MAPPING THE PROGRESSIVE GEOLOGIC HISTORY AT THE JUNCTION OF THE ALPINE MOUNTAIN BELT AND THE WESTERN MEDITERRANEAN OCEAN

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ABSTRACT

This contribution illustrates a new type of map, the "geological event map" (1:250,000 scale), which highlights the progressive steps of the geologic history recorded in the polycyclic orogenic belt of the European Alps, at their southwestern termination facing the western Mediterranean Sea. The formula of historical progression simplifies comprehension of significant phenomenal visions and reorients public curiosity towards geologic processes. This part of the Alpine belt records a geologic history starting with the Variscan convergence during Devonian, throughout the opening of the Tethys Ocean, Alpine convergence, followed by Apennine subduction driving the opening of the Ligurian-Provençal Ocean. Finally, from late Miocene to Present a progressive tectonic inversion characterizes the Ligurian-Provençal continental margin.

This geologic history, over a time period of 400 million years, which includes three successive Wilson Cycles, is displayed in 8 plates composed of maps and illustrations. Each map explains the effects of successive tectonic events by adding geologic changes that modify the petrogenetic and structural configurations. The last plate shows the finite state of the geologic history at present-time. The map legend is based on ten major geodynamic events of which rock associations, and their genetic environment, are described in simple divulgation terms, to stimulate interest of neophytes. Illustration of the evolution of rocks and structures side of each map aims at conveying to non specialists in tectonics and petrology the impact of mechanisms associated with the Earth's deep engine upon surface changes.

INTRODUCTION

Geographic maps of basic features that are distributed on Earth's surface, such as ocean and seas, continents, mountain belts, and icy polar regions, inspire observers with an apparent sense of diffuse natural permanence. Awareness of the geologic time scale, involving changes in palaeoclimate, polar wandering and migration of continents are concepts that can guide the observer to an understanding of the dynamic history of the Earth's surface. The Earth is called the "blue planet" because it is the only rocky planet in the solar system retaining immense oceanic spaces. It is also the only planet provided with an internal thermal engine that drives a relatively rapid construction and elimination of ocean basins and continental translations. These lithospheric processes, which influenced the Earth's surface for nearly four billion years (Dilek and Polat, 2008; Santosh et al., 2017), left imprints in the composition and fabric of rocks that specifically identify a history of environmental changes. Rocks are indeed fossil mineral aggregates that encrypt the history of geographic setting, geologic environments, climates, ecosystems, and even deep lithospheric conditions. Knowledge of genetic processes of rocks and structures, and of their geologic age is the tool that illustrates the time-depending diversity and mutation of terrestrial environments generated during the ocean-continent mechanical interaction, known for 50 years as Plate Tectonics theory. Fragmentation and spreading of continental masses, new formation of ocean gaps and the reverse process of continental collision and ocean closure generate the wealth of mineral, biological and environmental records that inspired the first interpretations of the plate wandering (Taylor, 1910; Argand, 1924; Hallam, 1972). The modern global theory of of Plate Tectonics (e.g. Dewey, 1972) suggests how logic links of phenomenal evidences from different branches of Earth sciences can become valuable indicators of a specific larger scale event of lithosphere motion. Such a modern understanding of plate tectonic mechanisms and related changes clearly arises from the termination of the Alpine belt (Maritime Alps) into the transecting western Mediterranean sea-basin, a particular geologic district, in which abundant continental and marine "mineral fossils" disclose so clearly a long geologic history to experts and to simple visitors as well.

Young mountain belts provide a wealth of these rocks and structures evolved as a result of lithosphere dynamics (Hsü, 1983; Turcotte and Schubert, 2002). New orogenic systems, better record varieties of superposed geological histories and full geodynamic processes ranging over hundreds of million years (e.g. Johnson and Harley, 2012). Challenges to modern society, such as sustainability of natural resources, readaptation to climate and sea level change, subsidence of coastal areas and safety of communities facing natural hazards demand for a better environmental awareness by the general public. Normal or rapid severe natural changes in the biosphere just recently turned out to be comprehensible in relation to the lithosphere, thanks to new developments of Earth sciences. In the last decades, public visiting regions of natural attractions may much better enjoy modern linear ways of disseminating Earth science basics and therefore consciousness of how processes and products are enchained and consequent to the Earth's dynamics.

