Accepted Manuscript

Journal of the Geological Society

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DOI: https://doi.org/10.1144/jgs2017-138

Received 21 November 2017
Revised 22 May 2018
Accepted 30 May 2018

To cite this article, please follow the guidance at http://www.geolsoc.org.uk/onlinefirst#cit_journal

Alluvial fan shifts and stream captures driven by extensional tectonics in central Italy

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Abstract: Subsidence of a normal fault bounded basin in central Italy in the last 0.78 Myr caused the deactivation and uplift of an Early-Middle Pleistocene alluvial fan at the fault footwall. Uplift of the fan occurred with a basin-bounding fault slip-rate in the order of 0.2 mm/yr. Subsidence produced the re-organization of the rivers network due to base-level fall, triggering headward erosion, stream piracy effects, and drainage inversion.

The mapped river inversions and catchment piracy were related with the distribution of a quantile regression of 134 alluvial fans Vs basin areas. Despite the two parameters are well-fitted by a power law relationship, all the fans corresponding to captured rivers lay above the regression line (in the fan area field), whereas those corresponding to capturing rivers, are below the regression line (in the basin area field).

We propose a general model of alluvial-fan growth in active extensional settings that helps interpret the scatter of fan vs basin areas distribution and to identify the most active fault segments. Such approach can better constrain fault activity in a time-window which bridges long-term deformation to present-day deformation inferred from geodesy and/or seismology increasing our understanding of fault steadiness/unsteadiness behaviour.

keywords: continental extension, alluvial fans, drainage response to faulting; sedimentary record of fault-bounded basins, stream piracy, Northern Apennines

Integration of different approaches, each best suited for different temporal scales, from tens of thousands to millions of years, helps unravel the spatial and temporal evolution of active tectonic environments. The combination of datasets at different time-scales with present-day geodetic and seismological data can help understand the seismogenic potential of master faults as well as and the activity of single fault segments (Keller, 1986; Leeder and Gawthorpe, 1987; Stewart and Hancock, 1994; Frankel and Pazzaglia, 2006; Burbank and Anderson, 2012).

At long time-scales (10^5 to 10^6 yr), the analysis of sediment records in fault-controlled extensional basins provides valuable information on the space–time evolution of active tectonics (Gawthorpe and Leeder, 2000) and on the mid- to long-term growth of individual fault segments (Jackson and Leeder, 1994).

A number of issues hampers the investigation of the sedimentary records in fault bounded basins. In settings characterized by a regional uplift, for example, the efficiency of normal faults in promoting hanging-wall subsidence is counterbalanced by erosion induced by regional uplift, which can reduce the volume of sediments delivered into the basins (Doglioni et al. 1998; Pucci et al. 2014). In addition, if active extension migrates, a shift occurs also in the position of the active depocenter (Gawthorpe and Leeder, 2000).

At short geological time-scales (up to 10^5 yr), the spatial variation of active tectonics can produce peculiar geomorphological features characterized by wind gaps, abandoned valleys, stream captures and drainage inversions (Pazzaglia, 2003; Molin et al. 2004; Cowie et al. 2006; Schiattarella et al. 2006; Picotti and Pazzaglia, 2008; Wegmann and Pazzaglia, 2009; Burbank and Anderson, 2012; Gioia et al., 2014).

A number of studies have shown that the geomorphological evidence of the landscape response to active extension (e.g., river anomalies) can be used to identify the (recent) evolution of normal faults, and to measure fault slip-rates and their temporal variations (Goldsworthy and Jackson, 2000; Peters and Van Balen, 2007; Whittaker et al. 2008; Boulton and Whittaker, 2009; Di Naccio et al. 2013).

Alluvial fans, a common geomorphological feature in different climatic regions and tectonic environments, are known to be key indicators of active tectonics, chiefly in the Quaternary (Bull, 1977, 1991, Ritter et al. 1995; Harvey, 2002).

In many regions Pleistocene alluvial fans are not only indicators of tectonic activity, but are also related to an increase in sediment transport soon after a main glacial period. In the Mediterranean area, during the Pleistocene cold stages, the upper catchments of mountainous regions were subjected to intense periglacial processes and sustained snow packs, even at relatively low elevations, with a resulting increase of sediment supply and formation of alluvial fans in the lowlands (Hughes and Woodward, 2017). Examples were described from Montenegro (Adamson et al., 2017), from Greece (Pope et al., 2017), as well as from the Apennines of Italy (Giraudi et al., 2011; Giraudi and Giaccio, 2017).

Active tectonics of basin margins controls the build-up of alluvial-fans and their variability, geometry and internal structure (Hooke, 1967; Blum and Törnqvist, 2000; Gibling et al.2011; Harvey et al. 2005). Tectonic forcing influences the morphology of the alluvial fans, providing the relief potential, increasing energy gradients along the river network that delivers sediments to the fan.(Ethridge and Wescott, 1984, Silva et al. 2003, Calvache et al. 1997; Barrier et al. 2010).

Various studies have revealed a correlation between morphometric measures of alluvial fans and their contributing catchments, including e.g., the ratio between the area of the fan and the area of the contributing catchment (Harvey, 1987), and the ratio between the fan slope angle and the average terrain gradient in the catchment (Viseras et al. 2003). The correlation also depends on local/regional environmental and tectonic settings (Harvey, 1987; Ferrill et al. 1996; Guzzetti et al. 1997; Sorriso-Valvo et al. 1998; Harvey et al. 1999; Viseras et al. 2003; Mather et al. 2015).

