



# Facies, composition and provenance of the Agnone Flysch in the context of the early Messinian evolution of the southern Apennine foredeep (Molise, Italy)

SALVATORE MILLI (1, 2), SALVATORE CRITELLI (3), EMANUELE AMICONE (4), GLORIA CAMPILONGO (3), FRANCESCO MUTO (3), VINCENZO TRIPODI (3), DANIEL TENTORI (2) & FRANCESCO PERRI (3)

## ABSTRACT

Clastic wedges deposited in deep-marine turbidite systems along the circum-Mediterranean region represent key tectonic elements that record the structural growing of the Apennine orogenic belt over the Adria margin. One of these clastic wedges is represented by the Agnone Flysch turbidite succession deposited in the Lagonegro-Molise foredeep basin in the early Messinian, for which the depositional facies and the related processes, as well as the sandstone and mudstone composition are poorly known. A combined sedimentology and sedimentary petrology study has been conducted on this turbidite succession that provides new insight to define the basin architecture and the provenance of the Agnone Flysch during late Miocene. Facies analysis suggests that this turbidite succession is constituted by depositional lobes that were emplaced in a sector of the basin showing a variable morphological confinement with frontal and lateral slope on which turbidite deposits overlapped. Consequently, this topographic context controlled the lateral and vertical distribution of turbidite facies, which record the effects of erosive processes, as well as impact, rebound and reflection processes, in turn related to the flow deceleration induced by structurally-controlled basin confinement. Detailed sandstones compositional analysis indicates a complex unroofing history that reflects structural changes in the source rock units and depositional basin physiography. By combining the sandstone composition with information deduced from the X-ray diffraction (XRD) patterns after thermo-chemical treatments (heating and ethylene glycol treatments), it was possible to explain and predict the sedimentary evolution and geological processes affecting fine grained sediments and, thus, the relationship developed between source area and sedimentary basin. In particular, clay minerals data show that Agnone Flysch experienced an early diagenetic condition as showed by the occurrence of the I/S R0 and I/S R1 on the XRD pattern of the glycolated specimens. The sandstone composition (mainly quartzofeldspathic) shows an increase in the metamorphic rock fragments and a decrease of sedimentary lithics up-section. This compositional trend records, together with the paleocurrents data, a derivation of this material from a mountain range located in the Tyrrhenian sector and from the Calabrian arc terranes.

**KEY WORDS:** *Agnone Flysch, turbidite facies, composition, provenance, sandstone, late Miocene, southern Apennines.*

(1) Dipartimento di Scienze della Terra, SAPIENZA Università di Roma, Piazzale Aldo Moro 5, 00185, Roma, Italy. E-mail: salvatore.milli@uniroma1.it

(2) Istituto di Geologia Ambientale e Geoingegneria (IGAG), Consiglio Nazionale delle Ricerche, Via Salaria km 29,300 - 00015 Montelibretti (RM), Italy

(3) Dipartimento di Biologia, Ecologia e Scienze della Terra, Università della Calabria, Ponte Pietro Bucci, Cubo 15B, 87036 Arcavacata di Rende, CS, Italy

(4) Freelance geologist  
Corresponding author e-mail: [salvatore.milli@uniroma1.it](mailto:salvatore.milli@uniroma1.it)

## INTRODUCTION

The southern Apennine Chain is largely studied to investigate the geodynamic evolution of the Cenozoic foreland region. However, as evidenced by several studies conducted in years (D'ARGENIO *et alii*, 1973; PATACCA *et alii*, 1991; MATTEI *et alii*, 2007; PATACCA & SCANDONE, 2007; BONARDI *et alii*, 2009; SCROCCA, 2010; VITALE & CIARCIA, 2013), the history of this chain is very complex and characterized by an assemblage of tectonic units whose organization and superimposition are not always clear. This is reflected in the regional geological models proposed by the Authors, for which the different interpretations often derive by an unclear knowledge of the physical stratigraphy and facies analysis of the deposits, especially for the turbidite deposits. For the latter, in fact, are better known the compositional trends that successfully were used to detect the geodynamic evolution and changes in provenance related to the growing of the Apennine orogenic belt (CRITELLI, 1991, 2018; CRITELLI & INGERSOLL, 1994; CRITELLI & LE PERA, 1994, 1995a, 1998; CRITELLI *et alii*, 2007, 2011, 2013, 2017; STALDER *et alii*, 2018). A noteworthy database of sandstone samples were reported in literature (e.g. ZUFFA, 1980; CRITELLI & LE PERA, 1990, 1994, 1995a, 1995b, 1998; CRITELLI, 1993, 1999, 2018; FORNELLI & PICARRETA, 1997; CRITELLI *et alii*, 1990a, b, 1994, 2007, 2008, 2011, 2013, 2017; BARONE *et alii*, 2006, 2008; PERRI *et alii*, 2012a, b; CARACCILO *et alii*, 2013; ZECCHIN *et alii*, 2013a, b, 2020; MATANO *et alii*, 2014, 2020; AMENDOLA *et alii*, 2016) and through these data, paleotectonic and paleogeographic interpretations were carried out. Moreover other important information, that represent significant constrains for evolutive renderings, were provided by chemical and mineralogical record of clastic sedimentary rocks because of their conditioning by factors such as source rock features, weathering, sorting processes during transport and sedimentation, and post-depositional diagenetic reactions (e.g. TAYLOR & McLENNAN, 1985; McLENNAN, 1989; McLENNAN *et alii*, 1993; CULLERS, 1994a, b, 1995; CULLERS & PODKOYVROV, 2002; CRITELLI *et alii*, 2008; PERRI *et alii*, 2012a, b; CORRADO *et alii*, 2019; SMERAGLIA *et alii*, 2019; ALDEGA *et alii*, 2020).

On the contrary a detailed facies analysis of the most southern Apennine turbidite deposits is lacking, apart from researches on single depositional units (see for example PESCATORE *et alii*, 1980; BOIANO, 1997; BUTLER & TAVARNELLI, 2006; CASCIANO *et alii*, 2019 for the Gorgoglione Flysch; MILLI & MOSCATELLI, 2000, for the Salto and Val di

Varri Turbidite Complex; MILLI, 2015 for the S. Bartolomeo Flysch). Consequently, several problems remain relatively unresolved for some of these turbidite successions: i) the facies description and related in place mechanisms; ii) the relationships between facies and basin topography that modify the local flow conditions; iii) the paleocurrent directions considering the post-Messinian tectonic movements (counter-clockwise rotations) including the Agnone Flysch, which is the subject of this paper. The depositional and compositional features of this Lower Messinian turbidite unit is, in fact, poorly known, with only the exception of the paper by CIVITELLI & CORDA (1988), in which the Authors make a brief description of the lithological and compositional characters, with little focus upon depositional processes and the provenance of this turbidite succession.

The present study combining sedimentological, petrographic and mineralogical observations, represents the first attempt to define facies partition, depositional processes, and sediment provenance of the Agnone Flysch in the context of the southern Apennine foreland basin system. As such this study could help testing previous paleotectonic and paleogeographic models and refine the spatial-temporal evolution of the southern Apennine foreland.

#### GEOLOGICAL AND PALEOGEOGRAPHIC SETTING

The Southern Apennines constitute the segment of the Apennine chain extending from the southern Abruzzi-Molise region to Sicily through the Calabrian Arc (Fig. 1). It is characterized by a complex geological structure formed by the superposition of several tectonic units. Each of these units is constituted by a single thrust sheet, or by a group of thrust sheets, which are separated by long thrust flat with low cutoff angles at the footwall (PATACCA & SCANDONE, 2007 with references therein).

These tectonic units are formed by thick stratigraphic successions in which several lithostratigraphic units derived by the deformation of the same paleogeographic domain occur (PATACCA & SCANDONE, 2007; VITALE & CIARCIA, 2013). Most of the authors agree that two main geodynamic phases are responsible for the construction of the Southern Apennines (DEWEY *et alii*, 1989; FACCENNA *et alii*, 2001): the Late Oligocene-Middle Miocene phase that was coeval with the opening of the Ligurian-Provençal back-arc basin, and the Tortonian-Pleistocene phase that was coeval with the opening of the Tyrrhenian back-arc basin. Single orogenic pulses were also recognized at (1) Late Burdigalian; (2) Langhian/Serravallian boundary; (3) Middle-Late Serravallian; (4) Middle-Late Tortonian; (5) Tortonian/Messinian boundary; (6) Late Messinian; (7) Zanclean; and (8) Early Piacenzian (VITALE & CIARCIA, 2013).

During the years, various paleogeographic reconstruction of the southern Apennine area before and after the two main deformations phases have been proposed, which foresaw a variable number of carbonate platforms separated by more or less deep basins (D'ARGENIO *et alii*, 1973; MOSTARDINI & MERLINI, 1986; SANTO & SGROSSO, 1987; CASERO *et alii*, 1988; MARSELLA *et alii*, 1995; MAZZOLI *et alii*, 2001; PATACCA & SCANDONE, 2007; BONARDI *et alii*, 2009; SCROCCA, 2010; VITALE & CIARCIA, 2013

with references therein; Fig. 2). The deformation of these domains led to the build-up of structural-stratigraphic units that have their own evolutionary tectonic history different from the overlying and underlying units (PATACCA & SCANDONE, 2007; MAZZOLI *et alii*, 2008; BONARDI *et alii*, 2009; VITALE & CIARCIA, 2013 and references therein). On this basis these Authors recognized several tectonic units forming the southern Apennine thrust belt that derived by the deformation of the following domains (Fig. 2): i) Internal Nappes; they represent the westernmost domain that include all the ophiolite-bearing Ligurian Units and the Sicilide Unit with a basement constituted by oceanic or a thinned continental crust; ii) Apenninic Platform; it constitutes the main structure forming the carbonate massifs of the Campania-Lucania Apennine and includes several carbonate units separated by thrust surfaces; iii) Lagonegro-Molise Basin; this wide basin was located between the Apenninic Platform and the Apulia Platform and includes several pelagic successions and turbidite units (e.g., Agnone Flysch); iv) Simbruini-Matese Platform; it includes an undifferentiated thick succession of shallow-water carbonate that consists of several thrust sheets; v) Western Marsica Platform; it is constituted by shallow-water Mesozoic carbonate deposits, on top of which the foreland hemipelagic sedimentation persisted until the early Messinian (see COSENTINO *et alii*, 1997); vi) Gran Sasso-Genzana, Montagna dei Fiori basinal realms and related marginal areas; such domain is characterized by two main tectonic units (Gran Sasso-Genzana Unit and Montagna dei Fiori Unit) constituted by thick basinal and shallow water Meso-Cenozoic carbonate deposits on top of which lower Messinian turbidite deposits or Messinian resedimented gypsarenite deposits occur respectively; vii) Apulia Platform; it includes several tectonic units mainly constituted by shallow-water and deep-water carbonate deposits. In Fig. 2 these different domains are distributed from west to east in the Central and Southern Apennines and are incorporated in the mountain chain during its eastward progressive migration. These movements were reconstructed by using paleogeographic maps, the spatial and temporal distribution of foredeep deposits and magmatic rocks and through the paleomagnetic data indicating a counterclockwise rotation of the Apennine successions of about 60°-70° from the Late Oligocene to Recent (see MICHARD *et alii*, 2002; CIFELLI *et alii*, 2007; MATTEI *et alii*, 2007; PATACCA & SCANDONE, 2007; BONARDI *et alii*, 2009; LUSTRINO *et alii*, 2009; HANDY *et alii*, 2010; ACCAINO *et alii*, 2011; VITALE & CIARCIA, 2013).

As regards the deposits of the Agnone Flysch, they are part of the Agnone Unit, which in turn constitutes one of the tectonic units deriving from the deformation of the Lagonegro-Molise Basin. The other tectonic units are those of Frosolone, Tuffillo-Serra Palazzo, and Daunia. The literature data indicate that the succession of the Frosolone Unit was deposited adjacent to the Simbruini-Matese platform (CLERMONTÉ & PIRONON, 1979; SCROCCA *et alii*, 1995; SCROCCA, 1996; PATACCA & SCANDONE, 2007); moreover data provided by these last Authors also suggest a physical contiguity between the Frosolone and Agnone domains and between the Tuffillo-Serra Palazzo and Daunia, as well as between Agnone and Tuffillo-Serra Palazzo (PATACCA & SCANDONE, 2007; VITALE & CIARCIA, 2013). Such paleogeographic relationships are evidenced in the palinspastic restorations reported in Fig. 2, indicating that

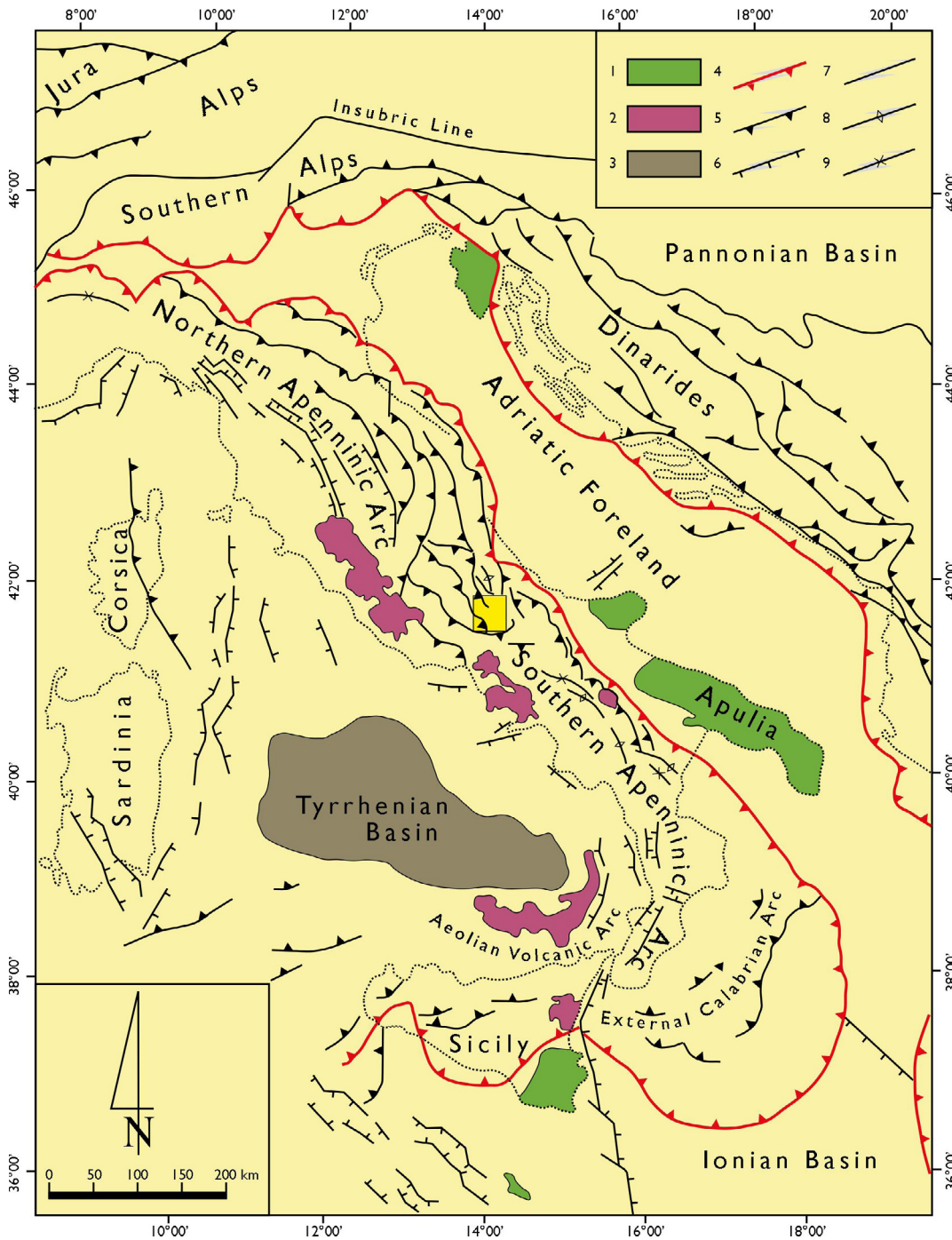


Fig. 1 - Structural sketch of the Italian Peninsula, showing its subdivision into Northern and Southern Apenninic Arcs. 1) Mesozoic-Tertiary carbonates of the foreland areas; 2) Main Quaternary volcanic complexes; 3) Sector of the Tyrrhenian Basin floored by oceanic or thinned continental crust; 4) Front of the Maghrebides, Apennines, Southern Alps and Dinarides; 5) Other thrusts including the front of the Alps; 6) Normal faults; 7) Strike-slip faults; 8) Anticline axis; 9) Syncline axis. (Redrawn from PATACCA & SCANDONE, 2007).

the Simbruini-Matese platform was part of the foredeep basin during the Late Tortonian and would be incorporated into the thrust belt during the early Messinian (PATACCA *et alii*, 1991; CIPOLLARI & COSENTINO, 1995; CIPOLLARI *et alii*, 1999; BILLI *et alii*, 2006; COSENTINO & CIPOLLARI, 2012). The latter interpretation is still the subject of controversy, since other authors consider only the inner portion of the Simbruini-Ernici ridge as deposited in isolated wedge-top basins in the early Messinian, whereas the eastern part of the Simbruini ridge and the adjacent Roveto Valley and Marsica area was still a portion of the foredeep affected by extensional tectonics, where carbonate clastic deposits (Breccie della Renga fm.) and northwestern-derived

siliciclastic turbidite deposits (Valle del Salto and Val di Varri turbiditic complex) sedimented (MILLI & MOSCATELLI, 2000, 2001; BIGI *et alii*, 2003; COMPAGNONI *et alii*, 2005; CRITELLI *et alii*, 2007; CAVINATO *et alii*, 2012; MARINI *et alii*, 2012; CARMINATI *et alii*, 2014; FABBÌ, 2016; FABBÌ & ROSSI, 2014; FABBÌ & SANTANTONIO, 2019). Based on these data and coherently with the interpretation of the above authors we retain that in the early Messinian the Simbruini and Marsica sector would have represented a structural high developed inside the foredeep, separating the northern sector of this basin where the north and northwestern derived siliciclastic turbidite flow impacted against this structural high (see MILLI & MOSCATELLI, 2001; BIGI *et alii*,

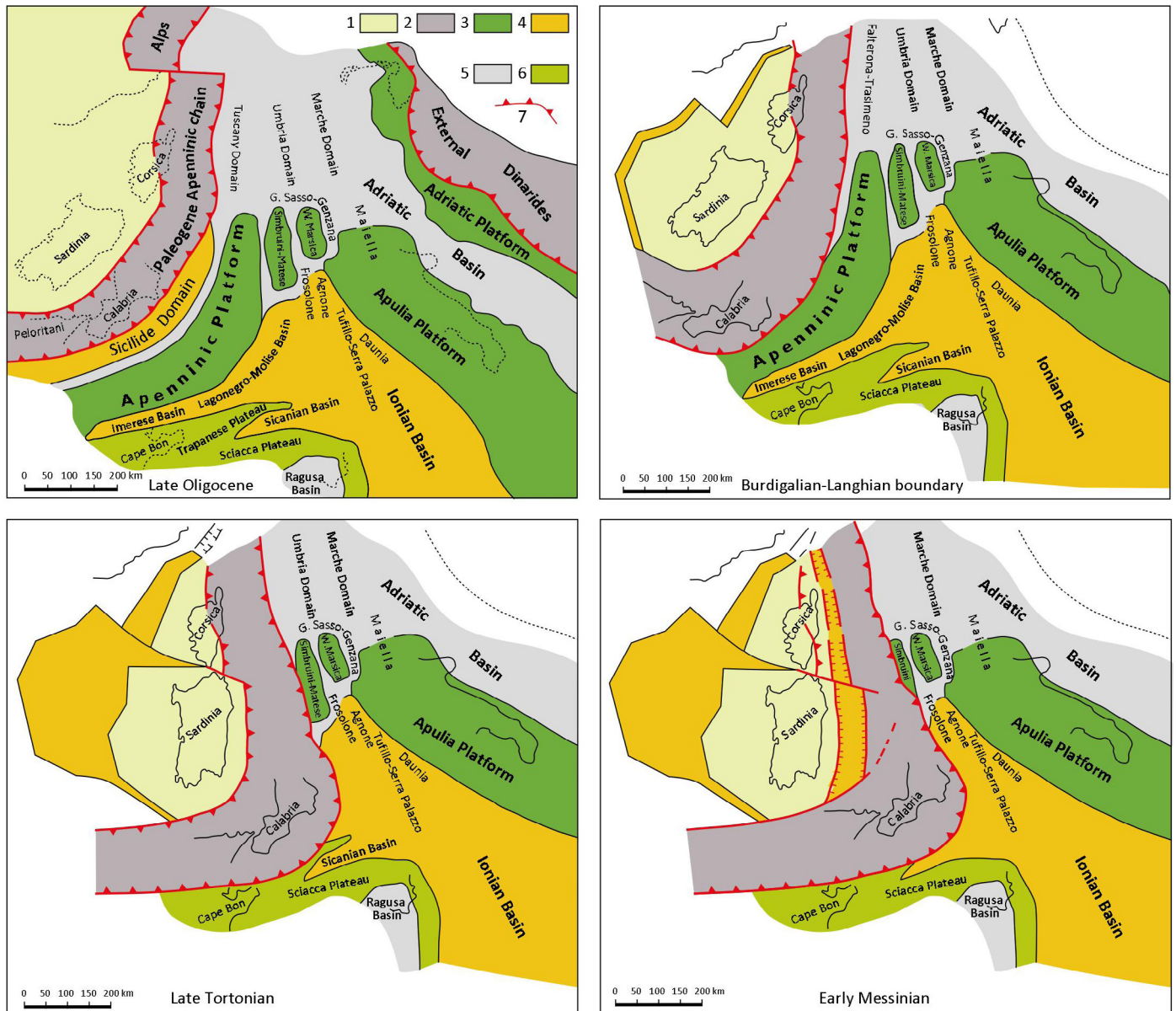


Fig. 2 - Palinspastic restoration of the Central Mediterranean area from Late Oligocene to early Messinian times. Legend: 1) European foreland; 2) Apenninic chains; 3) Shallow-water carbonate platforms; 4) Deep-water basins floored by oceanic or thinned continental crust; 5) Basinal areas with isolated structural highs; 6) Pelagic plateaux; 7) Front of the orogenic belts. (Redrawn and partially modified from PATACCA & SCANDONE, 2007).