For more than two centuries, tools as "geological maps" illustrate most of geologic knowledge at the research and technical level; this is done by a traditional full geologic dressing of a geographic document, through legend descriptors as colours, symbols, and categories that disclose the present-day observations on nature of observables as rocks and structures of any age; traditional maps are the finite accumulation of numerous long lasting geological events. Consequently, divulging any geologic history of a given area using a standard geological map is not straightforward for most of non-specialized public, amateurs or even as a basic source of information for land planning. Therefore it is essential that geoscientists should regard the disseminating of information in an understandable form as a duty (e.g. Arattano et al., 2018). In this contribution we present a map at a scale of 1:250,000, conceived as an information tool, named as a "geological event map" (or "incremental geological map") that aims at highlighting progressive stages in the geologic history recorded in the still active mountain range of the Maritime Alps and adjacent offshore. This region, which includes a recent collisional belt facing a recent ocean, is both a geologic playground and a territory of high value for basic science. This still active mountain belt is exposed mainly in the protected area of the Argentera-Mercantour, merges into the (similarly protected) space of the continental slope and the abyssal plain of the Ligurian-Provençal Ocean. Such sharp physiography, fully accessible on sea and mountain, formed by a relatively rapid truncation of the Alpine belt along a scar centred around Monaco-Montecarlo. A step-like map sequence explains the series of structural and petrogenetic events in sketches and panoramas that reorient focus from contemplation of static phenomenal views (observables) to mechanisms that trigger Earth processes and ultimately to universal tectonic principles. The combined continental and marine geology contain records that decrypted, over the last 50 years, tectonic events and rock-forming environments (rock factories) ranging from the closure of the Rheic Ocean during the Variscan convergence, to the opening of the western Tethys Ocean, and the continental suture, which defines its closure and the generation of the Alpine chain. The spectacular physiography of the junction between the Maritime Alps and their adjacent oceanic basin still manifests the truncation of the still active Alpine chain. The successful use of a similar presentation strategy of a geologic history involves the incremental mapping of progressive deformation of ice within an alpine glacier (Azzoni et al., 2017) and progressive deformation and mineral transformation of metamorphic rocks in the western Alps (Delleani et al., 2012; Lardeaux, 2014; Corti et al., 2017). By means of this type of progressive representation of rock units varying through time explains more clearly the awesome effects of the so-called Wilson Cycle (Wilson, 1966; Dewey and Spall, 1975; Shirey and Richardson, 2011) that involves the periodic opening and closing of ocean basins and migration of continental fragments. It generates new rock factories at the sites of destruction and construction of the oceanic and continental lithospheres, activated by plate motion, more visible. The new rock types progressively bred in time and accumulated at each tectonic event are reported in the step-like legend of the Plate sequence. Collocation of rock groups in all of the maps is however unrelated to the original geographic spaces in which they were generated (rock factories). The present day position of rock groups (Plate 8: the finite map) is gained after a summation of tectonic increments through geologic time. Representation of the generation sites of incoming rock types is not incorporated into a progression of geographic changes (paleogeography). Combining the changes revealed in geological maps with illustrations and informative texts provides non-specialists with a comprehensive view of the scientific evidence of phenomena that indicate the global processes of our planet.

GEOGRAPHICAL AND GEOLOGICAL CONTEXT

The area considered extends between Cuneo, San Remo, Montecarlo, Nice, and Barcelonnette, including territories of Italy, France, and Monaco states, as well as the continental slope and the deep sea floor adjacent to their coastal areas. The domain is located at the extreme end of the Himalayan-Alpine mountain system in the corner where it is interrupted abruptly by the more recent Ligurian-Provençal deep marine basin (Fig. 1).

The geologic history recorded within the Maritime Alps started with the formation of the Variscan belt throughout subduction and collision processes (von Raumer et al., 1999; Guillot and Ménot, 2009; Spalla et al., 2014). These tectonic events took place between the Devonian and Late Carboniferous. They were followed by the thinning of the lithosphere between the Permian and Triassic periods, which heralded the Alpine rifting, the opening of the Tethys Ocean and a period of sea floor spreading, between Jurassic and Early Cretaceous times (Lemoine et al., 1989; Schettino and Scotese, 2002). A new orogenic cycle was initiated by Alpine subduction and collision between Late Cretaceous and Oligocene times (Dardeau, 1987; 1988; Decarlis et al., 2014). The Apennine subduction generated a new rifting event followed by the creation of the Ligurian oceanic basin that was accommodated by the anticlockwise rotation of the Corsica-Sardinia continental lithosphere, which truncated the Alpine belt abruptly between late Oligocene to early Miocene times. The Ligurian continental margin experienced tectonic inversion from the late Miocene to Present (Séranne, 1999; Jolivet and Faccenna, 2000). The modern geodynamic setting of southwestern Europe is controlled by the complex interplay between the Alpine-Betic and Apennine-Magrebid belts, dominated by continuous convergence between Europe and Africa (Anderson and Jackson, 1987; Béthoux et al., 2008; 2016). Therefore the Maritime Alps and their termination down at the sea floor margin preserve a geologic heritage that includes the tectonic history of the last 400 million years of our planet, displaying the effects of three superimposed Wilson cycles.

METHODOLOGY AND DATA BASES

Geological maps of mountain belts classically portray the finite geologic architecture that represents the accumulated effects of all events, which occurred through time. The coloured maps mainly define the nature of rock types (*lithotypes*), possibly their ages and the environments in which they were generated.