Here, we address the issue of how the investigation of the recent geological history of a fossil alluvial fan system can provide information on the time and space migration of active tectonics and the resulting reorganization of the river network. We study how the reorganization of the river network causes river piracy, increasing the contributing area of some catchments at the expense of nearby catchments, and how this affects the statistics of the area of the fans and the catchments.

For the study, we selected the Bastardo and Foligno valleys, in the Northern Apennines of Italy (Fig. 1), a Pliocene-Pleistocene continental basin characterized by braided rivers and shallow lakes (Ambrosetti et al. 1987; Conti and Girotti, 1977; Bucci et al. 2016a). The area is tectonically active, with extension rates in the range 2.5-2.7 mm/yr (Hunstad et al. 2003; D'Agostino et al. 2009), and instrumental and historical seismicity (maximum epicentre intensity I0 = VIII, Rovida et al., 2011).

Geological setting

The study area is characterized by a gentle hilly morphology shaped on the flanks of the Montefalco ridge, about 400 m a.s.l. West of the ridge, in the Bastardo valley (Gregori, 1988), elevation is about 300 m a.s.l., whereas in the eastern Foligno valley it is about 200 m a.s.l. To the W and to the E of the study area, the Umbria-Marche Apennines provide the highest reliefs (about 1,070 m the Martani range, and 1,250 m the Foligno Mountains). The present-day climate of the area is temperate sub-continental Mediterranean, warm and dry in the summer and mildly cold in winter. In the area, the Topino River represents the main drainage system, which originates in the Apennine chain and flows from NE to SW toward the Foligno Valley (Fig. 1a). A main tributary of the Topino River is the Teverone River, that flows towards the NNW within the Foligno Valley. This river, in turn, collects the waters of the Attone River, draining the E portion of the Bastardo valley (Fig. 1a).

The Montefalco ridge dominates the Foligno valley towards E and the Bastardo valley towards W (Fig. 1a). These two valleys are shaped on the continental sequence deposited within the ancient "Tiberino lake", a depositional environment characterized by braided rivers and shallow lakes of Pliocene to Pleistocene age (Conti and Girotti, 1977; Ambrosetti et al. 1987; Bonini, 1997; Coltorti and Pieruccini, 1997; Martinetto et al. 2014).

Stratigraphy

The continental sequence consists of a series of laterally discontinuous deposits separated by palaeo-topographic ridges and thresholds overlying unconformably the pre-existing bedrock constituted by the Umbria-Marche meso-cenozoic carbonatic multilayer (UM, Fig. 2a, Cresta et al. 1989) and the Miocene siliciclastic Marnoso Arenacea fm (MA, Fig. 2a, Ricci Lucchi, 1986).

The outcropping continental deposits consist of three main groups: (i) a basal grey clay member represented by fine grained flood-plain, lacustrine lignitiferous clay of Late Pliocene age (Lotti, 1926; Ge.Mi.Na., 1962; Follieri, 1977; Coltorti and Pieruccini, 1997; ISPRA, in press), which crops out SE of the study area (Morgnano, Fig. 1a); (ii) a sandy clayish locally lignitiferous sequence with subordinated conglomerate Early Pleistocene in age (Ambrosetti et al. 1987); and (iii) a detritic assemblage mainly composed of layered conglomerate and sand. Based on the available subsurface data (Ge.Mi.Na., 1962; Barchi et al. 1991), the maximum thickness of the deposits is estimated to be larger than 600 m under the Foligno valley. The maximum thickness of the deposits decreases W of the Montefalco ridge, where it is estimated to be less than 400 m (Bucci et al. 2016a). Here we refer to the revised stratigraphy by ISPRA (in press) and Bucci et al. (2016a), in patrticular:

(1) the *Bevagna Unit* (BU, Fig. 2b, Early Pleistocene), a fine-grained floodplain and lacustrine Unit, that corresponds to unit (ii) described above.
(2) the *Montefalco Unit* (MU, Fig. 2b, Early-Middle Pleistocene), composed of gravels and conglomerates of both fluvial and fan delta environment, overlying the Bevagna Unit. It corresponds to unit (iii) described above.
(3) the *Colle del Marchese Unit* (CU, Fig. 2b, Early-Middle Pleistocene), fan-type conglomerates with poorly sorted and poorly rounded pebbles pertaining to a partially fluvial and partially subaerial fan deposition environment, coeval with the Montefalco unit.
(4) the *Pianacce Unit* (PU, Fig. 2b, Middle-Late Pleistocene), a deposit consisting of dark reddish and brownish clays and sandy clays with few pebbles which unconformably overlies the Bevagna Unit and is present only in the central, flat part of the basin. This unit represents the youngest lacustrine deposit in the basin. The south-western part of the deposit is characterized by different facies composed of red silty clay with Mesozoic-Cenozoic carbonate clasts named as Fabbri member (FM – Fig. 2b) by Bucci et al. (2016a), and interpreted as a palaeo-fan.
(5) Alluvial deposits (AD, Fig. 2, Late Pleistocene-Holocene), fine-grained floodplain sediments made of gray and yellowish clays and sandy clays.
(6) Alluvial-fans (AF, Fig. 2a,b Late Pleistocene-Holocene), coarse-grained fan-shape debris deposits in a silt and subordinately clay matrix.