2003; CRITELLI *et alii*, 2007), from the southern sector of the foredeep (the Lagonegro-Molise Basin) where during the early Messinian the Frosolone and the Agnone sandstones were deposited; both these units onlapped onto the southern margin of this structural high.

These considerations suggest that during the lower Messinian the wide Lagonegro-Molise foredeep basin may have had a more articulated morphology with a series of subbasin, north-south oriented and separated, probably, by incipient thrusts, where the turbidite deposits of the Frosolone and Agnone units, and of Tuffilo Serra-Palazzo and Daunia units sedimented. The turbidite deposits related to these last two units are represented, by the Olmi and Treste Formations, respectively; these formations have smaller thicknesses (a few hundred meters), finer sandy grain-size, and a greater content of mudstone sediments

(PATACCA & SCANDONE, 2007). This suggests and confirms a deposition of these units in the most eastern and external sector of the Lagonegro-Molise foredeep basin, just near to the western margin of the Apulia platform, on which these deposits onlapped.

#### THE STRATIGRAPHY OF THE AGNONE FLYSCH

The Agnone Flysch constitutes the upper portion of the Agnone tectonic unit, which is formed, from the bottom upwards (PATACCA *et alii*, 1991), by the Varicoloured Clays (upper Oligocene? - Burdigalian), by the pre-flysch carbonate deposits (Langhian-upper Tortonian) and by the turbidite deposits of the Agnone Flysch (lower Messinian). The stratigraphic relationships between these

formations are schematically drawn in Fig. 3, showing the onlap of Agnone Flysch onto the raised northern margin of the basin. Although not recorded in the outcrops, onlap relationships between the Agnone Flysch and the substratum are also hypothesized along the western margin of the basin. From this last sector resedimented carbonate debris, locally represented by large olistolith, originated. These carbonate debris, that occur at different heights within the turbidite deposits, were derived from dismantling of strongly tectonized sectors of the carbonate platform bordering the foredeep basin on the western and northern sectors.

Stratigraphic, sedimentological, and petrographic data of the Agnone Flysch are very scarce; a detailed facies analysis is lacking, while a relatively recent petrographic analysis on the sandstones was carried out during the survey of the Geological Map 1:50.000 Sheet 393 "Trivento" Italian Geological Survey (see CRITELLI, 2015). Previous information is presented in the paper of CIVITELLI & CORDA (1988) but with particular reference to heavy minerals. Further details on this lithostratigraphic unit occur in PATACCA *et alii* (1991) and PATACCA & SCANDONE (2007), which subdivide this succession into three members, from older to younger, the Verrino member (VM), the Poggio Villanelle member (PVM), and the Sente member (SM) on the basis of outcrop data and on the stratigraphy of the Belmonte del Sannio 1 well (Fig. 4). The same Authors, on the basis of the microfaunistic and nannofloristic assemblages, indicate that the deposition of this unit occurred during the early Messinian pre-salinity crisis.

The Verrino member (about 1200 m thick) is characterized by variable thickness and laterally continuous mudstone-sandstone beds, with several intercalations of bioclastic calcarenite beds. The thicker bioclastic carbonate layers show, locally, the presence of small flutes and groove casts indicating a provenance of the flows from the northwestern and western sectors (Fig. 5). This is consistent with what has been found by

CIVITELLI & CORDA (1988), which show that most of the calcarenite beds occurring in this member, as well as in the Poggio Villanelle member, derive from the carbonate platforms that were present on the western and northern margin of the Lagonegro-Molise basin. Locally siliciclastic and carbonate particles are mixed giving rise to hybrid arenite (*sensu* ZUFFA, 1980). The Verrino member shows a coarsening- and thickening-upward trend, being this portion of the Agnone Flysch characterized by a mudstone-dominated basal portion passing upward into a sandstone-dominated portion that continues in the lower part (about 300 m thick) of the overlying Poggio Villanelle member.

The latter (about 1100 m thick) is characterized by less regular and more discontinuous sandstone beds that can reach thicknesses of about 10 m in the lower portion of this member. Overall, the Poggio Villanelle member is characterized by thick and thin sandstone-mudstone couplets with complete and incomplete Bouma sequence, organized in thinning- and fining-upward units, about 100 m thick; the general thinning- and fining upward trend characterizing this member continues in the overlying Sente member (Fig. 4). The Poggio Villanelle member, like the Verrino member, shows also the presence of calcarenite and calcirudite intercalations, as well as scattered blocks of large olistolith consisting of bryozoan and *Lithothamnium* limestones, rudistid limestones, *Lepidocyclina* limestones and *Orbulina* marly limestones (see also PATACCA *et alii*, 1991).

The Sente member (about 400 m thick) crops out only in a few sectors of the investigated area and its most complete succession occurs in the Belmonte del Sannio 1 well. The deposits of this member are essentially characterized by thin sandstone-mudstone couplets with incomplete Bouma sequence that are organized to confer to this unit a general thinning- and fining-upward trend.

On the basis of the previous considerations the vertical distribution of the three members with their lithofacies associations allows us to broadly reconstruct

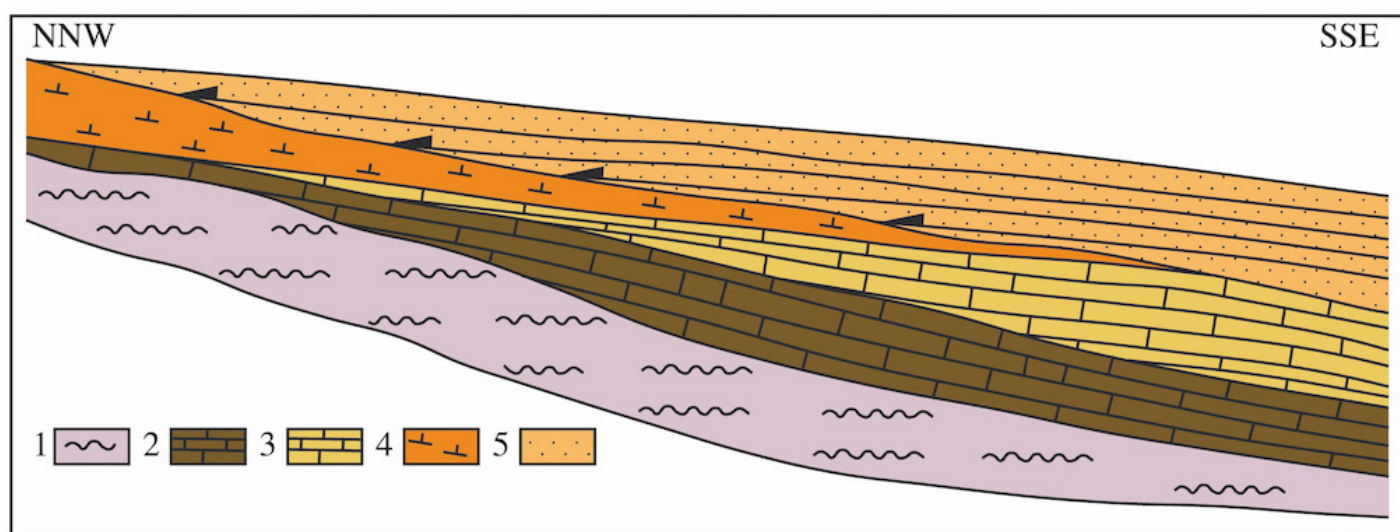


Fig. 3 - Stratigraphic relationships between the Agnone Flysch and underlying formations constituting the Agnone tectonic unit. This scheme has been reconstructed on the basis of literature data (Di Bucci 1995) and field observations. The lithostratigraphic units are those described by Di Bucci (1995): 1) Varicoloured Clay (upper Oligocene?- Burdigalian); 2) Calcirudites and calcarenites of the Pizzoferrato lithostratigraphic Unit (lower Miocene); 3) Marls, marly limestones and calcarenites of the M. Campo Unit (upper Langhian-upper Tortonian); 4) *Orbulina* calcareous marls (Serravallian-Tortonian); 5) Agnone Flysch (uppermost Tortonian-lower Messinian).

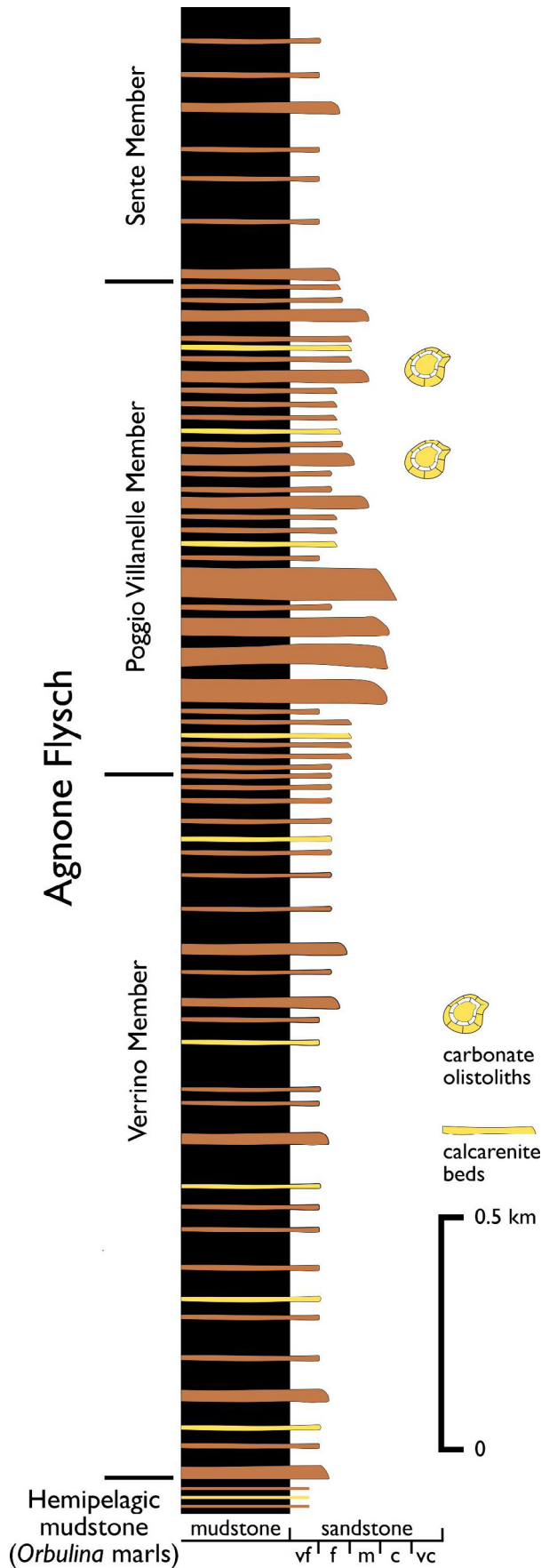


Fig. 4 - Stratigraphic log of the Agnone Flysch showing the three members and their internal stratigraphic organization (see text for more explanation).

the evolutionary trend of the Agnone Flysch in the Molise area. The basal portion of this succession is made up of a few meters thick hemipelagic mudstone with abundant planktonic foraminifers whose assemblage indicates an early Messinian age (PATACCA *et alii*, 1991; AMORE, 1992). Upward the increases in frequency and thickness of the sandy and silty beds constituting the Verrino member and the initial part of the Poggio Villanelle member, reflects the increasingly arrival of turbidite flows that deposited these sediments in the distal sector of the basin (lobes depositional zone). This indicates that the Verrino member and initial part of Poggio Villanelle member record a clear progradational trend (forestepping) of the Agnone turbidite system, which was followed by a phase of retrogradation and sediment starvation of the system during the deposition of the upper portion of the Poggio Villanelle and Sente members.

The sector of the Agnone Basin closest to the carbonate structures records, both in the basal mudstone hemipelagic facies and in the turbidite sandstone-mudstone unit, the presence of bioclastic calcarenite and calcirudite beds, whose deposition occurred through gravity flows coming from western and north-western sectors of the Lagonegro-Molise Basin where carbonate platforms were present.

#### SAMPLING AND METHODS

The investigated Agnone Flysch succession crops out in the Molise region, in the north-east of Isernia area. The area includes the villages of Agnone, Castelverrino, Poggio Sannita, and Pietrabbondante (Figs. 6 and 7). In this sector, the Agnone turbidite deposits form a homocline with beds striking from N20° to N40°, a dip direction between 110° to 130° (towards ESE and SE), and a dip angle between 30° and 40°.

In order to define the main sedimentological characters of the Agnone Flysch, 10 stratigraphic sections for a total thickness of about 1100 m were measured (Fig. 8). Turbidite facies have been distinguished according to grain size, texture, sedimentary structures, and paleocurrents as observed in the field; the paleocurrent data were also modified in their orientation in order to take into account the counterclockwise rotation of this area after the Messinian time. Two correlation panels were constructed in order to better define the geometry of the sandstone bodies and the facies relationships (Figs. 22 and 23).

In the attempt to reconstruct the stratigraphic relationships between the Agnone Flysch and the immediately underlying stratigraphic units (see also Fig. 3), the stratigraphy of the wells Ateleta1 (AT1), Ateleta2 (AT2), Belmonte del Sannio1 (BS1), Messer Marino1 (MM1), Pescopennataro1 (PE1), Pescopennataro2 (PE2), and Rossello1 (RS1) provided by the VIDEPI Project, and Lago Saletta1 (LS1), provided by ENI, drilled in the area for hydrocarbon exploration were utilized (Fig. 7). Two correlation panels oriented parallel (NW-SE) and perpendicularly (WSW-ESE) to the direction of the paleocurrents respectively were constructed allowing us to broadly define the possible morphology of the basin at the time of the Agnone Flysch deposition (Fig. 24).

The 10 logged sections were also sampled in order to perform a detailed petrographic analysis on a total of 67 samples (44 sandstone and 23 mudrock samples). In

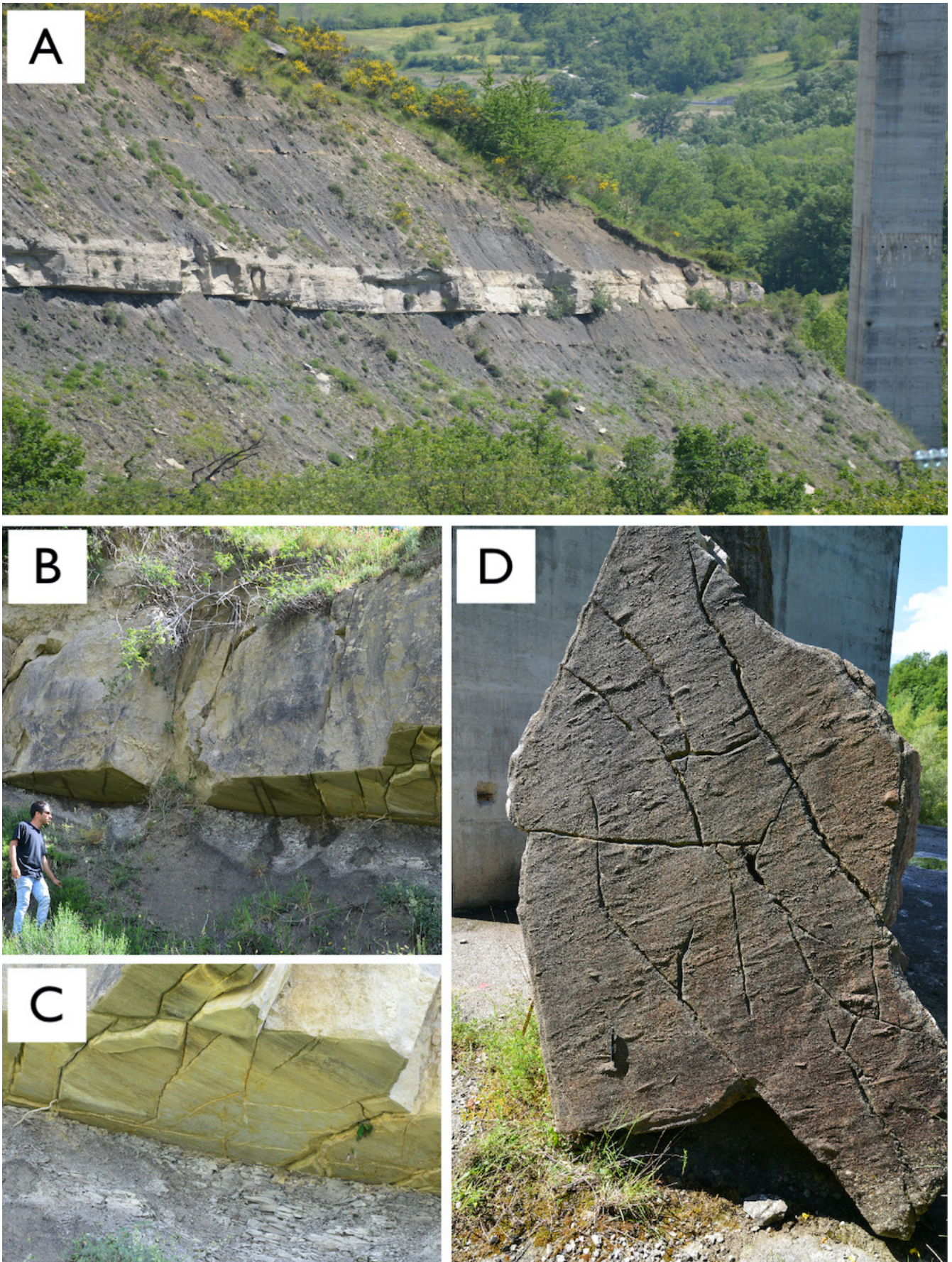


Fig. 5 - A) Thick calcarenite bed intercalated within the mudstone-sandstone deposits of the Verrino member. B) Detail of the calcarenite bed at the base of which flutes, grooves and parting lineations occur (C and D).

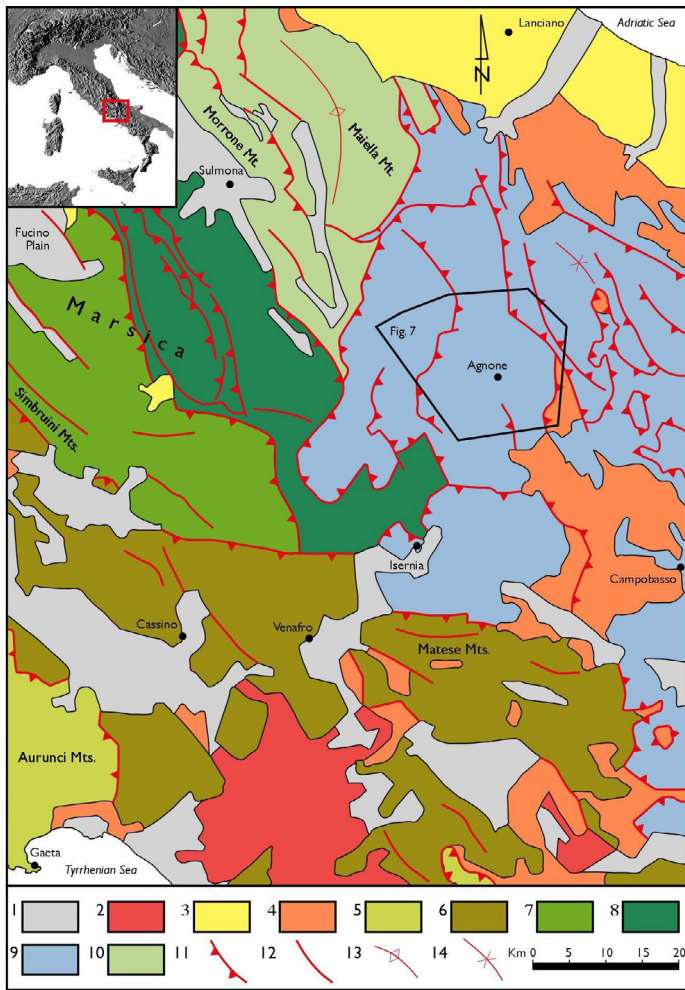


Fig. 6 - Simplified geological-structural map showing the main tectonic units of the Southern Apennines in the area surrounding the investigated sector (redrawn and modified by PATACCA & SCANDONE, 2007). 1 = Continental and shallow marine deposits (Quaternary); 2 = Volcanic deposits (Middle Pleistocene to Holocene); 3 = Continental and marine deposits (Lower-Middle Pleistocene); 4 = Thrust-sheet-top terrigenous deposits (Miocene-Pliocene); 5 = Tectonic units derived from the Apenninic Platform; 6 = Tectonic units derived from the Simbruini-Matese Platform; 7 = Tectonic units derived from the Western Marsica Platform; 8 = Tectonic units derived from the Gran Sasso- Genzana and related marginal areas; 9 = Tectonic units derived from the Lagonegro-Molise Basin; 10 = Tectonic units derived from the Apulia Platform; 11 = Thrusts; 12 = Faults; 13 = Anticline axis; 14 = Sincline axis.

particular 9 sandstone samples are representative of the Verrino member (VM) and 35 samples are representative of the Poggio Villanelle member (PVM). No samples were collected from the Sente member due to the absence of this member's outcrop in the investigated area. Medium to coarse-grained sandstones were selected for point-count and thin-section analyses. About 300 to 500 points were counted for each thin-section according to the Gazzi-Dickinson method to minimize the rock composition dependence on grain size (GAZZI, 1966; DICKINSON, 1970; INGERSOLL *et alii*, 1984; ZUFFA, 1985, 1987). Counted grains were assigned to monomineralic and polymineralic compositional categories and their spatial (extrabasinal versus intrabasinal) and temporal (coeval versus noncoeval) relationships defined using the parameters proposed by

INGERSOLL & SUCZEK (1979), ZUFFA (1980, 1985), DICKINSON (1985), CRITELLI & LE PERA (1994) and CARACCILO *et alii* (2011), and listed in Tab. 1. The results of modal analysis were recalculated using compositional parameters reported in Tab. 2. Calculated grains parameters and point-count results are shown in detail in Tabs. S1 and S2 (see supplementary material). The recalculated modal point in percent of Agnone Flysch sandstones are reported in Tab. S3 (see supplementary material). The optical microscopy allowed to highlight mineral assemblage and petrographic features of sandstones through textural and compositional analysis. Detrital modes were plotted in ternary diagrams and confidence regions of detrital-mode means were calculated using the procedures described by ARCHISON (1997); the samples distribution defines two field of variations (Figs. 9, and 10). Confidence regions (90 and 95%) were computed using log-ratio transformation of compositional data using 'R' (a software for statistical computing and graphics) and its software package "Composition" (BOOGAART & TOLOSANA-DELGADO, 2008; CARACCILO *et alii*, 2012). Geometric means were used, and confidence regions were plotted according to WELTJE (2002). In addition to QmFLt, QpLvmLsm, and LmLvLs diagrams (Fig. 9), we used RgRsRm and RgRvRm ternary plots, to evaluate phaneritic lithics proportions (Fig. 10). Rg rock fragments are retrieved from counts of monocrystalline quartz, k-feldspar, plagioclase, and phyllosilicate in coarse polycrystalline grains of phaneritic rock fragments (Rm and Rv, respectively) added with aphanitic metamorphic (Lm) and volcanic (Lv) lithics fragments; Rs rock fragments correspond to Ls.

