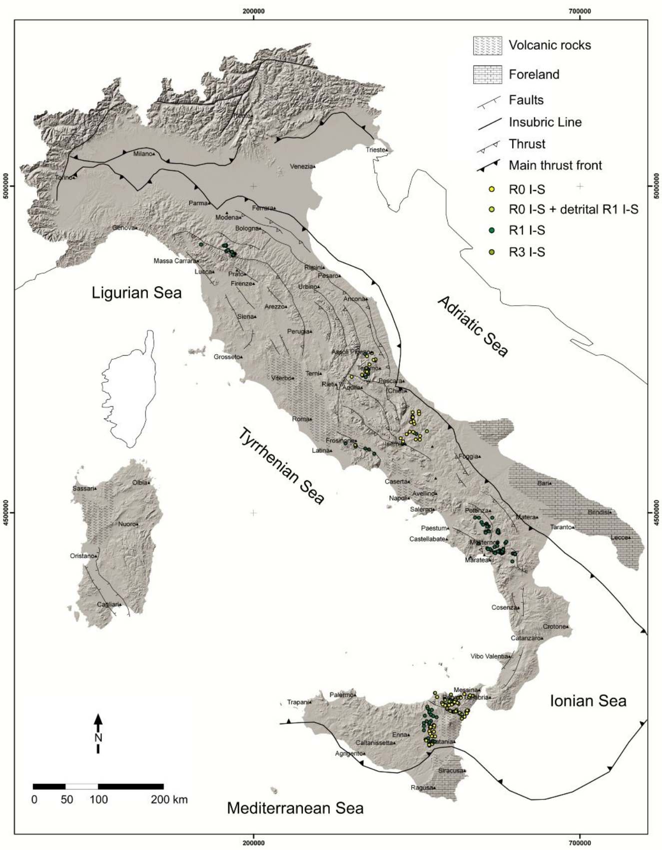
Digital Elevation Model of the Italian peninsula showing the distribution of vitrinite reflectance, Kübler Index, illite content in mixed layers I-S, apatite and zircon fission tracks and U/Th-He data along the Apennines and Sicily. Simplified main geological features from APAT (2004). Coordinates in UTM European Datum 1950 33N. Traces of cross-sections of Fig.6 are shown.

Figure 2. Distribution of organic matter thermal maturity data along the Apennines and Sicily



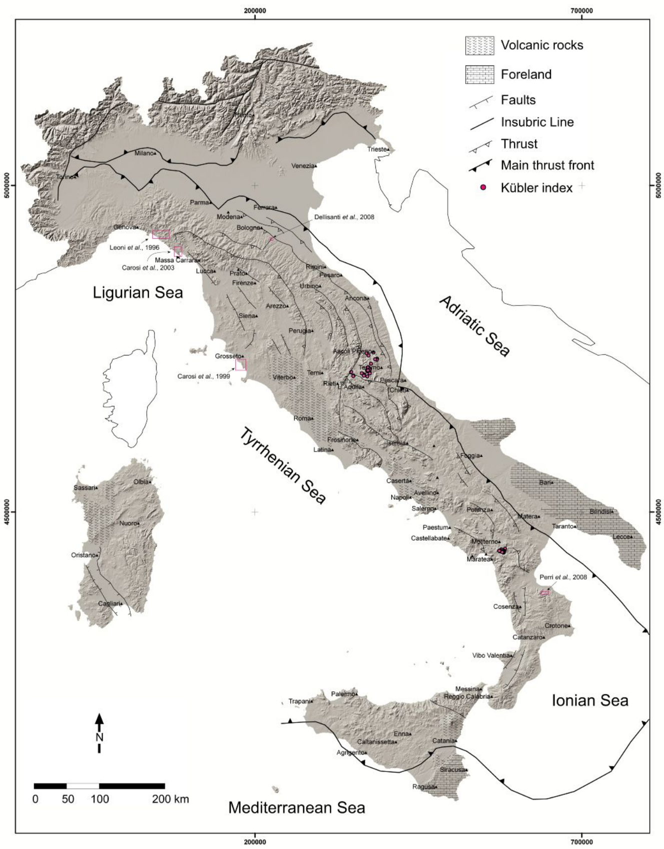
Digital Elevation Model of the Italian peninsula showing vitrinite reflectance data distribution along the Apennines and Sicily. Simplified main geological features from APAT (2004). Coordinates in UTM European Datum 1950 33N.

Figure 3. Distribution of illite content in mixed layers I-S along the Apennines and Sicily



Digital Elevation Model of the Italian peninsula showing the distribution of illite content in mixed layers I-S along the Apennines and Sicily. Simplified main geological features from APAT (2004). Coordinates in UTM European Datum 1950 33N.

Figure 4. Distribution of Kübler Index data along the Apennines



Digital Elevation Model of the Italian peninsula showing the distribution of Kübler Index data along the Apennines. Boxes define study areas which are not included in the database for the lack of sampling coordinates. Simplified main geological features from APAT (2004). Coordinates in UTM European Datum 1950 33N.

Figure 5. Distribution of thermo-chronological data along the Apennines and Sicily

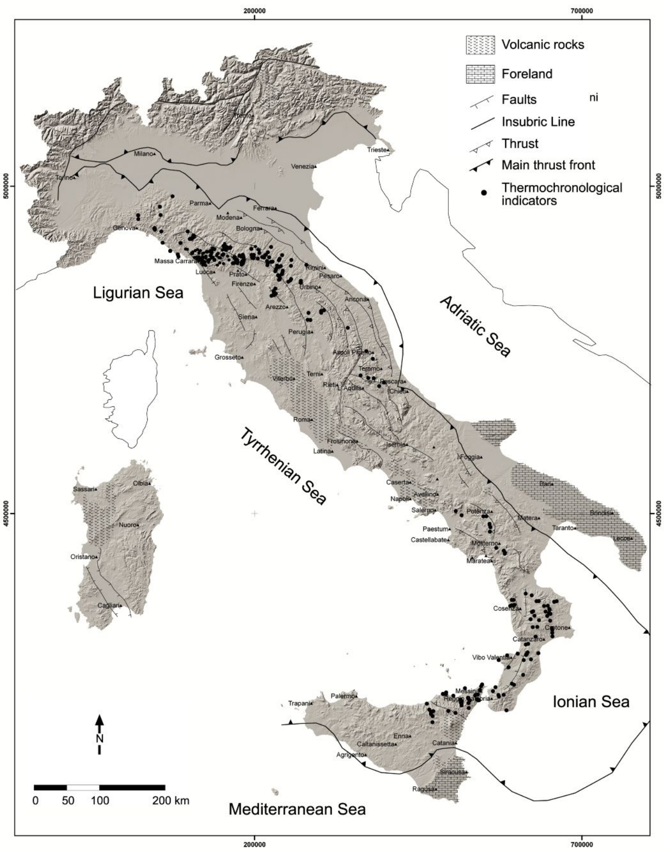


Fig. 5. Digital Elevation Model of the Italian peninsula showing the distribution of apatite and zircon fission tracks and U/Th-He dating along the Apennines and Sicily. Simplified main geological features from APAT (2004). Coordinates in UTM European Datum 1950 33N.

Brief geological setting

In the central Mediterranean region, the Apenninic-Maghrebian orogen is the result of the convergence between Eurasia and Africa that has been leading since Late Cretaceous to the juxtaposition of arcuate fold-and-thrust belts and associated back arc basins (Dewey *et al.*, 1989).

The Apennines and Sicily are the result of the development of a convergent orogenic wedge above subduction of the remnant of the Neotethys Ocean followed by collision with the continental passive margins of the Adriatic microplate and Africa plate and the opening of the Tyrrhenian Sea back-arc basin (Dewey *et al.*, 1989; Malinverno and Ryan, 1986; Boccaletti *et al.*, 1990; Faccenna *et al.*, 2004).

Since the Late Cretaceous to Middle Eocene, consistent portions of the Mesozoic oceanic lithosphere were subducted. The chain developed through the deformation of major paleogeographic internal domains (tectono-sedimentary sequences of the Ligurian-Piedmont Ocean) and external domains (sedimentary sequences derived from the deformation of the continental Adria-African passive margin). The continuity of the Apennine chain is abruptly interrupted in the Calabrian Arc by the Kabylo-Calabrian crystalline terranes. Major complexities (e.g., sharp deflections in the arcuate thrust belt configuration, thrusts out-of-sequence propagation) are referred to contrasting rheology and differential buoyancy of the subducted lithosphere and consequent differential rollback of the Adria plate margin, and to competence contrasts in the Mesozoic stratigraphic sequences, where multiple décollement horizons at different stratigraphic levels may have favoured significant differential shortening.

Since the Late Miocene, thrust belt geometry was strongly modified by extensional faulting, volcanic activity, crustal thinning and formation of oceanic crust related to the development of the Tyrrhenian Basin (Elter *et al.*, 2003).

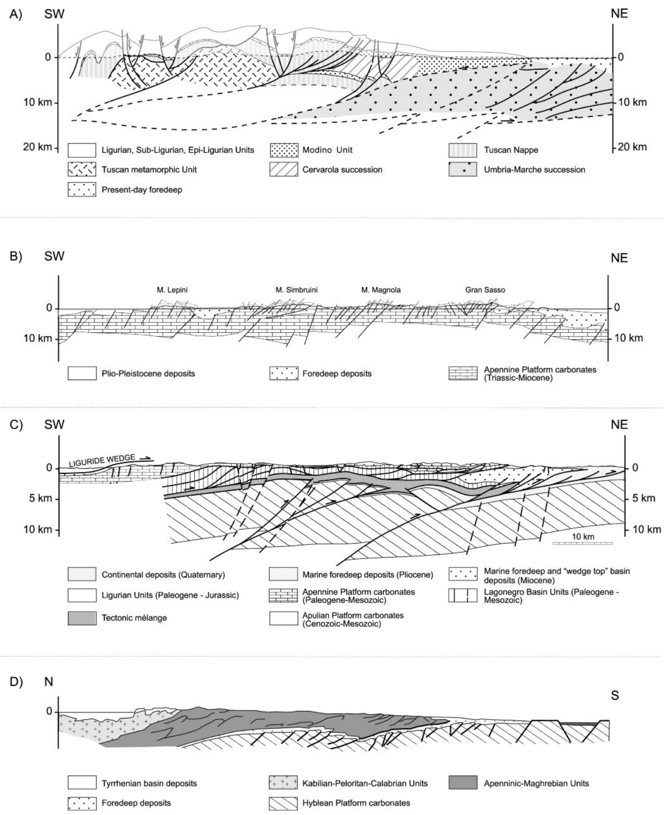
Northern Apennines

The oldest and uppermost tectonostratigraphic unit of the northern Apennines is the Ligurian unit: a mix of ophiolite, pelagic sedimentary rocks and continentally-derived ‘Helminthoid’ flysch deposits accreted during Late Cretaceous to Eocene subduction of oceanic crust of the Ligurian-Piedmont ocean basin below Corsica and Sardinia (Elter, 1975; Marroni *et al.*, 2001). The Ligurian rocks in the northern Apennines are unconformably overlain by Eocene to Pliocene sedimentary deposits known as the Epiligurian unit deposited in marine thrust-top piggyback basins (Ricci Lucchi, 1986; Barchi *et al.*, 2001; Cibin *et al.*, 2001). Both the Ligurian and Epiligurian units are disrupted by extensive tectonic and sedimentary mélange deposits commonly referred to as *argille scagliose* (Pini, 1999; Cowan and Pini, 2001; Pini *et al.*, 2004). Immediately underlying the Ligurian unit is a tectonic unit known as the Subligurian, made up of Paleocene-Eocene shales and limestones (Bortotti *et al.*, 2001) and thick early Oligocene siliciclastic turbidite rocks. The Subligurian unit is considered as the first and oldest

Apennine foredeep deposits marking the onset of collision of the Ligurian accretionary wedge with the former continental passive margin of the Adria microplate (Catanzariti *et al.*, 2003).

The Oligocene to Recent collisional history of the Apennine orogeny is characterized by thick and extensive syn-orogenic foredeep turbidite sedimentation. These deposits, along with their substrata of Paleozoic crystalline basement and Mesozoic-Cenozoic carbonate and evaporite rocks of the former Adria continental margin, were progressively deformed and accreted as a series of nappes into the northern Apennine orogenic wedge before being tectonically overridden by rocks of the Ligurian and Epiligurian units (Argnani and Ricci Lucchi, 2001; Fig. 6 cross section A). Two main units or domains are recognized: the Tuscan unit and the Umbria-Marche unit.

Figure 6. Simplified geological cross sections across the Italian Apennines



Simplified geological cross sections across the Apennines. Traces are shown in Fig.1. A: Northern Apennines after Laboume (1992) redrawn and modified; B: Central Apennines after Tozer *et al.* (2002) redrawn and modified; C: Southern Apennines after Mazzoli *et al.* (2006) redrawn and modified; D: Sicily after Lentini *et al.* (2000) redrawn and modified (Not to scale).

Each unit has a similar Mesozoic-Cenozoic succession of Triassic evaporites overlain by thick Jurassic to Paleogene platform and pelagic carbonates (Barchi *et al.*, 2001; Castellarin, 2001). The two units are distinguished by the age of onset and cessation of siliciclastic turbidite deposition and their paleogeographic position in relation to the advancing orogenic front; the Tuscan unit being accreted before, and lying tectonically above the Umbria-Marche unit. The turbidites of the Tuscan unit are subdivided into the Macigno (late Oligocene-early Miocene), and Cervarola (early Miocene) Formations (Ricci Lucchi, 1986; Sestini *et al.*, 1986).

Deeper metamorphosed and highly deformed Tuscan unit rocks are exposed in the Alpi Apuane tectonic window and include the Pseudomacigno (the metamorphic equivalent of the Macigno) as well as Paleozoic basement and the Mesozoic Carrara marbles. These rocks underwent late Oligocene to early Miocene HP-LT metamorphism (350-480°C; 5-9 kbar) in a stacked duplex thrust system and were then progressively exhumed from mid crustal depths before being structurally juxtaposed against overlying non-metamorphic rocks of the Tuscan unit along a major low angle detachment fault (Carmignani and Kligfield, 1990; Jolivet *et al.*, 1998; Carmignani *et al.*, 2001; Fellin *et al.*, 2004).

