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SCIENCE

The tectono-stratigraphic evolution of the Fucino Basin (central Apennines, Italy): new insights from the geological mapping of its north-eastern margin.

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ABSTRACT
We present the geological map of the north-eastern margin of the Fucino Basin, which is mainly characterized by Plio-Quaternary continental deposits that show transition from deeper-water lacustrine environment, marginal lacustrine system, and fluvial facies. These deposits unconformably overlie upper Messinian Lago-Mare sediments and pre-orogenic carbonate succession. The occurrence of *Caspiocypris tiberina* in the Plio-Quaternary lacustrine sediments, coupled with the normal magnetic polarity of Casa Colombaia section, led to suggest the onset of the sedimentation of these continental deposits to the late Piacenzian (2.58–3.04 Ma). The upper Messinian deposits are characterized by ostracod assemblages related to the *Loxocorniculina djafarovi* zone, pointing to the last Lago-Mare event of the Messinian Salinity Crisis (5.40–5.33 Ma). This new stratigraphic framework may be useful to refine the long-term slip rates of the still active normal faults that affect the north-eastern margin of the Fucino Basin.

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1. Introduction

The Fucino Basin is the largest intermontane basin of the central Apennines (Figure 1). It is located in the axial zone of the chain (Abruzzo region, central Italy) and is bordered by active normal faults showing historical and current seismicity (e.g. Amoroso et al., 2015; Beccacini et al., 1992; Galadini & Messina, 1994; Ghisetti & Vezzani, 1997 and reference therein), as evidenced by the 13th January 1915 M_w 7, Avezzano earthquake (Galadini & Galli, 1999). The Fucino Basin is a NW-SE trending half-graben that cuts the pre- and syn-orogenic succession of the Abruzzi Apennines. It is bounded by the southeast dipping Tre Monti – Celano – Aielli Fault (Cavinato et al., 2002), and by the southwest dipping fault system of the Pescina – Celano Fault (Cavinato et al., 2002) and the S. Benedetto dei Marsi – Gioia dei Marsi Fault (Alfonsi & Sagnotti, 1996) (Figure 2).

The Fucino Basin is filled by a thick late – to post-orogenic succession of Upper Miocene and Plio-Quaternary continental deposits (Cavinato et al., 2002; Giaccio et al., 2019), which unconformably overlay Meso-Cenozoic carbonate units and Upper Miocene terrigenous deposits of the Marsica Flysch (Figure 1) (Cosentino et al., 2010). In this context, the knowledge of the post-orogenic geological evolution of the Fucino Basin can be a key to understand the onset of the post-orogenic extensional tectonics in the axial zone of the central Apennines, and to define the long-term slip rate of the main bounding active faults.

Starting from the 30's (e.g. Beneo, 1939), the Fucino Basin captured the interest of several authors, who tried to define the stratigraphy of the continental deposits and consequently to determine the age of the onset of the extensional tectonics responsible for the creation of this intermontane basin (e.g. Bertini & Bosi, 1976; Bosi et al., 1995, 2003; Cavinato et al., 2002; Cavinato & De Celles, 1999; Zarlenga, 1987). Although many authors worked on the stratigraphy of the Fucino Basin, there is not a consensus on the stratigraphic setting of the basin infill. Indeed, starting from Bertini and Bosi (1976), different schemes for the Fucino Basin have been suggested, resulting in various stratigraphic architectures of its continental deposits (e.g. Bosi et al., 1995; Cavinato et al., 2002; Zarlenga, 1987).

In this paper, we present a new geological map of the north-eastern margin of the Fucino Basin (Main Map), where the oldest deposits of the basin infill crop out. Our map extends from Celano, to the north, to Pescina, to the south, covering an area of about 30 km^2 (Figure 2). The new geological map derives from field work, coupled with facies analysis, palaeontological investigation, and palaeomagnetic analysis. This multidisciplinary approach leads us to suggest a new stratigraphic setting for the oldest deposits of the basin infill, which is essential to better understand the early evolutionary stage of the Fucino Basin. In this study we define two new synthems: the

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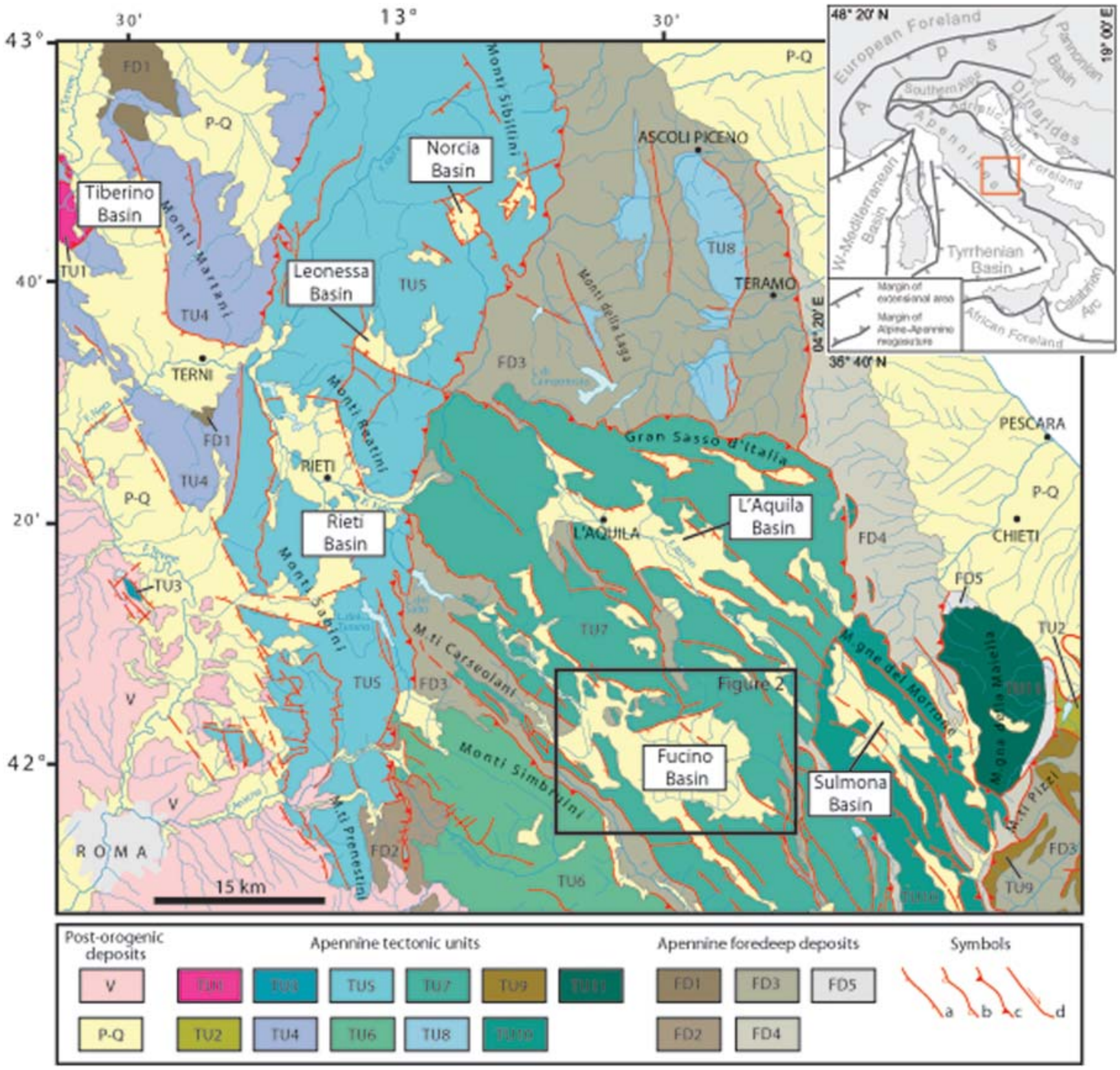