A set of 23 mudrock samples were collected for mineralogical analyses: seven samples belong to Verrino member; sixteen samples are representative of Poggio Villanelle member. Mudrock samples were cleaned from weather coats and veined surfaces were removed, subsequently the rocks, were crushed and milled in an agate mortar to a very fine powder. The mineralogy of the whole-rock powder and the fine fractions (clay fraction <2  $\mu\text{m}$ ) was determined by X-ray diffraction (XRD) using Bruker's X-ray Diffractometer D8 Advance at the Università della Calabria (Italy). In addition, through the WINFIT computer program (KRUMM, 1996) that measures peak areas, semiquantitative mineralogical analysis (e.g., LAVIANO, 1987) of the bulk rock was carried out on random powders (Tab. 3). The strongest reflection of each mineral was considered, except for quartz. For the latter, the peak at 4.26 $\text{\AA}$  was considered instead of that at 3.34  $\text{\AA}$  because its overlap on the values of the 10  $\text{\AA}$ -minerals and mixed layer series of clays. The amount of phyllosilicates was estimated measuring the 4.5  $\text{\AA}$  peak area. To identify the percentage of phyllosilicates in the bulk rock the diffraction profile of the random powder was observed and in it three areal divisions (peak areas) was considered, as follows: 10-15  $\text{\AA}$  (I/S = Illite/Smectite mixed layers + Chl/S = chlorite/smectite mixed layers), 10  $\text{\AA}$  (illite+micas), and 7  $\text{\AA}$  (kaolinite+chlorite) minerals (e.g., CAVALCANTE *et alii*, 2007; PERRI, 2008; PERRI *et alii*, 2011). Through some special laboratory techniques for sample preparation and to better distinguish the clay minerals present in the mixed layer packages the whole rock powders, in particular < 2  $\mu\text{m}$  grain-size fraction was separated by settling in distilled water and then a concentration of 4-10  $\text{mg}/\text{cm}^2$  was obtained by evaporation of clay-water (LEZZERINI *et alii*,



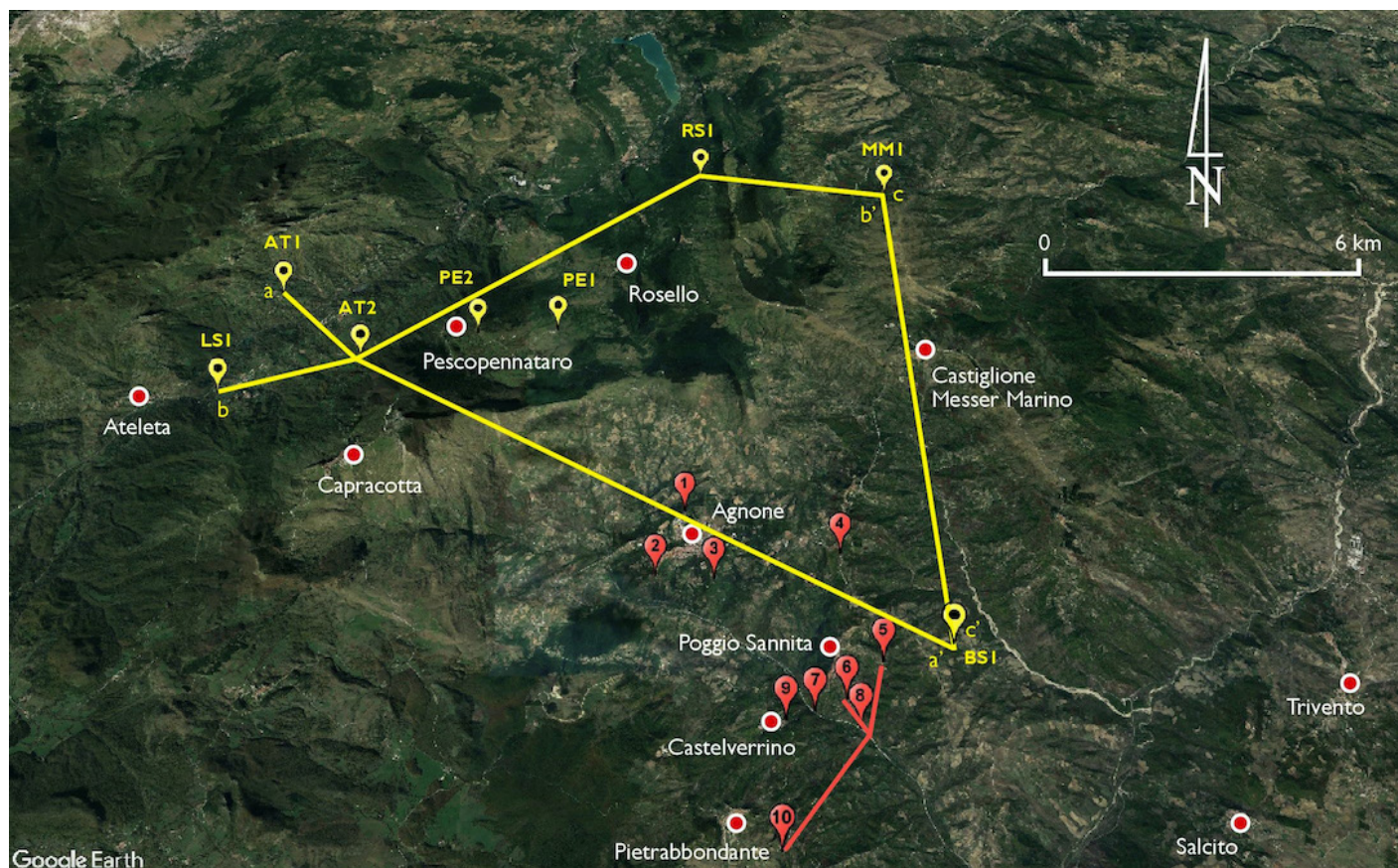


Fig. 7 - Satellite image of the investigated area showing: 1) the positions of the measured stratigraphic logs and the tracks of the correlation panels of figure 22 and 23 (in red); 2) the position of the exploration wells Lago Saletta 1 (LS1), Ateleta 1 (AT1), Ateleta 2 (AT2), Pescopennataro 1 (PE1), Pescopennataro 2 (PE2); Rosello 1 (RS1), Messer Marino 1 (MM1), Belmonte del Sannio 1 (BS1) and the tracks of the stratigraphic cross-section of figure 24 (in yellow).

1995). Subsequently, air-dried specimens were glycolated at 60°C for 8 hours and heated at 375°C for 1 hour (MOORE & REYNOLDS, 1997) and XRD analysis on oriented amounts was carried out again. The percentage of clay minerals in the < 2 µm fraction was estimated by measuring the peak areas on diffraction profiles of the glycolated and heated oriented mounts. The percentage of illite (%I) and stacking order (Reichweite R; JADGOZINSKI, 1949) of the I/S mixed layers were determined on the spectrum of the glycolated specimens using the  $\Delta 2\theta$  method according to MOORE & REYNOLDS (1997).

## RESULTS

### SEDIMENTARY FACIES: DESCRIPTION AND INTERPRETATION

Facies analysis conducted on the Agnone Flysch deposits allowed us to recognize seven main facies that are described and interpreted in terms of depositional processes. They essentially represent the product of down-current transformations and deposition of waning and depletive turbidity currents (the concept of facies tract, *sensu* MUTTI, 1992; MUTTI *et alii*, 1999, 2003). However, their sedimentary characters suggest a deposition in the lobe depositional zone, although flow modifications induced by sea-floor topography, in turn related to structurally-

controlled basin morphology variations and depositional reliefs, allowed the formation of many massive and cross-laminated sandstone beds, and muddy sandstone beds containing mudstone clasts, continental wood fragments and dispersed organic matter.

The facies FA1 is constituted by coarse to medium-grained sandstones forming thick (1-3 m) lenticular and laterally continuous massive to crude-laminated beds with pervasive dewatering structures (Fig. 11). Locally rounded small clay chips can be found in the thicker sandstone beds suggesting the presence of amalgamation surfaces. The base of FA1 beds is sharp with locally sole marks (flute and groove casts). These beds do not show at the top fine-grained deposits. Facies FA1 is interpreted as the product of deposition of a quickly aggrading high concentration basal layer of bipartite turbidity currents with overlying turbulent flows where, depending by the velocity of flow deceleration, massive or thick and thin traction carpets layers are formed (see also MIDDLETON, 1967; ARNOTT & HAND, 1989; MUTTI, 1992; KNELLER & BRANNEY, 1995; MUTTI *et alii*, 2003; FALCINI *et alii*, 2009a, b; TINTERRI & TAGLIAFERRI, 2015). The occurrence of dewatering structures is coherent with the rapid deposition of this facies indicating liquified conditions of the flows during deposition and shear from overriding turbulent flow that can produce traction carpets and by-passing of the medium-fine grained sand and mud. This facies transitionally pass, laterally and

TABLE 1

Categories used for sandstone modal point-counts of framework grains. Note: NCE, CE, CI, NCI: noncoeval vs coeval; NCE=non-carbonate extrabasinal grains; CE=carbonate extrabasinal grains; CI=carbonate intrabasinal grains; NCI=non-carbonate intrabasinal grains. These grains can be coeval (intrabasinal source) and noncoeval (extrabasinal source). Grain parameters: Q=quartz (Qm=monocrystalline quartz; Qp=polycrystalline quartz, inc.chert); P=plagioclase feldspar; K=potassium-feldspar; M=micas and chlorite; L=lithic rock fragments (Lv=volcanic-hypabyssal lithics; Lm=metamorphic lithics; Ls=sedimentary lithics); D=dense minerals.

Petrographic Classes		
<b>Quartz (Q)</b>		
NCE	Qm	Quartz (single crystal)
NCE	Qp	Polycrystalline quartz with tectonic fabric
NCE	Qp	Polycrystalline quartz without tectonic fabric
NCE	Qm	Quartz in metamorphic r.f.
NCE	Qm	Quartz in plutonic r.f.
NCE	Qm	Quartz in plutonic or gneissic r.f.
NCE	Qm	Calcite replacement on quartz
<b>Feldspar (F)</b>		
	F (K+P)	
NCE	K	K-feldspar (single crystals)
NCE	K	K-feldspar in plutonic r.f.
NCE		Calcite replacement on k-feldspar
NCE	P	Plagioclase (single crystals)
NCE	P	Plagioclase in metamorphic r.f.
NCE	P	Plagioclase in plutonic r.f.
NCE	P	Plagioclase in plutonic or gneissic r.f.
NCE	P	Plagioclase in volcanic r.f.
NCE	P	Calcite replacement on plagioclase
<b>Micas (M)</b>		
NCE		Micas and chlorite (single crystals)
NCE		Micas and chlorite in plutonic r.f.
NCE		Micas and chlorite in metamorphic r.f.
<b>Lithic fragments (L)</b>		
	L (Lm+Lv+Ls) (Lvm-Lsm)	
NCE	Lv - Lvm	Volcanic lithic with microlitic texture
NCE	Lv- Lvm	Volcanic lithic with felsic granular texture
NCE	Lv-- Lvm	Volcanic lithic with felsic seriate texture
NCE	Lv- Lvm	Volcanic lithic with lathwork texture
NCE	Lv- Lvm	Volcanic lithic with vitric texture
NCE	Lv- Lvm	Serpentine
NCE	Lm - Lm2-Lvm	Serpentine-schist
NCE	Lsm-Lm - Lm1	Phyllite
NCE	Lsm-Lm - Lm1	Fine-grained Schist
NCE	Lsm-Lm - Lm2	Fine-grained Gneiss
NCE	Lsm-Ls	Siltstone
<b>Dense Minerals (D)</b>		
	NCE	Dense minerals (single crystals)
	NCE	Dense minerals in plutonic r.f.
	NCE	Dense minerals in metamorphic r.f.
	NCE	Opaque minerals
<b>Carbonate Extrabasinal grains (CE)</b>		
	CE	Dolostone
	Lsm-Ls	Micritic Limestone
	Lsm-Ls	Sparitic Limestone
	Lsm-Ls	Microsparitic Limestone
	Lsm-Ls	Biomictitic Limestone
	Lsm-Ls	Biosparitic Limestone
	Lsm-Ls	Fossil (single skeleton)
	Lsm-Ls	Fossil in Limestone-Dolostone
	Lsm-Ls	Single spar (calcite)
	Lsm-Ls	Single spar (dolomite)
<b>Carbonate Intrabasinal grains(CI) and Non-Carbonate Intrabasinal grains (NCI)</b>		
	CI	Bioclast
	CI	Peloid and Ooid
	NCI	Glauconite
	NCI	Rip-Up clasts (argillaceous and siltitic)
<b>Interstitial component (Matrix and cement)</b>		
		Siliclastic matrix
		Carbonate matrix
		Carbonate cement (pore-filling)
		Carbonate cement (patchy calcite)
		Calcite replacement on undeterm.-grain
		Siliceous cement
		Phyllosilicate cement

TABLE 2

Compositional parameters used for recalculation.

<b>Qt=Qm+Qp</b>	Qt = total quartzose grains Qm = monocrystalline quartz grains Qp = polycrystalline aphanitic quartzose grains
<b>F=P+K</b>	F = total feldspar grains P = plagioclase-feldspar grains K = potassium-feldspar grains
<b>L=Lm +Lv+Ls</b>	L = unstable aphanitic lithic grains Lm = metamorphic lithic grains Lv = volcanic aphanitic lithic grains Ls = sedimentary aphanitic lithic grains plus extrabasinal carbonate grains
<b>L=Lvm+Lsm</b>	Lvm = volcanic and metavolcanic lithic grains Lsm = lithic sedimentary and metasedimentary aphanitic lithic grains

down current, to the Facies FA2.

The *facies FA2* is constituted by medium to fine-grained sandstones, forming beds 50-100 cm thick, with undulated lamination and water escape structures, whose deposition reflects an aggradation with a decreasing rate of fallout with respect to facies FA1 (Fig. 11). Water escape structures occur only in the upper portion of the beds. Differently from the facies FA1, the FA2 shows a sharp or transitionally vertical passage to the fine and very fine sandstones with undulated and convolute lamination of Facies FA4. Beds within the facies FA2 record always a deceleration of the high-density basal portion of bipartite turbidite currents, and the consequently by-passing down current of the more dilute portion.

The *facies FA3* forms medium to fine-grained sandstone beds, 15- 80 cm thick, consisting of a massive portion without or with mudstone clasts (Figs. 12 and 13). This portion passes upward to thin or relatively thick laminated fine-grained sandstone with ripples lamination, often deformed to give rise to a convolute lamination. The base of the FA3 beds is erosive and often shows flute and groove casts. Overall, the facies FA3 records a deceleration phase of turbidity currents with the massive portion reflecting a high-fallout rate that suppresses the turbulence, whereas the upper portion of the beds is deposited by traction-plus-fallout processes.

When mudstone clasts are present, they vary in dimension from a few millimeters to 10-20 centimeters and occur at different heights within the beds (Figs. 12 and 13). In order to better evaluate the process responsible of their formation and deposition we also considered other parameters (see JOHANSSON & STOW, 1995) such as the sorting, the shape (degree of roundness or angularity), the sphericity, the orientation respect to bedding surfaces, the position within the beds, the lateral extension of the area where the mud casts occur and their concentration. In particular in the Agnone turbidite deposits the mud clasts occur in diverse configuration; they can be isolated, dispersed, or concentrated forming small clouds into

the massive portion of the beds or at its top where the boundary between the denser basal flow and the dilute upper turbulent flow occurs (Figs. 12 and 13). In some cases, the mud clasts are found above an irregular scoured depression at the base of the sandstone beds where they are densely concentrated. Rarely, they are also present at the base of sandstone beds showing a marked loading at its base that cause the genesis of flame clasts due to the load impressed by the sandstone bed onto the underlying muddy layer. In all these cases, most of these mud clasts show scanty disaggregation and rounding, so suggesting a local bed erosion and deposition and not a long transport with distance. All these data indicate that the position of mud clasts is controlled by the buoyancy, by the motion into the flow, and finally by the frozen of the flow as was suggested by the model of MUTTI & NILSEN (1981).

The *Facies FA4* constitutes a variant of the facies FA2 being characterized by massive to crude-laminated fine-very fine sandstone beds (20-100 cm thick), passing upward to an alternation of undulated and convolute laminae and ripple lamination (Fig. 14). The characters of the FA4 facies with small scale hummocky-like undulated laminae, the presence of flat ripples with rounded crest, and with tangential foreset laminae in opposite direction suggest for these beds an origin related to rebound and reflection processes. Such type of processes can essentially originate along the marginal and frontal slope of the basin and against structural highs although it is not ruled out that these processes can also be active along the lateral slope of depositional lobes. For the type of structures produced by rebound and reflection processes see PICKERING & HISCOTT (1985), EDWARDS *et alii* (1994), KNELLER (1995), REMACHA *et alii* (2005), MUZZI MAGALHAES & TINTERRI (2010), TINTERRI & TAGLIAFERRI (2015).

The *Facies FA5* is characterized by beds 10-20 cm thick with a diffuse climbing ripple cross-lamination, often deformed in convolute lamination as result of syn and/or post-depositional liquefaction associated to upward escapes of pore water (ALLEN, 1982; GLADSTONE *et alii*, 2018)

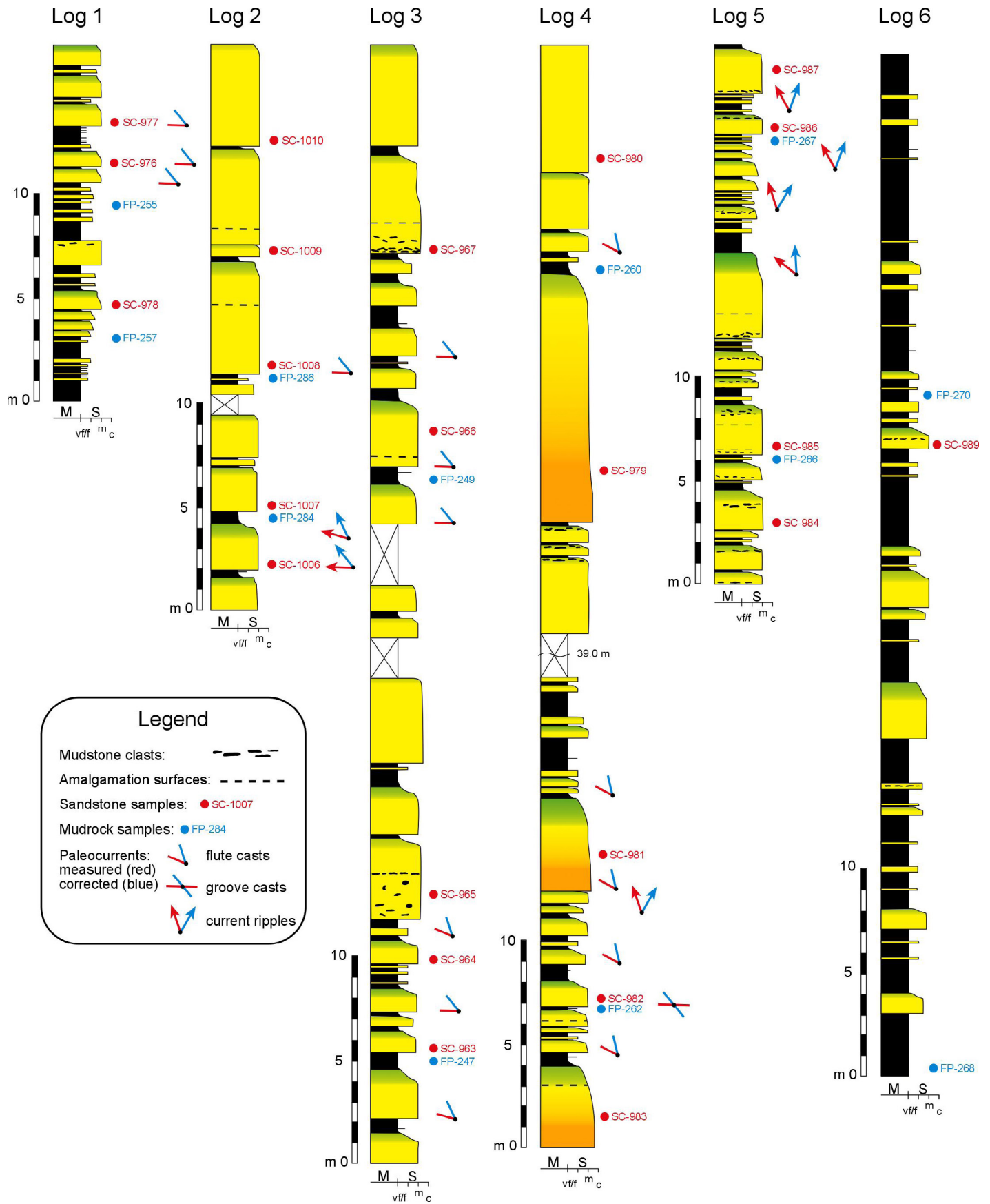


Fig. 8 - Measured stratigraphic logs showing the position of the sandstone and mudrock samples utilized for petrographic/compositional analysis and the measured (red)/corrected (blue) paleocurrents directions considering the post-Messinian counter-clockwise rotation of the investigated area. The logs 1, 2, 3, 4, 5, 6, 8, 9 and 10 were measured in the Poggio Villanelle Member, while the log 7 was measured in the Verrino Member.