The Umbria-Marche unit is characterized by extensive mid- to late-Miocene turbidites of the Marnoso-arenacea (MA) Formation. The MA Formation is capped by evaporite deposits marking the onset of the Messinian salinity crisis (Ricci Lucchi, 1986, 2003; Boccaletti *et al.*, 1990; Argnani and Ricci Lucchi, 2001; Zattin *et al.*, 2002).

Much of the syn- and post-Messinian sedimentary record of the northern Apennine accretionary wedge is currently buried beneath mid- to late-Quaternary alluvial deposits of the Po Plain. Post-Messinian deposits comprise mainly deep marine clastic turbidites (Fusignano, Porto Corsini, and Porto Garibaldi Formations). Late Pleistocene deposits record a shallowing upward trend, with marine sands (Sabbie Gialle Formation) grading upward into alluvial clastic deposits of the Po River (Castellarin, 2001).

The largely in sequence thrusting, accretion, and underplating of the Tuscan and Umbria-Marche units reached its maximum northward extent in the late Messinian-early Pliocene along the buried Monferrato, Emilia, and Ferrara-Romagna arcuate thrust fronts. The early Pliocene also marks the final NE advancement of the

Ligurian unit rocks to their current position tectonically overlying the foredeep deposits of the Marnoso-Arenacea Formation. The emplacement of the Ligurian nappe is proposed to have occurred by gravitational gliding below sea-level into the foredeep depression as a process independent from thrusting in the underlying deposits (Landuzzi, 1994; Zattin *et al.*, 2002). Several authors have proposed that since the middle Pliocene, shortening within the northern Apennines has become more complex with reactivation and out-of-sequence thrusting distributed across the more internal parts of the orogenic wedge (Castellarin, 2001; Ford, 2004) with emplacement of Macigno unit rocks over the Ligurian unit along the out-of-sequence Cervarola-Falterona thrust (Boccaletti and Sani, 1998) and shortening across the Apennine-Po Plain front (Montone and Mariucci, 1999; Argnani *et al.*, 2003).

On the internal Tyrrhenian (SW) flank of the northern Apennines, the accretionary tectonostratigraphy is disrupted by later widespread Miocene to Recent extension. The most important mode of extension is characterized by ductile stretching and generally east-dipping low angle extensional detachment faulting that began in Burdigalian times in northeastern Corsica (Jolivet *et al.*, 1990; Fellin *et al.*, 2005), migrated eastward from the Tortonian to Pliocene (Carmignani *et al.*, 1994; Keller *et al.*, 1994; Jolivet *et al.*, 1998) and is presently active along the Altotiberina low angle normal fault system in the internal southernmost northern Apennines (Boncio *et al.*, 2000; Collettini *et al.*, 2006). Low angle normal faulting and ductile thinning reflect between about 60% and 120% total extension since the early Miocene (Carmignani *et al.*, 1994; Bartole, 1995). A second mode of extension is typified by high-angle brittle normal faults and the development of orogen-parallel NNW-SSE trending graben and half graben and represents total extension of about 6-7%. The age of the basal sedimentary deposits within these graben gets younger in an eastward direction, ranging from Serravallian in the offshore northern Tyrrhenian Sea, to Pleistocene in the youngest graben located close to the current Apennine crest (Bartole, 1995; Boccaletti and Sani, 1998; Martini *et al.*, 2001). Carmignani *et al.* (1994; 2001) have proposed that extension occurred as two discrete events, with core complexes related to thinning of an overthickened crust followed by later development of high angle normal faults related to opening of the Tyrrhenian Sea. However, more recent analysis of the active Altotiberina low angle fault and exhumed low angle detachments in the Alpi Apuane and Elba Island to the west reveal that many of the high angle brittle normal faults and their related half graben root into the deeper low angle detachments and stretched ductile middle crust, supporting a cogenetic model for the two modes of extension (Bartole, 1995; Boncio *et al.*, 2000; Collettini *et al.*, 2006). To the south, the Neogene east- northeastward migration of extension is accompanied in its waning stages by significant magmatism that is lacking further north (Serri *et al.*, 2001).

Central Apennines

The backbone of the Central Apennines is made up of tectonic units accreted with a main E and NE sense of transport (Bigi *et al.*, 1990) dominated by pre-orogenic Triassic-Miocene, mainly carbonate sequences derived from the deformation of the Adria passive margin and overlain by Miocene to Quaternary syn-and post-orogenic sediments (Fig. 6 cross section B). Internal units, such as the Sub-ligurian at the top of the orogenic edifice, are scarcely preserved and are testified by olistostromes in the syn-orogenic deposits of the Latina Valley and on top of the innermost thrust sheets of this chain segment (Volsci Range).

The pre-orogenic setting is the result of various extensional events during the Triassic, Jurassic and Cretaceous-Paleogene (Centamore *et al.*, 1971; Decandia, 1982; Calabrò *et al.*, 2003) that created an articulated passive margin of Adria microplate where sedimentary successions in mainly carbonate platforms, pelagic basins, slope and intrabasinal highs facies range in thickness from about 1,000 (pelagic basins) to 5,000 m (carbonate platforms) (Parotto and Praturlon 1975; Damiani *et al.*, 1991 and references therein).

Different stratigraphic domains can be distinguished from the west to the east: the Umbria-Marche-Sabina slope-to-basin, the Latium-Abruzzi carbonate platform, the Molise-Sannio basin and the Apulian carbonate platform.

The Sabina unit consists of upper Triassic-Miocene sediments mainly of pelagic and slope facies and represents the southern extension of the Umbria-Marche basin. It is arranged at least in three main N-S and NW-SE striking thrust sheets verging toward the east. In the western side of this unit a N-S right-lateral strike-slip fault dissects the earlier thrust structure. The eastern tectonic boundary of this area is marked by the Olevano-Antrodoco out-of-sequence thrust (Cipollari and Cosentino, 1992) where the pelagic sediments of the Sabina region overthrust the Apenninic carbonate platform and its associated siliciclastic deposits.

The Apenninic carbonate platform comprises shallow-water Mesozoic carbonate successions strongly influenced by the pre-existing basin architecture. The region is particularly important because it contains the most dramatic lateral change in tectono-stratigraphic units in the Apennines. These units are now telescoped into several NW-SE oriented thrust sheets showing a NE transport direction (Accordi *et al.*, 1988). Along their south-western sides, these thrust sheets are dissected by steep NW-SE trending faults. Structural and stratigraphic data suggest both normal (prevailing) and left-lateral strike-slip motion for these faults, with earlier transcurrent faults being reactivated as dip-slip features. These faults bound NW-SE trending structural depressions filled with upper Miocene turbiditic deposits that are progressively younger (from Serravallian to Messinian age) toward NE (e.g., Cipollari and Cosentino, 1996).

In the eastern Marsica region, at the eastern boundary of the Apenninic carbonate platform, the Mesozoic facies evolve from carbonate platform to Meso-Cenozoic slope facies (Colacicchi, 1967; Miccadei, 1993). This region is organised in a series of E to ENE verging thrusts, overprinted by N-S trending strike-slip faults (Mattei and Miccadei, 1991; Corrado *et al.*, 1992).

To the southeast of the Apenninic carbonate platform, in the Matese Mts., and to the North, in the Gran Sasso range, the main contractional structures evolve into an E-W trend with a general north vergence and the pre-orogenic facies evolve to the surrounding pelagic basins (respectively Molise-Sannio and Umbria-Marche in Scrocca and Tozzi, 1999 and Ghisetti and Vezzani, 1991). They plunge to the north under Lower Messinian turbiditic deposits (Laga and Agnone flysch).

The more external Apulian carbonate platform crops out farther to the east with a predominant NNW trend of ENE vergent thrusts, offset by mainly NNW trending normal and strike-slip faults (Miccadei, 1993; Corrado *et al.*, 1995). The carbonate platform succession consists mainly of upper Triassic-Cretaceous deposits that locally evolve upward into slope and pelagic basin facies since the Jurassic. Upward in the succession, a Langhian to Tortonian carbonate ramp unit is overlain by upper Messinian-lower Pliocene siliciclastic deposits that become progressively younger toward the east (Patacca *et al.*,1992).

Farther to the east, the Apulian carbonates, unconformably overlain by Pliocene hemipelagic sediments, dip under the Sannio-Molise units and under the Plio-Pleistocene foredeep deposits (Patacca *et al.*, 1992), to crop out again in the Apulian foreland to the east.

The Sannio-Molise pelagic units detached on the top of the buried Apulian platform, include Oligocene and lower Miocene pelagic basin deposits made up of mainly smectite rich clays, known as “Argille varicolori”. The succession evolves upward into calcarenites interbedded with marly and calcareous turbidites of Miocene age. Overlying Upper Miocene syn-orogenic deposits show a more proximal facies in the Sannio units and a more distal facies in the Molise units (Patacca *et al.*, 1992; Di Bucci *et al.*, 1999), thus indicating that these thrust sheets originated from different portions of the same basin located between the Apenninic and the Apulian platform. These units, detached from their Meso-Cenozoic substratum along the “Argille varicolori” detachment zone, overthrust the buried Apulian carbonates forming a N to NE-vergent thrust system (Corrado *et al.*, 1997). On the other hand, “Argille varicolori” belonging to the inner Sicilide domain are mainly located in the Latina Valley. Since Miocene, pre-orogenic successions were deformed by E and NE verging folds and related thrusts interacting with the pre-existing structures and developing a variety of geometries. Pre-thrusting normal faults have influenced compressive deformation, have acted as focussing structures for thrust ramp localization or were positively inverted (Butler *et al.*, 2006, Scisciani, 2009). Contraction migrating towards the East was coupled with the progressive development of syn-orogenic deposits in front (foredeeps) and on top of the fold-and-thrust belt whose age is bracketed between Burdigalian and Lower Pliocene (Patacca *et al.*, 1992; Cipollari and Cosentino, 1995).

Besides most of accretion propagated in a piggy-back mode, several out-of-sequence reactivations or synchronous activity occurred within the belt. The most important is represented by the Olevano-Antrodoco line that marks the overthrust of the Umbria-Marche-Sabina domain onto the Latium-Abruzzi carbonate Platform in Lower Pliocene times (Parotto and Praturlon, 1975; Cipollari and Cosentino 1992). Furthermore strain partitioning along transpressional discontinuities active in Upper-Pliocene-Pleistocene marks the end of collision responsible of rotations about vertical axis (Alfonsi *et al.*, 1991; Corrado 1995; Mattei *et al.*, 1995; Corrado *et al.*, 1997; Butler *et al.*, 1997; Tavarnelli *et al.*, 2004; Sani *et al.*, 2004).

Extensional tectonics related to the opening of the back-arc Tyrrhenian Basin have been dissecting the compressive edifice since Miocene times (Serravallian) rejuvenating from hinterland to foreland accompanied by the development of syn-rift basins, presently well preserved at the rear of the chain. Some of these normal faults are still active in the axial zone of the chain and along the Adriatic margin (D'Agostino *et al.*, 2001).

Southern Apennines

The southern Apennines thrust belt is NE-directed and, except for the remnants of units from the Internal Zone (e.g., ophiolite-bearing Ligurian units) that occur on top of the thrust pile, it is composed entirely of Mesozoic and Cenozoic sedimentary rocks of the External Zone (e.g., Cello and Mazzoli, 1999; Patacca and Scandone, 2007). The Apulian promontory represents the orogenic foreland. Collectively, the Apulian foreland and the deformed strata of the Apennines represent a telescoped continental margin with complex sub-basins of different ages (e.g., Mostardini and Merlini, 1986; Sgrosso, 1998; Cello and Mazzoli, 1999, and references therein).

Large amounts of subsurface data, particularly oil wells, demonstrate large-scale thin-skinned thrusting in the shallow part of the southern Apennines. The thrust belt forms a displaced allochthon that has been carried onto a footwall of foreland strata essentially continuous with the Apulian platform (e.g., Mostardini and Merlini, 1986; Carbone *et al.*, 1991; Mazzoli *et al.*, 2000; Menardi Noguera and Rea, 2000; Butler *et al.*, 2004; Fig. 6 cross section C). The detachment between the allochthon and the buried Apulian shallow-water carbonates is marked by a mélange zone up to several hundred meters thick. It consists mainly of intensely deformed and overpressured deepwater mudstones and siltstones of Miocene to Lower Pliocene age, including blocks of material derived from the overlying allochthon (Mazzoli *et al.*, 2001; Butler *et al.*, 2004; Shiner *et al.*, 2004). Beneath the mélange zone, under a thin but variable thickness of Pliocene shales stratigraphically overlying the Mesozoic-Tertiary platform carbonates, the hinterland portion of the Apulian unit was involved in the final phases of compression (late Pliocene - early Pleistocene; e.g., Cello and Mazzoli, 1999, and references therein). This resulted in reverse-fault-related, open, long-wavelength, high-amplitude folds that form the hydrocarbon traps for the significant oil discoveries in this area (Shiner *et al.*, 2004). All recent, geologically realistic interpretations based on subsurface data indicate that deep-seated thrusting within the Apulian carbonates is characterized by relatively limited horizontal displacements, and probably by involvement of the underlying basement (Mazzoli *et al.*, 2000; Menardi Noguera and Rea, 2000; Speranza and Chiappini, 2002; Butler *et al.*, 2004; Shiner *et al.*, 2004). Therefore, during the late Pliocene, a switch from thin-skinned to thick-skinned thrusting appears to have occurred in the southern Apennines as the Apulian carbonates - and the underlying thick continental lithosphere - were involved in deformation (Mazzoli *et al.*, 2000; Butler *et al.*, 2004).