The stratigraphical, depositional and tectonic features of the continental deposits are summarized in Table 1. The age constraints of the outcropping deposits are scarce. Most ages are assigned on the basis of stratigraphic correlations with nearby deposits in similar structural and depositional settings. In particular, the Bevagna unit was assigned to the Early Pleistocene (Calabrian) on the basis of paleofloristic and palinological analyses (Ambrosetti et al., 1987). A recent paleomagnetic study by Bizzarri et al., (2011) performed in a quarry near Bevagna (Fig.2a) suggests that the uppermost part of this unit might be about 0.78 Ma. The Montefalco unit overlies the Bevagna unit. For these reasons it is considered to be Early-Middle Pleistocene in age.

These pieces of information on the age of both the Bevagna and the Montefalco units also fit with other evidences at a larger scale. About 50 km NW of the study area, still along the same continental basin (between Perugia and Città di Castello, see Fig. 1b) the Fighille unit (similar to the Bevagna unit) was assigned to the Early Pleistocene, ~1.8 Ma, by mollusk assemblages and mammal faunas (late Villafranchian, Tasso F.U., Ciangherotti and Esu, 2000; Argenti, 2004; Masini and Sala, 2007). On top of the Fighille unit, a facies of conglomerates and sands similar to the Montefalco unit was assigned to the Early-Middle Pleistocene on the basis of mammal records (Colle Curti F.U., and Early-Middle Galerian, post- Colle Curti F.U., 1.0-0.8 Ma; Petronio et al., 2002; Argenti, 2004; Masini and Sala, 2007).

The Colle del Marchese unit represents a proximal deposit which was emplaced by the rivers draining the M.Martani reliefs to the Bastardo valley: since it is in the same stratigraphical position of the Montefalco unit, the same Early-Middle Pleistocene age was inferred.

While the Montefalco e Bevagna units are mapped in both the Foligno and the Bastardo valleys, and represent the sediments deposited within the ancient "Tiberino Lake" (ISPRA, in press), the Colle del Marchese and Pianacce units are present only in the Bastardo valley (Bucci et al. 2016a) suggesting a differentiation of the sedimentation respectively W and E of the Montefalco ridge, after the end of the Early Pleistocene.

The Foligno and Bastardo valleys significantly differ in terms of present day river incision (Fig. 2a). The Foligno valley is about 7-km wide, it is flat and occupied by alluvial deposits. Here, there are no river terraces and the most prominent feature on the E side of the valley is represented by the Foligno alluvial fan, a 35-km^2 wide feature built by the Topino River flowing from NE to SW (Gregori and Cattuto, 1986; Cattuto et al. 2005). The Foligno valley has not been recently affected by incision, as testified by the absence of river terraces. Here, the Pleistocene continental deposits crop out only along the western side of the valley (Fig. 2a). On the contrary, the Bastardo valley is presently incised by the river system. The resulting morphology is gently hilly with remnants of erosional terraces (Bucci et al. 2016a). Incision is carved within the continental deposits which crop out within the basin, and only few alluvial deposits are concentrated along the valleys of the Puglia and the Attone Rivers. These two rivers form the divide between the waters flowing towards the Topino-Teverone streams to the E, and those flowing towards the Tiber River to the W (Fig. 2a).

Tectonics

Both valleys are elongated in a NW-SE direction, and bordered by a set of NE-dipping and SW-dipping normal faults (Barchi et al. 1991). The recent activity of the basin-bounding normal faults is testified by geological evidence, including e.g., faulted Pleistocene deposits (Barchi et al. 1991; Brozzetti and Lavecchia, 1995) and stream captures (Gregori and Cattuto, 1986; Gregori, 1988; Cencetti, 1990).

The normal faults belong to a well-known set of NW-SE striking faults that represent the youngest extensional structures which dissect the previously formed Northern Apennines (Fig. 1b), an Oligo-Miocene, east-verging fold and thrust belt later affected by extension (Malinverno and Ryan, 1986; Martini and Sagri, 1993; Barchi, 2010).

The W to E migration of compression-extension produced a characteristic setting, in which extension is always superimposed on compression (Lavecchia et al. 1994; Doglioni et al. 1999; Pascucci et al. 2006; Pauselli et al. 2006; Barchi, 2010). Compression is presently active all along the Adriatic coast, whereas extension is active along the axial culmination of the Northern Apennines. Present day geodetic data indicate active SW-NE extension rates along a NW-SE alignment of 2.5-2.7 mm/yr (Hunstad et al. 2003; D'Agostino et al. 2009). The recent tectonic history of the area reflects in the historical seismicity, which shows that the area was struck by several earthquakes with M ≥ 5

(Rovida et al. 2011) (Fig. 1a). Instrumental seismicity shows constant earthquakes release, and the available focal solutions provide nodal planes striking mainly NW-SE (Pondrelli et al. 2006).