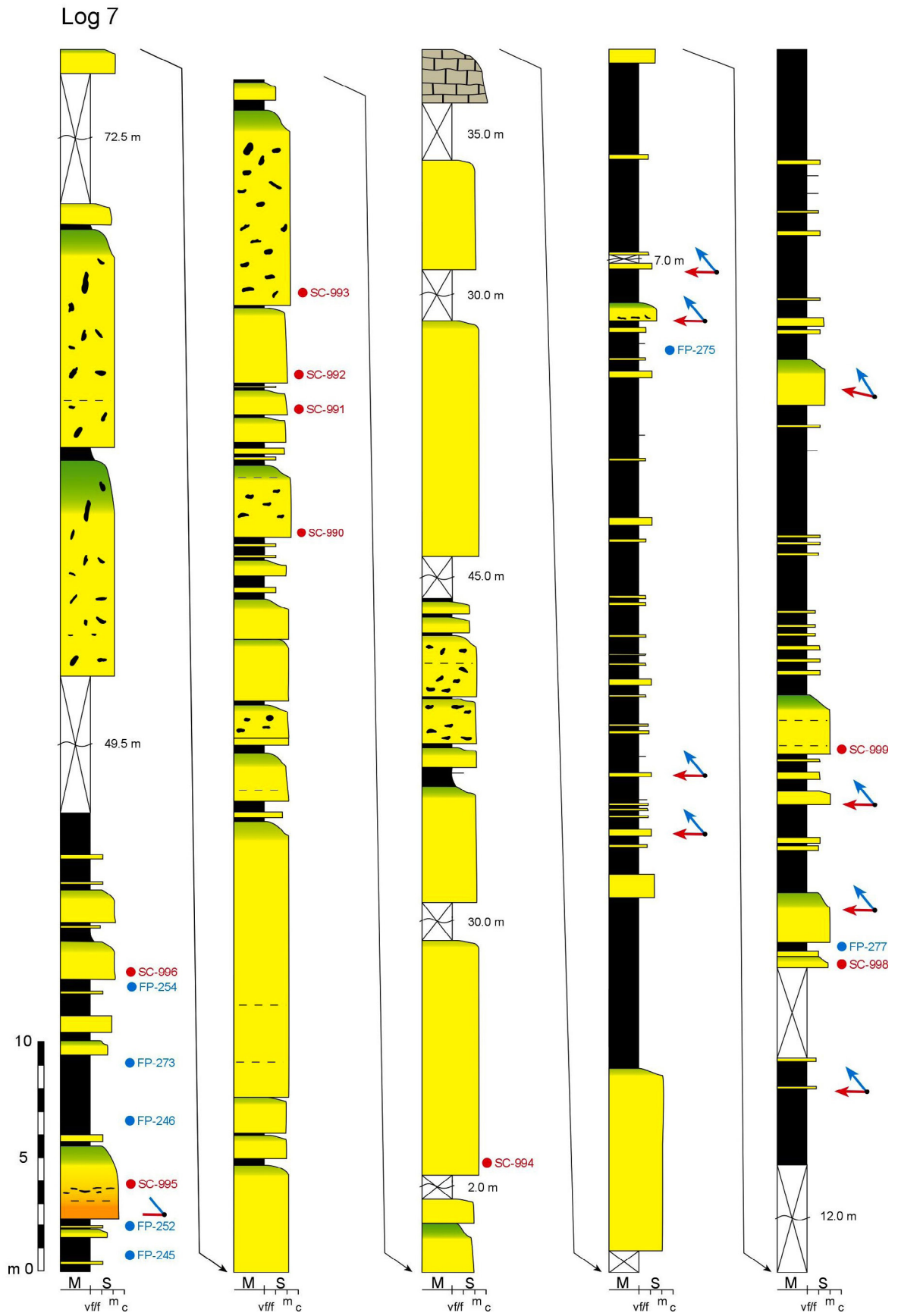


Fig. 8 - continued

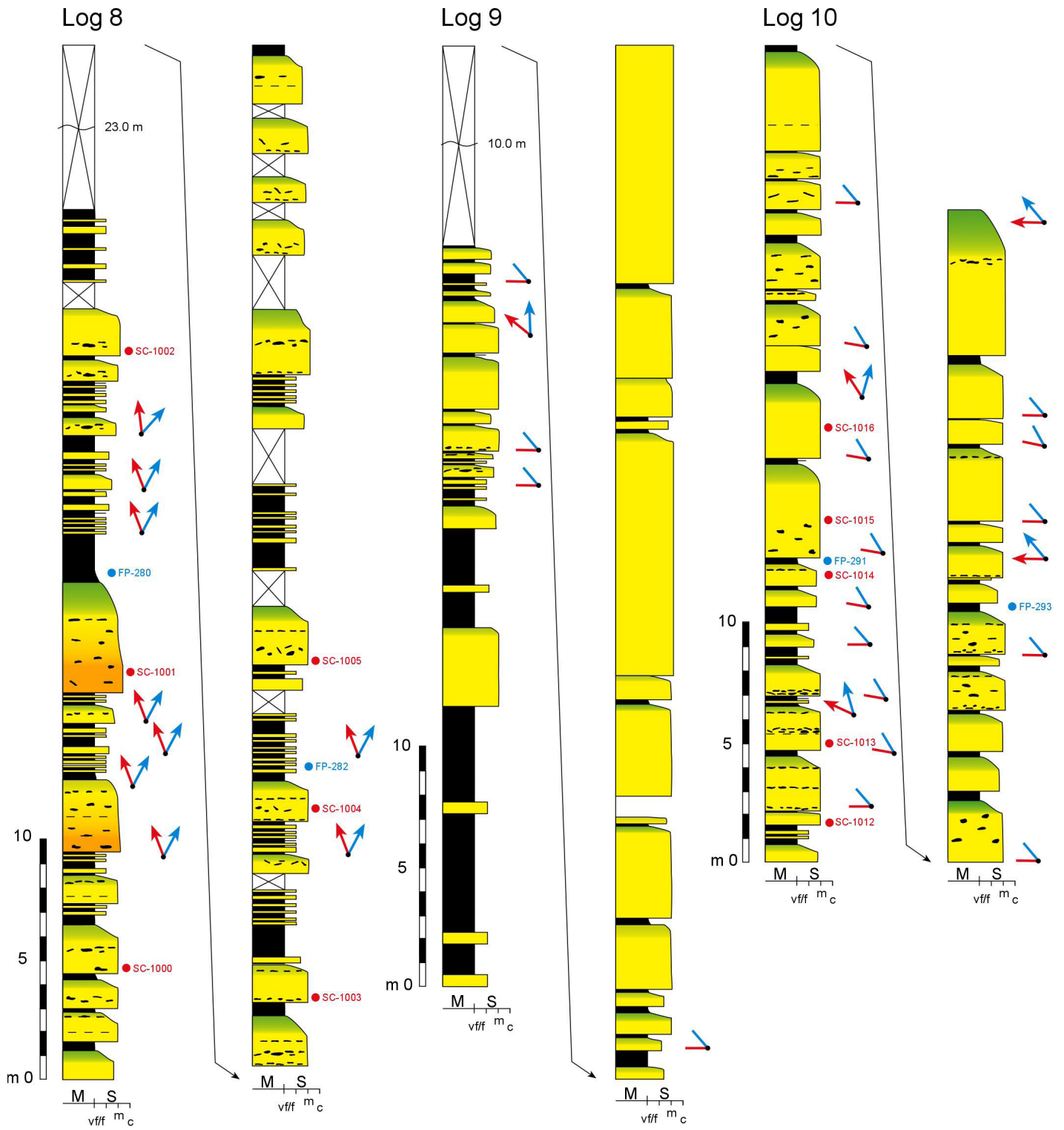


Fig. 8 - continued

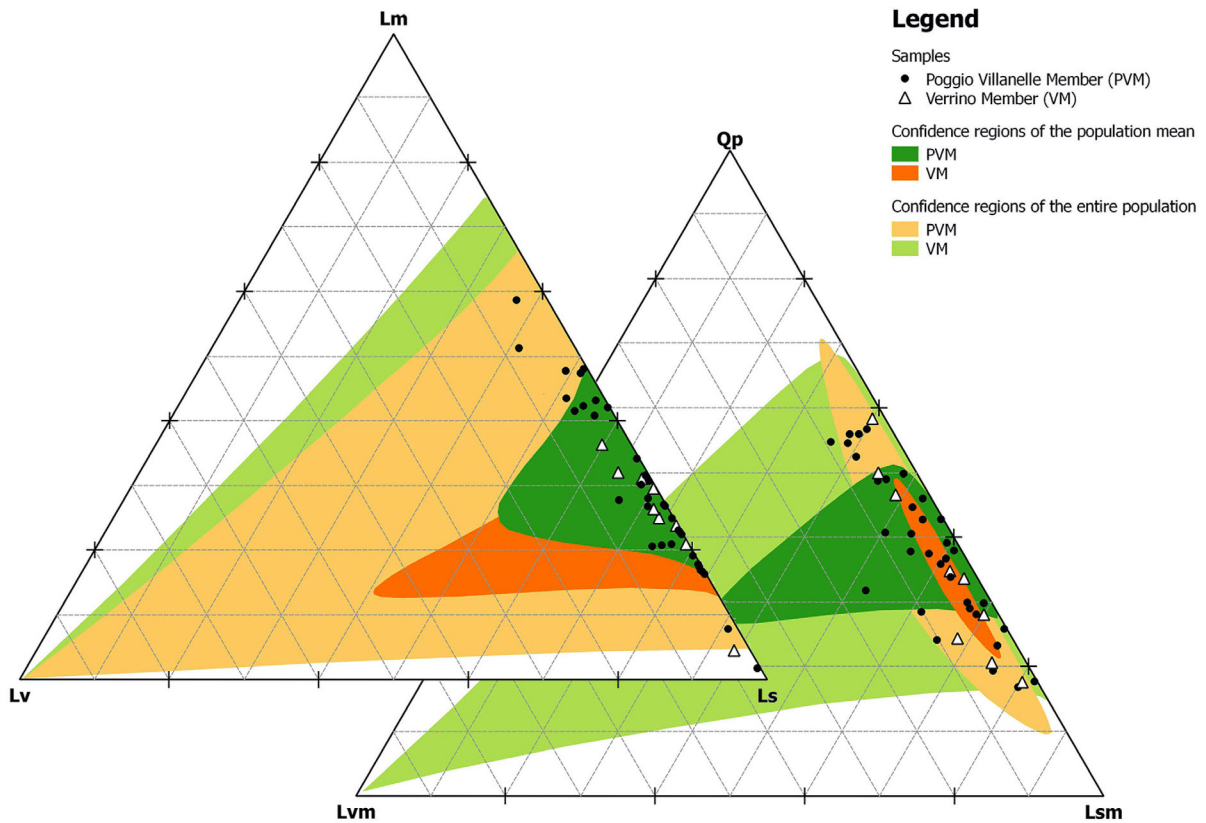
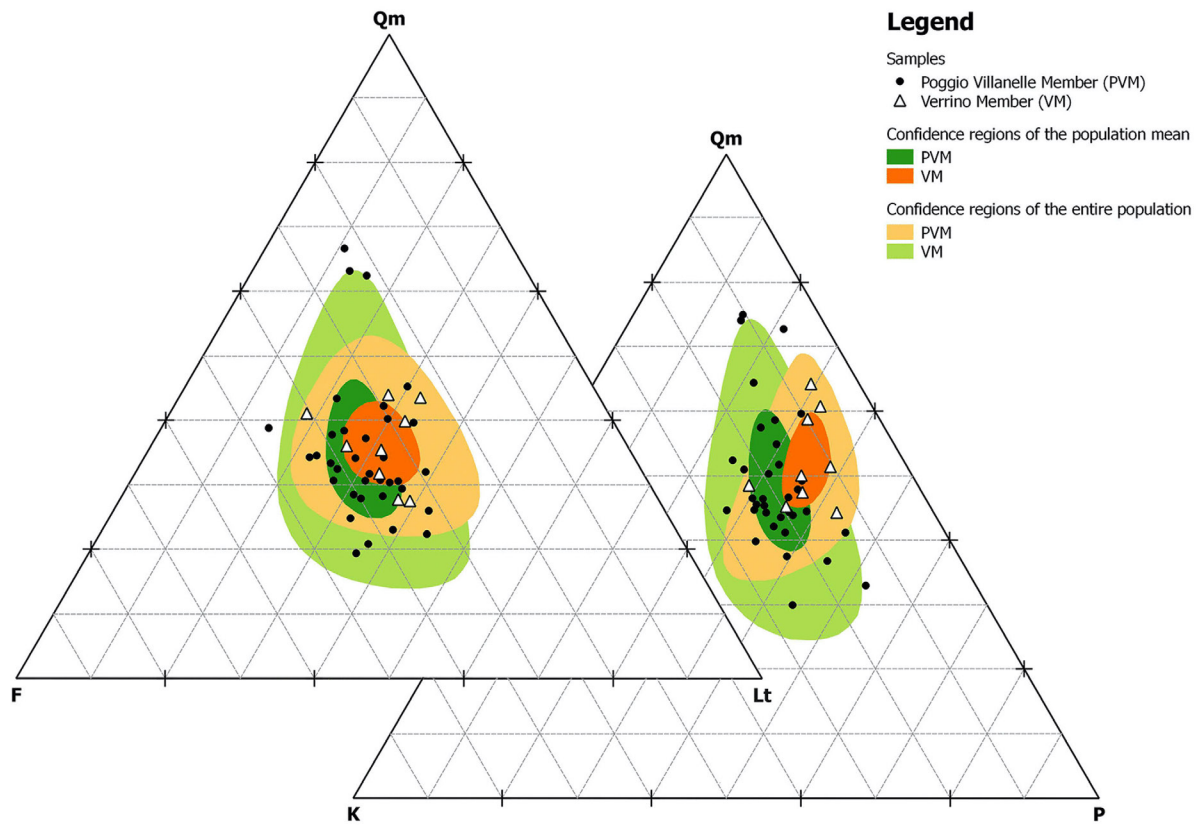


Fig. 9 - QmFLt, QmKP, QpLvmLsm, and LmLvLs ternary diagrams showing sandstone composition of the Agnone Flysch. Abbreviations: **Qm**, monocrystalline quartz; **F**, feldspar (K+P); **Lt**, aphanitic lithic fragments and fine-grained polycrystalline quartz; **K**, k-feldspar; **P**, plagioclase; **Qp**, polycrystalline quartz; **Lvm**, volcanic and metavolcanic lithics; **Lsm**, sedimentary and metamorphic lithics; **Lm**, metamorphic lithics; **Lv**, volcanic lithics; **Ls**, sedimentary lithics.

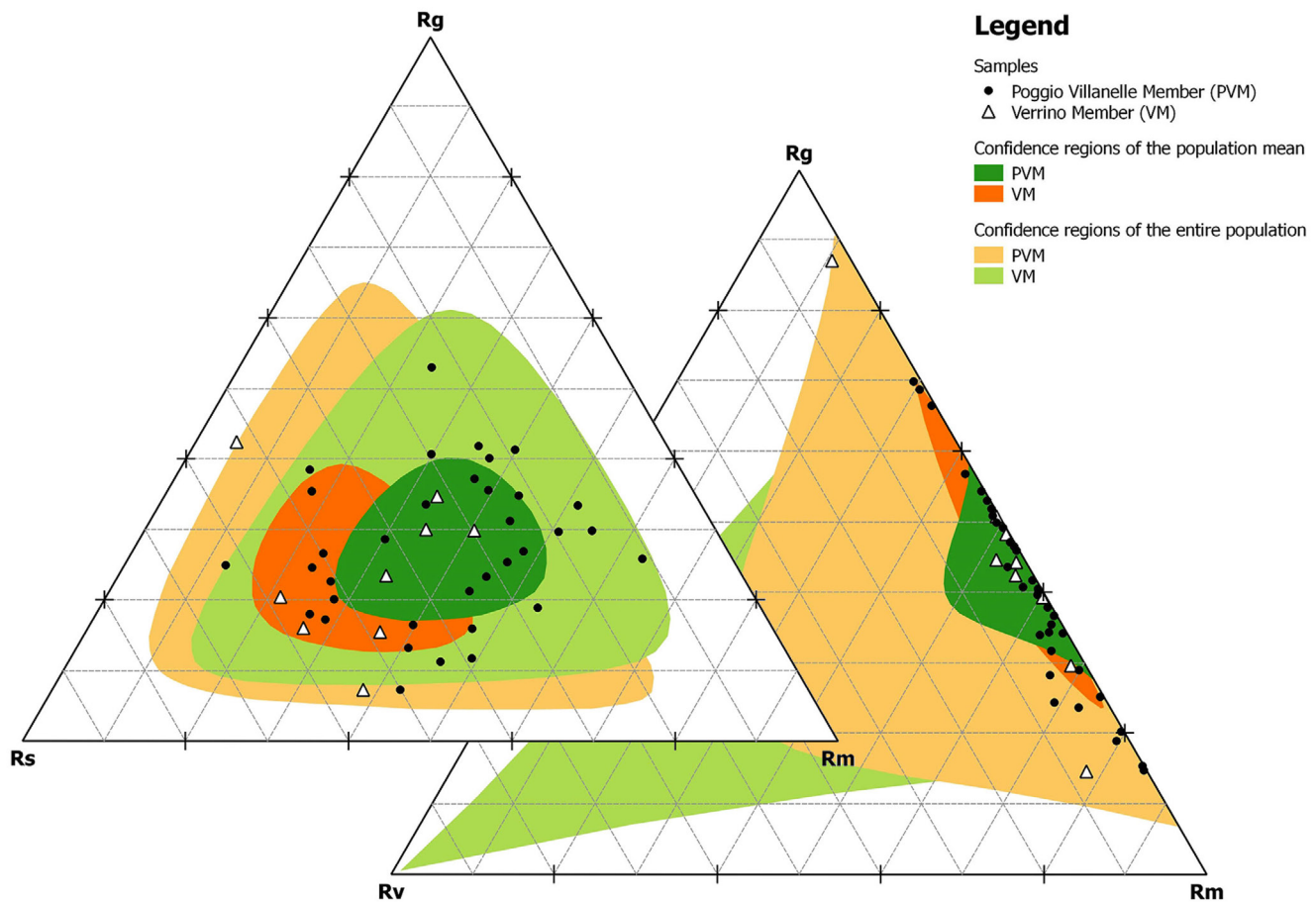


Fig. 10 - RgRmRs and RgRmRv ternary diagrams showing Agnone sandstone composition. Abbreviations: Rg, plutonic rock fragments; Rs, sedimentary lithic fragments; Rm, metamorphic rock/lithic fragments; Rv, volcanic rock/lithic fragments.

(Fig. 15). This type of beds generally occurs at the top of the FA1 and FA2 beds or form single beds passing upward and laterally to the laminated mudstone of Facies FA6. The Facies FA5 has some correspondence with the Tc-Td Bouma divisions and represents the product of traction-plus-fallout deposition from depletive and waning low-density turbidity currents (see MUTTI (1992), PICKERING *et alii* (1995), MUTTI *et alii* (1999) and PICKERING & HISCOTT (2016).

The Facies FA6 is constituted by medium to thin massive to laminated mudstones beds, often intercalated by very thin silty beds (Fig. 16). The deposits of this facies suggest a deposition from a decelerating mud-rich low-density turbidity currents (Td-e Bouma divisions); coherent with this interpretation is the position of these beds occurring at the top of the facies sequences containing in the lower portion the facies FA1, or FA2 or FA3. The absence of bioturbation in these beds suggests a rapid settling of the mud due to its high concentration in the final phase of turbidity current deposition. Thin sand injections that originate from the underlying or overlying sandy layers are locally present (Fig. 16). Characters of this facies are similar to the muddy portion of the Facies F9 of MUTTI (1992), MUTTI *et alii* (1999), and to the Facies E1.1 of PICKERING *et alii* (1995), and PICKERING & HISCOTT (2016). The Facies FA6 occurs as turbidite mud cap in the lobe zone from proximal to distal sectors, although

when it shows intercalations of silty layers it could be better interpreted as deposited in the inter-lobe packages (MUTTI, 1977). As recently discussed by MUTTI (2019), the thin-bedded and fine-grained turbidites of the Facies FA6 remain a problematic deposit whose sedimentary features can be also interpreted as the product of processes related to the proximity of delta systems developed in tectonically-active basins. MUTTI (2019) suggests, in fact, that on the basis of more recent experimental and field monitoring of modern deltas studies (see PARSON *et alii*, 2001; MULDER *et alii*, 2003; HIZZET *et alii*, 2018 and references therein), many of these thin-bedded and fine-grained turbidites, named by the Author *plumites*, could be generated from hypopycnal plumes and dilute hyperpycnal flows (see also MUTTI *et alii*, 2003; for more details on plumites facies description and interpretation see MUTTI, 2019). Such considerations have also been developed during the field observations of the Agnone turbidites, so it is not ruled out that Facies FA6 can be the result either distal sedimentation of decelerating dilute turbidite currents or the product of deposition of hypopycnal and dilute hyperpycnal flows (*plumites*, *sensu* MUTTI, 2019). Due to limited exposure of the intervals of Facies FA6, it is not possible to discriminate with certainty whether this facies is an inter-lobe facies or a plumite, although paleocurrent data and the paleogeography reconstruction of the investigated area seem to suggest that most of the FA6 beds could be interpreted as plumites.