Neogene thrusting in the Calabrian Arc and in the southern Apennines was accompanied by back-arc extension and sea-floor spreading in the southern Tyrrhenian Sea (e.g., Kastens *et al.*, 1988; Faccenna *et al.*, 1996, 1997, and references therein; Mattei *et al.*, 1999). Around the early-middle Pleistocene boundary (ca. 0.8 Ma B.P.), however, SW-NE-directed shortening ceased in the frontal parts of the southern Apennines, too. A new tectonic regime established itself in the chain and adjacent foothills (e.g., Cello *et al.*, 1982; Cinque *et al.*, 1993; Montone *et al.*, 1999). The structures related to this new regime, characterized by a NE-SW oriented maximum extension, consist of extensional and transcurrent faults that postdate and dissect the thrust belt (e.g., Cello *et al.*, 1982; Butler *et al.*, 2004).

Calabria

The nappe-structured belt of the Calabria-Peloritani orogen is a part of the peri-Mediterranean Alpine system that progressively drifted during the Neogene to Recent opening of the South Tyrrhenian basin and the subduction of the Ionian slab (e.g., Amodio Morelli *et al.*, 1976; Dewey *et al.*, 1989). Its structure and evolution has been classically separated from that of the Apennines, based on the exposed rock types and the evidence for pre-Neogene tectonism. It is unclear whether the Calabria block formed part of the European continental palaeomargin (e.g., Boullin *et al.* 1986; Cello *et al.* 1996; Jolivet and Faccenna 2000; Rossetti *et al.* 2001) or resulted at least in part from earlier periods of northwestward accretion and/or microplate collision and amalgamation (e.g. Amodio Morelli *et al.*, 1976; Grandjacquet and Mascle 1978; Bonardi *et al.*, 2001, Tortorici *et al.*, 2009).

In the northern part of the Calabria, three main groups of nappes may be distinguished: (1) crystalline basement nappes; (2) ophiolite-bearing nappes; (3) mostly calcareous nappes derived from the inner part of the Apulia continental margin. Group (1) includes Variscan metamorphic rocks and granitoids, and Mesozoic low-grade metasedimentary cover of the Bagni Units and sedimentary cover of the Sila Unit (Iannace *et al.*, 2007). These overlie ophiolite-bearing units ranging from greenschist-facies (Malvito unit) to blueschist-facies (Diamante-Terranova unit). Some of these units, the HP–VLT Frido unit and the unmetamorphosed North Calabrian unit (Bonardi *et al.*, 1988), crop out NE of the Pollino Massif. The ophiolite-bearing units tectonically overlie tectonic units of the southern Apennines fold and thrust belt, derived from Miocene to early Pleistocene deformation of the sedimentary cover of the Apulia passive margin. These tectonic units (group 3) are dominated by Mesozoic–Neogene sedimentary successions comprising kilometre-thick, shallow-water to slope carbonates and pelagic basin cherts, limestones and pelites, as well as a complex pattern of Neogene–Quaternary siliciclastic strata deposited in thrust-top and foredeep basin environments. Farther to the south, in the Aspromonte Massif only crystalline basement nappes are exposed.

The pre-Alpine history of the Calabria block is poorly defined. However radiometric data and rare occurences of Paleozoic fossils indicate that the entire basement was affected by Variscan-age metamorphism, locally superimposed on an older high grade metamorphic event (Bonardi *et al.*, 2001).

The first stage of the Alpine orogenic cycle was the result of subduction of Neotethyan oceanic litosphere between the Cretaceous and the Neogene. This led to the opening of the Ligurian Sea Basin, the formation of the Ligurian accretionary wedge (Knott, 1987), the Corsica-Sardinia rotation and major calc-alkaline volcanism in Sardinia (Savelli *et al.*, 1979). This phase of activity ceased during the Burdigalian around 18 Ma (Montigny *et al.*, 1981). Then a second compressive phase occured during the middle Miocene causing collision and emplacement of the Calabrian basement rocks on to the African and Adria plate margin.

Extensional tectonics overprinted Alpine and Apennine compressive events as suggested by Rossetti *et al.* (2001) on the basis of structural and petrophysical investigation. These authors documented that the Alpine- (west directed) versus Apennine- (east directed) verging structures in north Calabria resulted from the superimposition of a top-to-the-west postorogenic extensional shearing onto an early east directed nappe forming event. A similar northwest directed extensional shearing was also reported by Platt and Compagnoni (1990), recognized as responsible for controlling nappe contacts within the Calabrian units exposed in the Aspromonte region of south Calabria. This stage of tectonism was thin-skinned in nature and distrupts much of the pre-Miocene geometry of the crystalline basement rocks (Van Dijk and Okkes, 1991).

Eastern Sicily

In North-Eastern Sicily, the orogen is organised into two main tectono-stratigraphic domains: the Kabilian-Peloritan-Calabrian units to the North-East, and the Apenninic-Maghrebian units and the External Thrust-sheets System to the South (Catalano *et al.*, 1996; Lentini *et al.*, 1996; Grasso, 2001; Fig. 6 cross section D).

The Kabilian-Peloritan-Calabrian belt includes imbricate sheets of Paleozoic metamorphic and igneous rocks, and Mesozoic sedimentary covers. In NE Sicily, the belt crops out in the Peloritani Mts., which contains a series of south-verging thin continental crustal nappes (Messina *et al.*, 2004). Upper Oligocene-lower Burdigalian wedge-top deposits of the Stilo-Capo d'Orlando Fm. (Lentini *et al.*, 2000, and references therein) post-date their main emplacement. The crystalline nappes still widely preserve the Variscan signature (De Gregorio *et al.*, 2003; Somma *et al.*, 2005). Some nappes record Alpine metamorphism (Atzori *et al.*, 1994), followed by substantial exhumation prior to their final emplacement on top of the Apenninic-Maghrebian units, as indicated by zircon and apatite fission track data (Thomson, 1994). This early exhumation is controlled by syn-orogenic extension (Cutrupia and Russo, 2005) pre-dating the overthrusting onto the Apenninic-Maghrebian belt in early Miocene times (Amodio-Morelli *et al.*, 1976). The tectonic contact on land between the Kabilian-Peloritan-Calabrian belt and the underlying Apenninic-Maghrebian belt is marked by the Longi-Taormina lineament (Bonardi *et al.*, 1976). Its kinematic evolution is widely debated (see Catalano *et* *al.*, 1996; Pepe *et al.*, 2000; 2005; Billi *et al.*, 2007 for a review), and started in early Miocene (Amodio-Morelli *et al.*, 1976) with the Kabilian-Peloritan-Calabrian belt which overthrust the innermost sedimentary units of the Apenninic-Maghrebian belt. The Apenninic-Maghrebian belt, mostly formed during Miocene time, is made up of imbricate sheets of Mesozoic-Tertiary rocks (Lentini *et al.*, 1995). Its structurally highest, tectono-stratigraphic units are derived from the deformation of the distal pre-orogenic domain (Sicilide Complex; Ogniben, 1960) and were generally involved in the Neotethyan accretionary wedge (Lentini *et al.*, 2005). Their present-day geometric relationships are the result of frontal accretion, activation of extensional low-angle detachments and re-imbrication that significantly reorganized the original stratigraphic setting in different tectonic units (Lentini *et al.*, 1996). The Sicilide Complex includes south-verging units interpreted as trench deposits (M. Soro and Troina units) that are well exposed in the Nebrodi Mts. and the distant Sicilide units cropping out in the frontal zone of the present-day chain which were completely detached and scraped from the basal portion of the succession and transported to the front of the chain in early Miocene times (Bianchi *et al.*, 1989; Carbone *et al.*, 1990; Butler *et al.*, 1992). Gravity-driven transport might have contributed to its far-travelled location in the present-day structural setting (Corrado *et al.*, 2009).

Tectonically beneath the Sicilide Complex, more external tectono-stratigraphic units are present (e.g., Mt. Judica unit). They formed, in part, at the expense of the African continental paleo-margin and consist of rootless units, mainly derived from shortened and rotated pelagic Meso-Cenozoic basinal successions (Speranza *et al.*, 2003; Monaco *et al.*, 2004; De Guidi and Monaco, 2005). This deformation started in the early Miocene (Catalano and D’Argenio, 1982; Oldow *et al.*, 1990; Butler *et al.*, 1992) and continued until middle Pleistocene times (Lickorish *et al.*, 1999). The Numidian Flysch (cropping out in the Mt. Salici, Serra del Bosco and Nicosia units) represents the earliest foredeep deposit at the onset of collision. It was affected by contractional deformation since Langhian times and was followed by the deposition of the mid-Miocene (Gagliano Marls) and the upper Tortonian (Terravecchia Formation) clastic deposits (Catalano *et al.*, 1996). Terrigenous sedimentation continued until mid-Pliocene times in central Sicily and until the early mid-Pleistocene along the southern Sicilian margin (Bigi *et al.*, 1990).

In summary, two major shortening events generated the present-day structural configuration of the orogen following continental collision. The first event caused the superposition of the allochthonous units onto the Meso-zoic-Paleogene Hyblean foreland carbonates through low-angle thrusts in early Miocene times (Bianchi *et al.*, 1989; Butler *et al.*, 1992). The second event is considered to have occurred in late Miocene–early Pliocene times. It strongly modified the geometric relationships of the allochthonous units, producing the internal stacking of the Mount Judica succession (Bello *et al.*, 2000) and break-back, out of sequence, propagation of backthrusts in central-north Sicily (Carbone *et al.*, 1990; Grasso *et al.*, 1995).

Methodologies

Fission-track analysis

Fission tracks in apatite and zircon have been used in a wide range of studies in basin analysis since the early ’80, when many analysts moved from an absolute dating approach to a detailed definition of time-temperature paths (“thermochronology”). The most important difference with other low temperature indicators it that this methodology provides both temperature and time information. In fact, the annealing of fission tracks, particularly in apatite, can be used to reconstruct the thermal history of basins, from deposition and burial of sediments through subsequent cooling related to uplift and erosion. It is possible also to define localized temperature anomalies, such as those related to intrusions and to high-temperature fluids.

Fission-track dating is very similar to the other isotopic dating methods based on the decay of an unstable parent to a stable daughter atom. The age is function of the proportion between the abundance of the new stable isotope and the parent unstable atom. In fission-track dating methodology, these two quantities are substituted by the number of observable tracks and the amount of uranium present in the sample. Actually, the uranium content is determined through irradiation of sample with thermal neutrons in a nuclear reactor. Irradiation induces the artificial fission of ^{235}U whose relative abundance in respect of ^{238}U is constant in nature.

Both experimental data and the analyses on natural conditions have shown that tracks are shortened with increasing temperature (annealing process). The temperature range in which reduction of lengths occurs is known as Partial Annealing Zone (PAZ; Wagner and Van den Haute, 1992). According to this concept, temperatures of any geological setting are divided into three zones in respect to fission-track annealing:

- total annealing zone, in which the latent tracks are immediately erased after any fission event;
- partial annealing zone, where the ratio r/r_0 increases from 0 to 1 with the decrease of temperature;
- stability zone, where tracks are stable.

Temperatures at which annealing actually occurs depend on the rate of the geological process and the PAZ temperature range can not univocally defined. For apatite, temperatures between 140 and 120°C are cited for the bottom whereas 70 to 40°C for the top of the PAZ. More precisely, Gleadow and Duddy (1981), on the basis of data obtained from drill holes samples in the Otway basin, suggest a PAZ between 145 and 80°C for heating events 1 Ma long, and between 110 and 45°C for events 1 Ga long.

Since the tracks are used as a dating methodology, the cooling range in the PAZ have to be necessarily "simplified" in a single temperature value, to which the age has to be referred, defined by Dodson (1976) as the closure temperature. Wagner and Reimer (1972) suggest that the closure temperature corresponds to the temperature at which 50% of the tracks are retained. As for the annealing boundaries, closure temperature is function of the cooling rate but it can be reasonably estimated only if a sample cools monotonically through the PAZ. Using Dodson's (1979) equation, Brandon *et al.*, (1998) could calculate the following values: 128°C, 112°C, 98°C and 85°C for cooling rates of 100°C/Ma, 10°C/Ma, 1°C/Ma and 0.1°C/Ma respectively.

PAZ and closure temperature for zircon are not so well defined. However, a closure temperature of about 204°C is assumed for most common radiation-damaged zircon at cooling rates of 10°C/Ma (Reiners and Brandon, 2006).

Most data presented in this paper have been produced in the last fifteen years at Bologna University and CNR in Florence according to the following procedures. For details on analytical procedure see Zattin *et al.* (2002) and Balestrieri *et al.* (1996).

Apatite (U-Th)/He dating

Radiogenic He accumulated in apatite is lost by diffusion at even lower temperatures than the annealing of fission-tracks in the same mineral. Extrapolation of laboratory He diffusion experiments in apatite to geologic time (Farley, 2000), supported by evidence from borehole data (House *et al.*, 1999), show that He begins to be measurably lost above about 45°C, and entirely lost above about 85°C for a typical grain with radius of 60±20 µm (Wolf *et al.*, 1998). This range of temperatures - labelled the helium partial retention zone - is analogous to the apatite fission track partial annealing zone (e.g., Gallagher *et al.*, 1998; Reiners and Brandon, 2006; Wagner and Van den Haute, 1992). The closure temperature for He in apatite of typical grain radius is ~70°C at a cooling rate of ~10°C/Ma (Farley, 2000).

Most data presented in this paper have been produced in the last fifteen years at Yale University according to the following procedures. Dated crystals were handpicked and inspected under a high-powered binocular microscope with cross-polarization to eliminate grains with inclusions. Suitable grains were then measured in two orientations for later alpha-ejection correction, and loaded either as single or multiple grains into 1mm Pt tubes. Degassing of He was achieved by heating with a Nd-YAG laser in a high-vacuum laser cell connected to the He extraction and measurement line. Concentration of ^{4}He was determined by spiking with a known volume of ^{3}He and analyzing the isotope ratio in a quadrupole mass spectrometer according to the procedure outlined in Reiners *et al.* (2003). For U and Th analysis, degassed apatite grains were dissolved in situ from Pt tubes in HNO_3 and spiked with a calibrated ^{229}Th and ^{233}U solution. U and Th concentrations were determined by inductively coupled plasma mass spectrometry. Alpha ejection was corrected using the formula of Farley (2002). Based on the long-term reproducibility of Durango apatite standard analyses at Yale University, an analytical uncertainty of 6% (2σ) was applied to the apatite (U-Th)/He age determinations.