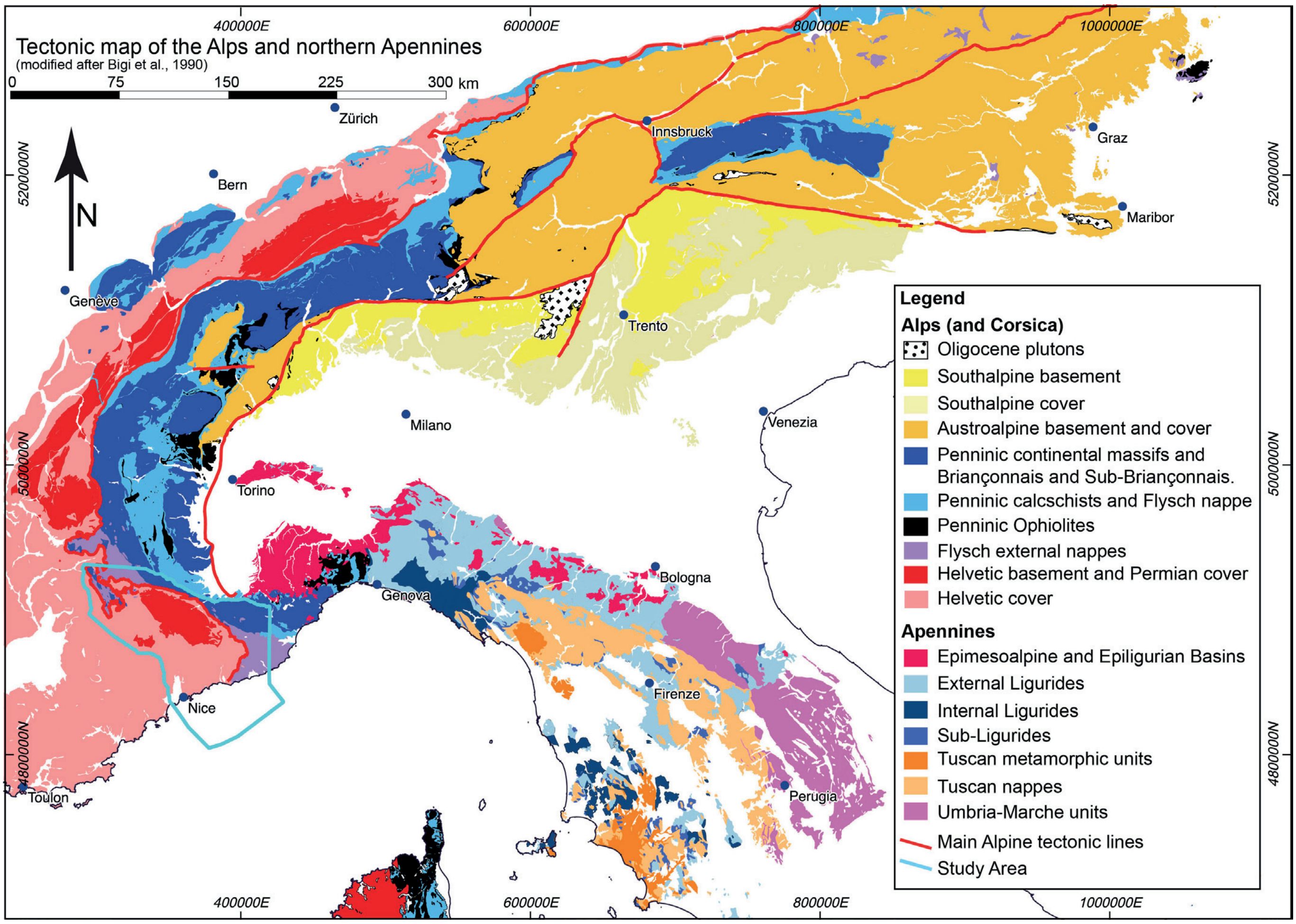

Fig. 1 - Tectonic map of the Alps, northern Corsica, and Northern Apennines, modified after Bigi et al. (1990). Reference system: WGS 84 / UTM zone 32N. Key to legend. *Alps (and Corsica)*: Oligocene plutons = intrusive magmatic bodies emplaced at late Alpine collision; Southalpine basement and cover = dominantly Variscan metamorphic rocks of the Africa/Adria plate margin uncomformably overlain by sedimentary covers starting from Carboniferous, affected by Alpine translation towards S; Austroalpine basement and cover = Variscan metamorphic rocks and sedimentary covers partially involved in Alpine metamorphism and translational tectonics towards N-NW; Penninic continental massifs and Briançonnais and Sub-Briançonnais = slices of continental crustal margins of the Alpine ocean (basement and covers); Penninic calcschists and Flysch nappe = prevailing metasedimetary covers of the Alpine ocean and subduction trench; Penninic Ophiolites = rocks of the Alpine ocean crust and mantle with dominant ultra-high pressure / high pressure metamorphism; Flysch external nappe = turbidite sequences from Alpine subduction trench; Helvetic basement and Permian cover = dominantly Variscan metamorphic rocks of the European continental margin and intramontane basin sediments; Helvetic cover = Triassic to Oligocene sedimentary rocks of the European margin. *Apennines*: Epimesoalpine and Epiligurian basins = sedimentary rocks of Oligocene to Miocene episutural basins; External Ligurides = Cretaceous to Eocene sedimentary rocks from the continent-ocean transition with scattered ophiolitic bodies and lenses; Internal Ligurides = ophiolitic rocks of the Alpine ocean crust and mantle weakly metamorphosed; Sub-Ligurides = mostly Palaeocene to Lower Miocene sedimentary rocks deriving from the Africa/Adria edge; Tuscan metamorphic units = metamorphic rocks deriving from Africa/Adria sedimentary protholits; Tuscan nappes = Triassic to Early Miocene sedimentary rocks from Africa/Adria plate; Umbria-Marche units = External thrust units consisting of Triassic to Early Miocene sedimentary rocks.

In the proposed "geological event map", the colours represent the addition of new rock associations generated of global changes in lithosphere dynamics (e.g. plate-scale tectonic events) during the whole history of the three Wilson Cycles: Variscan, Alpine, and Mediterranean/Apennine. Therefore the "geological event map" illustrates the progressive development through time and space of diverse "rock factories" and of their related tectonic settings. The final geological map is the product of the superimposition of these petrogenetic and tectonic events.

In the example of the Maritime Alps and the adjacent offshore bathymetry, the "geological event map" synthesizes the critical data derived from geological mapping projects (BRGM - Carte Géologique de la France, Servizio Geologico d'Italia and Regio Ufficio Geologico - Carta Geologica d'Italia and CARG), and from research projects on land and sea involving published data from 1832 up to the production of the recent map of Piemonte Region (Piana et al., 2017). The resulting synthetic maps are drawn over a digital elevation model obtained from SRTM (Shuttle Radar Topography Mission) and Géoazur.

The 8 maps are based upon the succession of 10 major tectonic events and present the basic relationships between rock types, structures and their genetic environments in accord with evolving plate motion regime (synthesis in Table 1).

THE INCREMENTAL GEOLOGIC HISTORY

The incremental geologic history is organized into tectonic events that activate the generation of new rocks, which are included in the three successive Wilson Cycles. The legend

Table 1. Synoptic view of the main geologic events, expressed by in the association of tectonic (geodynamic) characters, chronology (ages), rock types possibly related to their genetic environments. Fig. numbering refers to list of each plate.