Figure 1. Structural sketch of the central Apennines. The main Pliocene–Quaternary intermontane basins of the central Apennines are shown. V – Quaternary volcanic rocks; P-Q – Pliocene–Quaternary marine and continental deposits; TU1 – External Ligurian unit; TU2 – Sannio unit; TU3 – Mount Soratte tectonic unit; TU4 – Inner Umbria tectonic unit; TU5 – Umbria-Marchean-Sabine tectonic unit; TU6 – Simbruini-Ernici-Matese tectonic unit; TU7 – Gran Sasso–Western Marsica tectonic unit; TU8 – Molise tectonic unit; TU9 – Acquasanta-Montagnone tectonic unit; TU10 – Morrone–eastern Marsica tectonic unit; TU11 – Maiella tectonic unit; FD1 – Burdigalian foredeep deposits; FD2 – Tortonian foredeep deposits; FD3 – Messinian foredeep deposits; FD4 – Upper Messinian–lower Lower Pliocene foredeep deposits; FD5 – upper Lower Pliocene foredeep deposits; a – normal fault; b – minor thrust; c – major thrust; d – strike-slip fault. Modified from Cosentino et al. (2017).

Le Vicenne Synthem and the Celano-Collarmele Synthem, which are related, respectively, to the late Messinian and the Piacenzian-Gelasian evolution of the Fucino Basin.

2. Methods

The Main Map was realized at 1:17,000 scale by using the CTR topography maps (1:10,000 scale) of the Abruzzo Region, while fieldwork mapping was performed at 1:5000 scale. Regarding the Meso-Cenozoic succession, the lithostratigraphic units were mapped and grouped according to the related palaeogeographic domain as defined in the 1:50,000 scale Avezzano and Sulmona geological maps (CARG project, Centamore et al., 2006a, 2006b). The Plio-Quaternary continental deposits are defined as UBSU (Unconformity-Bounded Stratigraphic Unit) (Chang, 1975).

Fieldwork activities were integrated with micropalaeontological analysis (90 samples) on ostracod assemblages to provide age constraints and clues for more detailed palaeodepositional reconstructions. In addition, palaeomagnetic investigations were performed in two stratigraphic sections of the Celano-Collarmele Synthem to improve the constraints for the early evolutionary stage of the Fucino Basin.

3. Results: stratigraphic architecture and time constraints

Two synthems, the Le Vicenne Synthem and the Celano-Collarmele Synthem, characterize the

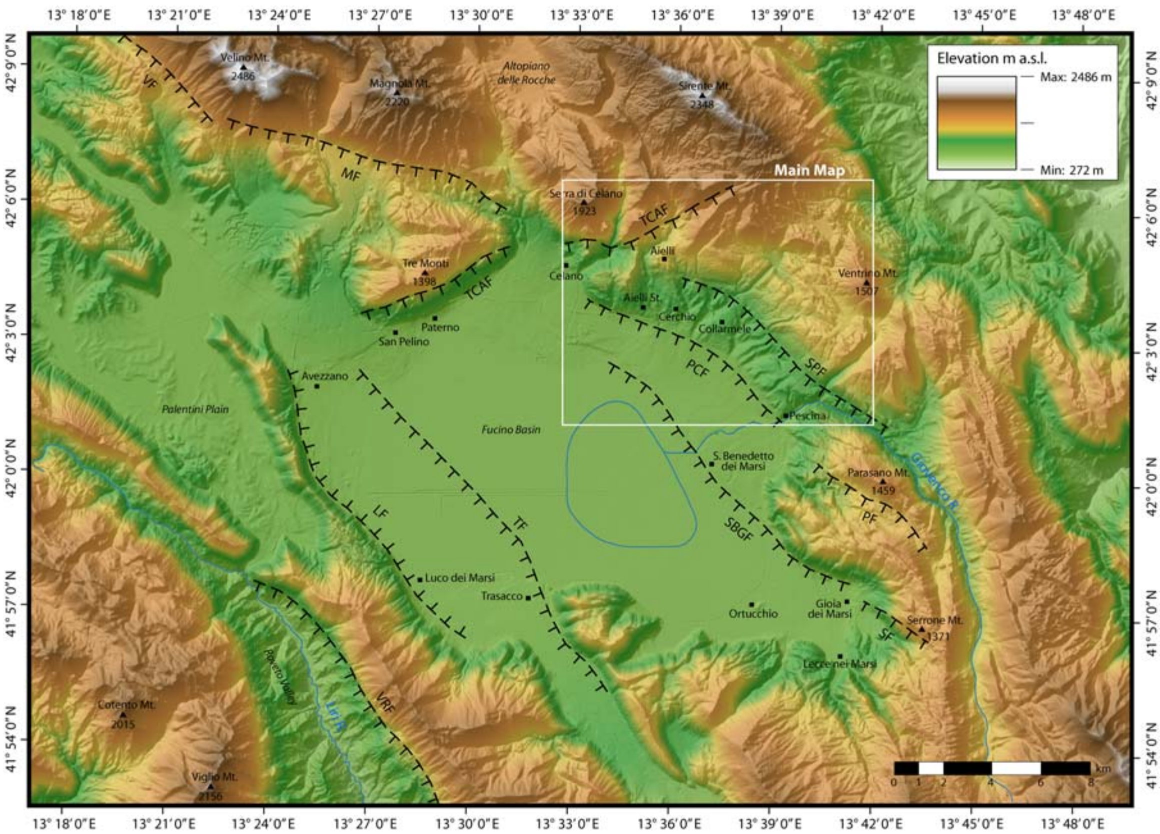

Figure 2. Topography of the Fucino intermontane basin and surrounding regions (m a.s.l. – metres above sea level); the major active fault planes in the area are shown by black lines with tick marks on downthrown block. VF = Velino Fault; MF = Magnola Fault; TCAF = Tre Monti-Celano-Aielli Fault; PCF = Pescina-Celano Fault; SPF = Stazione di Pescina Fault; SBGF = San Benedetto dei Marsi-Gioia dei Marsi Fault; PF = Parasano Fault; SF = Serrone Fault; TF = Trasacco Fault; LF = Luco dei Marsi Fault; VRF = Val Roveto Fault. The area mapped in the Main Map is shown.

stratigraphy of the outcropping succession. The Le Vicenne Synthem unconformably overlies both the pre-orogenic and syn-orogenic successions of the region. The Celano-Collarmele Synthem, which unconformably overlies both the Le Vicenne Synthem and the bedrock succession, is bounded by an upper flat surface, which correlates the 'Collarmele-Pescina terrace' (Bertini & Bosi, 1976; Blumetti et al., 1993; Bosi, 1989; Bosi & Messina, 1992; Demangeot, 1965; Messina, 1996; Raffy, 1983; Zarlenga, 1987).

3.1. Le Vicenne Synthem

In the study area, sands, clays, and marls, containing brackish water ostracods, unconformably underlie the Plio-Quaternary deposits of the Fucino Basin. Based on our new field evidence, we included these deposits, which are gently tilted toward the Fucino Basin, in a new synthem, namely the Le Vicenne Synthem. This synthem is characterized by a basal unconformity with the underlying bedrock. Within the Le Vicenne Synthem, we distinguished the Madonna delle Grazie Fm. (MDG), which was previously mapped as *Lazio-Abruzzi flysch* (Cavinato et al., 2002) or *Complesso torbiditico altomiocenico laziale-abruzzese Auct.* (Centamore et al., 2006a). MDG outcrops mainly in the Belvedere and Collarmele areas (Figure 3), and also between Mt. Etra and Mt. Secino (see map). Close to Collarmele village, the top of MDG is truncated by a clear erosional surface (angular unconformity), which is overlaid by the Celano-Collarmele Synthem.