Vitrinite reflectance

Vitrinite derives from the thermal degradation of lignin and cellulose, and can be found in kerogens rich in high plants fragments. Furthermore vitrinite is an important "maceral" group occurring in coals (Stach *et al.*, 1982). As the maturity increases, a progressive ordering takes place in the vitrinite molecular structure which determines an increasing reflection capacity of incident light. This parameter (vitrinite reflectance) strictly depends on the thermal evolution of the hosting sediments and is correlated to the stages of hydrocarbon generation, coal rank and other thermal parameters in sedimentary environments (Durand, 1980). Thus it is the most widely used parameter to calibrate basin modelling in hydrocarbon exploration (Dow, 1977; Mukhopadhyay, 1994). The ranges defining the different maturity levels of kerogen are shown in Table 1; a correlation with further maturity parameters derived from both optical and chemical analyses, indicative paleotemperatures and coal ranks are shown besides.

Table 1

Maturation rank: Kerogen		Maturation rank: Coal	Paleo Temp. (1) (°C)	Microscopic parameters: Vitrinite Reflectance (Ro %)	TAI (2)	SCI (2)	CAI	Fluorescence of alginite	Chemical parameters: T_{max}	Biomarker Isomerization: Sterane	Biomarker Isomerization: Hopane	Hydrocarbon main products
Immature	Diagenesis	Peat		0.2				Bue-green				Bacterial gas
		Lignite		0.3	1 Yellow	1	1 Yellow	Greenish -yellow				
		Sub-bituminous Coal		0.4		2		Golden yellow	420		0,10	
			50	0.5 – 0.55		3			430	0,10 0,50	0,50	Immature heavy oil (3)
Mature	Catagenesis	Bituminous Coal		0.7	2 Orange	4						
				0.8		5	2 Light brown	Dull yellow		Equilibrium values (0,55 – 0,60)	Equilibrium values (0,55 – 0,60)	Oil (3) and wet gas
Very Mature			100	1.0								
				1.35	3 Brown	6		Orange	450			
High Maturity			150	1.5		7		Red	465	None	None	Wet gas
				2.0		8	3 Brown	Nonfluorescent	500			
Overmature		Semi Anthracite			4 Brown/ Black							
Organic Methamorphisme	Metagenesis	Anthracite	200	2.5		9	4 Dark brown					Dry gas
				3.0								
			250	4.0	5 Black	10	5 Black		None			
		Meta Anthracite		5.0								

(1) Depending by duration (2) International standard is not available - a lot of correlation scales are present in literature (3) Depending also by kerogen type

Correlation chart among organic maturity parameters. It is an update of the one proposed by us in the previous edition, a simplification (modified) of the one proposed by Hunt (1995), that is in its turn an adaptation of those of Staplin (1969), Teichmüller (1974), Pearson (1990) and Mukhopadhyay (1994). After Scotti (2003), redrawn.

Vitrinite reflectance becomes anisotropic from maturity levels in the oil window (about 1%) and increases with increasing maturity. Thus, in organic diagenesis and catagenesis random reflectance (R_o%) is generally used whereas from metagenesis onward R_{max} is generally preferred to describe levels of coalification.

Most data presented in this paper have been produced in the last fifteen years at Roma Tre University and ENI Labs according to the following procedures. Samples were prepared according to standardized procedures described in Bustin *et al.*, (1990). Random reflectance was measured under oil immersion with a Zeiss Axioplan microscope, in reflected monochromatic non-polarised light. On each sample, at least twenty measurements were performed on vitrinite or bitumen unaltered fragments never smaller than 5 μm and only slightly fractured. Mean reflectance values (R_o for vitrinite and R_b for bitumen) were calculated from the arithmetic mean of these measurements. R_b values were converted into vitrinite equivalent reflectance data (R_{oeq}) using Jacob's formula (Jacob and Hiltman, 1985). R_{max} values are provided for metamorphic units (e.g. Alpi Apuane).

Clay mineralogy

Clay minerals in shales and sandstones undergo diagenetic and very low-grade metamorphic reactions in response to sedimentary and/or tectonic burial. Reactions in clay minerals are irreversible under normal diagenetic and anchizonal conditions, so that exhumed sequences generally retain indices and fabrics indicative of their maximum maturity and burial. The parameters generally used to provide information on the thermo-baric evolution of sedimentary successions are the Kübler and Árkai indices (Kübler, 1967; Árkai *et al.*, 1995), as well as the b0 value of K-white mica and the variation in the relative ratio between the discrete phases that form mixed layered minerals. In particular, mixed layers illite-smectite (I-S) are widely used in petroleum exploration as a geothermometer and, thus, as indicators of the thermal evolution of sedimentary sequences (Hoffman and Hower, 1979; Pollastro, 1990). The identified changes comply with the following scheme of progressive thermal evolution that has been correlated to the stages of hydrocarbon generation: di-smectite - disordered mixed layers (R0) [1] - ordered mixed layers (R1 and R3) - illite - di-octahedral K-mica (muscovite). Although the conversion to paleotemperatures depends on more than one factor (e.g., temperature, heating rate, protolith, fluid composition, permeability, fluid flow), Pollastro (1990; 1993) summarized the

[1] The term R expresses the probability, given a layer A, of finding the next layer to be B. The R parameter may range from 0 to 3. R=0 means that there is no preferred sequence in stacking of layers and illite and smectite layers are stacked randomly along the c-axis; R=1 indicates that a smectite layer is followed by an illite layer and order in stacking of layers appears in the interstratification sequence; R=3 indicates long-range ordering and that each smectite layer is surrounded by at least three illite layers on each side.

application of two simple time-temperature models for I-S geothermometry studies based primarily on the duration of heating (or residence time) at critical I-S reaction temperatures. The first model was developed by Hoffman and Hower (1979) for long-term, burial diagenetic settings that can be applied to most geologic and petroleum studies of sedimentary rocks and basins of Miocene age or older. In this model the major changes from R0 to R1 and from R1 to R3 occur in the temperature range of about 100-110°C and of 170-180°C respectively (Hoffman and Hower, 1979). The second model, which was developed for short-lived heating events, applies to young basins or areas characterized by relatively recent thermal activity with high geothermal gradients, or to recent hydrothermal environments. Such settings are those where relatively young rocks were subject to burial temperatures in excess of 100°C for <2 Ma. In this model the conversion from R0 to R1 and from R1 to R3 ordering occurs at about 130-140°C and 170-180°C respectively (Jennings and Thompson, 1986). In this paper, we applied the first model, as it is clearly the most appropriate to the study areas.

Another parameter successfully applied worldwide for determining the grade of diagenesis and very-low metamorphism of clay-rich and clastic sedimendary rocks is the Kübler index (KI). In the last four decades it has commonly been used as an empirical measure of the changes in sharpness of the X-ray 10 Å basal reflection of illite-dioctahedral K-white mica. The 10 Å peak width at half-peak-height is commonly considered to be primarily a function of illite crystallite thickness normal to (001). Several authors have shown how KI values decrease as metamorphic grade increases. The limits of metamorphic zones are as follows: KI = 0.42 °Δ2θ for the diagenetic zone to low anchizone boundary and KI = 0.25 °Δ2θ for the high anchizone to epizone boundary (Merriman & Frey, 1999).

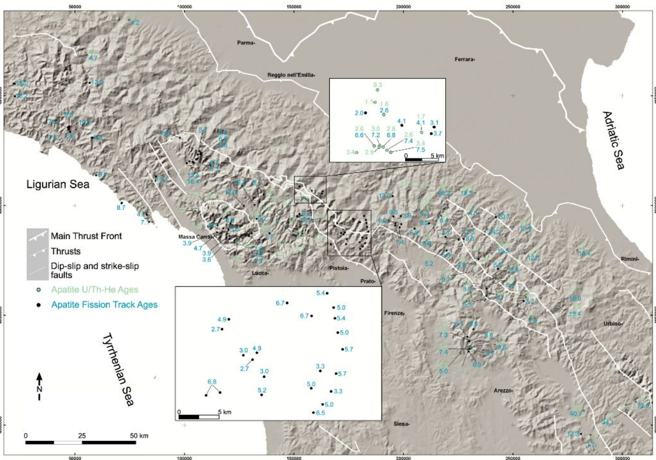
Each sample was prepared according to the procedures of Giampaolo and Lo Mastro (2000) and following Moore and Reynolds' (1999) recommendations. X-ray powder diffraction analyses have been carried out with a Scintag X_1 Diffraction system (CuK_α radiation) at Roma Tre University. Oriented slides (<2 μm grain-size fraction) were prepared by the pipette-on-slide method, keeping the specimen thickness as constant as possible, within the range of 1 to 3 mg of clay per cm^2 of glass slide. Air-dried mounts were scanned from 1 to 48 °2θ with a step size of 0.05 °2θ and a count time of 4 s per step at 40 kV and 45 mA. The presence of expandable clays was determined for samples treated with ethylene glycol at 25°C for 24h. Ethylene-glycol solvated samples were scanned at the same conditions as air-dried aggregates with a scanning interval of 1-30 °2θ. Diffraction peaks were analyzed using the X-ray system associated program by first removing a linear background level and then fitting them using a Pearson VII function. Data and X-ray diffraction patterns are available from the authors.

Results

Northern Apennines

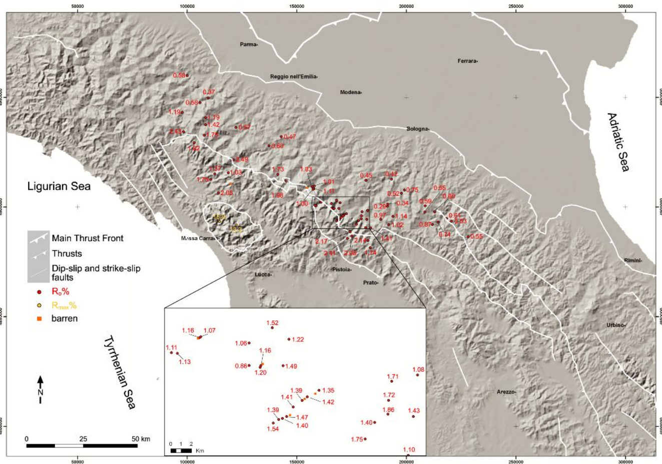
The Northern Apennines have been studied in details since the '80s and today they yield a very dense dataset obtained by different low-temperature thermochonological techniques: zircon fission-track (ZFT), apatite fission-track (AFT) and (U-Th)/He on apatite (AHe) (Fig. 7). Furthermore, a huge number of samples both from surface and bore-holes have been analyzed by the vitrinite reflectance technique (Fig. 8). These data have been integrated by some clay mineralogy analyses on sediments of the Cervarola succession (Botti *et al.*, 2004; Aldega and Eberl, 2005; Fig. 9). Within the pile of Ligurian and Tuscan nappes, the coal rank increases generally from top to bottom, to reach the low-grade metamorphism in the lowermost nappe. R_o% values in the Ligurian nappe vary from 0.5 at surface to 1.8% in the Quara1d and Sestola1 wells (Reutter *et al.*, 1983; Anelli *et al.*, 1994). KI data from the Ligurian Nappe collected near Chiavari range from 0.25°Δ2θ in the Cravasco/Voltaggio unit to 0.49°Δ2θ in the Bracco/Val Graveglia unit suggesting a significant and gradual increase in metamorphic grade from the highest to the lowest unit within the tectonic pile (Leoni *et al.*, 1996). The pressure conditions - estimated through the illite b_0 parameter - range from 2-3 kbar (Bracco/Val Greaveglia unit) to *ca.* 7 Kbar (Cravasco/Voltaggio unit; Leoni *et al.*, 1996).

Figure 7. Distribution of thermochronological data in the Northern Apennines



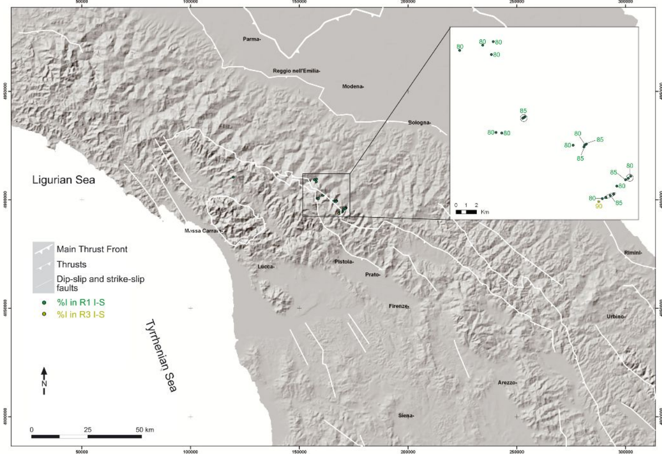
Digital Elevation Model of the Northern Apennines showing the distribution od apatite fission track and U/Th-He data. Simplified main geological features from APAT (2004) and Thomson *et al.* (in press). Coordinates in UTM European Datum 1950 33N.

Figure 8. Distribution of organic matter thermal maturity data in the Northern Apennines



Digital Elevation Model of the Northern Apennines showing the distribution of vitrinite reflectance data. Simplified main geological features from APAT (2004) and Thomson *et al.* (in press). Coordinates in UTM European Datum 1950 33N.

Figure 9. Distribution of illite contents in mixed layers I-S data in the Northern Apennines



Digital Elevation Model of the Northern Apennines showing the distribution of illite contents in mixed layers I-S. Simplified main geological features from APAT (2004) and Thomson *et al.* (in press). Coordinates in UTM European Datum 1950 33N.