Plates	events (tectonic, geodynamic regime)	age range of geodynamic regime	generation of critical rock types
Plate 1 Continental crust formation during the Variscan orogenic cycle: 400 - 290 Ma (Fig. 6)	1 -- Variscan subduction	Early Devonian (400 - 375 Ma)	Eclogites, serpentinised peridotites, and marbles (Fig. 1)
	2 -- Variscan collision	Late Devonian to early Carboniferous (375 - 320 Ma)	Migmatites and granitoids (Fig. 2, 3, 4)
	3 -- Erosion / dismantling of the Variscan chain	late Carboniferous (320 - 299 Ma)	Sandstones, carbonaceous schists, and conglomerates (Fig. 5)
Plate 2	4 -- Post-Variscan thinning (Fig. 5)	Permian to Triassic (290 - 201 Ma)	Permian clastic sediments and volcanics, Triassic evaporites and clastic and carbonatic sediments (Fig. 1, 2, 3, 4)
Plate 3	5 --Alpine rifting, formation of passive margins, and oceanisation (Fig. 4)	Jurassic to Early Cretaceous (201 - 100 Ma)	Jurassic limestones and dolostones in syn-rift basins and strucutral highs; Early Cretaceous limestones, marls, and sandstones in post-rift pelagic basins (Fig. 1, 2, 3)
Plate 4	6 -- Alpine subduction (Fig. 6)	Late Cretaceous to early Eocene (100 - 45 Ma)	Late Cretaceous turbiditic limestones and marls (Fig. 1, 2) Late Cretaceous Flysch with Helminthoids (Fig. 3, 4, 5) latest Cretaceous to middle Eocene, lacustrine and continental conglomerates, limestones, and red clay with mica
Plate 5	7 -- Alpine collision	late Eocene to Oligocene (45 - 23 Ma)	Flysch and fossiliferous limestones and marls (Fig. 1, 2, 3).
Plate 6	8 -- Apenninic subduction (Fig. 5, 6)	late Oligocene (28 - 23 Ma)	Subduction-related andesitic breccias and tuffs (Fig. 1).
Plate 7	9 -- Opening of the Western Mediterranean (Ligurian-Provençal basin) during the Corsica-Sardinia block rotation (Fig. 2, 3, 4)	late Oligocene to early Miocene (23 - 15 Ma)	Coastal, shelf, slope, and deep sea sedimentary rocks
Plate 8	10 -- Inversion of the Ligurian-Provençal margin (Fig. 3)	late Miocene to Present (from 15 Ma on)	Marine to continental deposits (Fig. 1, 2).

of the geological map presents the timing of cycles that merge into each other based on chronologic studies of petrogenetic signals. In this presentation, a single rock type or tectonic feature corresponds to a short time interval. A rock association, or structural complex, characterizes a larger time interval in which petrogenesis, or the generation of tectonic structures (tectogenesis), was triggered by major tectonic events on a lithospheric scale. A multiplicity of lithospheric tectonic events corresponds to a Wilson Cycle. This starts with the break up of a large eroded continent as a result of rift faulting and the fragmentation of continental crustal units, which were separated by a growing ocean basin. The cycle ends with collision, the closure of an ocean basin and the amalgamation of the continental units (Fig. 2). Viewers of the maps need to be aware that the precise dating of each tectonic event is an approximation that is limited by the availability of chronological information in the accessible rock record and is therefore subject to updating by new scientific research. Tectonic events involving huge lithospheric masses, rock types, and time intervals characterize the Variscan and Alpine continental collisions, Apennine subduction, and the opening of the Ligurian-Provençal ocean basin. For example, the opening of such basin was triggered by the northward descent into deep mantle of a lithosphere fragment of the Tethyan Ocean located close to the Alpine margin. This ocean subduction event marked the beginning of the Mediterranean/Apennine cycle, resulting in the transverse truncation of the Alpine belt during its active collision. In this case the left-hand side of the legend shows diagrammatically the temporal superposition of the two cycles (see map plates). Similarly the beginning of post-Variscan rifting (event 4) is considered to have initiated during the Permian (e.g. Diella et al., 1992; Marotta et al., 2009), but it is revealed in the record of younger sedimentary rocks.

The incremental geologic history recorded in the Maritime Alps and their present-day offshore component is therefore described by the events displayed in the following plates that incorporate single events within a global scale tectonic process. In the following, a connection within text and legend of maps is ensured by the numeration of rock boxes reported in brackets.