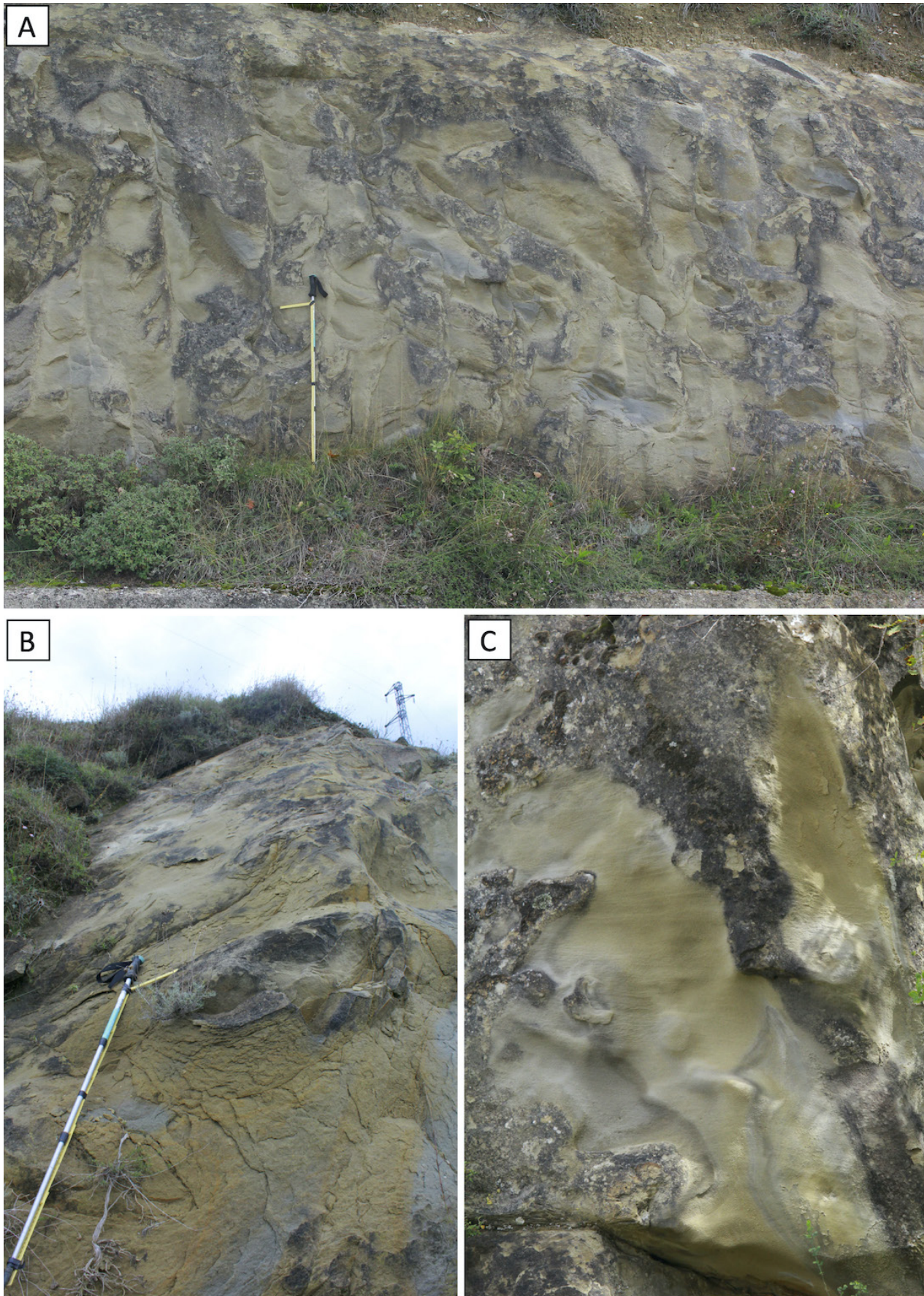
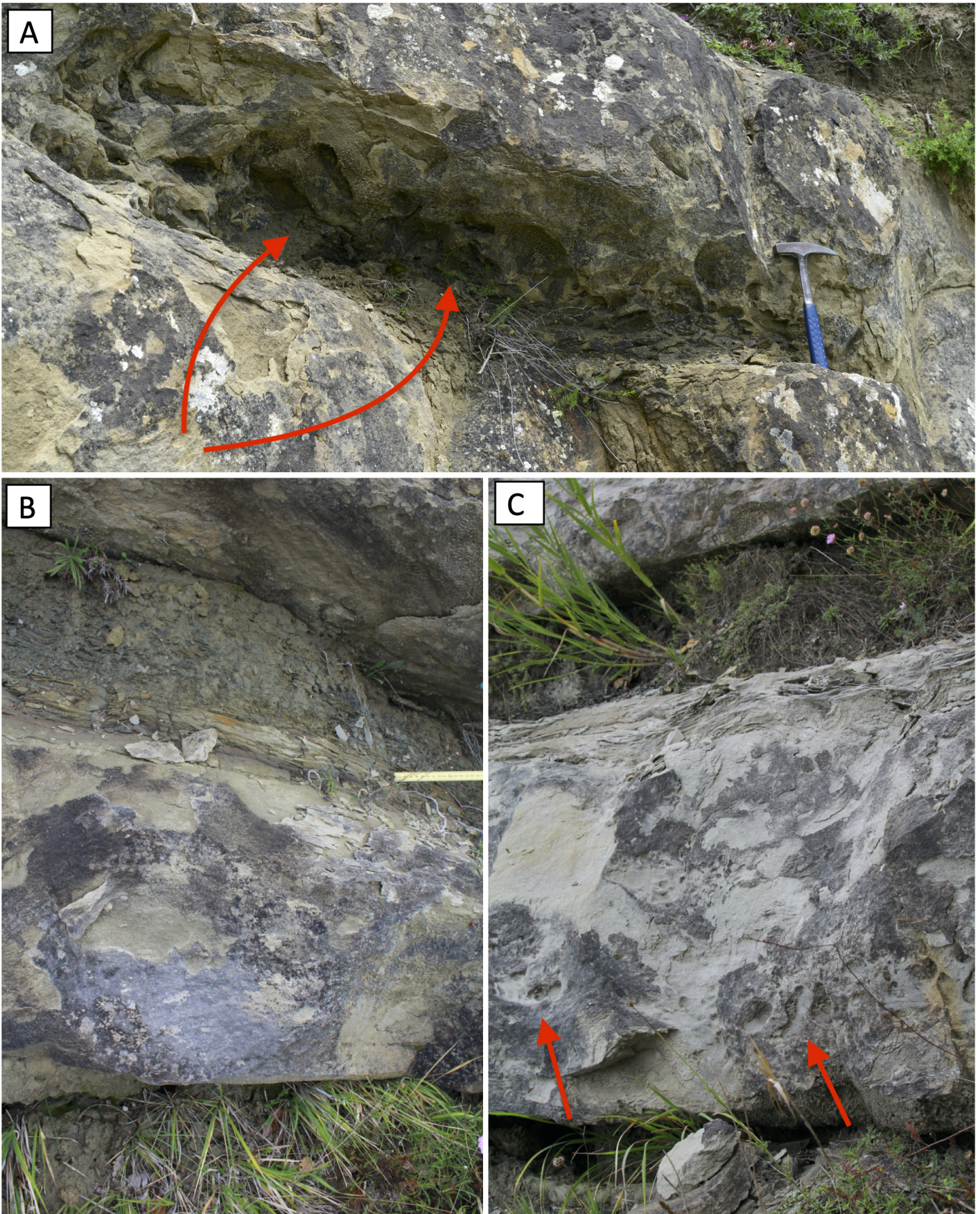


Fig. 11 - A) Typical aspect of the massive FA1 facies; B) top of FA1 bed showing the presence of bedforms (current ripples) induced by the overlying turbulent flow; C) Facies FA2 showing undulated lamination and water escape structure.



*Fig. 12* - The Facies FA3 may contain mudstone clasts at different height within the beds or can be completely free. A) Concentration of mudstone clasts at the base of massive deposits; B) FA3 bed free of mudstone clasts; C) Mudstone clasts positioned at different heights in FA3 bed (bed is 1.20 m thick).

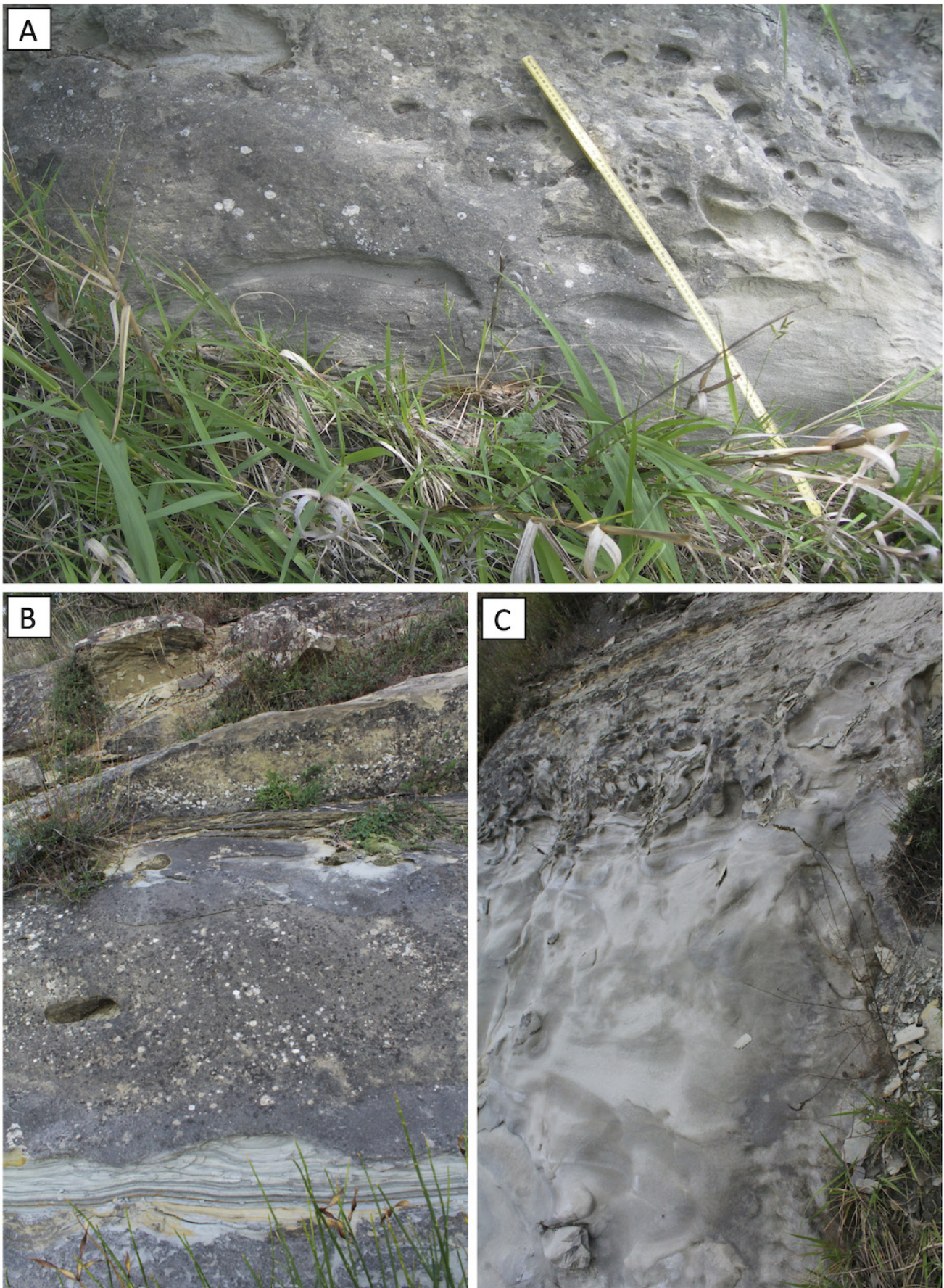
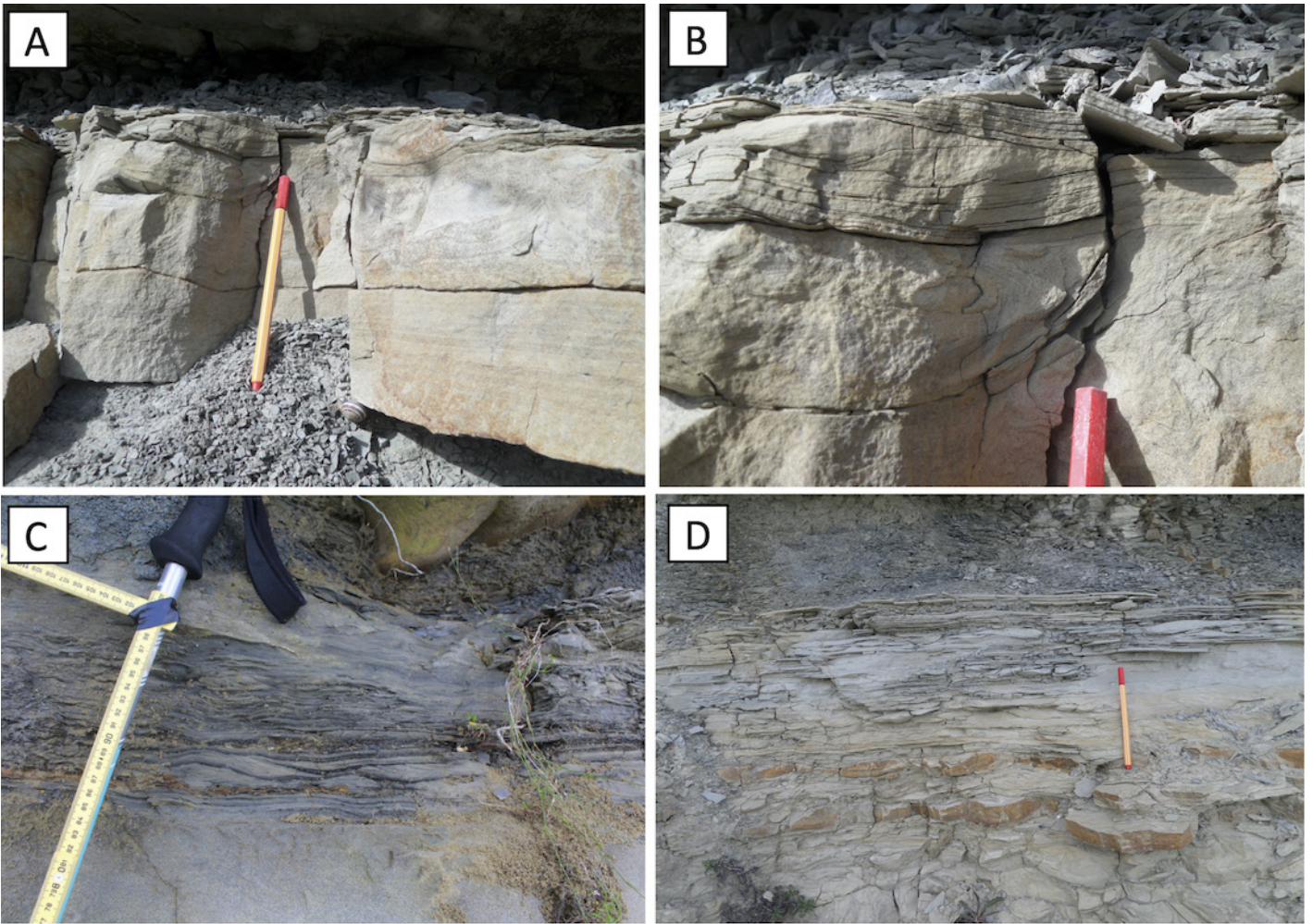


Fig. 13 - Other examples of facies FA3 with mudstone clasts concentrated at the base (A), isolated (B) or positioned at the top (C) of beds. The beds in B and C are 3 m thick respectively.



*Fig. 14 - A to D) Examples of facies FA4 characterized by massive to crude-laminated sandstones in the lower part, passing upward to low-angle wavy laminae (hummocky-like structures) interpreted as related to rebound and reflection processes.*



*Fig. 15 - Facies FA5: bedset with climbing ripple cross lamination.*

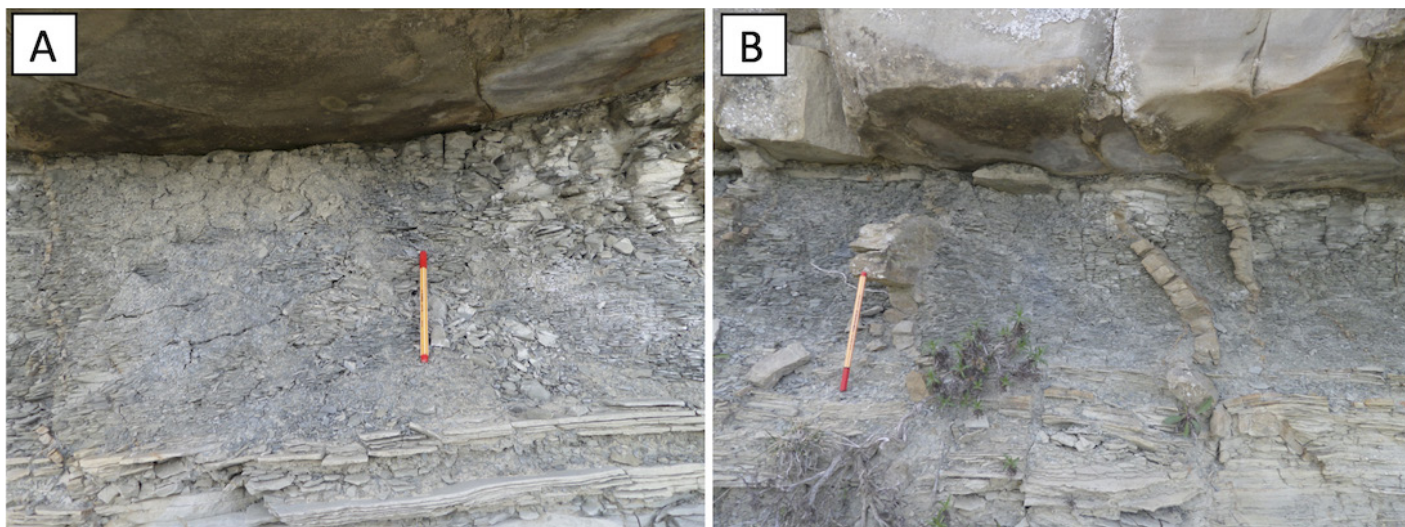


Fig. 16 - General aspect of the massive to laminated mudstone related to the facies FA6. Note in B the sand injection derived by the underlying and overlying sandstone beds.