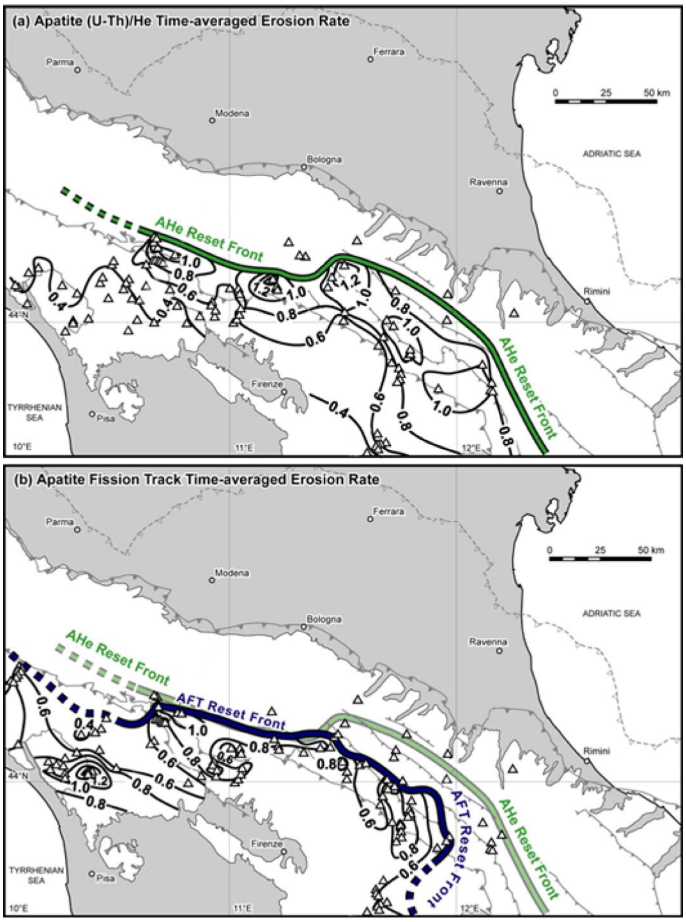
Data from wells in the Macigno, Cervarola and Marnoso-Arenacea successions show values up to advanced organic metamorphism whereas at surface both vitrinite reflectance and thermochronology data show a general decrease of the burial conditions from Tyrrhenian to Adriatic coast. For each of the thermochronometer it is thus possible to go from totally reset to partially reset regions. This regional trend is disturbed only locally by young post-coalification tectonics. Some post-orogenic heating is connected with the magmatic activity of Late Miocene to Pleistocene age in Tuscany. Except for these post-orogenic thermal events, the main coalification cause can be generally ascribed to nappes emplacement during the Apennine orogeny in the Miocene. This feature is evident both in the central region of the chain (e.g., Botti *et al.*, 2004) than in the external area where the maturity profile of the Palazzuolo1 well is nearly continuous across main thrusts (Anelli *et al.*, 1994). On the other hand, late orogenic extensional tectonics is clearly younger than time of maximum burial throughout the chain.

The shape of the maximum paleo-isotherms is nearly parallel to the chain axis with the noticeable exception of the Alpi Apuane window. This area represents the lowermost unit of the chain and therefore exhumed from larger depths than the surrounding units. Peak P-T conditions have been evaluated at 0.6-0.8 Gpa and 420-500°C (Massa unit; Molli *et al.*, 2002). The gap in burial conditions with the sediments out of the window is quite relevant as here maximum temperatures never exceeded the total annealing temperature of fission tracks in zircon.

The less buried sediments are presently exposed along the thrust fronts, on the pro-side of the chain, where the AHe system has been locally not reset (i.e. burial temperatures were lower than about 60°C) and the R_o% data are in the order of 0.5%. The positions of reset fronts is not well defined as total resetting of apatite in both the AHe and AFT systems is not only influenced by temperature, but also by factors such as variation in apatite chemistry and radiation damage, and because of the low dip of this front, thus influenced by local topography. It is important to note that most of the data were obtained on the foredeep units involved in the thrust belt whereas only a few data are from the Ligurian and Epiligurian units. The thermal history of these latter units is very different from the underlying foredeep thrust belt but, although the few existing constraints, in general rocks were affected by low burial temperatures during formation of the Apennine wedge.

The exhumation history follows the same pattern observed for the burial conditions. In fact, both AFT and AHe techniques indicate a general eastward decrease of the exhumation ages (Fig. 10). Close to the topographic front, older detrital and mixed AHe and AFT ages occur, which then rapidly decrease to fully reset ages towards the core of the orogen. More in detail, the youngest AHe ages (ca. 1 to 2 Ma) have been detected close to the core of the range (Mt. Falterona and Mt. Cimone areas) whereas youngest AFT at about 4 Ma close to the reset front.

Figure 10. Map of contoured AHe and AFT ages



Map of contoured AHe and AFT ages, with approximate position of reset fronts (where ages are significantly younger than stratigraphic age, and show no evidence of mixed ages) - For AHe between 6 and 7 Ma, for AFT between 10 and 12 Ma. a: AHe time averaged erosion rate; b: AFT time averaged erosion rate. After Thomson *et al.* (in press) modified.

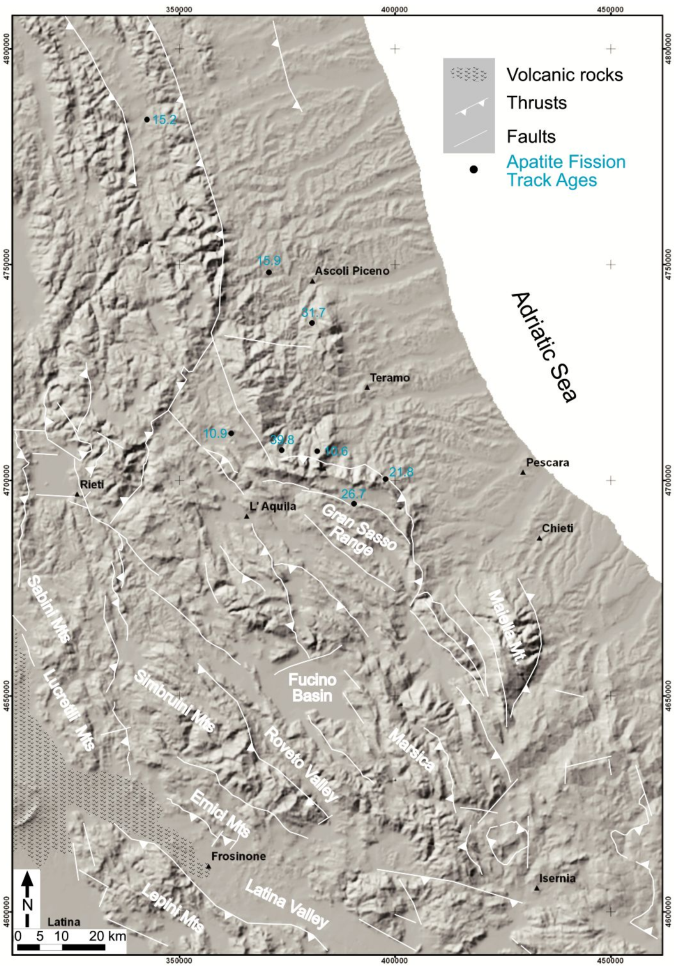
The onset of exhumation of the chain is recorded from the oldest ages, located west of the topographic divide. Here AFT data range up to about 13 Ma but it is not clear if some ages few million years older are related to partially or totally reset samples. However, a similar age has been detected by ZFT on the Alpi Apuane rocks, therefore marking to the Middle Miocene the cooling at about 240°C. As time of maximum burial for the Macigno Formation is constrained at 15-20 Ma, initial exhumation of the Apuane was coeval with tectonic thickening higher in the wedge. By 5 Ma the Apuane rocks were exhumed to 70°C and 2 km. Exhumation of the Ligurian unit is poorly constrained because of the low amount of data available, mostly characterized by not reset ages.

Variation of exhumation ages across the chain results of course in a variation of exhumation processes during time. If the long-term exhumation rate seems to be of about 0.7 km/m.y., episodes of enhanced erosion rates up to 1 km/m.y. have been recognized both in the contractional pro-side of the belt and in the core of the orogen. It is noteworthy that these rates are significatively higher than the drainage basin erosion rates of 0.2-0.6 km/m.y. determined by cosmogenic isotopes (Cyr and Granger, 2008).

Central Apennines

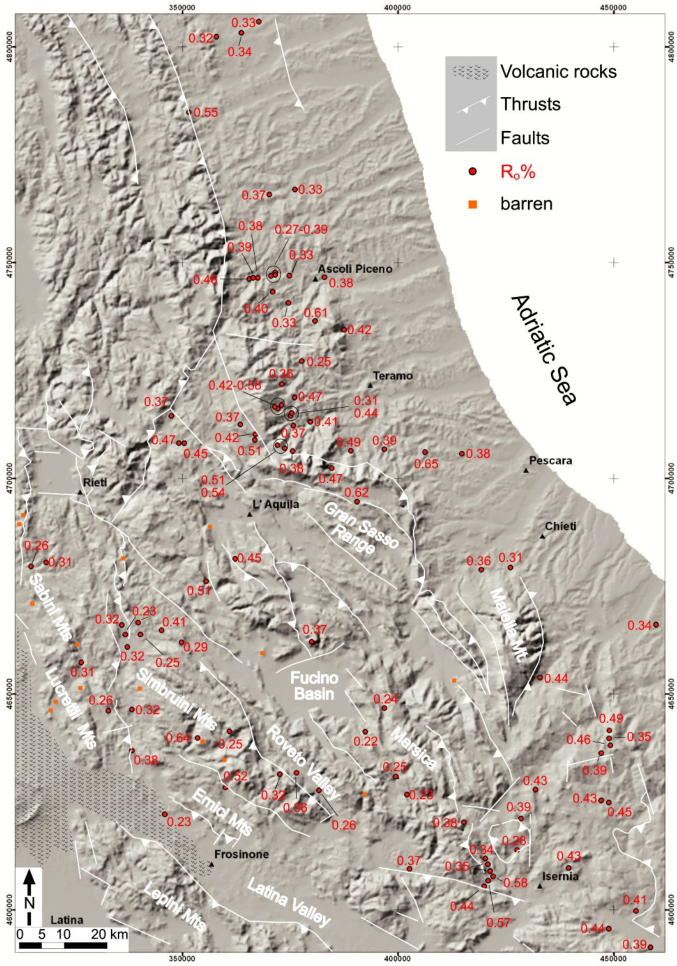
Thermochronological dataset is here very limited as only a few AFT ages have been obtained from the Gran Sasso Range and Laga Basin (on both pre-orogenic and syn-orogenic deposits; Rusciadelli *et al.*, 2005; Fig.11). However, more abundant is the dataset related to thermal indicators of maximum burial such as vitrinite reflectance (Fig.12), illite content in mixed layers I-S (Fig. 13) and Kübler Index (Fig. 14) (subordinately T max from pyrolisis, fluorescence colours, Thermal Alteration Index, not in the maps) that were mainly acquired on syn-orogenic siliciclastics and subordinately on pre-orogenic clayey and marly portions of pelagic basin successions (Molise, Sannio, Sabina and Umbria-Marche pelagic basins; Corrado, 1994; 1995; Corrado *et al.*, 1998; 2003; Di Bucci *et al.*, 1996, Rusciadelli *et al.*, 2005; Aldega *et al.*, 2007a). Mean vitrinite reflectance data from the Meso-Cenozoic pelagic successions (Sabina basin, Latium) at the top of the thrust stack of the Central Apennines indicate the immature stage of hydrocarbon generation ($R_o\%$ = 0.25-0.30%). Vitrinite reflectance might be suppressed by the influence of abundant amorphous matter and marine phytoplacton in palinofacies where woody particles may be less than 20%. Nevertheless reflectance data are in reasonable agreement with low T.A.I. values (ranging between 1.2 and 2.0) and bright fluorescence colours, described in details by Corrado (1994, 1995).

Figure 11. Distribution of thermochronological data in the Central Apennines



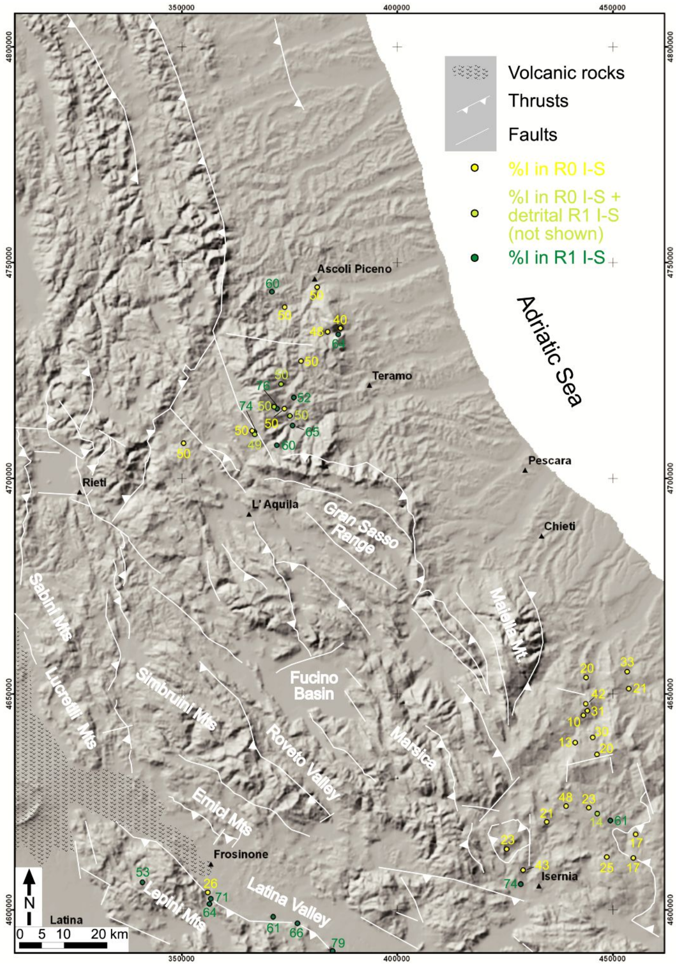
Digital Elevation Model of the Central Apennines showing the distribution of apatite fission track data. Simplified main geological features from APAT (2004) and Corrado *et al.* 2003. Coordinates in UTM European Datum 1950 33N.