At the regional scale, crustal extension is accommodated by a set of six sub-parallel E-verging low angle detachments, which have driven the onset of the hinterland extensional basins of the Northern Apennines (Barchi et al. 1998; Pauselli et al. 2006). In the area, the low angle detachment is represented by the Alto Tiberina Fault (ATF), an ENE-dipping low angle normal fault, the easternmost, youngest and presently active detachment (Barchi et al. 1998; Collettini and Barchi, 2002; Chiaraluce et al. 2007), which has accommodated up to 10 km of extension in the last 3 Myr (Mirabella et al. 2011; Caricchi et al. 2015). The superposition of extension on the already emerged compressional edifice brought a significant modification on the existing drainage pattern. At the end of the Late Cenozoic, when the fold-and-thrust belt emerged, rivers were draining mainly to the E, following the main regional slope and, in places, following the main arc-shaped valleys formed in correspondence of major synclines (Alvarez, 1999 and references therein). The onset of extension changed the relative elevation at the normal faults hanging-wall and footwall, forming a new landscape with new depocenters where the sediments could flow and deposit. The modification produced drainage inversions and stream captures in the area (Gregori and Cattuto, 1986; Cattuto and Gregori, 1988; Cattuto et al. 1988; Cencetti, 1988, 1993; Gregori, 1988, 1990) and elsewhere in the Northern Apennines (e.g., D'Agostino et al. 2001; Bartolini et al. 2003; Fidolini et al. 2013).

Methods

To understand the recent landscape modification caused by the active extension and the consequent river captures in the Bastardo and Foligno valleys, we combined field-based geological surveys, surface and sub-surface geology data, and detailed photo-geological mapping of the continental deposits. We performed field surveys to identify and measure the geometry and kinematics of the faults affecting the continental Quaternary sequence, and to measure palaeo-current data. Sub-surface geological data consisted of the interpretation of two high-resolution seismic reflection profiles in the Foligno valley, which portray the subsurface geometry of the latest basin infill close to the Montefalco ridge (traces Fo1 and Fo2 in Fig. 2a). The geomorphological analysis consisted in mapping the drainage pattern anomalies and stream captures, in comparing the present-day river network to palaeo-rivers deposits, and in the analysis of the present-day area of the alluvial fan and their contributing catchments. Furthermore, we analysed the long-profiles slope of the most representative streams crossing the recent-most normal faults on the NE-flank of the Montefalco.

Surface geology

We performed field-work to characterize the sedimentology of the continental deposits and the geometry and kinematics of the faults affecting the deposits. We integrated the sedimentological and structural information with a recent photo-geological map at 1:25,000 scale (Bucci et al. 2016a), and we compared this information with the existing geological and geomorphological maps, at different scales (Servizio Geologico d'Italia, 1969; Gregori, 1988; Cencetti, 1990, 1993; Regione Umbria, 2015a). The sedimentological data include the attitude of imbricate clasts within the conglomerates, that provides information on the provenance of the palaeo rivers. We computed the clustering of the orientation data using the 1% area contouring method and the mean value for the dip direction and plunge of the imbricate clast using Fisher statistics (Fisher et al. 1987). In addition, we treated dip directions of imbricate clasts as directional data, and compared our original data with published palaeo-current direction indicators. To analyse the structural data, including the attitude of fault planes and the orientation of fault slip indicators, we adopted the procedure proposed by Marrett and Allmendinger (1990), and Allmendinger et al. (2012). To quantify the relationships between the orientation of the fault populations and the slip vectors, we calculated the b-axis along fault systems, adopting the procedure proposed by Roberts (2007).

Subsurface data

We used high resolution seismic reflection data which provide information on the internal geometry of both the continental units and the tectonic structures at depth, and give constrains on the recent-most tectonic activity of the basins-bounding fault E of the Montefalco ridge. The E part of the Foligno valley is crossed by two high resolution seismic reflection profiles (Fo1 and Fo2, Fig. 2a) which were acquired by the Regione Umbria (2015a) in the framework of a regional geological cartography project. The two lines are 1.15 and 1.40 km long, respectively, and provide a good quality image up to about 0.8 second TWT (two-way-time traveling velocities of the seismic rays). According to published data, the interval velocity of the continental deposits is ~2.0 km/s (Bally et al. 1986; Buonasorte et al. 1988), which means that the profiles provide a detailed image of the upper part of the continental sequence, including the alluvial deposits i.e., up to a depth of about 800 m.

Geomorphological analysis

We executed a detailed, multi-scale geomorphological analysis using a large dataset of stereoscopic aerial photographs taken at different times and scales. Specifically, we used (i) a black and white flight taken in 1954 at 1:33,000 scales, (ii) a black and white flight taken in 1997 at 1:27,000 scale, and (iii) a colour flight taken in 1977 at 1:13,000 scale. The photogeological approach allowed us to map both geomorphological elements and geological and tectonic features including bedding indicators (e.g., lithological limits, Marchesini et al. 2013; Santangelo et al. 2015), structural features (e.g., faults and folds, Bucci et al. 2013, 2016b), sedimentary deposits (e.g., alluvial fans, alluvial deposits, Bucci et al. 2016a), and erosional features (e.g., erosional terraces, Bucci et al. 2016a). The geomorphological analysis focussed on a detailed inventory of the present-day alluvial fans, which we mapped together with their catchment areas. We analysed the river network to compare the present-day river paths to the distribution of the clastic deposits associated to palaeo-drainages, including the Montefalco conglomerates and the two fans pertaining to the Colle del Marchese conglomerates (Fig. 2a). We mapped evidence of river captures and piracy effects in the area, we compared them to the present-day river network, and we integrated our dataset with pre-existing evidences of river piracy (Gregori, 1988; Cencetti, 1990, 1993). In addition, as river long-profiles are known to register recent-most fault activity in different tectonic settings (e.g. Whittaker et al., 2007; Yanites et al., 2010 and therein references), we extracted the profiles of three rivers draining the NE flank of the Montefalco hill towards the Foligno valley to verify the possible correspondence between river anomalies (e.g. knick-points) and the mapped faults. The stream profiles were extracted from a 1:5.000 scale topographic map of area. To emphasise the knick-points which are due to local downstream changes in slope (dH) along the profile (dL) we plotted the downstream change in slope (dH/dL%) along the stream long-profiles.