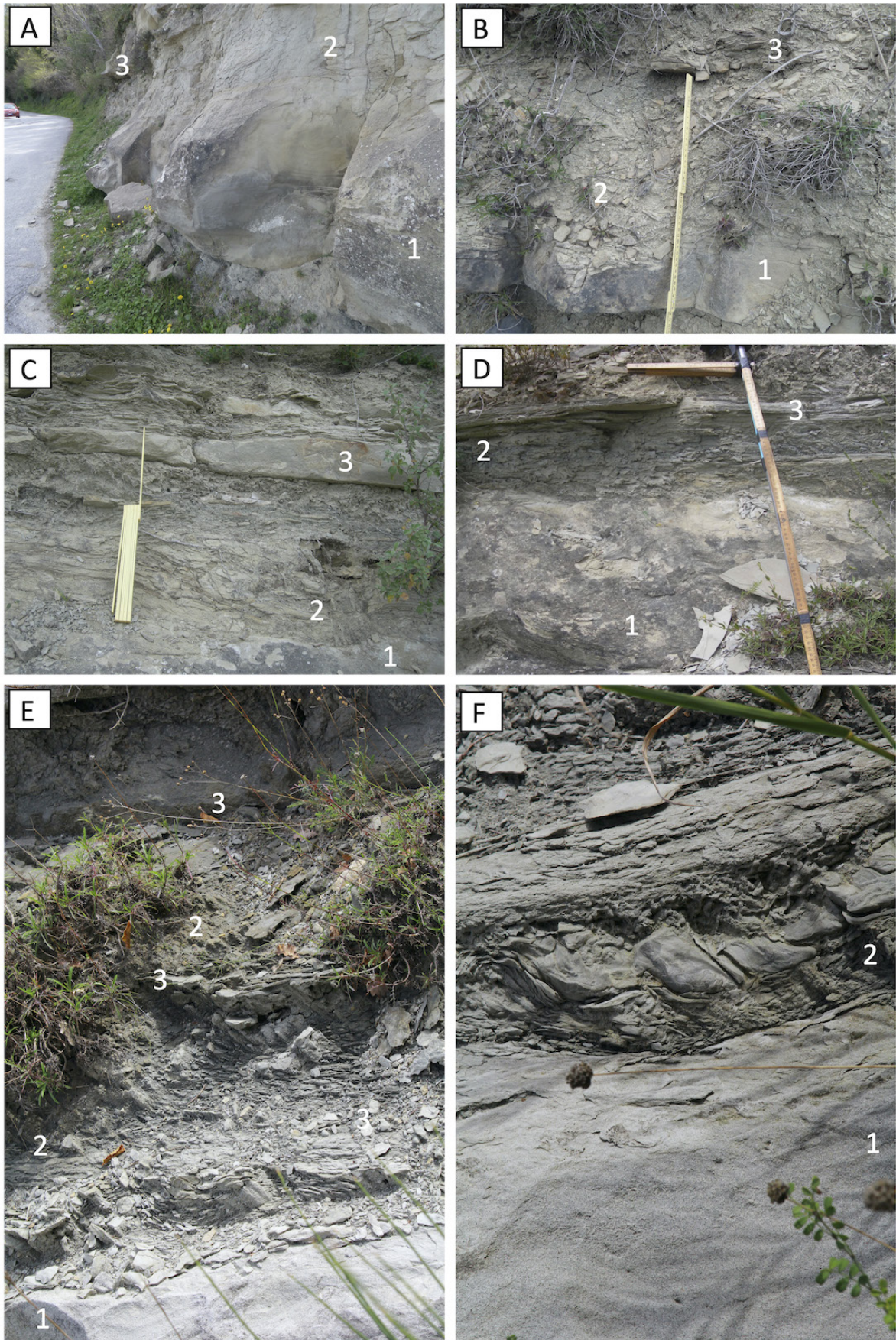
The *Facies FA7* is certainly the more complex facies being constituted by tripartite beds generally composed of 1) a lower ungraded to crudely graded medium-fine sandstone (30-100 cm thick), passing upward to 2) an intermediate muddy sandstone unit (30-40 cm thick) with mud clasts and woody fragments and finally to 3) an upper fine and very fine-grained cross-laminated sandstone unit (10-15 cm thick) that in some cases is lacking (Fig. 17). The unit 2 is poorly sorted and shows an internal deformation produced by liquefaction structures. Based on the reconstruction of the basin geometry in the investigated area (see after), this facies is here interpreted to form through the deceleration and transformations of the turbidity currents induced by submarine topography and in particular when the flows impact against the slopes of the basin and also the depositional reliefs (i.e., against the lobes). This process would produce a local hydraulic jump (see also POSTMA *et alii*, 2009), which would favor erosion of the cohesive mud where zones of lateral and vertical constriction occur, the mixing with the sand transported by the current, and the successive deposition of the bed due to the rapid deceleration forced by flow expansion. Such type of beds have been described in the literature since the 60's of the last century (see RICCI LUCCHI, 1965; MARSCHALCO, 1970; VAN VLIET, 1978; MUTTI *et alii*, 1978; RICCI LUCCHI & VALMORI, 1980, slurry beds; MUTTI & NILSEN, 1981). More recently many papers have discussed the processes responsible for the formation of these beds (see LOWE & GUY, 2000; HAUGHTON *et alii*, 2009; SYLVESTER & LOWE, 2004; TALLING *et alii*, 2004; AMY & TALLING, 2006; BAAS *et alii*, 2011; HODGSON, 2009; SUMNER *et alii*, 2009; MUZZI MAGALHAES & TINTERRI, 2010; PATACCI *et alii*, 2014; MARINI *et alii*, 2011, 2015; SOUTHERN *et alii*, 2015; TINTERRI & TAGLIAFERRI, 2015; FONNESU *et alii*, 2016, 2018; KANE *et alii*, 2017; SPYCALA *et alii*, 2017 with references therein), known in literature as "hybrid beds", although they are nothing more than the expression of local modifications of the rheology of turbidite currents interacting with the submarine topography. Most of these beds characterize the depositional lobe zone and the marginal sectors of

the Agnone Basin where turbidite deposits onlapped onto the frontal and lateral slopes.

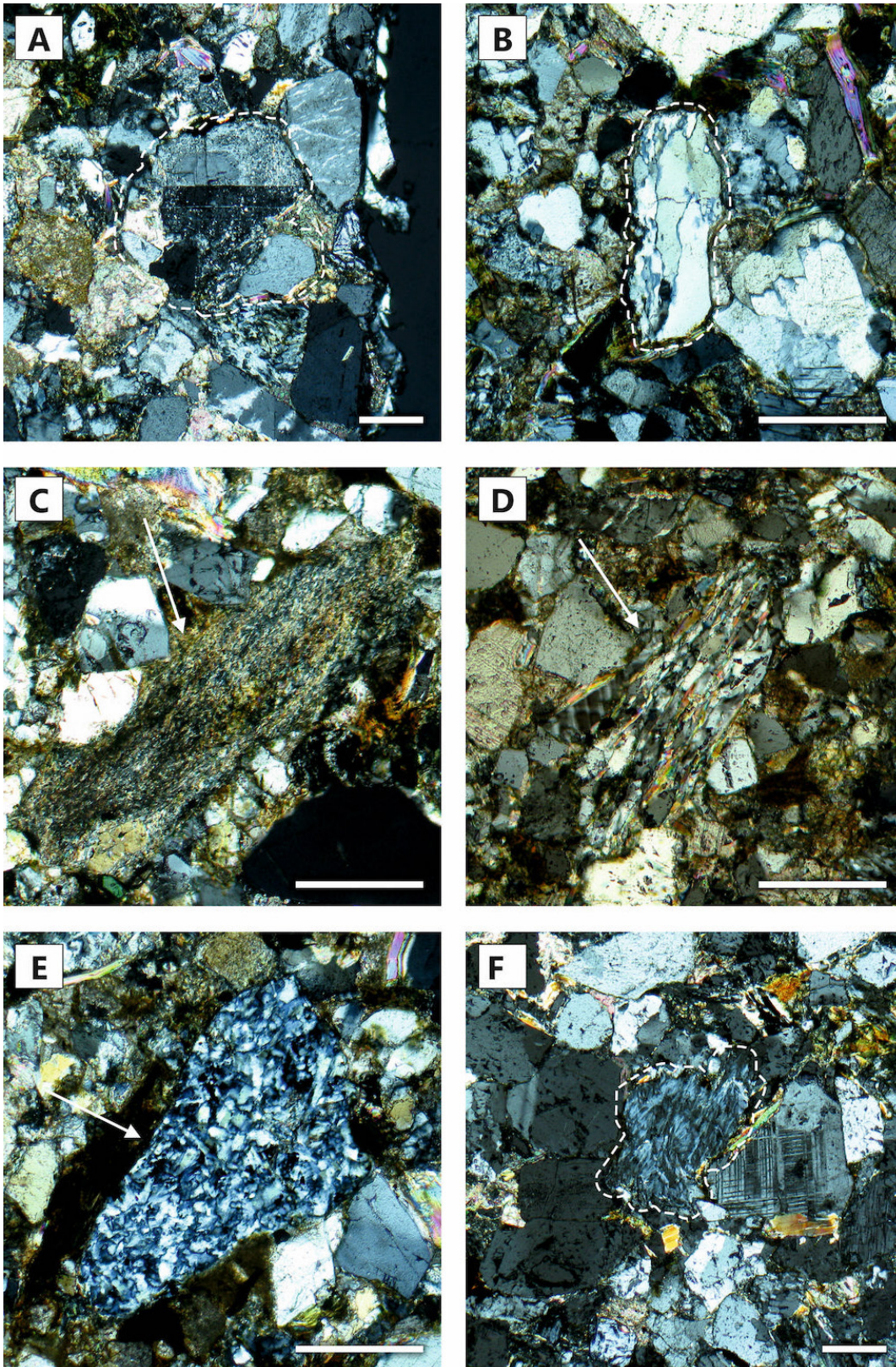
Overall, even if not treated in a statistical way, the observations of the measured sections allow us to say that the facies FA5 and FA6 are mainly developed in the Verrino member and constitute the upper portion of the beds with the facies FA1, FA2, FA3, and FA7. The latter, together with the FA4 facies, are instead mainly developed in the lower and middle portion of the Poggio Villanelle member, which records both the general progradational phase of the Agnone turbidite system and the greater confinement of the basin, probably connected to the eastward migration of the Apennine thrusts.

#### SANDSTONE PETROGRAPHY

Sandstones samples from Verrino and Poggio Villanelle members have a quartzofeldspathic composition. In spite of its quartzofeldspathic composition, two distinctive petrofacies can be recognized based on different lithic fragments proportions (Figs. 9, 10 and 18). Sandstones, in general, are characterized by phaneritic (single crystal >0.0625mm) detritus with abundant quartz (single crystals and polycrystalline quartz with and without tectonic fabric; Fig. 18B), feldspar (plagioclase greater than K-feldspar), and micas derived from plutonic rocks (Fig. 18A), schist and gneiss rock/lithic fragments. The aphanitic (single crystal <0.0625mm) lithic fragments include sedimentary and metamorphic fragments. Lithic fragments include both non-carbonate extrabasinal (NCE; ZUFFA, 1980), and extrabasinal carbonate fragments (CE; ZUFFA, 1980). Metamorphic fragments consist of common phyllite and fine-grained schist (Figs. 18C and 18D). The most common grains are the fine-grained schists. Minor ophiolitic lithic fragments include serpentinite and serpentine-schist (Figs. 18E and 18F). Dense minerals include apatite, epidote, garnet, rutile, tourmaline and zircon. The main interstitial component is sparitic and microsparitic carbonate cement with patchy calcite and pore-filling texture. The interstitial component also



*Fig. 17* - Example of FA7 beds showing the tripartite subdivisions with a 1) a lower ungraded to crudely graded medium-fine sandstone; 2) an intermediate muddy sandstone unit with mudstone clasts; 3) an upper fine and very fine-grained cross-laminated sandstone unit that in some cases is lacking.



*Fig. 18* - Thin sections showing photomicrographs of diagnostic grains. A) Plutonic rock fragment (Rg in the compositional diagram of figure 10) highlighted by the white dashed lines; B) Polycrystalline quartz with tectonic fabric (stretched metamorphic quartz (Qp) highlighted by the white dashed lines; C) Sedimentary lithic fragment (Ls), white arrow; D) Fine-grained schist (Lm), white arrow; E) Massive serpentine lithic fragment (Lv), white arrow; F) Schistose serpentine lithic fragment (Lm), highlighted by the white dashed lines. All white bars (scale) are 200  $\mu\text{m}$ . All photos are under crossed polars.

includes common siliciclastic and minor carbonate matrix.

Textural analysis allows identification of two types of grain-contacts: lower member sandstones (VM) show few 'floating' grains or punctual contacts, whereas in the middle member (PVM), grains contacts are mainly

long and tangential. The nature of the contacts between sandstone grains is indicative of a gradual increase of packing up-section. Packing is largely dependent on the sorting and shape: the VM sandstones are composed of well/moderately sorted and sub-angular/rounded grains with a loose packing texture; instead, poorly/

moderately sorted sediments and sub-angular/rounded grains of PVM have a much closer packing.

### Petrofacies

Recalculated and next plotted point-count data from aphanitic lithic fragments (QpLvmLsm; LmLvLs, Fig. 9) and phaneritic rock fragments (RgRsRm; RgRvRm, Fig. 10) allow to discriminate two distinct detrital populations (petrofacies A1 and A2) that have a good correspondance with the VM and PVM members respectively, which record a change in source areas over time. Means and standard deviations for the parameters that define the two petrofacies are given in Tab. S3 (see supplementary material). The A1 petrofacies shows a quartzofeldspathic composition (mean values of  $Qm_{36}F_{33}Lt_{31}$ ; P/F=0.72). The VM aphanitic lithic fragments average composition shows  $Qp_{35}Lvm_4Lsm_{61}$  and  $Lm_{26}Lv_2Ls_{72}$ , with a clear abundance of sedimentary debris which is in part confirmed by the modal recalculation of the phaneritic rock fragments that shows an abundance of sedimentary rock fragments (mean  $Rg_{24}Rs_{46}Rm_{30}$ ), and metamorphic and plutonic debris ( $Rg_{45}Rv_2Rm_{53}$ ). Also, the A2 petrofacies is characterized by quartzofeldspathic composition ( $Qm_{37}F_{37}Lt_{26}$ ; P/F=0.66). The aphanitic lithic fragments show an abundance of sedimentary and metasedimentary lithic fragments ( $Qp_{43}Lvm_4Lsm_{53}$  and  $Lm_{43}Lv_2Ls_{56}$ ) (Fig. 9); phaneritic rock

fragments show a prevalence of metamorphic fragments over sedimentary, volcanic and plutonic fragments  $Rg_{26}Rs_{29}Rm_{45}$  and  $Rg_{38}Rv_1Rm_{61}$  (Fig. 10).

### MUDROCK MINERALOGY

#### Bulk rock composition

Mudrock samples from Poggio Villanelle member are mainly composed of phyllosilicates that prevail over the quartz and felspar, whereas the Verrino member samples show more carbonates (calcite and dolomite). The XRD patterns and semiquantitative data of the whole rock and clay fraction are shown in Fig. 19 and Tab. 3, respectively. The average value of the phyllosilicates both in the VM and PVM mudrock samples are quite similar, whereas of the non-phyllosilicate phases that show different percentages in the studied samples. In detail, the phyllosilicates show very similar amounts in the two members, ranging from 20-30% to 55-60%, and are composed of mixed-layer phases, illite and micas, chlorite, with minor amounts of kaolinite. The non-phyllosilicate phases, ranging from 40-45% to 70-75%, are mainly composed of calcite, quartz, feldspars (K-feldspar and plagioclases) and dolomite and show a different trend in the two members. In particular, the mudrock samples of the VM show high amounts of calcite with values ranging from 5-10% to 55-60%, and

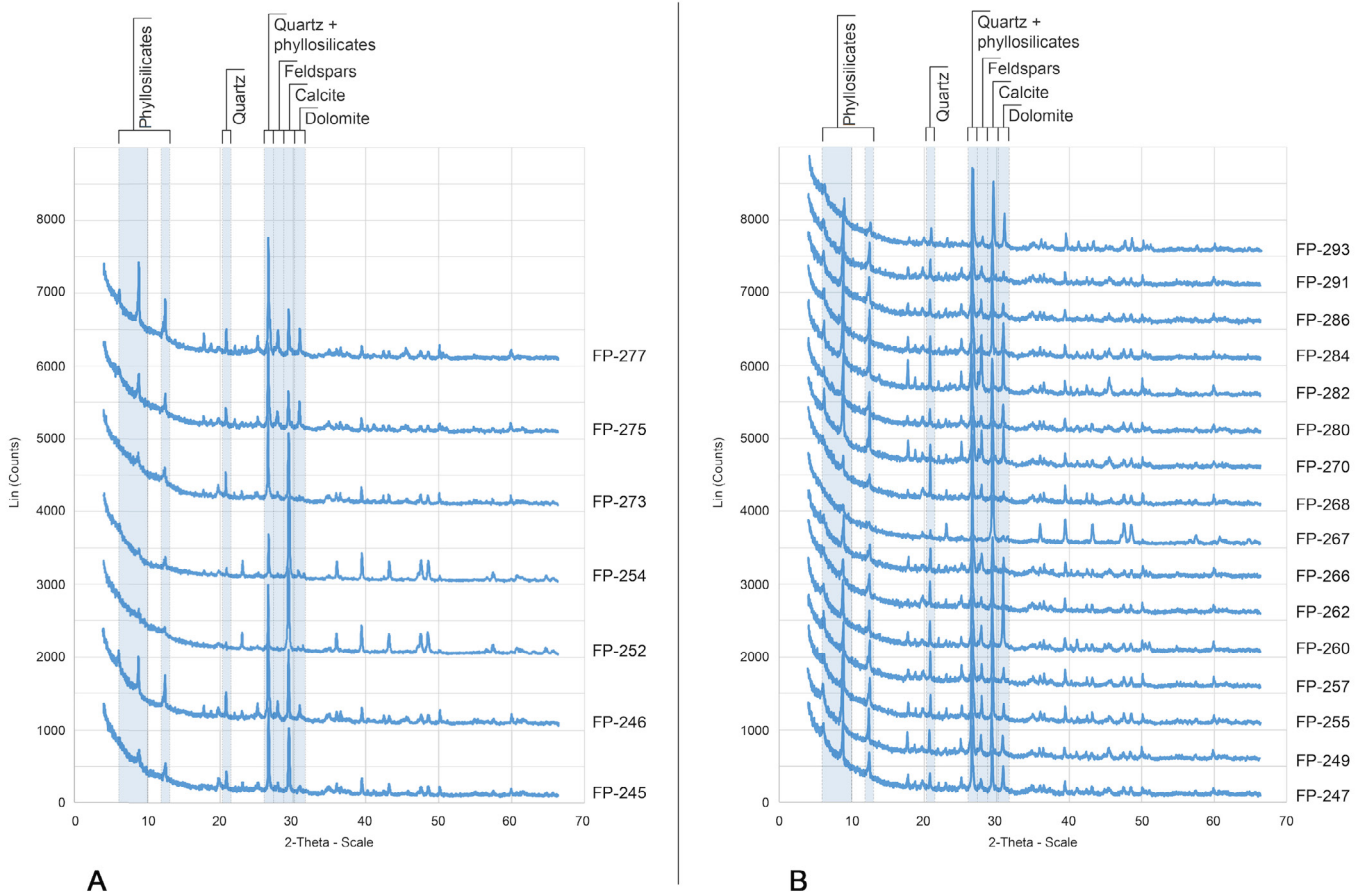


Fig. 19 - X-Ray Diffraction patterns of the studied mudrock samples. The mineralogical components are indicated in correspondence of the significant peaks. A) XRD patterns of the Verrino Member; B) XRD patterns of the Poggio Villanelle Member.



TABLE 3

Semiquantitative abundances of mineralogical components observed in mudrock samples. The increasing intensity is indicated by the “+” symbol: mineralogical concentrations range from absent (-), low (+), normal (++) , high (+++) to very high (++++), in particular: - = 0%; + = 1 ≤ x ≤ 5; ++ = 5 < x ≤ 20; +++ = 20 < x ≤ 40; ++++ = 40 < x ≤ 60; Dol = dolomite; Calc = calcite; Pl = plagioclase; Kfs = potassium feldspar; Qz = quartz; ΣPhyl = phyllosilicates (= Mixed-layer phases + Micas and illite+Kln+ Chl); Chl = chlorite; Kln = kaolinite.

Member	Sample	Mixed-layer phases	Micas and illite	Kln	Chl	ΣPhyl	Qz	Kfs	Pl	Cal	Dol
VERRINO MEMBER (VM)	FP-245	++	+++	++	+	++++	++	+	+	++	+
	FP-246	+	+++	++	+	+++	++	+	++	++++	+
	FP-252	+	+++	++	+	++++	++	-	-	++++	+
	FP-254	++	+++	++	+	+++	++	-	+	++++	+
	FP-273	+	+++	++	+	++++	+++	-	+	+++	-
	FP-275	+	+++	++	+	+++	+++	+	++	++	++
	FP-277	+	++	++	+	+++	+++	+	++	+++	++
POGGIO VILLANELLE MEMBER (PVM)	FP-247	+	+++	+	++	+++	+++	+	++	++	++
	FP-249	+	++	++	+	+++	+++	+	++	++	++
	FP-255	+	+++	+	++	++++	+++	+	++	++	+
	FP-257	+	+++	+	++	++++	+++	+	++	++	++
	FP-260	++	++	++	+	+++	++	+	++	++	++
	FP-262	++	+++	+	++	++++	+++	-	+	++	++
	FP-266	+	++	+	+	+++	+++	+	++	++	+
	FP-267	++	++	++	+	++++	+++	-	+	++	++
	FP-268	++	+++	+	++	++++	+++	+	++	++	+
	FP-270	+	+++	+	+	++++	+++	++	++	++	++
	FP-280	+	+++	+	++	++++	++	+	+	++	++
	FP-282	+	+++	+	+	+++	+++	++	++	++	++
	FP-284	+	+++	+	+	+++	++	+	++	++	++
	FP-286	+	+++	+	+	+++	+++	+	++	++	++
	FP-291	++	+++	+	++	++++	+++	+	++	++	+
	FP-293	+	+++	+	+	+++	+++	+	+	++	++

minor amounts of quartz, feldspars (K+P) and dolomite in a decreasing order of abundance. The samples of the PVM, show more abundance of quartz, ranging from 5-10% to 35-40%, than calcite, with a mean value of 15%, compared to the samples of the VM, and minor amounts of feldspar and dolomite as shown by the XRD patterns in figures 19A and 19B. The mudrock mineral abundances of both members retrieved by X-ray diffraction show a quite similar trend to the above-mentioned evolution of the sandstone petrofacies.

#### Clay mineralogy

Selected mudrock samples (three from VM and five from PVM) were also studied to characterize in detail the clay minerals, on the oriented specimens. XRD analyses of the air-dried specimens, glycolated and heated were carried out (Figs. 20A and 20B).

The < 2 μm grain-size fraction (Tab. 4) is mainly composed of I/S mixed layers, with a percentage ranging from 40% to 60%. Illite content has a similar percentage on average (15-20%) in both members

and these contents are witnessed by X-ray diffraction patterns of the ethylene-glycol solvated specimens that show particularly broad reflections between 8.5-9.5° 2θ. Chlorite and kaolinite contents usually are low, with a percentage ranging from 5% to 15% (see Tab. 4).