Events 1, 2, and 3 (Plate 1) are the three oldest events recorded in the Maritime Alps and were generated during Palaeozoic times. They correspond to the formation and subsequent dismantling of the Variscan collisional belt. In Early Devonian times the Variscan convergence involved the subduction of the Rheic Ocean (Matte, 2001; Cocks and Torsvik, 2002; 2006; Franke et al., 2017). This event is testified by the association of variably sized disrupted layers, boudins or lenses of eclogite, peridotite, calcsilicate, and marble (1-1, 1-2, 1-3), within the partially molten (migmatite 2-2 to 2-6) rocks of the Argentera-Mercantour Massif (Faure-Muret, 1955; Latouche and Bogdanoff, 1987; Ménot et al., 1994; Malaroda, 1999; Rubatto et al., 2001; Ferrando et al., 2008; Guillot and Ménot, 2009; Rubatto et al., 2010; Spaggiari, 2015; Volante, 2015; Jouffray et al., 2018). The complete closure of the Rheic Ocean led to the Variscan collision and consequent construction of the Pangea super-continent, during Late Devonian and Early Carboniferous times (Matte, 1991; von Raumer et al., 1999; Stampfli and Borel, 2002). This event is represented within the whole of the Argentera-Mercantour Massif (located across the French Italian border) by migmatite (2-2 to 2-6) rock associations (e.g. Malaroda and Schiavinato, 1957; 1958; 1960; Blasi and Schiavinato, 1968; Bortolami and Sacchi, 1968; Malaroda et al., 1970; Blasi, 1971; Bogdanoff and Ploquin, 1980; Bogdanoff, 1986; Bogdanoff et al., 1991; Compagnoni et al., 2010). These are intruded by a late collisional granitic plutons (2-1) and mafic dykes (Sacco, 1911; Boucarut, 1967; 1969; Ferrara and Malaroda, 1969; Monié and Maluski, 1983; Colombo, 1996; Debon and Lemmet, 1999; Corsini et al., 2004; Filippi, 2017). Migmatitic and granitic rocks record the thermally mature stage of the Variscan collision at deep and shallow crustal levels, respectively. The erosion and dismantling of the Variscan belt started in the Late Carboniferous and is demonstrated by terrigenous rocks (3-1) such as sandstones, conglomerates, and carbonaceous schists that contain plant fossils (Bertrand, 1898; Corsin and Faure-Muret, 1946; 1951; Faure-Muret and Fallot, 1955). These rocks represent the sedimentary fill of immature intramountain basins, the opening of which was controlled by strike-slip fault systems. Their remnants are now exposed mainly along mylonitic zones (Faure-Muret, 1955; Malaroda et al., 1970; Bortolami et al., 1974; Musumeci and Colombo, 2002; Corsini et al., 2004; Carosi et al., 2016; Simonetti et al., 2018) produced by the reworking of the Argentera-Mercantour crystalline rocks during a later event (see Event 8 in Panel 6 and description below).

Event 4 (Plate 2) corresponds to the tinning of the post-Variscan orogenic lithosphere, which occurred between the Permian and Triassic and led to the initiation of Pangea disaggregation (Diella et al., 1992; Marotta et al., 2009). This event is confirmed by the occurrence of Permian terrigenous rocks (conglomerates, sandstones, arkose sedimentary rocks, and pelites; 4-3), typical of alluvial, and lacustrine environments (Faure-Muret, 1955; Malaroda, 1974; 1999; Barrier et al., 2009), and volcanic deposits (4-4) (Romain and Vernet, 1978) that partly filled the intra-continental basins (Decarlis et al., 2013). During the Early Triassic, the geodynamic setting evolved progressively towards that typical of lithospheric thinning of a passive continental margin characterized by the deposition of transgressive coastal conglomerates, sandstones, and pelites (4-2) (Faure Muret, 1955; Malaroda et al., 1970; Richards, 1983); During the Middle Triassic the area evolved into a continent - marine basin transitional environment characterized by deposition of limestones and dolostones (4-2) (Faure-Muret, 1955; Lanteaume 1968; Carraro et al., 1970; Bersezio and d'Atri, 1986). The Middle Triassic event heralded the generation of the Alpine ocean as a component of the Central Atlantic. During the Late Triassic continental thinning and rifting processes continued and rock associations such as marls, dolostones, and evaporites (4-1) represent a transitional sedimentary environment from continental to a marine basin (Gèze et al., 1968; Carraro et al., 1970; Bersezio and d'Atri, 1986; Decarlis et al., 2013).

Event 5 (Plate 3) represents the incremental evolution up to a phase of Alpine rifting and the petrogenetic construction of the ocean floor between the Jurassic and Early Cretaceous. During the Jurassic, continuous lithospheric extension led to the differentiation between marine basins and platforms with limestones and dolostones (5-2; 5-3) (Pareto, 1832; Franchi, 1894; Lanteaume, 1968; Carraro et al., 1970; Dardeau, 1983; Debrand-Passard et al., 1984; Barale et al., 2015; 2016; Bertok et al., 2018). Marine sequences of Middle Jurassic age indicate the opening of the Alpine ocean (Piedmont-Ligurian Tethys) and the creation of the European and Adriatic passive margins (Dardeau, 1988; Lemoine et al., 1989). The oceanic expansion continued until the Early Cretaceous times, which were characterized by pelagic deposition and blanketing of the ocean floor by thin-bedded limestones and marlstones (5-2). The condensed sequence of Early Cretaceous limestones predates a hiatus, from latest Cretaceous to middle Eocene, (e.g. Nice arc area) related to weak instabilities of the European passive margin (Barale et al., 2015) before the onset of Alpine subduction.

Event 6 (Plate 4) records the beginning of the Alpine convergence attested by inversion of the lithospheric movement

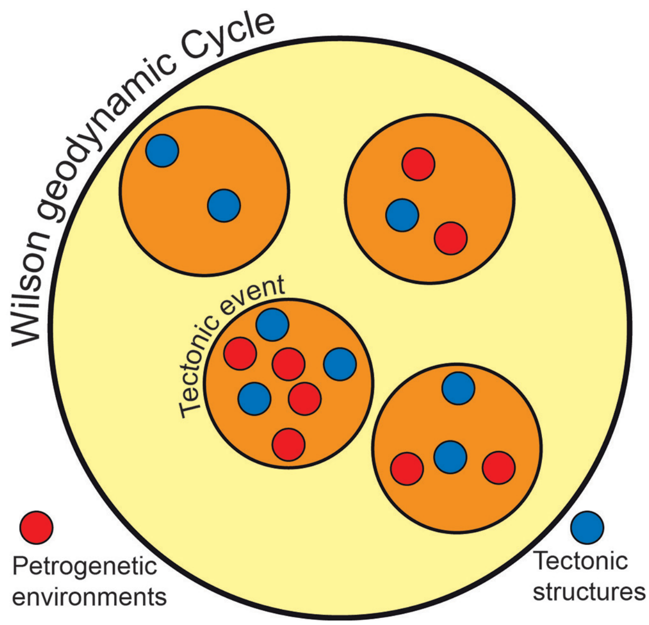

Fig. 2 - The image of a set-diagram shows the logics of the geological components forming a Wilson Cycle, that is a long-lasting process of tectonic dispersion of a mega-continent into fragments, followed by their regroupement, going along with opening and closure of new ocean branches. Well defined complexes of rock associations and the related tectonic structures, as determined during the field investigations of geologists, constitute a single tectonic event. The set of tectonic events including divergence and convergence of lithospheric plates represents a complete Wilson Cycle. The progressive construction of the map legends in the 8 Plates (see online supplementary material) is generated by the types of observations that characterise each of the cycles through time.