Results

Surface geology

Our sedimentological data, integrated with data collected by Regione Umbria (2015a), show palaeo-currents clustered from the NE (Fig. 3a). The layers containing the imbricate clasts are sub-planar, or gently dipping to the SW (Fig. 3b). Palaeo-currents and bedding data indicate that the source area of the Montefalco conglomerate was located NE from the fan. The NE provenance of the sediments is further supported by a fining trend of the conglomerate from NE to SW, which indicates that the fan proximity is to the NE, close to the apex of the Foligno fan (Fig. 3 c, d).

The structural data concern faults that offset pre-Quaternary rock assemblages and Quaternary deposits (Fig. 4). Where evident, fault kinematics is mostly dip-slip, with a SW-NE trending direction of extension (Fig. 4 a, b), consistent with the Apennines regional strain field (Boncio and Lavecchia, 2000). Figure 4c shows the pole to the fault population obtained with the b-axis method for the Giano dell'Umbria fault system. The pole of the fault population is parallel to the striae measured in the pre-Quaternary carbonate rocks (Fig. 4d), and to the slip vector obtained for the striated fault of the Montefalco fault system (Fig. 4a). The findings reveal a dip-slip kinematics, with a top-to-the-NE direction for both the Montefalco and the Giano dell'Umbria fault systems.

Despite the kinematic similarities, the two fault systems show different relationships with the recent deposits. The map pattern (Fig. 2a) shows diffuse faulting of the pre-Quaternary rocks along the Giano dell'Umbria Fault system. Most of the faults cut the continental sequence, Early Pleistocene in age, but do not affect the sediments of the Pianacce Unit, Late Pleistocene in age, which are undeformed. No aggradation was found at the hanging wall of the Giano dell'Umbria Fault system, where fluvial incision exposes the basal unconformity between the pre-Quaternary rocks assemblages and the Quaternary continental deposits. These evidences constrain the activity of the Giano dell'Umbria Fault system up to the Early-Middle Pleistocene. In contrast, the Montefalco Fault system is characterized by a staircase geometry (Bucci et al. 2016a) developed within the sediments of the Bevagna and the Montefalco units, Early-Middle Pleistocene in age. The map pattern reveals that the lower fault strand bounds the present-day aggrading plain of the Foligno basin, suggesting the involvement of Holocene deposits in the active faulting along the base of the Montefalco ridge.

Overall, the structural analysis indicates the geometry and the kinematics of the studied fault systems, consistent with those of other Quaternary faults in the Northern Apennines (Brozzetti and Lavecchia, 1995; Boncio and Lavecchia, 2000). Evidence of recent (Late Quaternary) faulting is recognized along the Montefalco Fault system, whereas evidence of fault activity is constrained to the Early-Middle Pleistocene along the Giano dell'Umbria Fault system.

Seismic reflection data

The line Fo1 is characterized by a clear lateral heterogeneity (Fig. 5a). The seismic signal sharp change is confirmed by the velocity analysis that indicates, in the SW part of the line Fo1, at the CMP 30, a mean velocity in the range between 1900 m/s and 2100 m/s, up to about 150 m/s TWT, whereas for the CMP 205 the same velocity is observed up to about 470 m/s TWT. Line Fo1 shows a set of chaotic, NE-dipping reflectors which correspond at surface with the trace of the NE-dipping normal faults, bordering the Foligno valley (Fig. 5a). These reflections, which we interpret as the subsurface expression of the normal faults, are in contact with a set of sub-horizontal reflectors at the fault hanging-wall, which identify the presence of a stratified sedimentary sequence interpreted to be the Bevagna Unit .

The line Fo2 does not show a significant lateral velocity variation up to 800 m/s TWT. The mean velocity of this line is the same observed in Fo1 for CMPs greater than 205, and TWT greater than 470 ms. The obtained mean velocities are in agreement with the published data for the continental deposits i.e., about 2000 m/s (Bally et al. 1986; Buonasorte et al. 1988). The Fo2 seismic profile (Fig. 5b) shows that the Bevagna Unit prosecutes down to at least 0.8 sec (TWT), corresponding to about 800 m, a depth similar to other continental basins along the upper Tiber River valley NW of the study area (Barchi and Ciaccio, 2009; Pucci et al. 2014). The Bevagna Unit is characterized by a significant tilt of the beds towards SW (Fig. 5b). The amount of tilt decreases towards the surface and we interpret this as the evidence of syn-depositional, NE-dipping fault activity. The depth conversion of the seismic data indicates a tilt in the order of 3° to the SW (Fig. 5c). The upper part of the Fo2 seismic line shows a more chaotic pattern, which we interpret as due to the presence of a thick alluvial sequence (Fig. 5 a,b). The interpretation is further supported by deep water wells in the area, which provide a maximum thickness of the alluvial deposits of about 150 m (Regione Umbria, 2015b).