MDG, which is more than 300 m-thick, has been divided in two members: Fonte Nuova (lower member) and Belvedere (upper member). However, due to poor outcrop conditions, in the main map these two members are not distinguished. The Fonte Nuova Member is made up of compact massive dark-grey clays, with a high content of organic matter (Figure 3a). These clays are characterized by centimetric layers bearing coalified plant fragments. Intercalations of ca. 50 cm-thick sandy and silty-sandy layers, showing wavy-parallel and crossed laminations can also be found. This member generally shows a coarsening upward trend, with the occurrence of planar laminated silty beds and centimetric compact sandy layers. The upper part of the Fonte Nuova Member shows slump folding related to soft sediment deformations characterized by 5-10 cm-scale folds with vertical axial planes.

The Belvedere Member consists mainly of a sandy succession. The lower part of this member shows

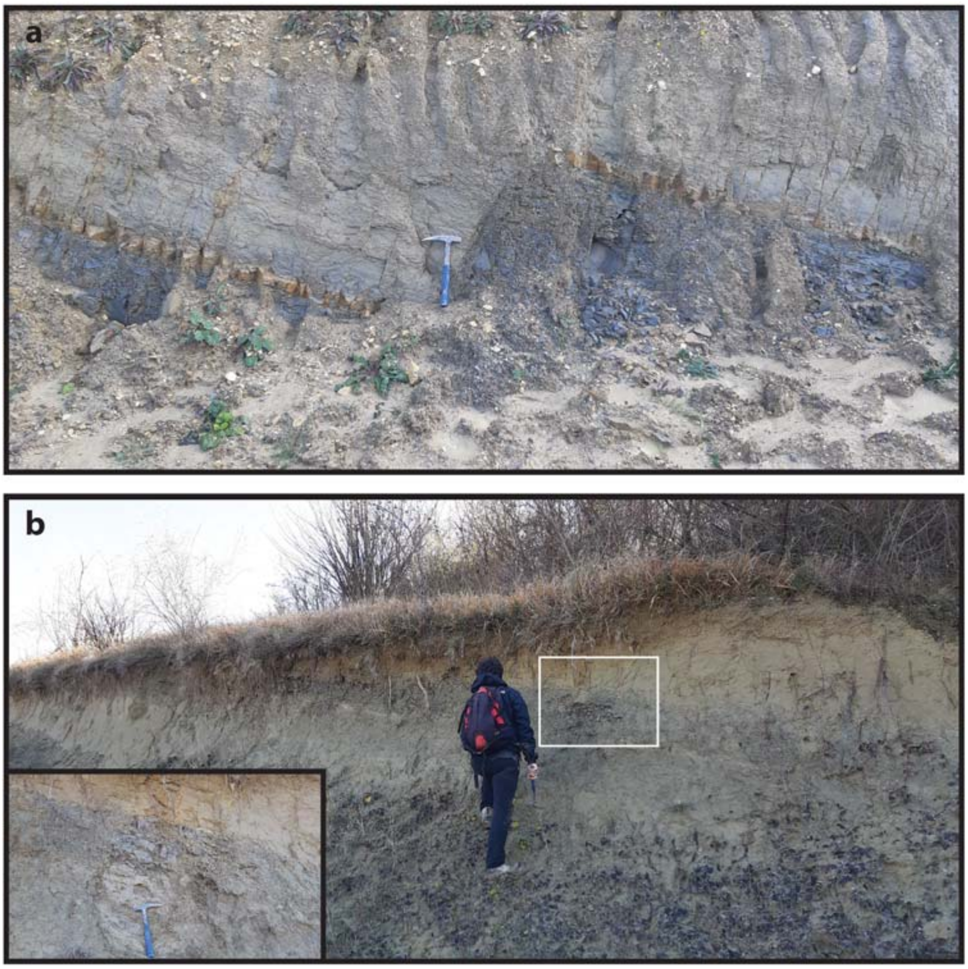

Figure 3. Le Vicenne Synthem: outcrops of the Madonna delle Grazie Fm. (a) compact massive dark-grey clays of the Fonte Nuova Member, characterized by high content of coalified plant fragments and intercalations of thin sandy layers; (b) thick massive yellowish sandy layers, with intercalations of laminated silts, of the Belvedere Member. The insert shows a close up view of the area in the white rectangle, showing the intercalation of a grey silty horizon between massive sandy layers.

grey laminated silty clays, with intercalations of thin highly oxidized layers, rich in plant fragments. The middle and upper part of this member show thick massive yellowish sandy layers, with intercalations of laminated silts (Figure 3b). Somewhere, the massive sandy layers pass upward to planar laminated sands.

In both the MDG members, the micropalaeontological analyses show the presence of brackish water ostracod assemblages, which are defined by the occurrence of nine species of ostracods, referable to seven genera. The recognized ostracods are (Figure 4): *Loxoconcha* cf. *L. ludica* Olteanu, 1989; *Loxoconcha eichwaldi* (Livental, 1929); *Loxoconcha schweyeri dacica* Olteanu, 1995; *Loxocorniculina djafarovi* (Schneider in Suzin, 1956); *Amnicythere* cf. *A. idonea* (Markova in Mandelstam et al., 1962); *Cyprideis anlavauxensis* Carbonnel, 1978; *Caspiocypris alta* (Zalanyi, 1929); *Camptocypria* sp. 1 Gliozzi & Grossi, 2004; *Zalanyella venusta* (Zalanyi, 1929).

3.2. Celano – Collarmele Synthem

The Celano – Collarmele Synthem (CCS) includes all the continental deposits cropping out at the footwall of the Pescina – Celano Fault (Cavinato et al., 2002), which unconformably overlie the MDG and the carbonate bedrock. This synthem contains six heteropic formations, which are mainly characterized by fluvial deposits and deltaic conglomerates that laterally pass to silty sands, and silts, referring mainly to marginal lacustrine environment (Figure 5). Close to the northern border of the palaeolake, especially where dip slope cliff occurred, the lacustrine fine deposits are interbedded with carbonate breccias (i.e. Aielli area). The distinguished heteropic formations are: Casa Colombaia Fm., Alto di Cacchia Fm., Colle Caprino Fm., Aielli Fm., Stazione di Pescina Fm., and Ponte della Valle Fm.

The Alto di Cacchia Fm. (ACF) crops out in the north-western sector of the study area. It is ca. 150 m-thick and consists mainly of clast-supported conglomerates with a sandy-silty matrix (Figure 5a). The clasts are mainly sourced from a Meso-Cenozoic carbonate platform succession. This formation shows different carbonate conglomerate facies, characterized by planar bedding and different grain size, which have been interpreted as lags and bar sheets on a fluvial fan. The presence of a horizontal stratification and