Figure 12. Distribution of organic matter thermal maturity data in the Central Apennines



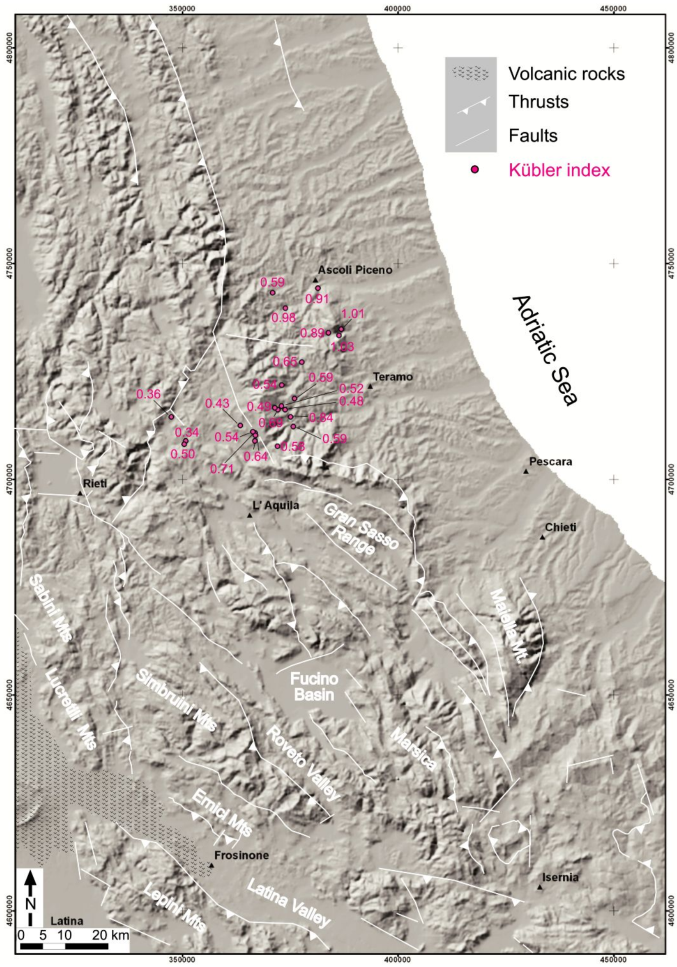
Digital Elevation Model of the Central Apennines showing the distribution of mean vitrinite reflectance data. Simplified main geological features from APAT (2004) and Corrado *et al.* 2003. Coordinates in UTM European Datum 1950 33N.

Figure 13. Distribution of illite content in mixed layer I-S data in the Central Apennines



Digital Elevation Model of the Central Apennines showing the distribution of illite content in mixed layers I-S. Simplified main geological features from APAT (2004) and Corrado *et al.* 2003. Coordinates in UTM European Datum 1950 33N.

Figure 14. Distribution of Kübler Index data in the Central Apennines



Digital Elevation Model of the Central Apennines showing the distribution of Kübler Index data. Simplified main geological features from APAT (2004) and Corrado *et al.* 2003. Coordinates in UTM European Datum 1950 33N.

For the Umbria-Marche basin, the Montagna dei Fiori structure shows low thermal maturity levels (about $R_o\%$ = 0.40% for the Bonarelli level, illite contents in mixed-layers I-S between 40 and 64% and KI data ranging from 0.89 to 1.03 °Δ2θ for the pre-orogenic succession). On the other hand, along the Gran Sasso range, fission tracks on three samples have been totally reset as the stratigraphic age (Late Triassic-Early Jurassic) is much older than the AFT age (27-40 Ma; Rusciadelli *et al.*, 2005). Rusciadelli *et al.* (2005) try to do some thermal modelling on these ages by integration with some vitrinite reflectance data. Their results seems to indicate an exhumation phase in the last 5 m.y., confirming the geological evidence of the existence of a Middle Pliocene unconformity (Crescenti *et al.*, 2004).

Thermal constraints for the Molise and Sannio Basins were provided only by X-ray diffraction (Corrado *et al.*, 1998). The Upper Oligocene(?)-Lower Miocene varicoloured clays show two different types of mixed layers I-S: diagenetic smectite-rich I-S that are almost present in all samples, and detrital illite-rich I-S. The predominance of discrete smectite and small amounts of random-ordered mixed layers I-S with illite content between 10 to 50% were recorded for the Molise succession whereas smectite-rich I-S with illite layers between 20 and 40% were observed for the Sannio succession. These data indicate the early diagenetic zone and low burial termperatures according to Merriman and Frey (1999).

Syn-orogenic siliciclastics are from Latium, Abruzzi, Molise and Marche regions. They are mainly preserved at the footwall of regional thrust sheets that are progressively younger from hinterland to foreland with ages bracketing between the Upper Tortonian and the Messinian. Organic palinofacies are generally rich in woody continental particles, generally exceeding 60%, where indigenous vitrinite macerals are clearly distinguishable.

Upper Tortonian foredeep and Lower Messinian? thrust-top basin deposits cropping out along the Latina Valley at the footwall of the Volsci Range display low levels of thermal maturity with vitrinite reflectance values ranging from 0.25 to 0.40% in the immature stage of hydrocarbon generation. Lower Messinian siliciclastics cropping out in the Roveto Valley at the footwall of the Simbruini-Ernici ridge and to the East of the Olevano-Antrodoco line at the footwall of the Sabina structures in pelagic facies, show palinofacies with vitrinite reflectance of indigenous macerals between 0.25 and 0.35%. Lower Messinian siliciclastics cropping out in the narrow valleys to the West and to the East of the Montagna Grande carbonate ridge show an extremely low thermal maturity with values ranging between about 0.2 and 0.3%. Slightly higher values (between 0.3 and 0.4%) are detected to the south of the ridge at the footwall of the Meta Mountains carbonate thrust sheet as result of tectonic loading.

Lower Messinian foredeep deposits on top of the pelagic Molise basin that extensively crop out to the East and to the North of the structures of the Latium-Abruzzi carbonate platform show slightly higher values than those to the West with about 0.6% at the base and 0.3% at the top of the siliciclastic succession. T.A.I. values are between 2.3 and 2.5.

In the Laga Basin, Messinian siliciclastics show increasing vitrinite reflectance as function of depth (from 0.31 to 0.6%) in the basin depocentre and values of 0.45-0.5% in the immediate footwall of the Gran Sasso Range and of the Sibillini thrust front. Tmax data (412-446°C) and diagenetic random-ordered and short ordered I-S with an illite content ranging from 50 to 76% mirror the same spatial distribution confirming vitrinite reflectance data (Aldega *et al.*, 2007a). On the other hand, KI data (from 0.34 to 0.84 °Δ2θ) indicate more evolved stages of thermal maturity when compared to organic and other inorganic thermal parameters. These data mainly refer to detrital 10 Å phases, either metamorphic or sedimentary, associated with the uplift of the Alpine-Apennine chain. In this case, KI do provide information on provenance and thermal conditions of the source rock and cannot be used for the reconstruction of the thermal history of the Laga Basin. The AFT dataset (Rusciadelli *et al.*, 2005), given the "young" depositional age, indicate that burial temperatures never exceeded the PAZ range. Therefore, only detrital ages could been obtained and they can be interpreted in terms of erosion of a source rock more than bedrock exhumation.

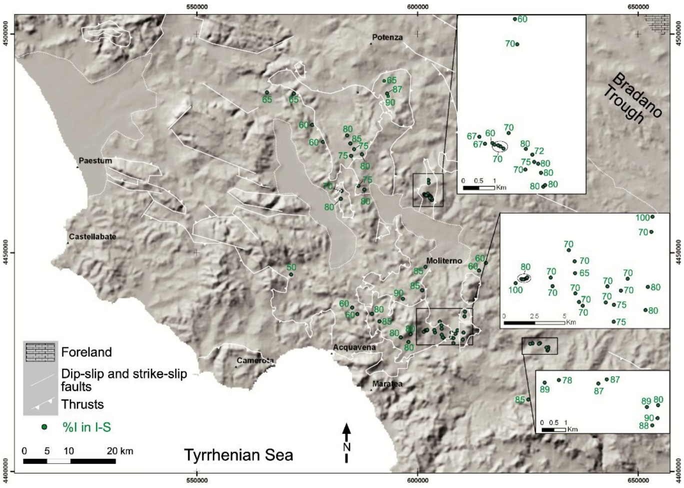
Low maturity levels characterise the pre-orogenic successions in carbonate platform, slope and pelagic basin facies. Organic and inorganic thermal parameters suggest that both frictional heating and tectonic loading that commonly enhance thermal maturity in thrust belt systems were unimportant for the acquired levels of diagenesis of the pre-orogenic succession (Bustin, 1981; Underwood *et al.*, 1988). In addition, sedimentary burial during subsidence and foredeep migration which is a major cause of thermal maturity increase during mountain building was also relatively ineffective in pre-orogenic facies maturation as suggested by field analysis. The low maturity of the slope (Sabini-Reatini Mts.) and carbonate platform (Simbruini-Ernici Mt.) successions strongly suggests that the present-day lack of turbiditic deposits in these areas is due to the deposition of reduced volumes of these deposits or, at least to non deposition.

For the syn-orogenic siliciclastic deposits, organic and inorganic indicators show a substantial thermal immaturity, with only few local exceptions that exceed R_o values of 0.6%, at the front of the carbonate core of the belt. These results indicate that the main cause of thermal evolution of the siliciclastic deposits is sedimentary burial. Occurrence of relevant tectonic loading (e.g., Gran Sasso area), now totally removed, or shear heating concentrated along regional strike-slip fault zones are very locally testified in the Central Apennines.

Southern Apennines

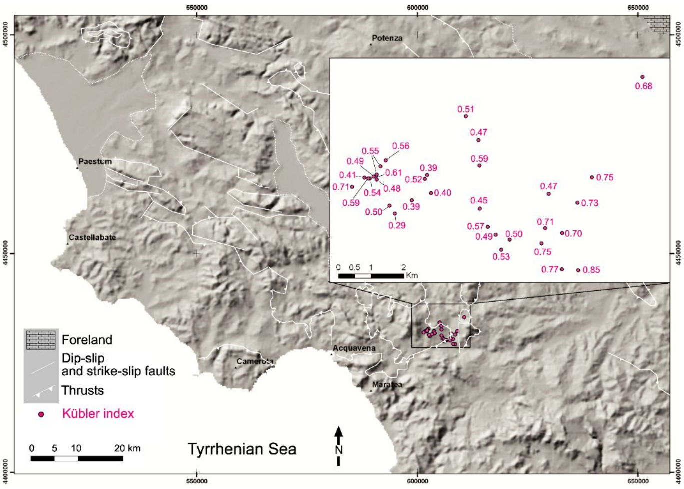
The dataset includes ~144 samples for XRD analysis, 24 samples for vitrinite reflectance and 18 for AFT ages (Figs. 15-18). XRD and AFT analyses were performed on the sedimentary cover of the ophiolite-bearing Ligurian units, on Miocene sediments on top of the Mesozoic Apennine platform (Bifurto, Monte Sierio, Castelvetere and Gorgoglione Formations), on the Lagonegro Units (Monte Facito, Calcari con Selce, Scisti Silicei, Galestri Formations) and on the Messinian transgessive cycle of the Apulian Platform. Most vitrinite reflectance data are from siliciclastic sediments and from the Monte Facito Fm. Thermal and thermochronological constraints indicate that the Southern Apennines can be divided into two distinct thermotectonic plates: an upper plate that records limited burial and only minor heating, and a lower plate that has been extensively tectonically buried and heated. The upper plate consists of the rocks of the Apennine Platform domain the tectonically overlying "internal" units (Ligurian and Sicilide). The former are characterized by illite contents in mixed layer I-S ($50<\%I$ in I-S<70) and $R_o\%$ values ($0.25<R_o\%<0.55$) in the range of the early diagenetic zone and the immature to early mature stage of hydrocarbon generation and by no annealing of AFTs. Thermal modelling (Corrado *et al.*, 2005) suggests the minor effect of burial (never exceeding 2 km) for the rocks of the Apennine Platform domain. A cooling age of 86.9 ± 11.8 Ma from a sample of the overlying Sicilide unit – which is older than the stratigraphic age – can be interpreted in terms of erosion of a source rock and is consistent with the maximum temperatures calculated for the Apenninc Platform domain. To the South, rocks from the Apennine Platform Domain (Pollino ridge) experienced higher levels of thermal maturity exceeding the PAZ range with an age of exhumation of 6.0 ± 1.1 Ma (Invernizzi *et al.*, 2008). The Ligurian unit (Loc. San Severino Lucano village) shows an illite content in mixed layer I-S in the range of 62-89% and $R_o\%$ values of about 1.02% indicating early to late diagenetic conditions and mature stage of hydrocarbon generations with a cooling age of 11.4± 1.2 Ma (Invernizzi *et al.*, 2008).