Geomorphology

River captures. We mapped the evidences of river captures and drainage inversion as derived by the rivers network and the morphology of the area (Fig. 6). In the E part of the study area we mapped several captures of rivers pertaining to the Menotre River network (Fig. 1, 6), in agreement with the geomorphological map of Cencetti (1993). In particular, we find that the upper reach of the Menotre River (river n. 3 in Fig. 6) is part of a palaeo-river (i.e., the palaeo-Menotre) which was flowing in the opposite direction, to the South. We identify four possible watersheds of the palaeo-river which we interpret as the progressive reduction of the size of the palaeo-Menotre catchment before being definitively captured and inverted by the Topino River (Fig. 6). As a result, while the palaeo-Menotre drastically reduced its catchment, the Topino River increased its contributing area. The present-day Pettino stream (n. 6 in Fig. 6 and Fig. 1a) and Spina River (stream n. 7 in Fig. 6 and Fig. 1a) are remnants of the palaeo-Menotre River draining into the area of Campello sul Clitunno (Fig. 1, 6).

In the W part of the study area, we identified evidence of stream captures in the eastern flank of the Mt. Martani range towards the Bastardo Valley basin and along the Puglia and Attone River systems (Bucci et al. 2016a). Comparing the Colle del Marchese Unit outcrop with the position of the present-day river network, we find that there is no one-to-one correspondence between the location of the present-day rivers and the Pleistocene deposits (Fig. 2). The north-western apron is re-incised but still connected to the drainage system of the Torinetto stream, a tributary of the Puglia river to the W (Fig. 2). On the contrary, the SE apron is disconnected from its original drainage system, suggesting that the main stream responsible for the conglomerates deposition was captured elsewhere, presumably in the present day Foligno valley which represents the active subsiding basin (Fig. 2). In this case, the captured river could be the Rovicciano stream (Fig. 2, and stream n. 15 in Fig. 6), a tributary of the Teverone-Topino rivers system to the east (Fig. 6). In the W part of the study area, the Attone and the Puglia Rivers form the watershed between the waters flowing to the NE and those flowing to the west (Fig. 2, 6). The peculiarity of the divide is that it lays in the Bastardo valley rather than along the alignment of the maximum elevations (Fig. 1a, 2). We interpret this finding as evidence that the Attone River has caused a strong headward erosion in response to the downthrow of the Foligno Valley since the Middle-Late Pleistocene. When headward erosion cut the topographic threshold represented by the bedrock E of Gualdo Cattaneo, the Attone River entered the pre-existing Bastardo valley, and expanded its source area capturing some of the rivers which were previously feeding the Puglia River. As a result, the Pianacce Unit, which represents the latest palustrine deposit, was incised. Deep incised gorges and hanging palaeo-valleys detected in the middle part of the Attone basin (Fig. 6) support this interpretation.

Allometry of alluvial fans. We mapped a total of 134 alluvial-fans and their catchments (Fig. 2). The fan planimetric area spans 4.5 orders of magnitude, from ~ 0.01 km^2 to ~ 35 km^2 which is the size of the Foligno fan, built by the Topino River, (Fig. 2). The basin areas span about 5 orders of magnitude, from less than 0.05 km^2 to about 390 km^2 (the Foligno River basin). On a log-log plot, the cloud of the empirical points of fans areas (A_f) and basin areas (A_b) shows a clear trend (Fig. 7a). Based on our data, we obtained a regression line fitting the data with equation,

$$A_f=0.16A_b^{0.9}$$

Figure 7b shows a map of the alluvial fans and their contributing catchments which are related to rivers which were captured, or underwent capturing by a nearby river system as described in Fig. 6. In particular, we mapped as red the fans and catchments which are related to captured rivers and dark grey/black the fans related to capturing rivers. With the same colours, we show the position and number of the fans in Fig. 7a. The data comparison shows that the fans of capturing rivers (dark grey/black) are systematically placed below the regression line, whereas the fans of captured rivers are above the regression line (Fig. 7a). Below we report some specific examples of rivers drainage inversions and captures.

The identified stream piracies, combined with the alluvial-fan areas and their catchments areas, allowed us to identify some rivers which included nearby catchments into their contributing areas. The present-day Topino River (n. 3 in Fig. 7) captured the palaeo-Menotre River leaving two rivers, Pettino (n. 6) and Spina (n. 7) the fans of which are too large for their current catchments (Fig. 7). The capture operated by the Topino River also affected fans n. 4 and 5, which are also too large for the size of their catchments (Fig. 7a). The Topino River basin (n. 2 in Fig. 7) also captured the Menotre River, the fan of which is very small compared with the catchment size (n. 3 in Fig. 7). We interpret these features as evidence of the progressive capturing operated by the Topino River, reflected in the presence of the intra-catchment fans which plot above the regression line. As a result of the repeated captures, the shape of the Topino catchment is elongated in a direction that is orthogonal to the Foligno fan feeding channel, and extends northward and southward (Fig. 7b), sub-parallel to the active fault bounding eastward the Foligno valley.

On the other side of the Foligno valley, the fan areas are smaller mainly because of the low relief of the catchments (Fig. 6, 7). Here, the largest catchments are those corresponding to fans n. 14 and n. 15, which are far smaller compared to their contributing areas. Such catchments are the result of stream piracy. In particular, stream n. 15 (Figs. 6, 7) captured the Rovicciano stream, which was draining the SE apron of the Colle del Marchese Unit. To the N of Montefalco, fan n. 17 captured the drainage area of fan n. 16.