Decomposition of X-ray diffraction patterns of the glycolated oriented slides was performed: as regard the illite percentage in I/S and the stacking order R, patterns of all eight samples show broad reflections at about 5°2θ (I/S R0) and weak peaks at about 9.4°2θ (I/S R1) and 10°2θ (I/S R0). The percentage of illite (%I) and stacking order (R) of the I/S mixed layers was determined on the spectrum of the glycolated oriented slides using the MOORE & REYNOLDS (1997) method. XRD pattern of the glycolated specimens mainly show the occurrence of the I/S R0 and I/S R1, with illite percentage ranging from 40% to 70%, that imply an early diagenetic condition for the Agnone Flysch (see also MERRIAM & FREY, 1999; ALDEGA *et alii*, 2007; BIGI *et alii*, 2009). The occurrence of randomly interstratified illite/smectite and ordered I/S mixed layers suggest a complex history for the studied successions (e.g., CAVALCANTE *et alii*, 2007; CORRADO *et alii*, 2010). In particular, the presence of ordered I/S mixed

TABLE 4

Mineralogical composition of the mudrock <2 $\mu$ m fraction (semiquantitative abundances). Kln = kaolinite; Chl = chlorite; Illt = illite; I/S = illite/smectite mixed layers; R = Reichweite (stacking order of the illite/smectite mixed layer); +, increasing intensity where: + =  $x \leq 10$ , ++ =  $10 < x \leq 20$ , +++ =  $x > 20$ .

Formation	Sample	Kln	Chl	Illt	Mixed layer phases (I/S)	I/S feature	
						Reichweite	% illite
VERRINO (VM)	FP-246	++	+	++	+++	R0 and R1	40-50 and 60-70
	FP-252	++	+	++	+++	R0 and R1	40-50 and 60-70
	FP-254	++	+	++	+++	R0 and R1	40-50 and 60-70
POGGIO VILLANELLE (PVM)	FP-249	++	++	++	+++	R0 and R1	40-50 and 60-70
	FP-257	+	++	++	+++	R0 and R1	40-50 and 60-70
	FP-260	++	++	++	+++	R0 and R1	40-50 and 60-70
	FP-262	+	++	++	+++	R0 and R1	40-50 and 60-70
	FP-291	+	++	++	+++	R0 and R1	40-50 and 60-70

layers could be also related to a provenance of inherited minerals from the neighboring area at the time of deposition, as is the case of fore-arc and foreland basins (e.g., MERRIMAN, 2005; CAVALCANTE *et alii*, 2007).

## DISCUSSION

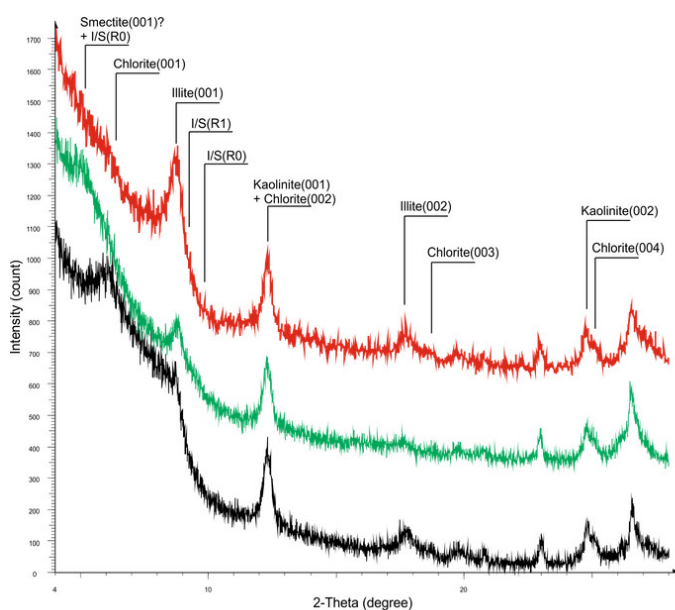
### COMPOSITIONAL CHARACTERS

#### *Provenance of detritus*

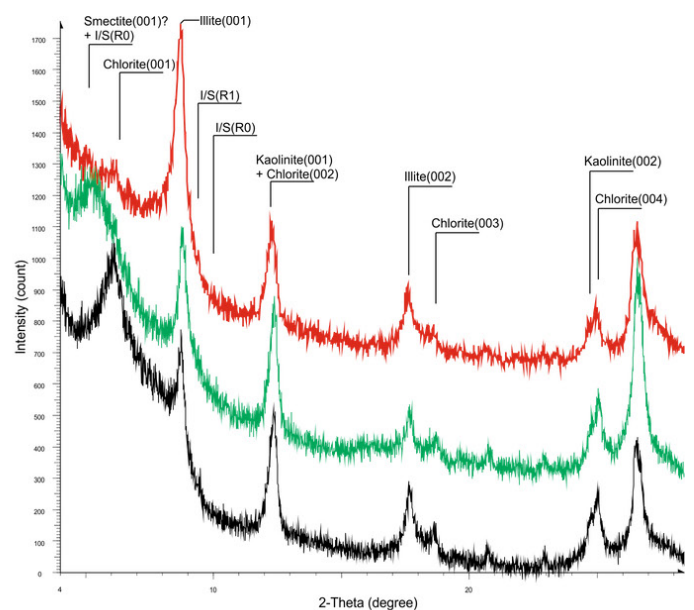
Two petrofacies (VM and PVM) are identified by visual inspection of the sandstones distribution (see ternary

plots in Figs. 9 and 10) and main compositional data are reported in Tab. S3 (see supplementary material).

An upsection increase of feldspar was observed by comparing the mean values of both sandstone members, in particular the QmFLt and QmKP relative proportions (Fig. 9). This evidence suggests a change to increased metamorphic and plutonic contribution, which is also reflected in the Lm and Rm content (in LmLvLs and RgRvRm, ternary diagrams respectively) and in the Rg and Rm (see RgRsRm ternary diagram), that increased up-section too. A strong support to the metamorphic detrital contribution during PVM deposition is confirmed by plagioclase/feldspar ratio that decreases from lower member with 0.72 value to 0.66 in the overlying member.



(A) - FP252



(B) - FP249

Fig. 20 - XRD pattern of the < 2 $\mu$ m fraction of air-dried (black line), glycolated (green line) and heated (red line) specimens. The most representative patterns of the Verrino Member (A) and the Poggio Villanelle Member (B) are shown.

Furthermore, an upward decreasing trend of lithic rocks fragments (Rs) and especially sedimentary lithic component (Ls), was observed (see LmLvLs and RgRsRm in Tab. S3; see supplementary material).

The mudrock mineral abundances (non-phyllsilicate phases) of each member retrieved by X-ray diffraction show a quite similar trend to the above-mentioned evolution of the sandstone petrofacies. In fact, there is an upward increasing of feldspar and a similar pattern about the P/F ratio (0.74 for VM and 0.69 for PVM). Moreover, the high sedimentary content recorded by VM sandstone samples was confirmed by the greater carbonate content in the associated mudrock samples.

As previously highlighted, the analysis of clay minerals suggests conditions of early diagenesis for the Agnone Flysch. This is consistent with the results occurring in Di BUCCI *et alii* (1996) and CORRADO *et alii* (1998, 2010) who sampled the VM of the Agnone Flysch and the underlying Varicoloured Clays. These Authors investigated these lithostratigraphic units using optical indicators of organic matter maturity (vitrinite reflectance and thermal alteration index) and clay mineralogy arriving at the following results: 1) the VM turbidite deposits show low levels of organic maturity so indicating early mature hydrocarbon generation that suggests an early diagenesis for these deposits; 2) the clay minerals of the Varicoloured Clays are essentially constituted by highly smectitic interstratified illite/smectite and are similar to the clay composition of the VM and PVM. These data were used to calibrate burial and thermal evolution of this investigated sector. The results indicate that these lithostratigraphic units were never overthrust at least before the Pliocene, so suggesting a consistency with our data indicating an early diagenesis for the Agnone Flysch and a detrital origin of the clay minerals. These considerations, based on the sandstone petrography and the mudrock mineralogy, provide useful information about the evolutionary history of the Agnone Flysch.

Clastic contributions from different sources were supposed by a) a calciclastic Apenninic source and, b) a terrigenous siliciclastic source mainly from metamorphic and magmatic sources, that should derive, according to our interpretation of the sandstone petrography and mudrock mineralogy data, from crystalline terranes occurring in the Tyrrhenian sector and from Calabrian Paleozoic rocks. In detail, the formation of VM could be linked to a period of strong tectonic activity, also recognized in a nearby areas to the west of the Agnone Basin (M. Massico ridge) and dated to late Tortonian and early Messinian time (SMERAGLIA *et alii*, 2019), that should be related to rearrangement, accretion and eastward migration of the southern Apennines (BARONE *et alii*, 2006; CRITELLI, 2018). The abundance of crystalline debris in the PVM, should reflect a derivation from Tyrrhenian crystalline terranes (now partially disappeared) (e.g., DAL PIAZ *et alii*, 1983), and from unroofing of the Calabrian terranes (CRITELLI *et alii*, 2017). This last interpretation is confirmed by the coexistence of sub-angular feldspar debris and sub-angular quartz crystals in skeleton sandstones that are an evidence of fresh debris deriving from terranes affected by physical weathering first uplifted and then exposed to erosion (e.g., SCARCIGLIA *et alii*, 2007, 2016).

Because of the potential importance of the metamorphic detritus, a Ls-Lm1-Lm2 diagram (DORSEY,

1988) has been used in which lithic fragments are divided into: i) sedimentary (Ls); ii) low-grade metamorphic (Lm1); and iii) medium-high-grade metamorphic (Lm2). This diagram shows a trend in lithic grains in sandstones that move from a high content of Ls (at the top of the triangular diagram) and proceeds downward showing an increase of Lm1 and mostly Lm2 (Fig. 21). This trend starts with Ls<sub>74</sub>Lm1<sub>17</sub>Lm2<sub>10</sub> in VM and move to Ls<sub>56</sub>Lm1<sub>21</sub>Lm2<sub>22</sub> in PVM, so suggesting a change in relative abundance of sedimentary and metamorphic lithic fragments through time and space.

#### PALEOCURRENTS

Paleocurrents measurements have been treated separately as they represent a fundamental point, together with the compositional data, for the paleogeographic reconstruction of the Agnone Basin.

A total of 66 paleocurrents were measured in both the Verrino and Poggio Villanelle members along the logged sections, subdivided into flute and groove cast and ripples. A separate discussion must be made for the calcarenite beds that with different thicknesses are intercalated in the deposits of the Verrino and Poggio Villanelle members. For these beds, emplaced through sediment gravity flows, the paleocurrent data (CIVITELLI & CORDA, 1988), suggested to the Authors their provenance from the western and north-western sectors of the basin, where the carbonate platforms of Matese, Simbruini and western Marsica were located.

In the sandstone beds, flute and groove casts indicate that the paleocurrents moved toward the western sectors, having a dispersion angle between 270° and 320°. Similar indications are suggested by the ripples foreset laminae, although the dispersion angle is between 270° and 360°.

Considering the present paleocurrents direction, it seems evident that the turbidite currents should come from the eastern sectors, from an area currently, and even in the past occupied by the Apulia carbonate platform. This is entirely in contrast to the compositional data which, on the contrary, suggest an origin of these sediments from a source area where magmatic, metamorphic and sedimentary rocks cropped out.

In order to reconcile the sandstone compositional data with those ones of the paleocurrents, we took into consideration the paleomagnetic analysis from the Upper Miocene sedimentary succession of the Molise area (SPERANZA *et alii*, 1998) and other paleomagnetic data reported in VITALE & CIARCIA (2013). These paleomagnetic results suggest that the investigated area (sector of the Matese-Frosolone thrust sheets) underwent a counter-clockwise rotation at least of 35° after the Messinian time. On this basis, it is evident that the direction of the paleocurrents measured in the turbidite deposits of the Agnone Flysch, must be corrected in order to consider the post-Messinian tectonic movements and the partial reorientation of the flows due to the basin topography and the depositional reliefs themselves. By making these corrections, it follows that the turbidity currents which supplied the Agnone Basin came, essentially, from the southwestern and southern sector and moved towards the northern sectors, with a dispersion range between NNW and NNE. This interpretation is consistent with the compositional data suggesting a provenance of turbidite

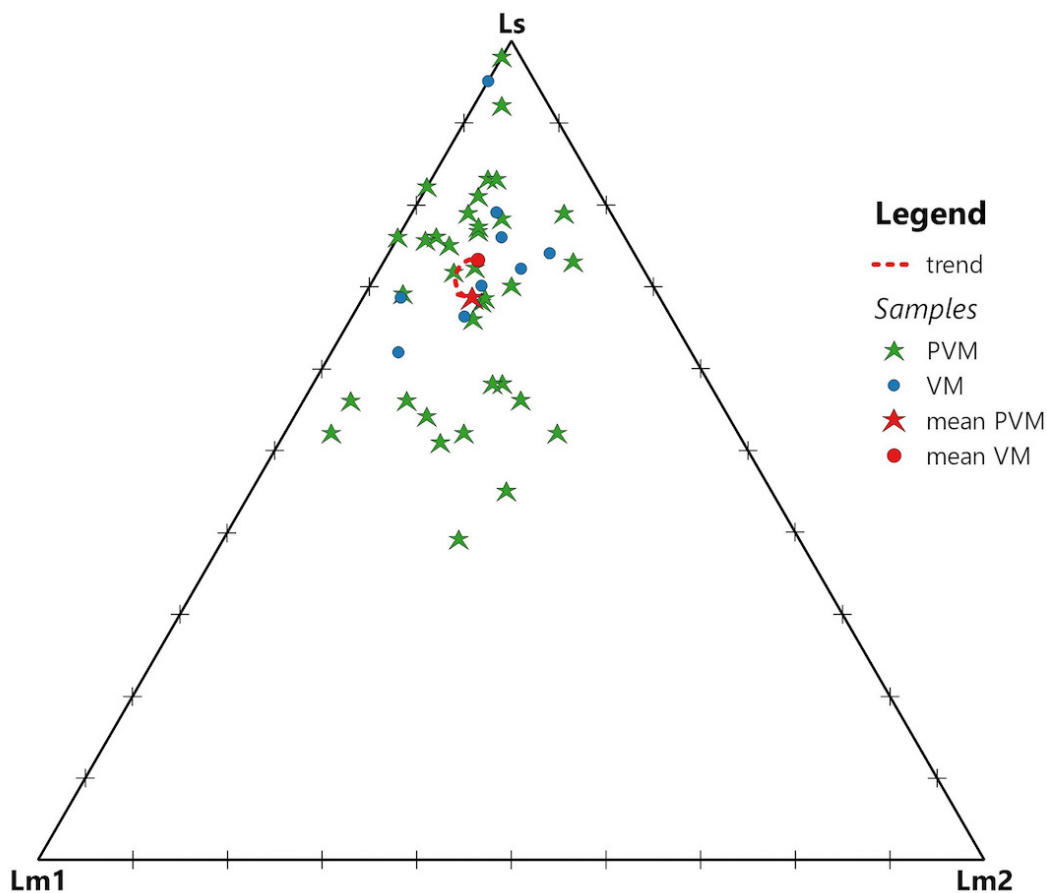


Fig. 21 - Unroofing trend in Ls-Lm1-Lm2 diagram of sedimentary and metamorphic complex of fold-thrust belt (see Tabs. 1, 2, and S3 (see supplementary material) for the significance of Ls-Lm1-Lm2).

flows from the southwestern and southern areas, where a mountain range with metamorphic and magmatic rocks stretched in the Tyrrhenian sector to the Calabrian Arc terranes.

#### GEOMETRY OF THE AGNONE BASIN IN THE INVESTIGATED AREA AND TOPOGRAPHIC CONTROL ON FACIES PARTITIONING

The sedimentary characters of the facies described above together with paleocurrents, texture and composition of sandstone and mudstone beds, suggest a deposition of these sediments in the lobe depositional zone (for the lobes nomenclature we followed MUTTI *et alii*, 1999, PRÉLAT *et alii*, 2009, and MARINI *et alii*, 2015, distinguishing proximal, distal and distal fringe subenvironments from the up- to downcurrent and lobe axis, off-axis and lateral fringe subenvironments perpendicularly to flow direction). Coherent with this interpretation are the sharp bases and the lenticular and tabular laterally continuous geometry of the sandstone bodies (see detailed correlation panels of figures 22 and 23) and their hierarchy, which would record at large scale and on the bases of basinal trend (see Fig. 4) a change from a confined to less confined basin conditions (see e.g., MARINI *et alii*, 2011, 2015). However, many evidences also suggest that although we are in a depositional zone, erosive processes and the generation of facies indicating local flow modifications related to impact, rebound, and reflective processes were active. These considerations derive from the geometry of the Agnone Basin in the investigated sector (see Fig. 24) that was tentatively reconstructed correlating

a set of hydrocarbon exploration wells whose stratigraphic successions are characterized, from bottom to the top, by the Varicoloured Clays (VA), by the pre-flysch carbonate deposits (PFC), and by the turbidite deposits of the Agnone Flysch (AF) (Fig. 23).

The stratigraphic cross-sections of Fig. 24 show a raised sector of the basin that was bordered to the north and north-west by the Apennine carbonate platforms and a southern and south-eastern sector that constituted a more depressed and subsiding area where the highest thicknesses of the Agnone Flysch were deposited. The cross-sections a-a' and c-c' (NW-SE and N-S oriented respectively, Fig. 24) show the wedging and the onlap termination of the VM and PVM turbidite deposits towards the northern sectors of the basin. In particular the major thickness of mudstone deposits characterizing the VM is thought to be also an expression of the probable ponded effect against the frontal onlap of the basin when the latter shows the major confinement. With the aggradational phase and filling of the basin the VM and MPV are characterized by evident lateral facies change that passes, from up to downcurrent, from arenaceous and pelitic-arenaceous deposits of proximal lobes to the arenaceous-pelitic and pelitic deposits of distal lobe and lobe fringe respectively, thus highlighting a closure of turbidite deposits against the frontal slope of the basin. In other words, the aggradational arrangement of the VM lobes followed by the lobes progradational arrangement characterizing the lower portion of the PVM, would reflect the deposition within a confined basin, strongly supplied during a period of strong tectonic activity,

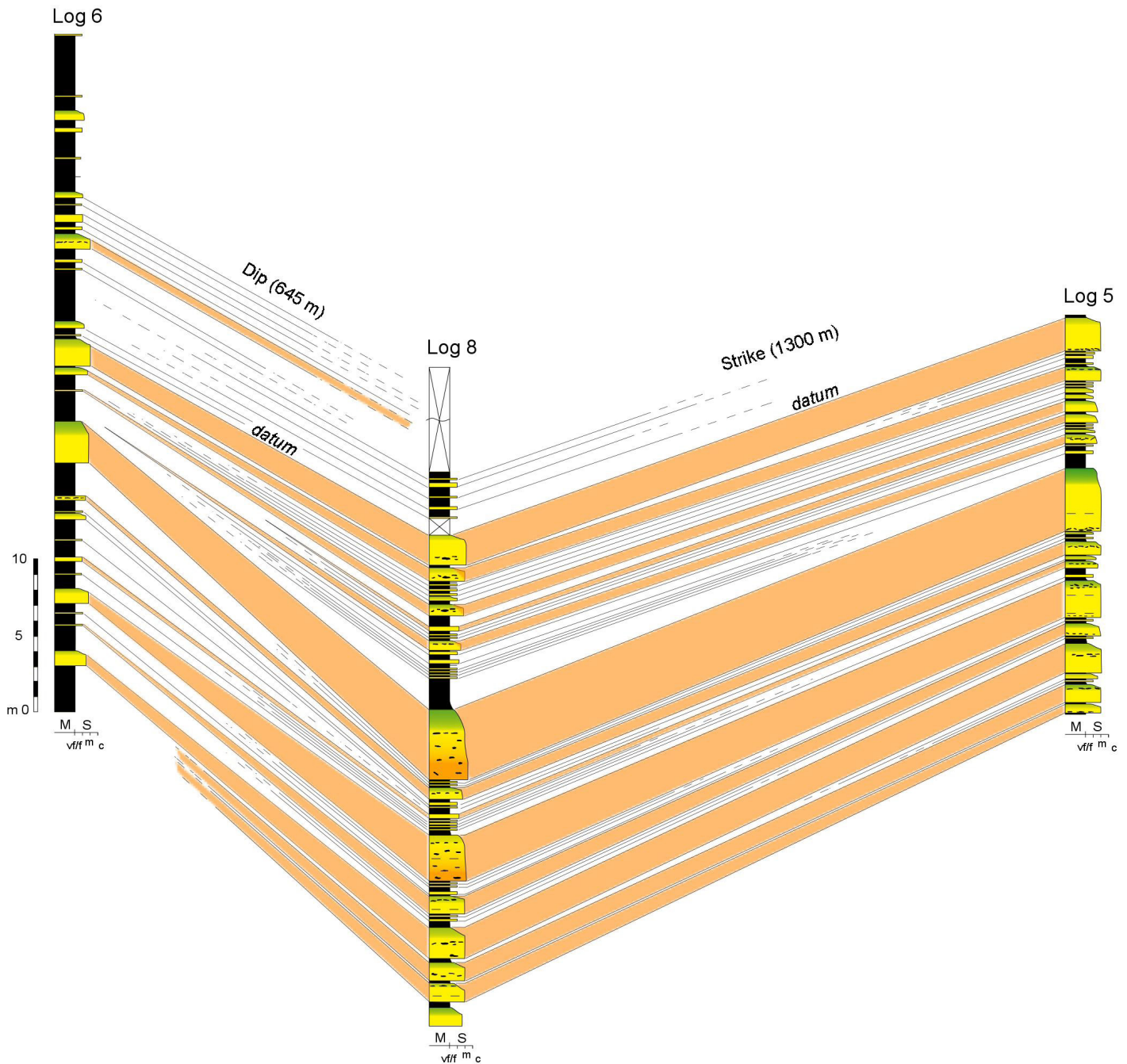


Fig. 22 - Detailed strike and dip oriented stratigraphic panel of the correlable portions of logs 6, 8, and 5. The panel shows the tabularity and lateral continuity of the sandstone bodies in strike section and their pinch out closure (downcurrent) in dip section.

as also suggested by compositional data and literature data (BARONE *et alii*, 2006; CRITELLI, 2018; SMERAGLIA *et alii*, 2019). Instead, the retrogradational lobe arrangement of the PVM upper portion and the SM would suggest a basin widening and a decrease of basin confinement with the following onlapping of the turbidite deposits onto the frontal and lateral margin of the basin.