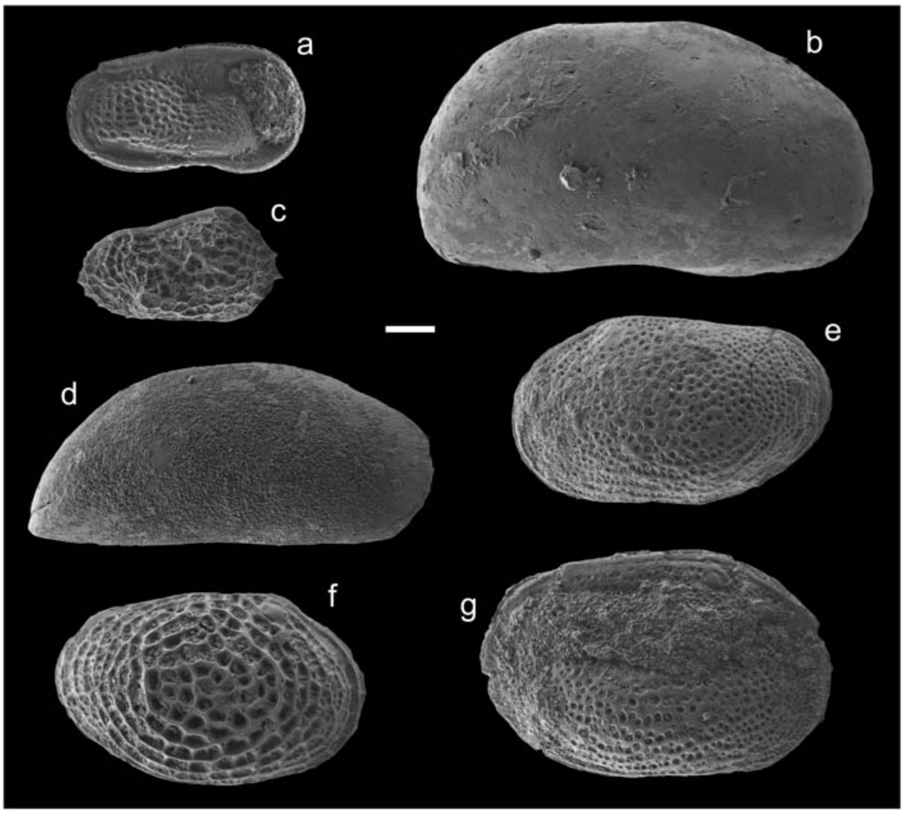

Figure 4. SEM pictures of selected ostracods from the Madonna delle Grazie Fm. (a) *Amnicythere* cf. *A. idonea* vel *pontica,* carapace in right lateral view, sample BE17; (b) *Caspiocypris alta*, right valve in external view, sample BE17; (c) *Loxocorniculina djafarovi*, right valve in external view, sample COF4; (d) *Camptocypria* sp. 1, right valve in external view, sample COF4; (e) *Loxoconcha* cf. *L. ludica*, left valve in external view, sample BE17; (f) *Loxoconcha schweyeri dacica*, right valve in external view, sample COF4; (g) *Loxoconcha eichwaldi*, carapace in right lateral view, sample BE17. The white bar corresponds to 0.1 mm.

imbricate clasts suggest a bedload deposition from stream flow. On the base of these observations, ACF is interpreted as channel lag deposits (Gh, Miall, 2006). The Alto di Cacchia Fm. partially corresponds to the *Complesso di Cupoli* (Bosi et al., 1995), *Depositi del I Ciclo fluvio-lacustre* (Zarlenga, 1987), and to the *La Selvotta Unit* and *Cupoli Unit* (Cavinato et al., 2002).

The Casa Colombaia Fm. (CCF), which takes its name from the Casa Colombaia section, is at least 70 m-thick and consists of clast-supported conglomerates, silty-sands, and silts (Figure 5b). The conglomerates are well organized in tabular bodies with thickness between 40 cm and 1 m, showing clinoform geometries (fan-delta). In the western part of the study area, the high number of imbricated clasts allow us to define a main palaeocurrent flowing from NW to SE. These conglomerates pass laterally to fine-grained deposits, which are characterized by alternations of: (1) silty layers with planar-to-wavy laminations, associated with symmetric and climbing ripples; (2) sandy and sandy-silty layers, defined by wavy parallel lamination; and (3) silty layers with no sedimentary structures. This formation crops out along the piedmont zone of the study area, from the base of Alto di Cacchia relief to Pescina village.

The fine-grained deposits of CCF are characterized by rather homogeneous ostracod assemblages consisting of: *Candona* cf. *C. triangulata* Klie, (1939); *Candona weltneri* Hartwig, 1899; *Caspiocypris tiberina* Spadi et al., 2018; *Caspiocypris* sp. 2; *Caspiocypris* sp. 3; *Cypria* sp. n. sp.; *Neglecandona neglecta* Sars, 1887; *Neglecandona* cf. *N. angulata* Müller, 1900; cf. *Typhlocypris alumna* (Stepanaitys in Mandelstam et al., 1962) *sensu* Krstić, 2006; *Ilyocypris gibba* (Ramdohr, 1808); *Ilyocypris bradyi* Sars, 1890; *Ilyocypris inermis* Kaufmann, 1900; *Eucypris* sp.; *Trajancypris clavata* (Baird, 1838); *Potamocypris zschokkei* (Kaufmann, 1900); and *Paralimnocythere bicornis* Fuhrmann, 1991. These ostracod assemblages are sometimes accompanied by Characeae gyrogonites and *Bithynia* opercula. The presence of Candoninae and *Ilyocypris*, together with Characeae and *Bithynia*, suggests a shallow freshwater lacustrine environment (Figure 6).

In the Casa Colombaia section, we performed a palaeomagnetic analysis that shows in both the basal conglomerates and in the fine-grained deposits a normal polarity (Figure 7), which allows us to better constrain the chronostratigraphy of CCF. Magnetic mineralogy results indicate the dominance of a low coercivity component, as evidenced by Hcr values generally lower than 50 mT (Figure 7b) and suggested