A peculiar case is represented by the Attone River (n. 18, Fig. 2, 6, 7), with a basin that extends for 60 km^2, and no morphological evidence of an alluvial fan (see star on the basin area axis in Fig. 7b). According to the size of the basin, the expected fan should be of ~ 6 km^2. We hypothesize that the absence of such a large fan is due to the fact that when the Attone River entered the Bastardo valley, due to progressive headward erosion, it found an area already characterized by a gentle topography, with a low local relief that prevented erosion and transport. The hypothesis is supported by the evidence that the Attone River is depositing sediments in the Bastardo valley, far from its outlet in the Foligno valley (Fig. 2). However, we cannot exclude that a fan deposit rests below the topographic surface at the outlet of the Attone River, covered by the recent-most alluvial deposits. This indicates high aggradation rates, in agreement with active tectonic subsidence expected at the hanging-wall of the Montefalco Fault. Geo-archaeological evidence, consisting of remnants of a Roman Temple of 1700 years ago, sealed by 2 m thick alluvial deposit (Colacicchi and Bizzarri, 2008), seems to confirm an aggradation rate in the order of 1.17 mm/year at the outlet of the Attone River.

River long-profiles. We extracted three stream long-profiles from the Mauro, La Fornace and La Torre streams, which we consider representative of the rivers draining the NE-flank of the Montefalco hill from SW to NE (Fig. 8a). The streams range in length between 1000 and 2500 m, and they flow on the Montefalco unit mostly composed of conglomerates with abundant sand and clay layers. Visual inspection of the stream profiles reveals clear knick-points, the most prominent of which are well evidenced by the slope variation (dH/dL%, Fig. 8a), in good agreement with the mapped NE-dipping normal faults (Fig. 8b). We note that some of the knick-points are due to the presence of deep-seated landslides, which are abundant in the area (Bucci et al., 2016a), and to less erodible layers.

The correspondence between the faults and the knick-points evidences that the faults were active very recently. In addition we point out that the lowest knick-point along the stream profile (red star in Figure 8b, c) clearly affects the present-day alluvial-fan suggesting that the fault is active also during the Holocene.

Morphotectonic evolution

We recognize three main stages of the Quaternary morphotectonic evolution of the area (Fig. 9).

First, the initial formation of the ancient “Tiberino Lake” during the Early Pleistocene was due to the activity of the normal faults bounding the basin. Subsidence produced the accommodation space for the deposition of the Bevagna Unit and of the Montefalco gravels up to the Middle Pleistocene(Fig. 9a). In the W part of the study area, the Colle del Marchese Unit was deposited by rivers flowing from the Martani range into the basin, including the palaeo-Torinetto and the palaeo-Rovicciano streams. During this stage, the Puglia River was flowing to the SE into the present day Bastardo valley, and the Menotre River was still flowing to the SW into the present day Foligno valley. The main divide followed the alignment of the highest ridges (Fig. 6).

Second, the activity of the NE-dipping fault which (presently) borders the Montefalco hill to NE increased, hence downthrowing the Foligno valley and uplifting the Montefalco alluvial fan at its footwall (Fig. 9b). The event resulted in the establishment of two distinct sedimentary basins, the Foligno and the Bastardo valley, respectively E and W of the newly formed Montefalco ridge. The Bastardo valley hosted an endorheic basin, where a palustrine environment developed, testified by the deposition of the Pianacce Unit (Fig. 2, 9b). The deactivation of the Montefalco fan produced a (complete) re-organization of the drainage network, inducing a change in the position of the alluvial fans position and the size of the contributing catchments. On the other hand the lowering of the Foligno valley triggered headward erosion of the Attone, Topino, and Menotre Rivers. This stage is also marked by a stream capture of the palaeo Rovicciano stream which was diverted from its original NE direction towards the Spoleto valley to the SE. This is testified by the fact that the (two) Colle del Marchese gravels deposits which were formed by two NE flowing rivers have a different relationship with the present-day river network. Whereas the NW deposit is still connected to a river i.e., the Torinetto stream, the palaeo-Rovicciano stream is no longer connected to a river and the Rovicciano stream was captured towards the SE (Fig. 6, 9c).

Third, the last stage consisted in the further downthrowing of the Foligno valley, which produced enhanced stream headward erosion (Fig. 9c). The erosional event induced the Puglia and the Attone Rivers to enter the Bastardo valley, and triggered the onset of incision of the Pianacce Unit (Fig. 9c). As a result, the present-day divide is located in the centre of the Bastardo valley. We suggest that this differentiation occurred likely between the Late Pleistocene and the Holocene. In order to provide better constraints on the age of the two last evolution stages, it would be needed to have data about the timing of the river captures as testified by the age of the Pianacce Unit within the Bastardo valley. Unfortunately, to date, no good fauna content within the unit has been found which can provide an absolute age, and the only information is from relative dating obtained by stratigraphic relationships. Headward erosion of the Topino River reached the catchments of the palaeo-Menotre River inverting the course of the Menotre River. As a result, the present-day shape and size of the Topino catchment is wide, and elongated orthogonally to the outlet direction (Fig. 6, 9c).

Discussion

A fossil alluvial fan

The Montefalco alluvial fan is fossil, and down cut on the NE flank by a set of normal faults responsible for the deepening of the Foligno valley. The fan is presently about 100 m higher in elevation than the Bastardo valley to the W, and about 200 m higher than the Foligno valley to the E.