and the onset of Alpine ocean subduction, which occurred between the Late Cretaceous and early Eocene. The subduction of the Alpine ocean led to tectonic activation of the Adriatic margin and formation of an accretionary sedimentary wedge (Dardeau, 1987; 1988; Decarlis et al., 2014) in which both continent-derived and marine sediments were deposited. Limestones and marls (6-2; 6-3) represent sediments deposited during the Late Cretaceous and Palaeocene in turbidite-type basins (e.g. Vanossi, 1980; Vanossi et al., 1980; Bersezio et al., 2002), whereas the so called "Helminthoid Flysch" (6-2) (Elter et al., 1961; Lanteaume et al., 1963; Alesina et al., 1964; Lanteaume, 1968; Gosso et al., 1983; Manivith and Proud'Homme, 1990; Argnani et al., 2006; Giammarino et al., 2010; Argnani, 2012) represents detrital rock sequences deposited within the subduction trench. Between the early and middle Eocene, conglomerates, limestones, and white mica-bearing clays (6-1) overlie the Cretaceous succession unconformably (e.g. Faure-Muret, 1955; Sturani, 1965; Varrone and Clari, 2003), within deeply carved canyons or in lacustrine and shallow coastal environments that mark the transition from subduction to a new tectonic regime, characterized by continent-continent collision.

Event 7 (Plate 5) illustrates the origin of the newly formed structures and rocks deposited during the Alpine collision, which involved the passive European and the active Adriatic continental margins, and occurred between late Eocene and Oligocene. This continental collision is responsible for the widespread NE-SW shortening accommodated by fold and thrust systems (Bertrand, 1923a; 1923b; Goguel, 1936; Fallot, 1949; Gèze et al., 1968; Siddans, 1979; Brizio et al., 1983; Vanossi and Gosso, 1983; Guardia and Ivaldi, 1985; Menardi-Noguera, 1988; 1989; Carminati and Gosso, 2000; Carminati, 2001; Schreiber et al., 2010; Schreiber, 2010; Maino et al., 2015). A significant number of these thrust fault systems results from the tectonic inversion of former normal faults or strike-slip fault systems within sedimentary basins (Lemoine et al., 1989; Guardia et al., 1996; Ivaldi et al., 1998; Decarlis et al., 2014). Thickening of the European continental crust is admirably demonstrated by excellent studies of the Pennine front (frontal override of materials from the external margin of the Piemontese-Ligurian Tethyan Ocean) (Figs. 3 and 4) and by geophysical imagery (Bertrand and Deschamps, 2000; Paul et al., 2001; Lardeaux et al., 2006; Béthoux et al., 2007; Thouvenot et al., 2007; Schreiber, 2010). The crustal thickening is responsible for the loading of the European foreland and consequently the formation of NW-SE trending flexural basins (Ford et al., 1999; Carminati, 2001; Lacombe et al., 2009). These foreland basins host shallow marine and hemipelagic deposits predating several types of flysch deposits (7-1; 7-2; 7-3) (Campredon, 1977; Campredon and Giannerini, 1982; Sinclair and Allen, 1992; Joseph and Lomas, 2004) whose depositional sequences, interpreted in terms of fluid dynamics, constitute a worldwide standard reference for turbidity sequences (the famous "Bouma Sequence", Bouma, 1962). Locally these sedimentary rocks contain spectacular accumulations of fossils such as the large foraminifera *Nummulites* (7-3) (Lanteaume, 1968; Bodelle, 1971; Campredon, 1977).

Event 8 (Plate 6) records the interference between Alpine collision and the Mediterranean/Apennine subduction, which resulted in the opening of the western Mediterranean basin. Indeed, the entire Alpine collisional edifice was transversally affected by a new phase of subduction that led to the construction of the Apennine belt during the Late Oligocene, e.g. before the end of the Alpine collision (Doglioni et al., 1998a; 1998b; Séranne, 1999; Carminati and Doglioni, 2005). This tectonic interference is well attested by the concomitant presence of E-W trending thrust faults and folds (Schreiber, 2010) and NNW-SSE trending strike-slip faults that produced, in the Argentera-Mercantour massif, greenschist facies mylonites dated between 28 and 22 Ma (e.g. Corsini et al., 2004; Sanchez et al., 2010; 2011a; 2011b; Filippi et al., submitted). These tectonic features accommodated NNW-SSE compression and are particularly well documented in the southern and central Maritime Alps region, where they were active until Miocene times (Bulard et al., 1975; Ivaldi et al., 1998; Mondielli, 2005; Courboulex et al., 2007; Giannerini et al., 2011). During the Apennine subduction calc-alkaline volcanism occurred along the European margin. This magmatic activity is recorded from 30 to 18 Ma by extensive exposures of andesites, basaltic andesites, dacites, and andesitic breccias and tuffs (8-1) (Ivaldi et al., 2003; Réhault et al., 2012) well exposed along the coast across the border between France and Monaco (area of Cap d'Ail).