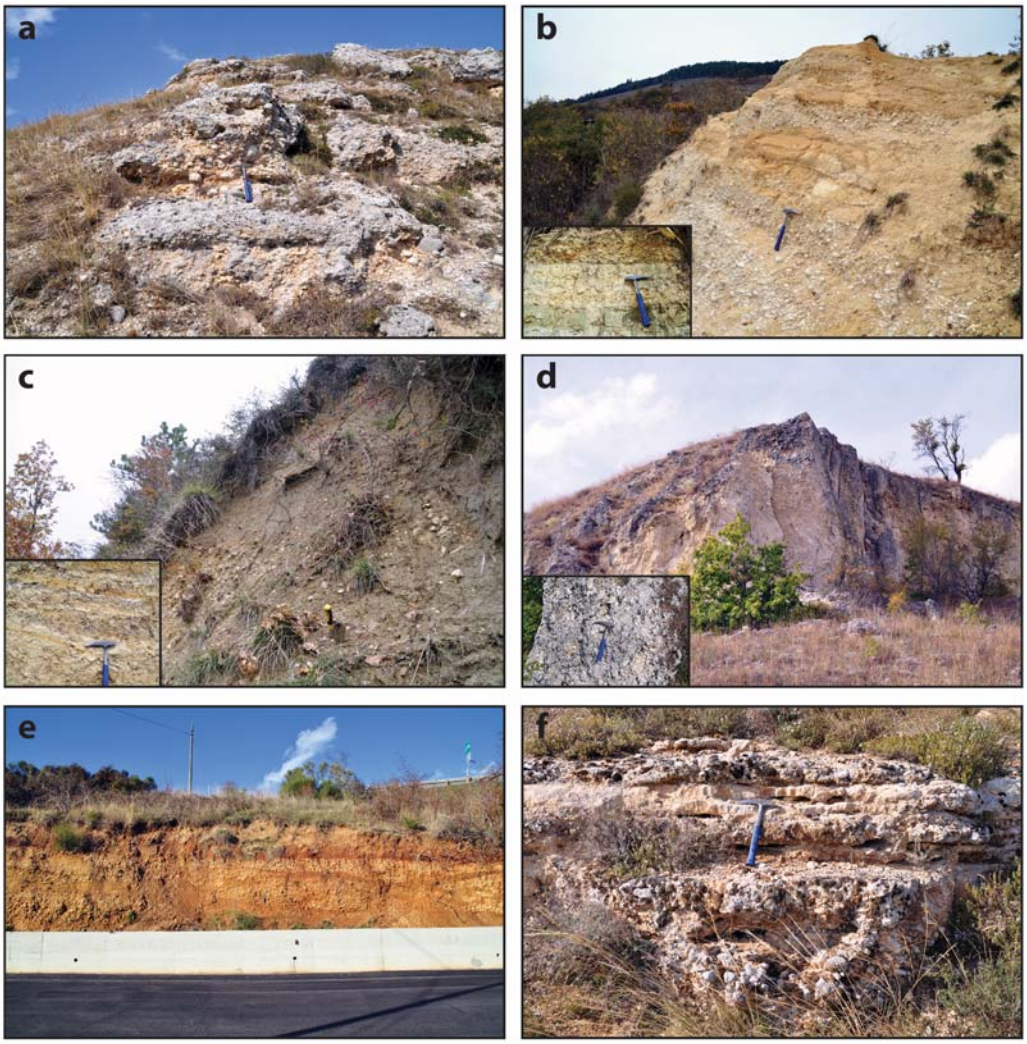

Figure 5. Outcrops of the formations of the Celano-Collarmele Synthem. (a) clast-supported conglomerates with a sandy-silty matrix of the Alto di Cacchia Fm.; (b) clast-supported conglomerates, silty-sands and silts of the Casa Colombaia Fm. The insert shows a detail of the tabular geometry of the conglomerate bodies; (c) laminated grey clays and brownish silty clays, with thin layers of carbonate breccias, of the Colle Caprino Fm. The insert shows a detail of the laminated character of the clayey deposits of the Colle Caprino Fm.; (d) poorly-sorted and well-cemented carbonate breccias of the Aielli Fm. The insert shows a detail of the carbonate breccias of the Aielli Fm.; (e) channelized fluvial facies of the Stazione di Pescina Fm., characterized by overbank fine-grained deposits and palaeosols; (f) well cemented sheet-like breccias, with interbedded lacustrine carbonates and silty sandy layers of the alluvial fans and fan delta deposits of the Ponte delle Valli Fm.

by IRM acquisition curves that reach magnetic saturation in the applied field of 0.1 T (Figure 7c).

A stable and coherent ChRM was isolated in most of the measured samples, using both thermal and alternating field (AF) demagnetization techniques. The normal polarity ChRM has been isolated between 180–230 and 480-630°C (Figure 7d, e) or between 5 and 60-100 mT (Figure 7f), suggesting the presence of magnetite as the main magnetic carrier, together with a small fraction of hematite. All the samples are characterized by a single component of magnetization with normal polarity (Figure 7g, h).

CCF partially corresponds to the *Complesso di Cupoli*, *Formazione di Casoli*, and *Formazione di Collarmele* (Bosi et al., 1995), *Depositi del IV Ciclo fluvio-lacustre* (Zarlenga, 1987), and to *Case Colombaia Unit*, *Aielli Stazione Unit* and *Cerchio Unit* (Cavinato et al., 2002).

Moving from Casa Colombaia section to the north, ACF and CCF are partially interlayered with clayey deposits that we refer to the Colle Caprino Fm. (COF). COF is more than 220 m-thick and mainly consists of laminated grey clays and brownish silty clays. These fine-grained sediments are interbedded with thin layers of carbonate breccias, maximum 2 m-thick, which are characterized by poorly sorted sub-angular to angular clasts (Figure 5c). On the base of sedimentological and lithological features, together with the ostracod assemblage showing only *Caspiocypris*, the fine-grained deposits of COF refer to a deeper-water lacustrine environment, which was characterized by the arrival of debris flows sourced by the active tectonic margin of the sedimentary basin.

COF partially corresponds to *Depositi del I Ciclo fluvio-lacustre* (Zarlenga, 1987), *Complesso di Aielli* (Bosi et al., 1995), and *Colle Caprino Unit* (Cavinato

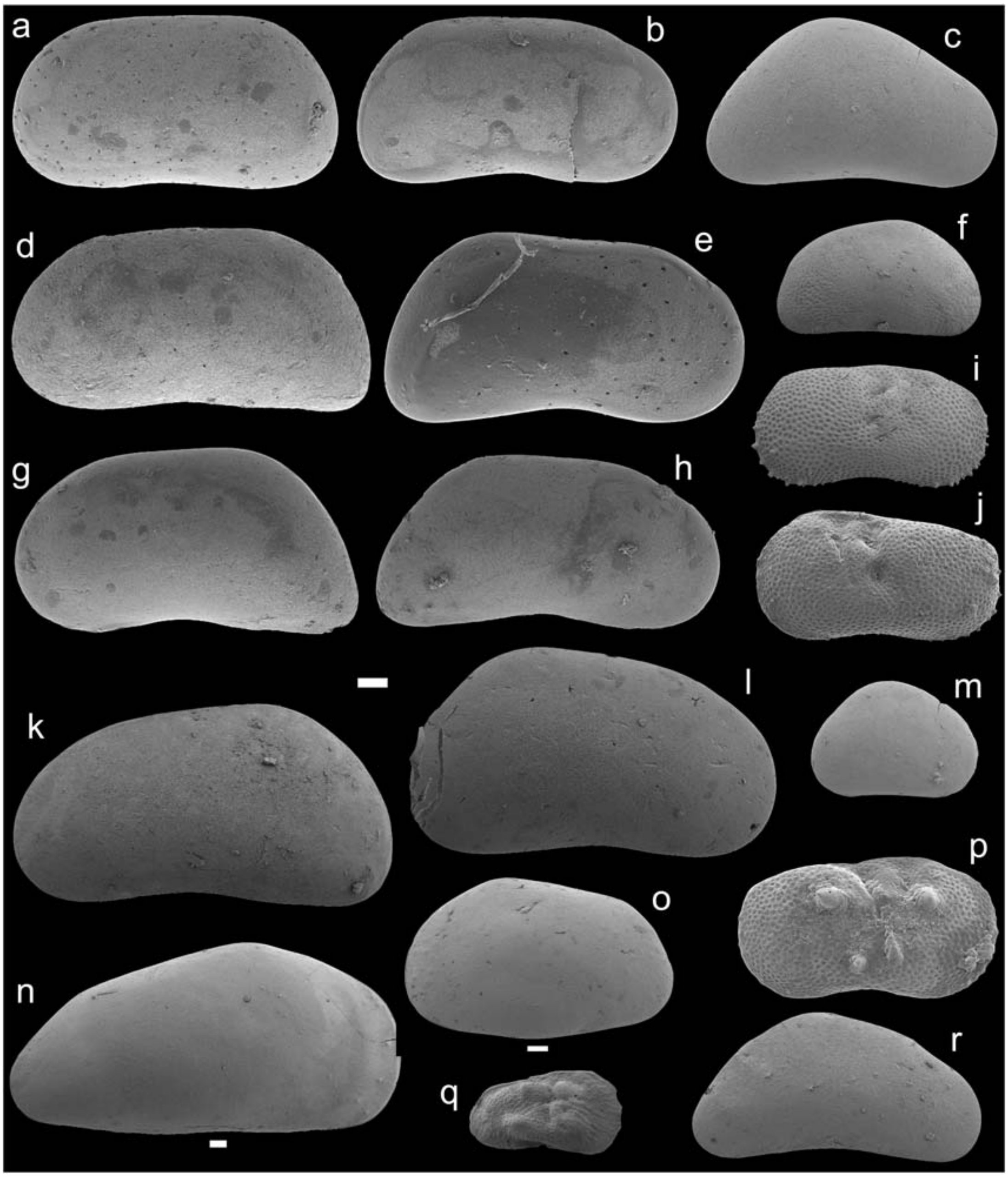

Figure 6. SEM pictures of selected ostracods from the Casa Colombaia Fm. (a) *Caspiocypris tiberina*, left valve in external view, sample CC1; (b) *Caspiocypris tiberina*, right valve in external view, sample CC5; (c) cf. "*Typhlocypris*" *alumna*, right valve in esternal view, sample CC5; (d) *Caspiocypris* sp. 2, left valve in external view, sample CC4; (e) *Caspiocypris* sp. 2, right valve in external view, sample CC12; (f) *Potamocypris zschokkei*, right valve in external view, sample Cava di Cupoli N 4C; (g) *Caspiocypris* sp. 3, left valve in external view, sample AS5; (h) *Caspiocypris* sp. 3, right valve in external view, sample CC11; (i) *Ilyocypris inermis*, right valve in external view, sample VDC1; (j) *Ilyocypris bradyi*, left valve in external view, sample AS5; (k) *Neglecandona* cf. *N. neglecta*, left valve in external view, sample CC5; (l) *Candona weltneri*, right valve in external view, sample CC6; (m) *Cypria* sp. n. sp., right valve in external view, sample CC3Car; (n) *Trajancypris clavata*, right valve in external view, sample Ponte dei Ponti; (o) *Eucypris* sp., left valve in external view, sample Cerchio 14; (p) *Ilyocypris gibba*, right valve in external view, sample PF1; (q) *Paralimnocythere bicornis*, right valve in external view, sample CHP3; (r) *Candona* cf. *C. triangulata*, right valve in external view, sample CC3Car. The white bars correspond to 0.1 mm.

et al., 2002). Toward the top of the formation, the increase of debris-flows defines a gradual transition to a massive carbonate breccias, which refers to the Aielli Fm.