Figure 15. Distribution of illite content in mixed layer I-S data in the Southern Apennines



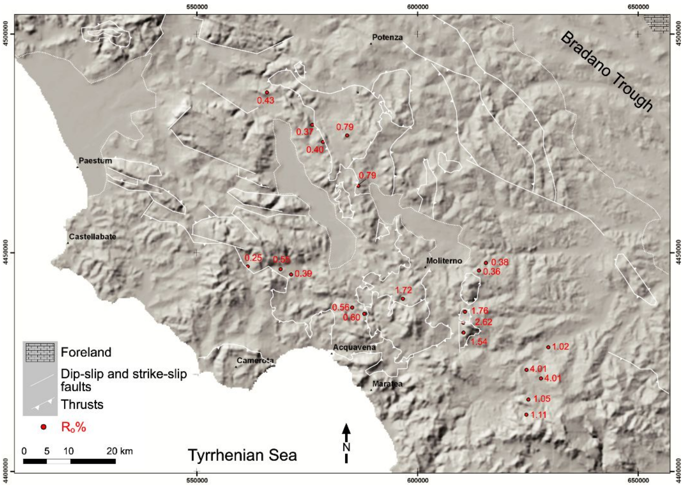
Digital Elevation Model of the Southern Apennines showing the distribution of illite content in mixed layers I-S. Simplified main geological features from APAT (2004) and Patacca and Scandone (2007). Coordinates in UTM European Datum 1950 33N.

Figure 16. Distribution of Kübler Index data in the Southern Apennines



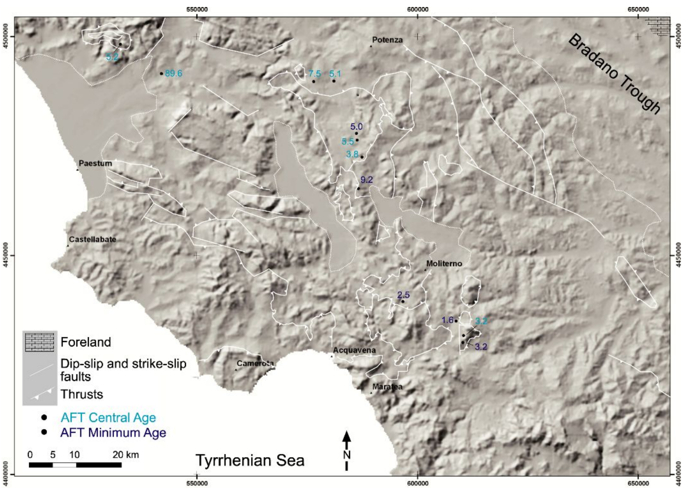
Digital Elevation Model of the Southern Apennines showing the distribution of Kübler Index data. Simplified main geological features from APAT (2004) and Patacca and Scandone (2007). Coordinates in UTM European Datum 1950 33N.

Figure 17. Distribution of organic matter thermal maturity data in the Southern Apennines



Digital Elevation Model of the Southern Apennines showing the distribution of mean vitrinite reflectance data. Simplified main geological features from APAT (2004) and Patacca and Scandone (2007). Coordinates in UTM European Datum 1950.

Figure 18. Distribution of thermochronological data in the Southern Apennines



Digital Elevation Model of the Southern Apennines showing the distribution of apatite fission track data. Simplified main geological features from APAT (2004) and Patacca and Scandone (2007). Coordinates in UTM European Datum 1950.

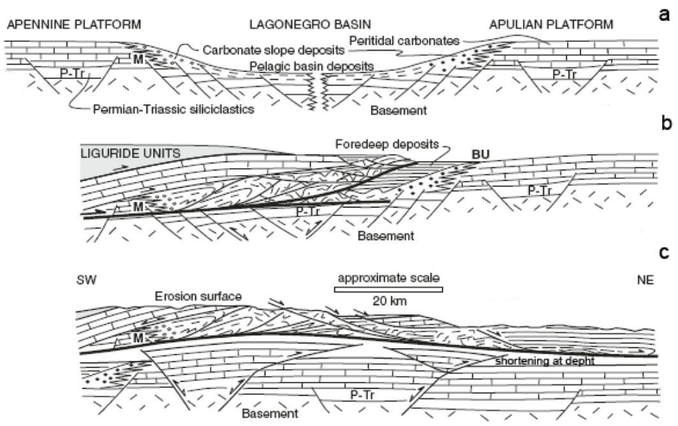
The lower plate includes rocks of the Lagonegro Basin, the Monte Croce, and the Apulian Platform domains. For the Lagonegro Basin successions, organic and inorganic thermal indicators show an increase of thermal maturity as a function of depth. Illite crystallinity, expressed as Kübler Index, ranges from 0.45 to 0.86 °Δ2θ , illite content in mixed layer I-S from 60 to 99% and R_o% from

1.06 to 1.76% recording late diagenetic conditions and overmature hydrocarbon generation (Aldega *et al.*, 2003; Corrado *et al.*, 2005). KI data lower than 0.45 °Δ2θ are affected by detrital K-white mica and cannot be considered for grade determinations.

For the Miocene siliciclastic deposits transgressive on the Lagonegro unit, data show a general decrease in thermal maturity between the mature and the immature stage of hydrocarbon generation from the west (constrained by mineralogical and organic matter data) to the east (constrained by organic matter data). The data from Monte Alpi, representing the unique outcrop of Apulian Platform rocks within the thrust belt consistently fall into the late diagenetic zone and late mature stage of hydrocarbon generation and indicate burial depths in excess of 5 km (Corrado *et al.*,, 2002; Mazzoli *et al.*,, 2006). Data from productive wells drilled in southern Apennines show lower thermal maturity for the Apulian Platform Domain in the range of 0.5-1.35 R_o% (Scotti, 2003). As opposed to the rocks belonging to the upper plate, all samples from the lower plate were affected, during the Neogene, by maximum temperatures higher than total annealing temperature. Therefore, ages reflect time of recent cooling through the isotherm ~110°C, effectively dating the exhumation of the previously buried successions. Thermal modelling (Aldega *et al.*, 2003; 2005) constrained by mixed layered clay minerals and vitrinite reflectance indicate slight differences in thermal maturity along the strike of the chain related to different amounts of tectonic loads and in the timing of exhumation. Calculated maximum temperatures are between 124-142°C at the top and ~160-171°C at the base of the Lagonegro succession. Generally, AFT data indicate a late Miocene (<10 Ma) onset of exhumation of previously deeply buried rocks in the southern Apennines. In particular, a substantial decreasing of exhumation ages is shown from the North to the South of the Agri River Valley. For the Lagonegro Basin rocks, AFT ages to the North (5.1-3.8 Ma) are ~2 Ma older than those observed to the South (3.2-2.5 Ma) with important implications for oil generation (Mazzoli *et al.*, 2008). In the northern sector, thinning of the allochthonous units have started before their emplacement onto the Apulian Platform carbonates with respect to the southern area where cooling ages display an exhumation following the deep burial of the Apulian Platform. For this reason, productive oil wells are located only to the North of the High Agri River Valley.

A possible evolutionary scenario based on these data is reported in Figure 19 (see also the section on the geological setting of the Southern Apennines).

Figure 19. Interpreted tectonic evolution of the Southern Apennines

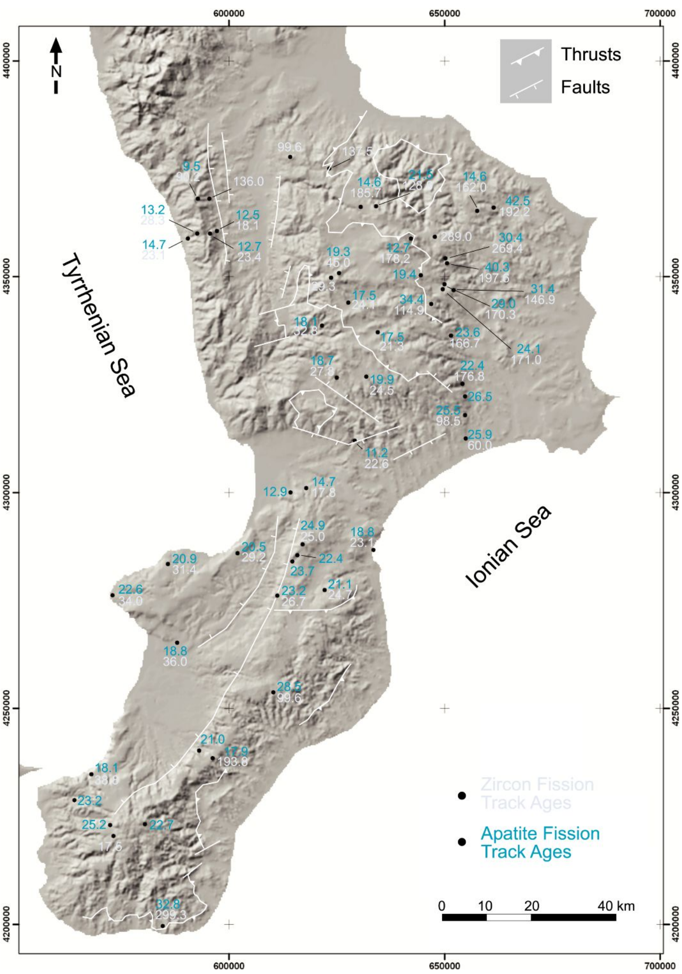


Simplified sketches showing the tectonic evolution of the Southern Apennines. Carbonate slope facies associated with the eastern margin of the Apennine Platform and western margin of the Apulian Platform are shown with white and black dots, respectively. The location of the eastern margin (M) of the Apennine Platform is held fixed through the three panels for reference. a: Mesozoic setting of the continental margin subsequently telescoped in the Southern Apennines. The Liguride oceanic domain was located to the west of the Apennine Platform. The Lagonegro Basin is shown in reduced width (note that the original width of the basin remains poorly constrained); b: "closure" of the Lagonegro Basin, initiating buttressing of the allochthonous wedge against the western inherited rifted margin of the Apulian Platform (BU); c: following emplacement of the allochthonous wedge above the westernmost portion of the Apulian Platform, gravitational readjustments dominate within the allochthonous wedge, triggering denudation and tectonic exhumation (assisted by erosion). Active shortening migrated to the underlying Apulian crust, producing basement-involved inversion at depth. After Mazzoli *et al.* (2008), modified.

Calabria

The dataset includes published data on low temperature chronological indicators such as apatite and zircon fission track by Thomson, (1994, 1998; Fig. 20). They provide low temperature and time constraints on the late orogenic cooling and exhumation history of the Calabrian crystalline basement rocks. The AFT ages display a relatively narrow scatter of ages between 40±5 Ma and 7±1 Ma. A general trend is observed with younger AFT ages in the lower and inner basements units, and older AFT in the tectonically higher and external units. The ZFT ages show a much wider age scatter between 299±21 Ma and 14±1 Ma. Fission track data reveal that both Alpine and high-grade Hercynian metamorphic rocks experienced a phase of increased cooling rates between 35 Ma and 15 Ma. Cooling has ceased in the majority of the basement rocks by 11 Ma which is the maximum age of the overlying sedimentary rocks throughout most of the Calabrian Arc (Van Dijk and Okkes, 1991). The period of increased cooling during the Oligocene-Miocene was interpreted as the result of two coeval exhumational processes: extensional tectonism (Platt and Compagnoni, 1990) and erosion (Bonardi *et al.*, 1980) which affect the late tectonic evolution of the Calabrian Arc.

Figure 20. Distribution of thermochronological data in Calabria



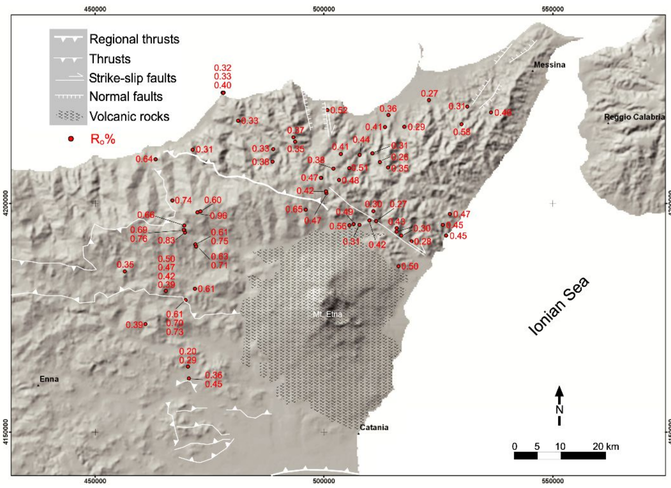
Digital Elevation Model of Calabria showing the distribution of apatite and zircon fission track data. Simplified main geological features from APAT (2004). Coordinates in UTM European Datum 1950 33N.

Thermal constraints on the sedimentary units of the Calabrian block are lacking. Available mineralogical data (%I in I-S and KI) are from Perri *et al.* (2008) who constrained the burial evolution of continental redbed conglomerates, sandstones, shallow-marine carbonates and turbidites of the Longobucco Group sequence (Hettangian-Toarcian) in the northeastern margin of the Sila Mountains. They observed low expandable mixed layers I-S and KI values between 0.50 and 0.86 °Δ2θ estimating maximum temperatures ranging from 100 to 160°C and a lithostatic/tectonic loading in excess of 4km.

Eastern Sicily

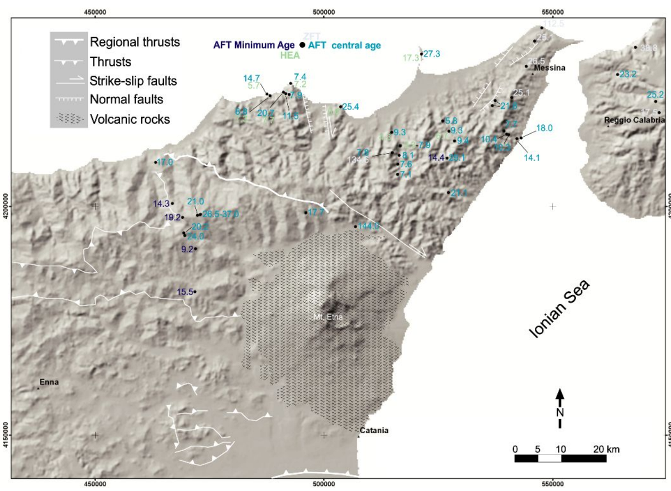
The dataset includes 330 data. They correspond to illite content in mixed layer I-S determinations (190), vitrinite reflectance measurements (95) and AFT dating (45) (Figs. 21-23). Mostly the north-eastern sector of Sicily has been investigated to detect levels of thermal maturity and exhumation ages of the Apenninic-Maghrebian orogen. Vitrinite reflectance data are from siliciclastic sediments of the Sicilide accretionary wedge, the overlying thrust-top and foredeep deposits and from the Stilo-Capo d'Orlando Formation. XRD analysis have been performed on the different structural units constituting the accretionary wedge and related thrust-top deposits and on Africa-passive margin units. AFT data mainly refer to crystalline and metamorphic units of the Peloritani Mts and to the Sicilide accretionary wedge. The integration of organic and inorganic thermal and thermochronological indicators allowed us to distinguish three main areas at different structural level which experienced variable tectonic loads and exhumed in different times: the Sicilide accretionary wedge, the Africa-passive margin units and the thrust-top and foredeep deposits.