The cross-section b-b' (WNW-ESE oriented; Fig. 24) shows a greater variability of the turbidite deposits thickness and an evident lateral change of facies moving from the western sectors to the eastern ones. Starting from the Rosello 1 well, the arenaceous facies are replaced by

the pelitic-arenaceous and pelitic facies of the Tuffillo Serra Palazzo and Daunia units respectively, which show very few intercalations of thin arenaceous layers. This suggests that such turbidite layers were essentially deposited onto a weakly inclined slope where the turbidite currents, now completely diluted, deposited the thin arenaceous layers onlapping onto the lateral slope of the basin.

A detailed analysis of the onlap geometries of the Agnone Basin is beyond the scope of this work and would require further data. Several studies have addressed this issue and defined numerous and possible styles of frontal and lateral onlap terminations of turbidite successions (PICKERING &

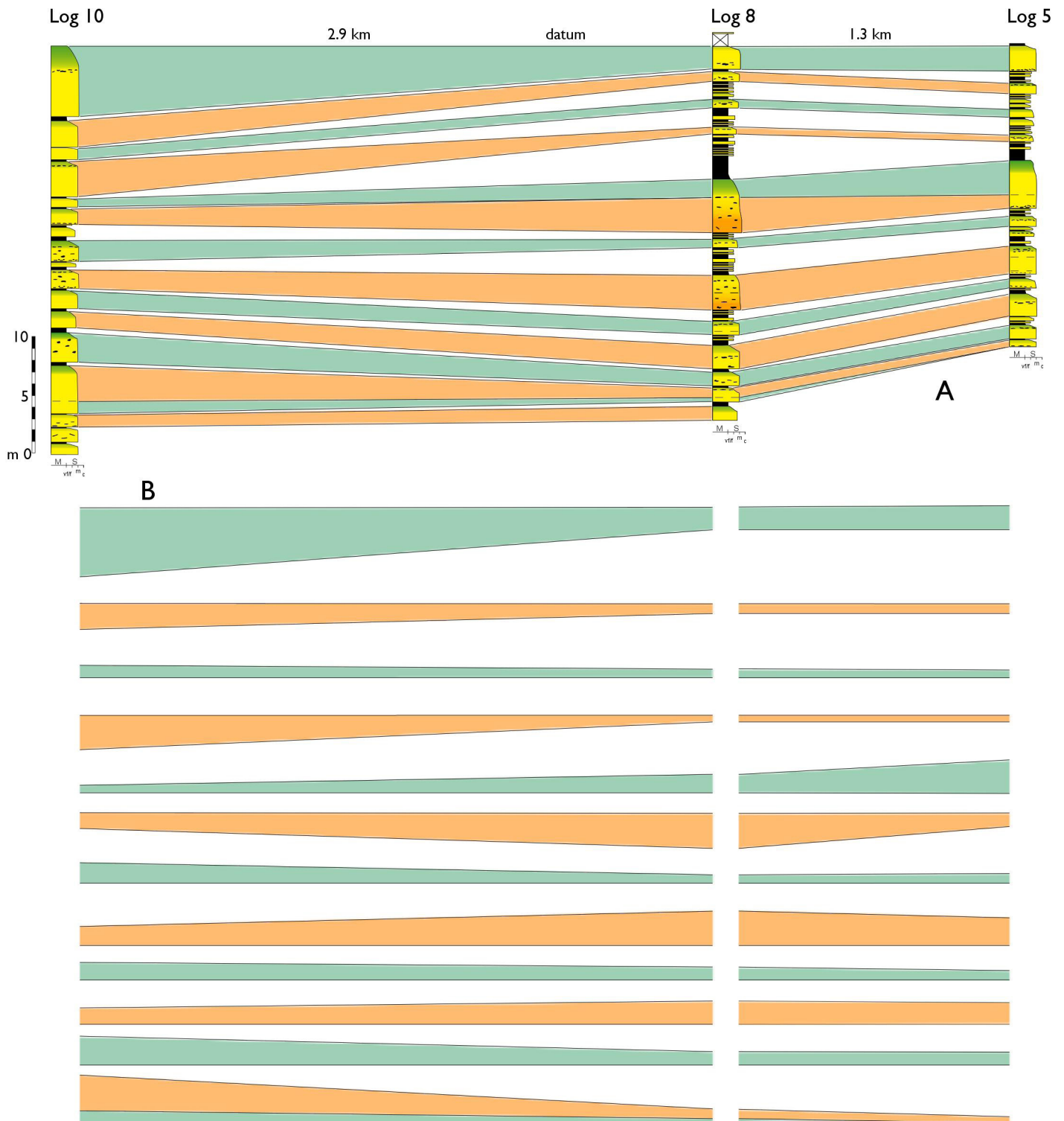


Fig. 23 - A) Detailed stratigraphic panel of the correlable portions of logs 10, 8, and 5. The panel is strike oriented (perpendicular to the paleocurrents). The panel has been correlated using a flattening procedure for the thicker sandstone bodies that also containing mudstone clasts and muddy sandstone layers. B) The panel shows the geometry of these sandstone lobes, how they are laterally compensated and the position and concentration of the mudstone clasts.

HILTON, 1998; KNELLER & McCAFFREY, 1999; SINCLAIR, 2000; PUIGDEFÁBREGAS *et alii*, 2004; SMITH & JOSEPH, 2004; BAKKE *et alii*, 2013; PATACCI *et alii*, 2014, 2015). In our case, however, some preliminary considerations suggest that the northern frontal onlap of the basin would develop on a depositional

slope of about  $1.5^\circ$  that rose very slowly, so giving rise to an onlap termination similar to the “draping onlap” by BAKKE *et alii* (2013). This onlap termination would be coherent with the facies and geometry of the turbidite beds and with the aggradational-progradational trend recognized in the

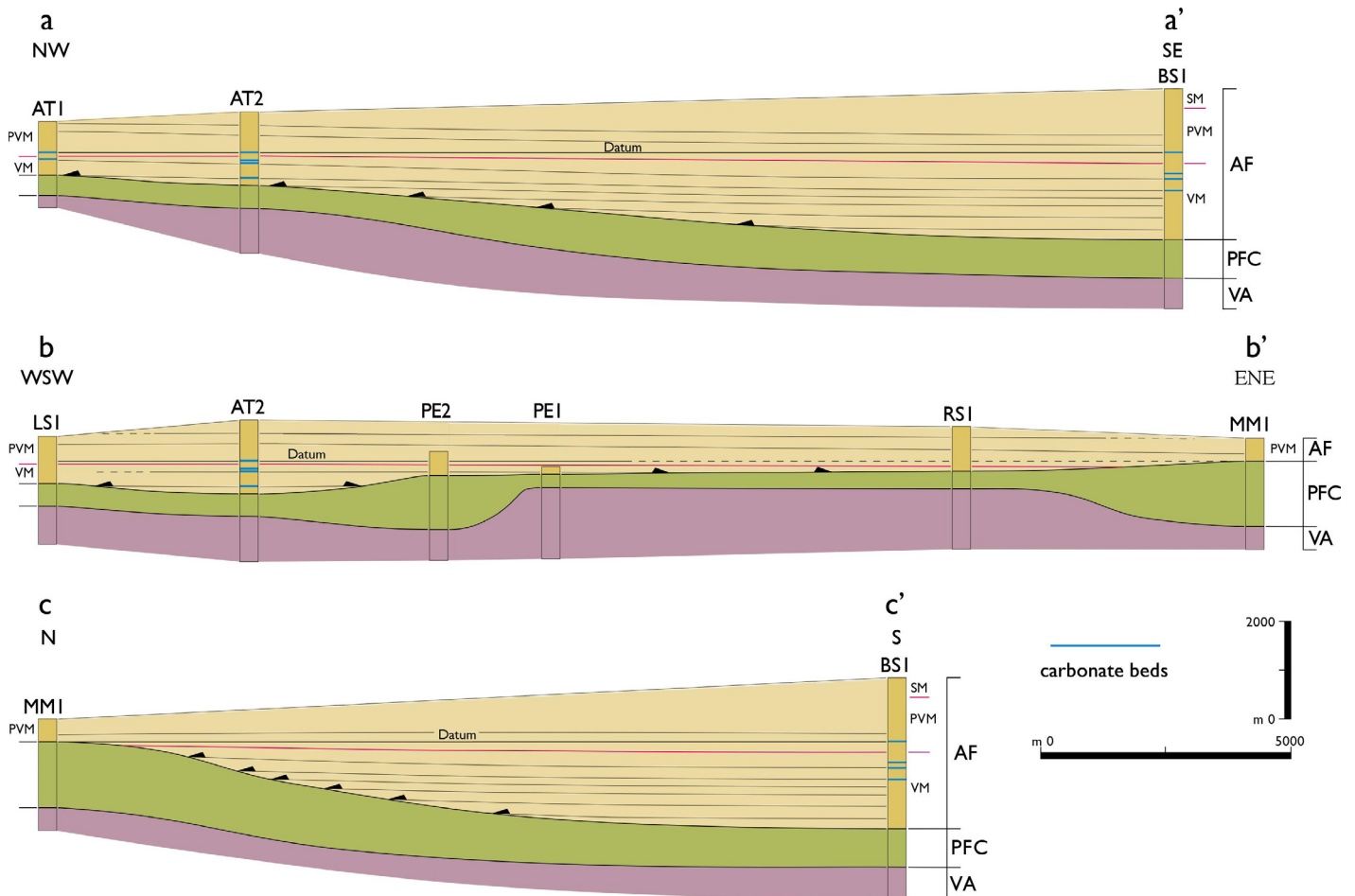


Fig. 24 - Stratigraphic cross-sections of the Agnone Basin oriented parallel (a-a' and c-c') and perpendicular (b-b') to flow directions. To note the onlap of the turbidite deposits onto the frontal and lateral margins of the basin. Wells: Ateleta1 (AT1), Ateleta2 (AT2), Belmonte del Sannio1 (BS1), Messer Marino1 (MM1), Pescopennataro1 (PE1), Pescopennataro2 (PE2), Rossello1 (RS1), Lago Saletta1 (LS1). VM: Verrino Member; PVM: Poggio Villanelle Member; SM: Sente Member. VA: Varicoloured Clay; PFC: Pre-Flysch Carbonate Deposits AF: Agnone Flysch.

VM and in the lower portion of the PVM.

Regarding the relationships between facies and basin geometry, we can say that they have many characters that record the interactions between flows and topography of the basin and/or the local depositional reliefs (lobes). In particular the facies FA1 e FA2 are the product of deposition of a rapidly aggrading high concentration basal layer of bipartite flows with different aggradation rate. They record a deceleration of the flows in correspondence of the frontal and lateral slope of the basin and mainly occur in the more depressed and subsiding sector of the basin; they characterize the proximal sectors and the axial/off-axial zones of lobes. Both these facies thinning downcurrent and laterally in the distal and distal fringe subenvironments and pass to the fine-grained laminated sand and mud (facies FA5 and FA6) that are deposited near and above the structural highs.

The facies FA3, FA4, and FA7 represent, for different reasons, the product of a close interaction between the topography of the basin and the flows, and record processes of erosion, rebound, and reflection of the

flows in relation to their impact against both the lateral and frontal slopes of the basin, and against the same depositional reliefs (lobes). In this perspective, the degree of confinement of the Agnone Basin that changes during its vertical aggradation and filling phase, relegates these facies especially in the final portion of the Verrino member and in the initial and middle portion of Poggio Villanelle member. This occurred during a sedimentation phase in which the Agnone's turbiditic system is in a clear phase of aggradation and progradation due to the arrival of a major sediment supply that was probably linked with an increase of tectonic uplifting of the source areas, as also testified by the compositional data.

## CONCLUSIONS

The integration of physical stratigraphy and facies analysis with sandstone petrography of the Agnone Flysch allowed to define the main depositional features, the main direction of sediment transport, and the source rocks

composition supplying the Agnone turbidite deposits during the late Miocene, in the context of the southern Apennine evolution. The main results of this research are the following:

- 1) Facies analysis indicates that the turbidite deposits of the Agnone Flysch are characterized by seven main facies whose sedimentary characters together with geometry of the sandstone beds suggest their deposition in the lobe depositional zone, and in the sectors of the Agnone Basin where topographic confinement occurred. These facies and their lateral and vertical distribution are interpreted to reflect all the processes related to the flow deceleration against the depositional reliefs (lobes) and the frontal and lateral slope of a structurally-confined basin. This promoted the deposition of massive sandstones through hydraulic jumps as well as the by-passing of the turbulent portions of the flows which, impacting against the slopes of the basin, gave rise to the beds rich in mudstone clasts.
  - 2) The stratigraphic organization of the Agnone Flysch broadly shows two main trends: a lower coarsening- and thickening-upward trend which includes the arenaceous-pelitic portion of the VM and the pelitic-arenaceous and arenaceous portions of the PVM, and an upper fining- and thinning-upward trend, which includes the pelitic-arenaceous portion of the PVM and the arenaceous-pelitic and pelitic portions of the SM. This organization reflects a clear aggradational and progradational trend for the lower portion of the turbiditic succession which is believed being related to a continuous increase in sedimentary supply, in turn linked to a period of strong tectonic activity of the source areas and, more generally, to the eastward propagation of the Apennine thrusts. The upper portion, on the other hand, records a reduced sedimentary supply which could be linked to a decrease of tectonic activity, or even to a general lowering of the relief. At smaller scales, coarsening-thickening and fining-thinning-upward trends are recognizable in the Agnone Flysch; in these cases, these trends can be ascribed either to autocyclic processes connected to the vertical and lateral overlap of the depositional lobes (compensational cycles by MUTTI & SONNINO, 1981), or to allocyclic processes induced by climatic variations, in turn responsible for the variations in sedimentary supply. In this light the recognized large-scale trends in the Agnone Flysch are considered to be mainly controlled by tectonics (pulses of thrust migration), whereas the medium and small-scale trends could be mainly controlled by climatic, and intrinsic depositional dynamics of the turbidite system processes, respectively.
  - 3) The paleocurrent data and the compositional analysis of the calcarenites and sandstones of the VM and PVM indicate that the former come from the western and north-western sectors of the basin where carbonate platforms of the Matese, Simbruini and western Marsica occurred. On the contrary the sandstone paleocurrent data, indicate a prevalent direction of flows from the southern sectors towards the northern sectors. This is consistent with the sandstones compositional data, which indicate the presence in the Tyrrhenian area of an emerged mountain range continuing in the sectors of the Calabrian Arc. This mountain range represented the main source area of detritus that fed the Agnone turbidite system essentially through hyperpycnal flows generated at the mouth of deltaic systems (Fig. 25), fed by rivers with high-gradient small drainage basins, occurred along this tectonically active margin (e.g. MILLIMAN AND SYVITSKY, 1992; BORNHOLD *et alii*, 1994; MULDER & SYVITSKY, 1995; MULDER *et alii*, 2003; MUTTI *et alii*, 1994, 1996, 2000, 2003; PARSON *et alii*, 2001; HIZZET *et alii*, 2018; MUTTI, 2019). This depositional context is very similar to the present Calabrian Ionian margin (PERRI *et alii*, 2012a; CRITELLI, 2018), a tectonically active margin characterized by small- and medium-sized mountainous rivers (Fiumare), at the mouth of which occur the head of canyons, which constitute the main transit routes of fluvial flood events that should generate hyperpycnal flows and in turn turbidite currents.
  - 4) The topography of the Agnone Basin in the investigated area can be subdivided in at least four sectors: 1) a raised northern sector, forming the frontal slope of the basin, transitionally passing to the drowned carbonate platforms of the central Apennine constituting structural highs in the foredeep basin, where the Agnone turbidite deposits overlapped; 2) a western sector, just close to the Apennine thrusts from which sediment gravity flows derived, giving rise to the calcarenite beds and olistoliths occurring within the Agnone Flysch; 3) an eastern sector transitionally passing to a low gradient slope with mudstone sedimentation on which the most diluted and distal portions of the turbidite flows deposited and overlapped (mudstone and muddy-siltstone facies of the coeval Tuffillo-Serra Palazzo and Daunia units). The latter sector passed further eastward to the carbonate pelagic and shallow water sedimentation areas of the Apulia Platform; 4) a southern and more depressed and subsiding sector which constituted the depocentral area of the basin, where the bulk thickness of the Agnone turbidite deposits was accommodated. This geometry of the basin is evident from the stratigraphic cross-sections of Fig. 24, which show how the Agnone Basin was stretched in the N-S direction having a raised sector to the north and a depressed sector to the south.
- In conclusion, the study of the turbidite deposits of Agnone Flysch has allowed us to expand the sedimentological and stratigraphic knowledge of this formation having better characterized: i) the types of facies and the relative depositional mechanisms; ii) the main architectural elements of this turbidite depositional system; iii) the paleocurrent directions and the source areas supplying these turbidite flows and finally iv) the sandstone and mudstone composition. All these data suggest that this turbidite succession was deposited in a confined basin within the larger foredeep Lagonegro-Molise Basin. These observations suggest that this basin presented an articulated geometry and an asymmetric shape in the W-E section, with the most depressed sector close to the Apennine thrust front and a sector with a slight gradient towards the east that passed laterally to the Apulia Platform (Fig. 25).



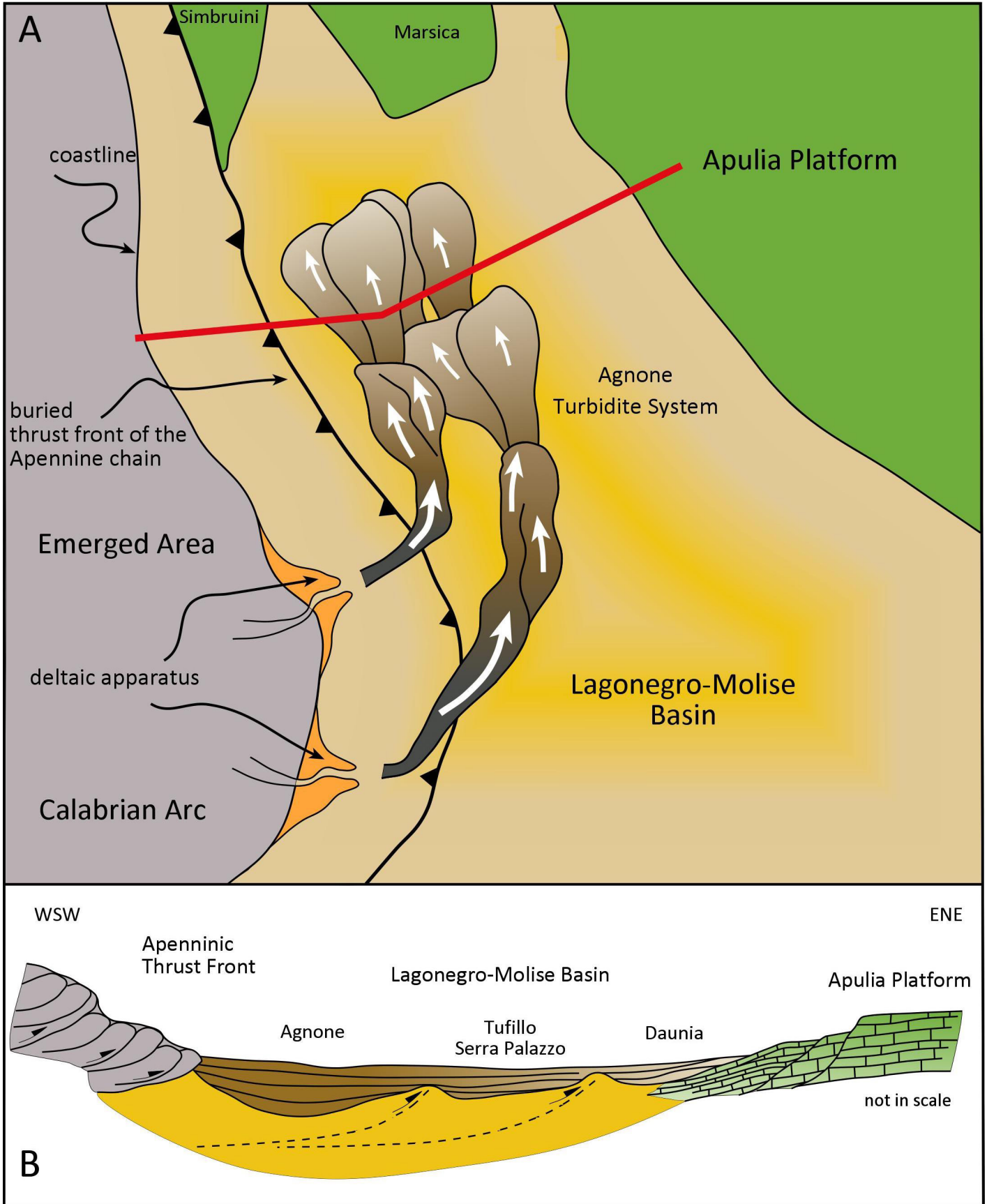


Fig. 25 - A) Paleogeographic scheme showing the possible feeding areas of Agnone Flysch according to paleocurrent data and sandstone composition. The red line indicates the trace of section B. B) Section showing the stratigraphic relationships between Agnone's Flysch and the clayey-silty and clayey deposits of the Tufillo Serra Palazzo and Daunia units. Note the onlap of turbidite deposits onto the lateral slope of the basin which makes the transition to the western sector of the Apulia Platform.

## ELECTRONIC SUPPLEMENTARY MATERIAL

This article contains electronic supplementary material which is available to authorised users.

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