The Aielli Fm. (AIF) is ca. 70 m-thick and consists mainly of clast-supported, poorly-sorted, well-cemented, and slope-derived carbonate breccias (Figure 5d), often characterized by the presence of metric blocks, more than 1 m in size. The internal organization of this deposit is chaotic. Thickness can vary from 10 m up to 50 m. AIF mainly outcrops around Aielli village, with some outcrops also in the area of Colle Caprino and La Selvotta. AIF shows many similarities with the 'Brecce dell'Aquila Auct.' (Colle Macchione-L'Aquila Synthem, Cosentino et al., 2017), which suggest for its deposition air-lubricated inertial

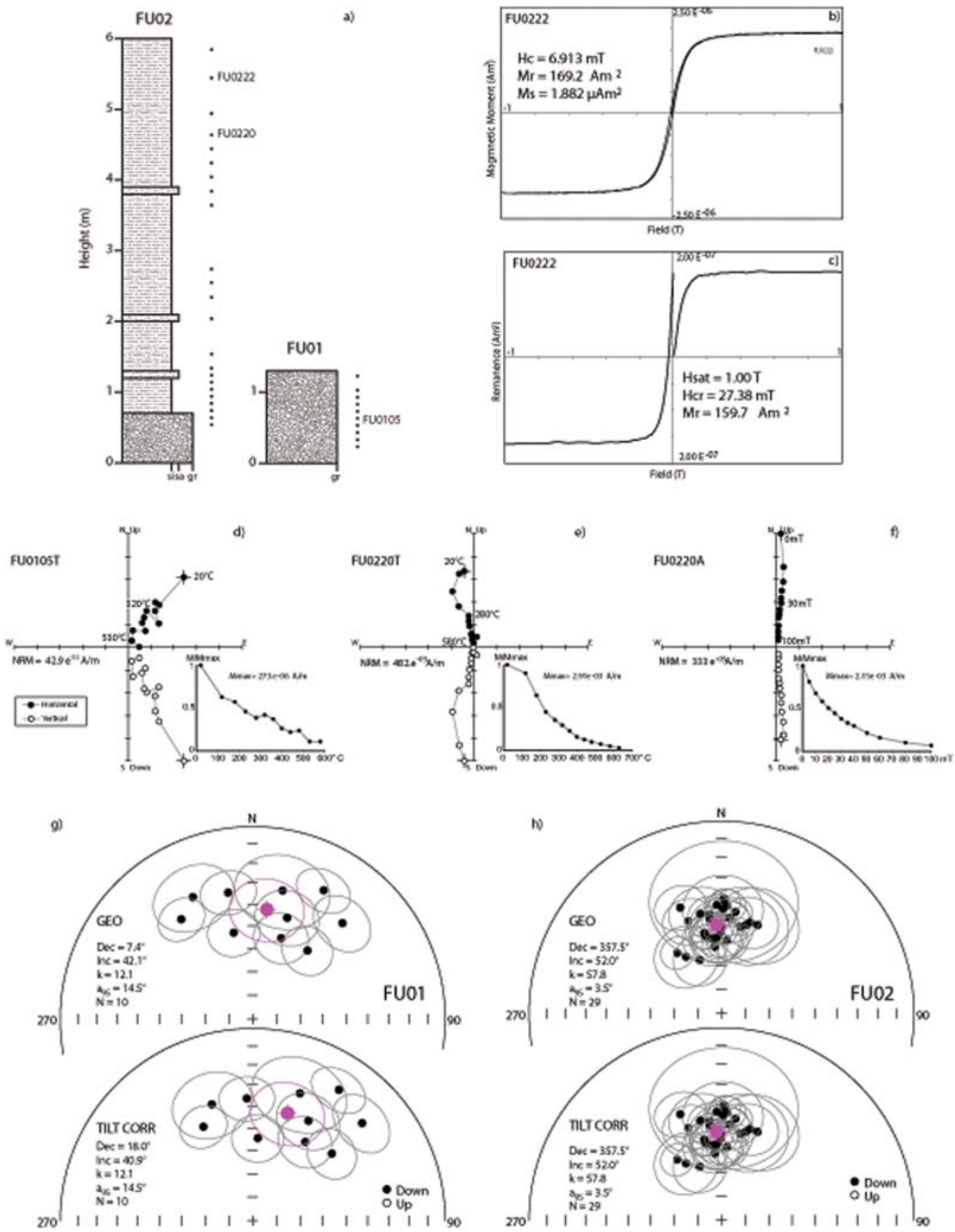

Figure 7. Casa Colombaia sampling section for paleomagnetic analyses (a). Hysteresis loop (b) and stepwise acquisition of an isothermal remanent magnetization (IRM) in fields up to 1 T and back-field demagnetization curve (c) for FU0222 sample. (d-f) Representative vector component diagrams of demagnetization data for representative samples. For each sample, progressive thermal (d, e) or AF (f) demagnetization steps are reported. (g-h) Equal area projection of sample characteristic remanent magnetization (ChRM) directions and 95% confidence ellipse from FU01 (g) and FU02 (h). Full circles represent projection on the lower hemisphere.

granular flows (sturzstrom, sensu Hsü, 1975; Pierson & Costa, 1987), which can arrive also into the lacustrine environment. AIF correlates the *Brecce antiche* of Zarlenga (1987), is included in the *Complesso di Aielli* of Bosi et al. (1995), and is described inside the *Colle Caprino Unit* (Cavinato et al., 2002).

The Stazione di Pescina Fm. (SPF), which crops out at the eastern sector of the study area, is ca. 80 m-thick and mainly consists of coarse-to-medium, clast-supported, and moderately sorted conglomerates. Somewhere, palaeosols with thickness ranging from 50 cm to 1 m were observed. The internal architecture of these coarse-grained deposits is mainly characterized by channelized structures (Figure 5e), showing fining upward channel-fill conglomerates. The channel facies laterally pass to fine-grained sediments with sheet-like and lenticular forms, interpreted as overbank deposits due to overflow events. The channelized fluvial facies suggests a stacked multi-storey gravel channels of a braided plain environment. The upper boundary of the SPF is a flat surface (abandonment surface) located to the north of Pescina village, which lies at elevations of 855 and 865 m. This surface corresponds to the upper boundary of the Celano-Collarmele Synthem, which correlates the 'Collarmele-Pescina terrace'. This palaeosurface is downthrown toward southwest by NW-SE normal faults. SPF partially corresponds to *Depositi del II Ciclo fluvio-lacustre* (Zarlenga, 1987), *Formazione di Pescina* (Bosi et al., 1995), and to the *Pescina and Collarmele Unit* (Cavinato et al., 2002). In fluvial deposits that correlates SPF, Blumetti et al. (1997)found a fragment of an equid jawbone, which was referred to *Equus* cf. *altidens*.