Fig. 3 - Three tectonostratigraphic events, ranging in age from late Permian to early Eocene, which formed in different environments and describing arcuate structure of the Penninic front of the Maritime-Ligurian Alps, viewed over a distance of about 40 km due west from the southern crest of Monte Armetta, towards the skylines of the Mongioie-Marguareis group. The prominent arcuate ridge (in the middle of the image, highlighted in pale blue) consists of Mesozoic to early Eocene Ligurian Briançonnais carbonates and marls; to its left the carbonates are flanked by the intensively forested Helminthoid Flysch (highlighted in pale brown) and, to the right, by the silicic rocks of the Briançonnais sequence (highlighted in pale green). In this regionally arcuate tectonostratigraphy the oldest tectonic episode, e.g. the initiation of the Permian-Triassic rift event, is represented by the intracontinental silicic deposits. The subsequent rifting event involves Mesozoic and Cenozoic deposits, marked by Mesozoic deposits representing the transition from lower Triassic shelf dolomitized carbonates to early Jurassic continental slope and early Eocene basinal marls and carbonates). The coupling and general deformation of the three domains is Alpine. The internal structure of the central ridge is a continuous regional package of hundred metre- to kilometre-scale superimposed isoclinal folds, which disrupts and interfingers the Mesozoic carbonate sequence and interfingers it with Eocene turbidite deposits. Refer to legend of the progressive event map. Image credit to Menardi-Noguera.

Fig. 4 - Structural setting of the Penninic tectonic Front in the Jurassic to Eocene sequence of the Ligurian Briançonnais. The complex tectonostratigraphy results from the superposition of the tectonic event of involving early Cenozoic Alpine collision upon the rifting event of Mesozoic-early Cenozoic age that gave rise to the Briançonnais rock association. The distinctive disruption of the layered sedimentary sequence is the product of the repeated superposition of Alpine fold systems of various wavelengths. View due north of the Marguareis south face, from Route du Sel, near the meadow of Margerie du Plan Ambreuge, at France-Italy border. From left to right, the prominent tops are Castel de l'Aigle (light brown tooth), Cime de l'Armuse (whitish knob in the centre), and top of Mt. Marguareis (summit with Créte de la Galine ridge, degrading to the east).

Event 9 (Plate 7) is a consequence of the anticlockwise rotation of the Corsica-Sardinia block generated by the Mediterranean rifting, during the late Oligocene and early Miocene (Biju-Duval et al., 1977; Jolivet and Faccenna, 2000; Gattacceca, 2001; Guennoc et al., 2005). This rotation is explained by back-arc extension processes and subsequent opening of the deep Ligurian-Provençal Basin within the recently thickened European lithosphere (Séranne, 1999; Contrucci et al., 2001; Faccenna et al., 2001; Rollet et al., 2002). As a consequence, the new oceanic lithosphere was soon and rapidly created (Auzende et al., 1973; Recq et al., 1979; Réhault, 1981; Horvath and Berckhemer, 1982; Kastens and Mascle, 1990; Pasquale et al., 1994; Gueguen, 1995; Doglioni et al., 1997; 1998a; Carminati et al., 1998; Gueguen et al., 1998; Rollet, 1999; Gelabert et al., 2002; Rollet et al., 2002; Rosenbaum et al., 2002; Bache, 2008; Artemieva and Meissner, 2012). The creation of this new oceanic basin led to an abrupt rupture across the Alpine belt, which, at present is a steep natural slope exposed from 3000 to 2800 metres above and below sea level, respectively (Recq et al., 1976; Chamot-Rooke et al., 1999; Chantraine et al., 2003; Brosolo and Mascle, 2008). Event 9 is testified by normal and strike-slip block faulting seen along the coasts just east of Nice (Irr, 1984; Béthoux et al., 1988; Gorini et al., 1994; Mauffret et al., 1995) and imaged by geophysical data (seismic reflection profiles) beneath the continental margin between San Remo and Nice (Sage et al., 2011; Seno et al., 2017). Evidence for a huge amount of submarine instability including scars and canyons, as well as of turbidity current deposits (9-1) are recognized all along the whole of the Ligurian continental slope (Hassoun et al., 2009; Migeon et al., 2009; 2012; Petit et al., 2015; Soulet et al., 2016).

Event 10 (Plate 8) displays the effects of the tectonic inversion, which affects the recently formed Ligurian continental margin. This plate shows the complete geological accumulation of rock sequences and successions (10-1 to 10-4) of structures and thus presents the complete map of the geologic events (or "finite map" in the sense of total accumulation of rocks and tectonic structures at the end of the whole tectonic history). The inversion, which started about 15 Myr ago that is just after the creation of the small oceanic space, is a direct consequence of the continuous global convergence between the Europe and Africa/Adria plates since the Alpine evolution (Béthoux et al., 1988; 1992; 2008; Chaumillon et al., 1994; Marotta and Splendore, 2014). As a consequence, some of the Apennine subduction-related thrusts and strike-slip faults were reactivated inducing large-scale thrust systems such as the Nice Arc (Gèze, 1960a; 1960b; Campredon et al., 1977; Giannerini et al., 1977; Guardia and Ivaldi, 1985; Ritz, 1992; Schrötter, 1998; Sanchez et al., 2010; Giannerini et al., 2011; Sage et al., 2011; Bauve et al., 2012). Reactivated fault zones within the Argentera-Mercantour massif, hosted vigorous conduits for hydrothermal veining (e.g. Fig. 5) (Perello et al., 2001; Musumeci et al., 2003; Baietto et al., 2008; Ribolini and Spagnolo, 2008), and its final denudation (Bigot-Cormier et al., 2000; 2006; Bogdanoff et al., 2000). At the base of the continental slope a few normal faults, generated during the construction of the Ligurian Basin margin, were reactivated as reverse faults (Bigot-Cormier et al., 2004; Larroque et al., 2009; 2011; 2012). The tectonic reactivation of the Ligurian margin is considered to be partly responsible for the seismicity of the region (Madeddu et al., 1996; Larroque et al., 2001; Calais et al., 2002; Courboulex et al., 2007; Béthoux et al., 2008; Bauve et al., 2014; Béthoux et al., 2016). During this final stage, marine sediments, locally exposed along the coast (Anglada et al., 1969; Bellaiche et al., 1976; Campredon, 1977; Dubar et al., 1992) were deposited during the early Miocene to Pliocene (10-2; 10-3); they include (Mascle and Mascle, 2019), within the deep basin, thick Messinian salt layers and locally conglomerates along the slope (salinity crisis, Fig. 6).