Figure 21. Distribution of organic matter thermal maturity data in the Eastern Sicily



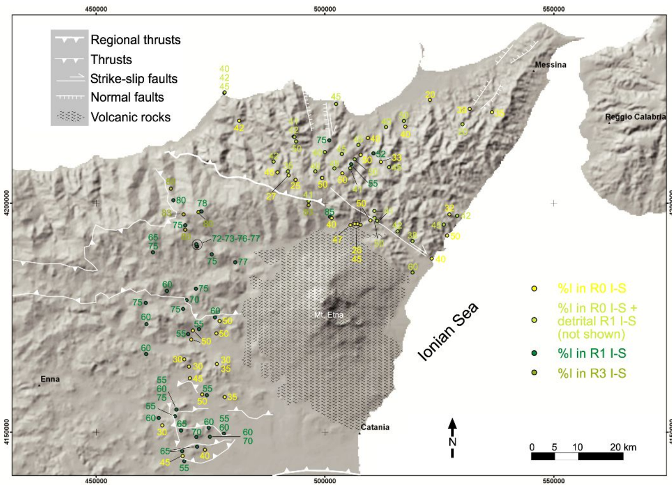
Digital Elevation Model of the Eastern Sicily showing the distribution of mean vitrinite reflectance data. Simplified main geological features from APAT (2004), Carbone *et al.* (1990) and Lentini *et al.* (2000). Coordinates in UTM European Datum 1950.

Figure 22. Distribution of thermochronological data in the Eastern Sicily



Digital Elevation Model of the Eastern Sicily showing the distribution of apatite fission track data. Simplified main geological features from APAT (2004), Carbone *et al.* (1990) and Lentini *et al.* (2000). Coordinates in UTM European Datum 1950.

Figure 23. Distribution of illite content in mixed layers I-S data in the Eastern Sicily

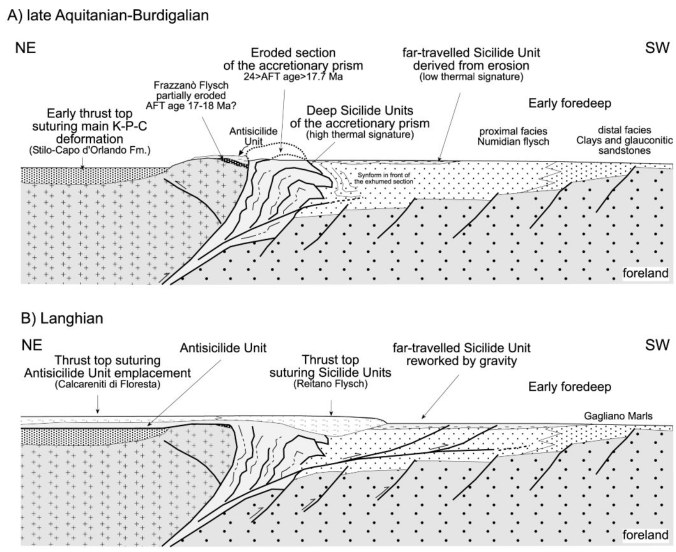


Digital Elevation Model of the Eastern Sicily showing the distribution of illite content in mixed layers I-S discussed in the text. Simplified main geological features from APAT (2004), Carbone *et al.* (1990) and Lentini *et al.* (2000). Coordinates in UTM European Datum 1950 33N.

In particular, within the Sicilide accretionary wedge, sectors with different thermal signature and evolution can be further identified. A warmer part of the wedge made up of the Mount Soro and Troina units and two colder rims constituted by the far-travelled Sicilide and Antisicilide units. The former are characterized by the highest values of vitrinite reflectance (0.6-0.96%) and illite content in mixed layer I-S (60-85%) corresponding to the first stages of the late diagenetic zone and the catagenesis of hydrocarbon generation (Aldega *et al.*, 2007b; Corrado *et al.*, 2009). This maturity level was acquired before the deposition of the unconformable thrust-top deposits of the Reitano Flysch that show low maturity levels (R_o %<0.5%) and is due to the tectonic load provided by the remains of the previously exhumed Peloritani Mts. This jump in thermal maturity suggests that Mt. Soro and Troina units' thermal evolution was achieved before Burdigalian times. AFT data, together with the paleotemperature estimates from vitrinite-reflectance data and clay mineral-based geothermometers, indicate that fission tracks were partially to totally annealed during wedge accretion and that the subsequent exhumation occurred mainly in Burdigalian times (17.7-20.2 Ma; Corrado *et al.*, 2009). The "far-travelled" and Antisicilide units are characterized by low R_o% values (0.41-0.56% for the

Antisicilide units), illite contents in mixed layer I-S between 25 and 50% and by no annealing of fission track indicating low levels of thermal maturity in early diagenetic conditions. A cooling age of 144 ± 51 Ma for a sample from the Antisicilide Unit, older than the stratigraphic age confirms low temperatures and provides information on the cooling history of source rocks rather than on the exhumation of the sediment. This data distribution suggests differences in the Cenozoic tectonics of the Sicilide accretionary wedge (Fig. 24). The Mount Soro and Troina units were involved into trench development before early Miocene times and acquired a late diagenetic signature due to thrust-stacking at deep levels whereas the far-traveled Sicilide and Antisicilide units kept their early diagenetic signature at shallower or outer structural levels of the accretionary wedge and were remobilized since late Aquitanian-Burdigalian times by gravity-driven processes (Corrado *et al.*, 2009).

Figure 24. Evolution of burial-exhumation of the Sicilide accretionary wedge in Eastern Sicily

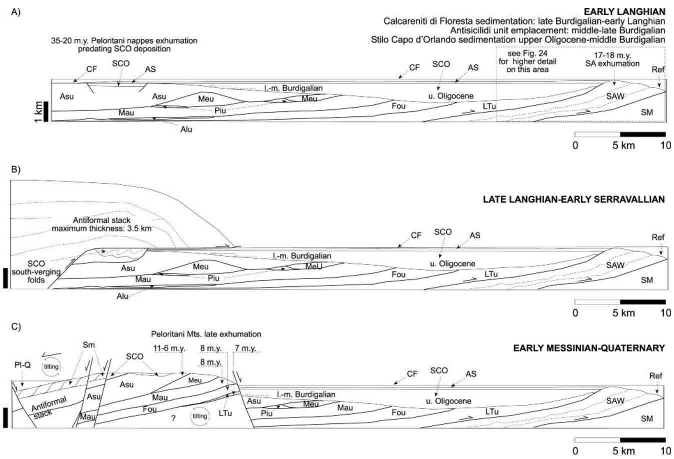


Schematic evolution of burial-exhumation of the accretionary wedge made up of Sicilide Units of the Apenninic-Maghrebian orogen in Eastern Sicily in Aquitatian-Langhian times after Corrado *et al.* (2009, modified). Not to scale.

For the Africa passive margin units in the Mt. Judica area, thermal constraints from mixed layered clay minerals indicate a thermal evolution in the first stages of the late diagenetic zone with increasing illite layers in I-S as a function of depth from 55 to 75%. This trend is observed in each thrust sheet of the Mt. Judica succession suggesting that internal stacking did not overprint the acquired thermal maturity. Thermal modelling suggests the effect of tectonic burial (~3 km), nowadays eroded, as the main factor for the acquired levels of diagenesis since late Miocene-early Pliocene times. The range of maximum temperatures experienced by the Africa passive margin units (Monte Judica succession) can be constrained between 100 (top) and 125°C (bottom).

Syn-orogenic sediments in early and late thrust-top settings (Reitano Flysch; Pliocene clays and Terravecchia Formation; Stilo-Capo d'Orlando Formation) show the lowest R_o% values (0.20-0.48%) and illite contents in mixed layer I-S (20-50%) consistent with the early diagenetic zone and in the immature stage of hydrocarbon generation. Sedimentary burial is considered to be the main factor responsible for the acquired thermal maturity. Only a small area exposed in the northern sector of the Peloritani Mts. display higher R_o% values than those identified in the depocentre of the Stilo-Capo d'Orlando Formation. These values (0.46-0.58%) are too high considering the Stilo-Capo d'Orlando thickness in that sector and they suggest greater thermal imprint and tectonic signature. This interpretation is strongly supported by AFT analysis performed on the crystalline substratum of the basin which indicates, for an intermediate portion of the Peloritani Mts., temperatures of 80-120°C partially to totally annealing the fission tracks after the Stilo-Capo d'Orlando sedimentation (Balestrieri *et al.*, 2008). Young AFT ages (<15 Ma) and thermal indicators constrain a thermal anomaly in the north-eastern area of the Peloritani Mts. characterized by short duration and a localized area of influence that is the result of compressive reactivation at the rear of the chain with emplacement of an out-of-sequence south-verging thrust stack (Aldega *et al.*, in press; Fig. 25). The main exhumation phase of the Peloritani Mts. is ascribed between 35 Ma and 20 Ma with significant erosion and marked by the sedimentary record of the Stilo-Capo d'Orlando Fm in Oligocene-Miocene times.

Figure 25. Evolution of burial-exhumation of the Peloritani Mts. since middle Miocene



Schematic evolution of burial-exhumation of the Peloritani Mts. since middle Miocene. a) early Langhian; b) late Langhian-(?)early Serravallian; c) early Messinian-Quaternary. Acronyms - Pl-Q: Pliocene-Quaternary deposits; Ref: Reitano Flysch; SAW: Sicilide Accretionary Wedge; Sm: Serravallian-Messinian siliciclastic deposits; AS: Antisicilide unit; CF: Calcareniti di Floresta; SCO: Stilo-Capo d'Orlando Fm.; Internal Zone (nappes from top to base) - Asu: Apromonte unit; Meu: Mela unit; Piu: Piraino unit; Mau: Mandanici unit; Alu: Alì-Montagnareale unit, Fou: Fondachelli unit; LTu: Longi-Taormina unit. External Zone - SM: Sicilian Maghrebids. After Aldega *et al.* (in press, modified).

Conclusion

Data about maximum burial and exhumation history from key areas of the Apennines and North-eastern Sicily are presented in this paper through maps based on an ArcGIS database, providing information on paleo-thermal and thermochronological constraints derived from organic matter optical analyses, X-ray diffraction of clay-rich sediments, fission tracks and (U-Th)/He dating.

In synthesis, main results concerning the single areas may be summarised as follows:

In the Northern Apennines, burial conditions (mainly detected through organic matter analyses) and timing of exhumation (through a huge dataset of thermochronological data) progressively decrease eastwards from the inner toward the outer zones and through the nappes from the lowermost to the uppermost unit. Apart from large outcrops of metamorphic rocks well exposed in Tuscany, most of the rocks of the Northern Apennines reached only diagenetic conditions.

In the Central Apennines, organic matter analysis and X-ray diffraction of clay-rich sediments are mainly provided for both pre-orogenic and syn-orogenic successions with subordinate apatite fission tracks data in the external zones. Low levels of diagenesis are recorded for both Meso-Cenozoic carbonate hanging-walls and siliciclastic footwalls of regional thrust sheets in the stage of immature to early mature stages of hydrocarbon generation. These results suggest a thick-skinned compressive style prevailing on thin-skinned style with strong influence of pre-existing paleogeography on thrust localisation and geometries that enhanced scarce tectonic loading during Upper Miocene-Lower Pliocene chain building.

In the Southern Apennines, both thermal and thermochronological data are available mainly for the axial portion of the chain comprising the outcropping tectonic units derived from the Apenninic Platform, the Mesozoic portion of the Lagonegro basin and the Apulia Platform.

Main novelties concern the detection of a jump in thermal maturity between the Apenninic Platform (shallow burial of tectonic origin in Basilicata with an along strike increase of tectonic loads toward the South at the Calabria-Basilicata border) and the outcropping Lagonegro basin-Apulian carbonate Platform (deep burial of tectonic origin locally exceeding 4 km). Data distribution suggests a switch from thin-skinned (Miocene) to thick-skinned (Pliocene-Quaternary) compressive tectonics as a result of influence in paleogeography at the passive margin scale coupled with the buttressing of the allochthonous wedge against the Apulia Carbonate platform margin. Exhumation of the Lagonegro derived units due to gravitational collapse through extensional detachments in the axial zone may be kinematically linked to severe shortening in the external portions of the chain.

In North-eastern Sicily, localised exhumation different in time and amounts develops in a general trend of decreasing thermal maturity from hinterland to foreland with the lowest values for syn-orogenic siliciclastics (mainly thrust-top basins). Compressive reactivation at the rear of the chain with creation of a few kilometres tectonic burial and subsequent exhumation since Serravallian times due to extension is also suggested in the Peloritani Mts. Accretionary prism made up of Sub-ligurian unit (namely Sicilidi) in the footwall of the Peloritani Mts. mainly exhumed in Burdigalian times (17-19 Ma) from depths of a few kilometers due to erosion, gravitational collapse and backthrusting. Frontal thrust stack derived from late deformation of Mesozoic passive margin successions mainly exhumed in Tortonian-Pliocene times from depths of about three kilometers.

Data from the crystalline units of Calabria manly concerning thermochronology are still too scarce to draw a burial-exhumation evolutionary scenario.

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