The Ponte della Valle Fm. (PVF) is ca. 20 m-thick and includes several proximal and distal alluvial fans and fan delta deposits. It consists of well cemented sheet-like breccias, with few interbedded lacustrine carbonates and silty sandy layers (Figure 5f). In the area of Collarmele, these alluvial fans and fan delta deposits lie on the Meso-Cenozoic bedrock through an angular unconformity. Close to Pescina, distal alluvial fans of PVF are interfingered with fluvial conglomerates of SPF and are characterized by the precipitation of a fibrous to radial carbonate cement. PVF corresponds to the *brecce a cemento terroso rossastro* included within the *Depositi del II Ciclo fluvio-lacustre* of Zarlenga (1987), to the breccias and alluvial fans within the *Formazione di Pescina* (Bosi et al., 1995), and to the *coalescing alluvial fan and fan delta deposits* described by Cavinato et al. (2002).

4. Discussion

The field work carried out at the north-eastern margin of the Fucino Basin allows us to suggest a new stratigraphic setting for its filling deposits, which are arranged in two synthems: (1) the Le Vicenne Synthem (uppermost Messinian); and (2) the Celano-Collarmele Synthem (upper Piacenzian-Gelasian). The occurrence of the fine – and medium-grained deposits related to the late Messinian Lago-Mare event (MDG) is of great interest to better understand the role that the Fucino Basin played during the evolution of the central Apennine fold-and-thrust belt and to reconstruct the latest Miocene palaeogeography of the Marsica region at that time.

The analyses carried out on the deposits of the MDG allowed us to discover well-diversified ostracod assemblages, both in the Fonte Nuova and in the Belvedere members. Ostracod species from MDG show affinities with the Paratethyan ostracod contingent (Gliozzi et al., 2012), which defines the Lago-Mare event at the end of the Messinian salinity crisis (Gliozzi et al., 2007; Grossi et al., 2008; Roveri et al., 2008; Stoica et al., 2016). The presence of *L. djafarovi*, associated with 'pointed' *Candoninae*, *Leptocytheridae* and *Loxoconchidae*, defines the *Loxocorniculina djafarovi Zone* of the Lago-Mare biozonation (Grossi et al., 2011). The first occurrence of *L. djafarovi* in the Mediterranean has been calibrated to 5.40 Ma in the Maccarone section (Grossi et al., 2011), lasting till the end of the Miocene, at 5.33 Ma. Based on this evidence, it is possible to refer the whole sedimentary succession of MDG to the second stage of the Late Messinian Lago-Mare event (5.40-5.33 Ma), which occurred throughout the Mediterranean at the end of the Messinian Salinity Crisis (Cita, 1982; Hsü et al., 1973; Roveri et al., 2014). The ostracod assemblages from MDG point to a shallow aquatic environment, characterized by a range in salinity between oligohaline to mesohaline. Thus, we can infer that, during the latest Messinian, the Fucino area was characterized by a large brackish lagoon in connection with the Mediterranean base level.

MDG correlates the sedimentary succession of the latest Messinian Le Vicenne Basin (Cipollari et al., 1999a; Gliozzi, 1999; Gliozzi et al., 2012), which crops out 10 km to the southeast, along the Aschi-Pescina country road. The Le Vicenne sedimentary succession, which is characterized by polygenic conglomerates, clays, and silty clays bearing Paratethyan ostracod assemblages, unconformably overlies a highly deformed Meso-Cenozoic carbonate succession (Cipollari et al., 1999a; Colacicchi et al., 1967). Moreover, the Le Vicenne stratigraphic succession shows an open syncline structure, characterized by an E-W axis. This evidence points to consider the Le Vicenne Basin as a latest Messinian thrust-top basin, developed during the compressional deformation of the Marsica region of the central Apennines (e.g. Cipollari et al., 1999a, 1999b; Cosentino et al., 2010; Cosentino & Cipollari, 2012).

The high diversity ostracod assemblage of the Le Vicenne Basin (Gliozzi, 1999; Gliozzi et al., 2012) allows us to identify some ostracod species shared with the MDG, which are: *Loxoconcha eichwaldi*, *Loxoconcha cf. L. ludica*, *Loxocorniculina djafarovi*, *Zalanyella venusta*, *Camptocypria* sp. 1, *Cyprideis anlavauxensis* [reported by Gliozzi (1999) as *Cyprideis* aff. *tuberculata*], and *Amnicythere idonea* vel *pontica*.

Based on the proposed correlation, we consider MDG as sedimented in a thrust-top structural setting, during the deformation of the frontal zone of the central Apennines. Hence, the upper Messinian deposits of both the Fucino and Le Vicenne basins would represent the rest of a wider thrust-top sedimentary basin developed during the first compressional deformation that involved in the Apennine Chain the 'Gran Sasso – Western Marsica' tectonic unit (Cosentino et al., 2010).

In the Fucino Basin, the Plio-Quaternary deposits related to the early stage of the post-orogenic evolution of the Marsica region unconformably overlie both the upper Messinian MDG and the bedrock succession. The facies architecture suggested in this work for the Plio-Quaternary deposits represents something new with respect to the stratigraphic setting proposed for the study area (Bosi et al., 1995; Cavinato et al., 2002; Zarlenga, 1987). Except for the Upper Pleistocene continental deposits and the recent covers, the rest of the Plio-Quaternary succession is grouped in a single synthem: the Celano-Collarmele Synthem (Figure 8).

Within the Celano-Collarmele Synthem, the facies distribution of these continental deposits allows us to reconstruct some lateral changes in the depositional environment of the Fucino Basin, from the deeper-water lacustrine deposits (COF) to the marginal lacustrine facies of CCF, which laterally passes to channelized coarse-grained fluvial deposits of the Palaeo-Giovenco River (SPF). In the Aielli area, a quasi-homogeneous chaotic body of carbonate breccias (AIF), which rests above COF, can be related to air-lubricated inertial granular flows and rock-avalanches, likewise the *Brecce dell'Aquila Auct.* (Antonielli et al., 2020; Cosentino et al., 2017). Similarly to the SE margin, where marginal lacustrine facies (CCF) are heteropic to fluvial deposits (SPF), to the NW, deltaic to alluvial-fan conglomerates (ACF) show progradation into the palaeolake environment of the Fucino Basin.

The age of the Celano-Collarmele Synthem is well constrained by the presence of *Caspiocypris tiberina* within the ostracod assemblages of CCF, combined