DISCUSSION AND CONCLUSIONS

The example of a newly conceived "geological event maps" discussed in this paper aims, through the example of the Maritime Alps, at highlighting the progressive geologic history recorded inside the western termination of the polycyclic orogen of the Alps and its associated ocean basin. This approach, by using incremental maps, allows imaging of the past history included in the sector of the Alpine mountain chain. A prototype of this map turned out to be

Fig. 5 - Vertical fracture field of the Mediterranean/Apennine deformation event, impressed upon the partially molten Variscan gneisses and shapes the southwest (and northeast) walls of Corno Stella. The fractures scaling the gneisses into variably thick laminae are nearly vertical and intersect an oblique, over 10 metres thick white dilatant vein, sealed by recrystallized hydrothermal quartz. Viewed due east from the surroundings of the historical L. Bozano mountain hut. Northwestern cirque of Serra dell'Argentera.

operative for a concise scientific revelation of the geological complexities of the discussed region and will be of efficacy when installing events of scientific divulgation. The "geological event maps" may as well stimulate experts to refine existing maps by further research in this especially complex region, and improve the record of petrogenetic and tectonic events related to the Variscan, Alpine, and Apennine/Mediterranean stages (Wilson Cycles). The superimposition of the last two cycles implies the reworking of a large cross section of the former Alps under the influence of the subduction during the Mediterranean/Apennine cycle resulting in the Mediterranean rifting (e.g. Ford et al., 2006; Argnani, 2012) that actually interrupted the standard completion of normal dismantling of the Alpine belt by classic collapse and erosional processes. The sequence of maps displays a less condensed view of chronological, lithological, and structural readjustment during progressive geodynamic changes of tectonic regimes over large time spans. The maps encourage scientifically interested amateurs to appreciate how geologists treasure the record of changing rock types and tectonic regimes to build innovative theories about the Earth, by testing the validity of the Wilson Cycle in the less explored parts of our planet.

The selected area appeared particularly suitable for creating "geological event maps". It contains a section across the young Alpine orogen almost from to -2500 to 3300 m high ridges, and includes, with no intervening continental shelf, the submarine slope of a younger ocean basin down to the abyssal plain. Moreover, such onshore-offshore step-like maps reveal the spatial-temporal distribution of multiply reactivated tectonic structures imprinted on rock sequences that accumulated over the last 400 Ma, which may be sensible to geological hazards. Thus sites subject to natural risk can be easily located within the complete evolutionary context of a geologically active area.

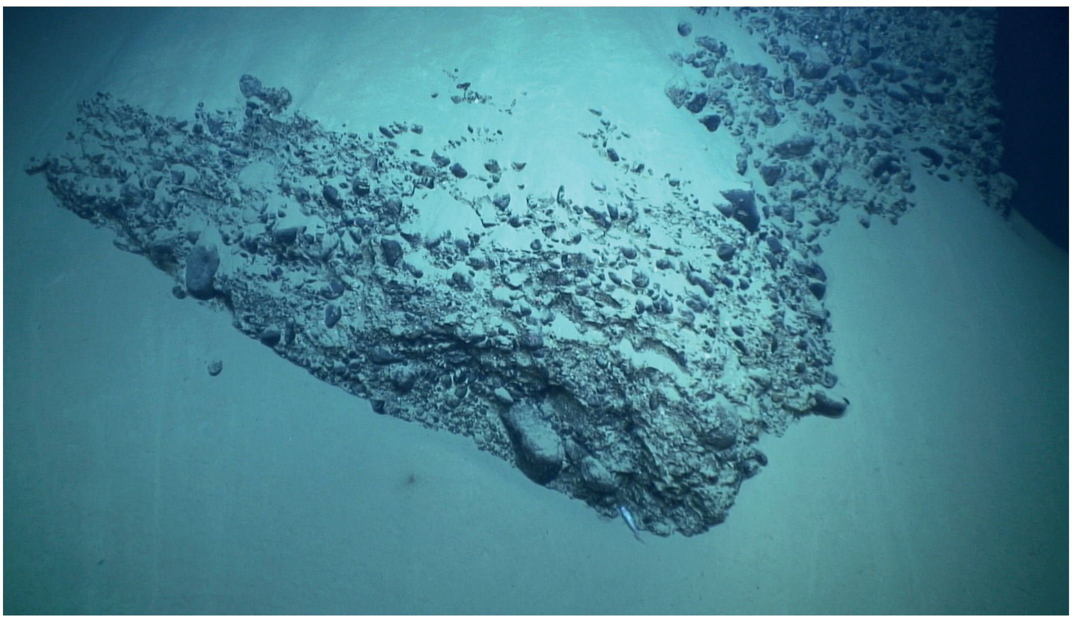

Fig. 6 - Submarine image of a conglomerate block and mud, inside the submarine Monaco Canyon. This material is exposed at more than -2100 m sea-depth off the Monaco-Montecarlo shore, nearly at the foot of the Alpine belt slope flanking the Ligurian-Monaco-Côte d'Azur coast. This consolidated gravel block crops out of a dense mud level; it is interpreted as a clastic Messinian fluviatile deposit. Locality: Site A of ROV Victor 6000 Dive-Sept.2018, down the Monaco Canyon. Courtesy of F. Poydenot, RAMOGE Exploration Programme.

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