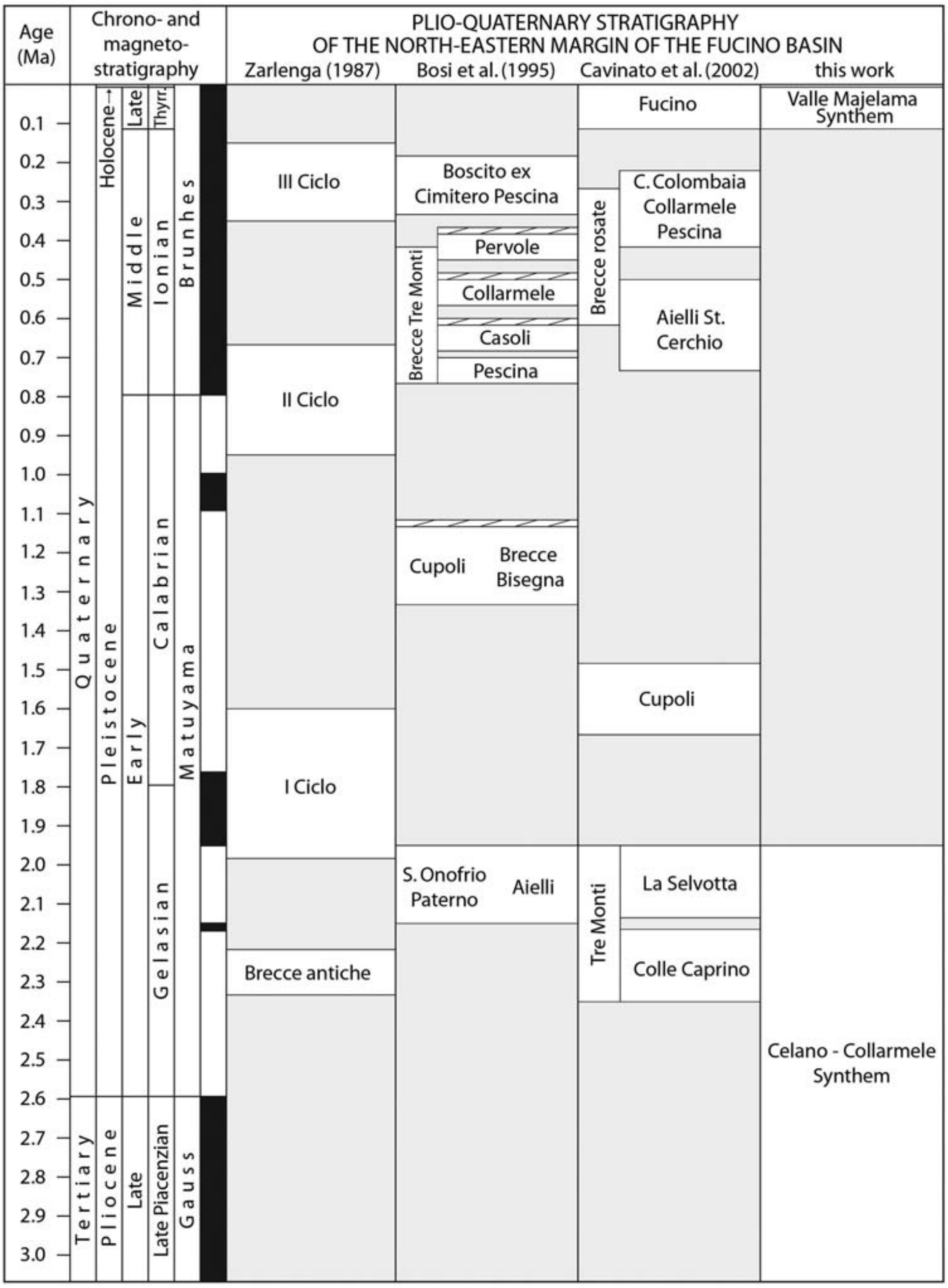

Figure 8. Comparison among the chronostratigraphical schemes of the Plio-Quaternary deposits of the north-eastern margin of the Fucino Basin as proposed by previous authors and the chronostratigraphy defined in this work.

with palaeomagnetic results. *Caspiocypris tiberina* was previously recorded at Cava Toppetti section (Tiberino Basin) (Spadi et al., 2018, 2019) and its distribution was dated, through magnetostratigraphy, palynology, and mammals biochronology, to a time span between the late Piacenzian and the pre-Olduvai Gelasian interval (Abbazzi et al., 1997).

The combination along the Casa Colombaia section of *Caspiocypris tiberina* and normal magnetic polarity allows us to correlate this section to the Gauss Normal Chron, particularly to the C2An1n sub-chron (late Piacenzian, 2.58-3.04 Ma), as for the lowermost part of the Cava Toppetti section (Tiberino Basin, Abbazzi et al., 1997; Spadi et al., 2018). Given its stratigraphic position, the Casa Colombaia section seems to be the oldest part of the Plio-Quaternary succession of the Fucino Basin. For this reason, we consider the starting age of the post-orogenic extensional tectonics responsible for the creation of the Fucino Basin as late Piacenzian, likewise in other extensional intermontane basins of central Italy (Cosentino et al., 2017).

Possibly, the Celano-Collarmele Synthem could reach the Gelasian in its upper part, like in the correlatable upper Piacenzian-Gelasian synthems of the central-northern Apennines (Cosentino et al., 2017). It is worth noting that similar *Caspiocypris*-dominated ostracod assemblages were recently recognized in the San Nicandro Fm. (L'Aquila Basin, Nocentini et al., 2018; Spadi et al., 2016). In this chronostratigraphic framework, the occurrence of mammal remains referred to *Equus* cf. *altidens* (Blumetti et al., 1997) in fluvial deposits that correlate SPF is at odds with the *Caspiocypris*-bearing ostracod assemblage of the Celano-Collarmele Synthem, which points to a late Piacenzian-Gelasian age. According to Gliozzi et al. (1997) and Palombo (2009), *E. altidens* shows a distribution from the late Early Pleistocene (ca. 1.4 Ma) up to the Middle Pleistocene (ca. 0.46 Ma), whereas Masini and Sala (2007) indicates the presence of *E. altidens* since the base of the Early Pleistocene (ca. 1.8 Ma). It is possible to explain this controversy with the uncertainty in referring an equid jawbone to a well-defined species of *Equus*, coupled with the uncertain attribution of the equid jaw made by Blumetti et al. (1997)to *Equus* cf. *altidens*. A possible species of fossil equid consistent with the chronostratigraphy of the upper part of the Celano-Collarmele Synthem could be *Equus stenonis* (ca. 2.5-1.3 Ma, Gliozzi et al., 1997), which can be easily distinguished from *E. altidens* mainly by the different proportions in the leg bones (Caloi, 1994).

5. Conclusions

This work on the Fucino Basin provides new data to better understand the early stage stratigraphic evolution of this post-orogenic intermontane basin. The new stratigraphic architecture of the continental deposits of the Fucino Basin, which we suggest in this paper, reveals some novelties in the evolution of this sedimentary basin. The Plio-Quaternary succession unconformably overlies both the late Messinian deposits of Le Vicenne Synthem, which were previously referred to as late Miocene foredeep siliciclastic deposits (Bosi et al., 1995; Cavinato et al., 2002), and the pre-orogenic bedrock succession. The Le Vicenne Synthem shows a Paratethyan ostracod contingent (*Loxocorniculina djafarovi* Zone, Grossi et al., 2008), which characterizes the last Lago-Mare event of the Messinian Salinity Crisis (5.40-5.33 Ma). These late Messinian ostracod assemblages define a brackish shallow-water environment and allow us to correlate these Lago-Mare deposits with that cropping out in the Le Vicenne Basin (Cipollari et al., 1999a; Gliozzi, 1999; Gliozzi et al., 2012). As a consequence, during the latest Messinian the Fucino area was a part of a more extended thrust-top basin that was developing at the leading edge of the central Apennines, at the Mediterranean base level.

Except for the recent covers, the deposits of the Plio-Quaternary succession cropping out at the north-eastern margin of the Fucino Basin are considered as part of the same synthem (e.g. the Celano – Collarmele Synthem). This synthem includes six different heteropic formations that show transitional environments from fluvial to marginal lacustrine facies, with indication also of deeper-water lacustrine environments.

Ostracod assemblages from the marginal lacustrine deposits of the Celano – Collarmele Synthem (CCF) are characterized by the presence of *Caspiocypris tiberina*, already found within the late Piacenzian-Gelasian Fosso Bianco Fm. of the Tiberino Basin. In addition, palaeomagnetic analysis carried out in the Casa Colombaia section shows normal polarity, allowing us to refer the section to the C2An1n sub-chron (2.58-3.04 Ma) of the Gauss Normal Chron. These evidence allow us to constrain the onset of the extensional tectonics, hence the continental post-orogenic deposition of the Fucino Basin, to the late Piacenzian (ca. 3 Ma), likewise in the Tiberino and L'Aquila intermontane basins (Cosentino et al., 2017).

Finally, the new stratigraphic framework for the Fucino Basin may be also useful to refine the long-term slip rates of the still active normal faults that affect the north-eastern margin of the Fucino Basin.

Software

The vector and raster data for the making of the geological map were elaborated with QGIS 3.4 Madeira, while geological cross-sections, stratigraphic correlation scheme, layout and final editing were performed using Adobe Illustrator®.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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