The Montefalco fan delivered materials into a gulf of the ancient "Tiberino Lake", represented by the Bastardo valley. Today, the valley is incised by the Puglia and the Attone rivers, whereas active subsidence characterizes the Foligno valley occupied entirely by alluvial deposits. The Montefalco conglomerate overlies the Bevagna Unit. Stratigraphic correlations, faunistic assemblages that correlate with the Tasso faunal units (Rook et al., 2010), and palaeomagnetic measurements (Gliozzi et al. 1997; Bizzarri et al. 2001), concur in establishing an age for the Bevagna Unit between ~ 1.8 and 0.78 Myr. We conclude that the drainage inversion caused by the uplift of the Montefalco fan is younger than 0.78 Myr. If we consider the 200 m difference in elevation between the top of the Montefalco hill and the Foligno valley as a proxy for the vertical component associated to the extension in the last 0.78 Myr, we infer a minimum vertical deformation rate of ~ 0.25 mm/yr, similar the slip-rates along the same alignment of normal faults in the upper Tiber River valley, NW of the study area (Fig. 1b, Pucci et al. 2014).

The high resolution seismic reflection profiles in the Foligno valley show that the alluvial deposits in the valley reach at least 150 m of thickness . The seismic reflection line (Fo1) shows that the continental infill below the alluvial deposits is at least 700-800 m thick. The reflectors underneath the fluvial deposits are tilted towards SE, testifying the activity of the NE-dipping fault bordering the Montefalco ridge in the Holocene.

Previous work (Gregori, 1988) depicted a tectonic evolution in which a master fault dipping to the SW first created the Foligno valley. This was followed by the activation of a NE-dipping fault bordering the valley, and by the migration of the active subsidence from E (Foligno valley) to W (Bastardo valley). The main implication of this interpretation was that the Montefalco conglomerate flew from the SW (Gregori and Cattuto, 1986; Cattuto et al. 2005). We discard this interpretation because, based on our data, we infer that the Montefalco fan represents an ancient analogue of the present-day Foligno fan (Fig. 3d) built by the Topino River flowing from NE to SW. Our interpretation is supported by the presence of small outcrops of the Montefalco Unit near the town of Foligno (locality "I Cappuccini", Fig. 2). These deposits, laying at about 315 m of elevation, exhibit the same lithology and the same depositional environment as the Montefalco deposits. Moreover, the size of the clasts is larger than those on the Montefalco hill (Fig. 3b), and their roundness is lower than the gravel found in the Montefalco hill, indicating a more proximal depositional environment. We interpret the deposit of the Montefalco Unit in the Foligno area as a remnant of the palaeo-fan which was built by a palaeo-Topino River before the activation of the Montefalco Fault system. The activation of this fault system induced subsidence in the Foligno valley and the deactivation of the Montefalco fan which was uplifted at the normal fault footwall.

Late Pleistocene - Holocene normal faults activity

Extensional tectonics reached the study area in the Late Pliocene - Early Pleistocene (Barchi, 2010). Today, the extension rates are ~ 2.7 mm/yr (Hunstand et al. 2003; D'Agostino et al. 2009) and interact with a regional uplift of ~ 0.5 mm/yr, which has affected the area since about 1.5 Myr (Ambrosetti et al. 1982a, 1982b; Cinque et al. 1993; D'Agostino et al. 2001). The interaction produced a configuration in which the active subsiding basins do not always coincide with the active depocenters, depending on the balance between the efficiency of the basin-bounding faults in producing subsidence and the regional uplift. Where normal faults are efficient in producing subsidence at rates larger than the regional uplift, mainly aggradation occurs. Conversely, where normal faults are active but their vertical component rate is lower than the regional uplift, incision prevails (Pucci et al. 2014).

Today, the Foligno valley is flat and infilled with a thick sequence of alluvial deposits (about 150 m). We interpret this configuration as evidence of the valley being subsiding, despite the regional uplift of the Apennines.

Previous studies showed that a 600 m – thick Pleistocene sequence is present underneath the alluvial deposits (Barchi et al. 1991). The upper-most part of this sequence is shown by the high-resolution profile Fo1 (Fig. 5) down to about 800 m. Considering the presence of the Pleistocene sequence and of the overlying thick alluvial deposits, as well as the absence of river terraces, we conclude that the Foligno valley has been a subsiding basin roughly continuously since the Early Pleistocene.

Along the same fault system, NW of the study area there exist three extensional basins elongated in a SE-NW direction (Ponte Pattoli, Umbertide, and Sansepolcro, Fig. 1b). Previous studies suggested that the three basins behave differently in terms of the basin bounding faults efficiency in producing active subsidence (Melelli et al. 2014; Pucci et al. 2014). In particular, it was suggested that the Ponte Pattoli and Umbertide basins are subsiding at rates smaller than the Sansepolcro basin, which is similar to the Foligno valley. Also in the Sansepolcro valley, similar values of Pleistocene continental sequence (about 1.2 km, Barchi and Ciaccio, 2009) and of alluvial deposits (about 150 m) are found together with the absence of river terraces (Pucci et al. 2014). The Foligno and the Sansepolcro basins differ from the Ponte Pattoli and Umbertide basins also in terms of historical seismicity. In the Foligno and Sansepolcro basins the historical seismicity shows a maximum epicentral intensity I0 = VIII (Rovida et al., 2011), whereas in the area between Ponte Pattoli and Umbertide only a few events of smaller intensity have been recorded. In our interpretation, the difference in the active subsidence revealed by the greater thickness of the alluvial deposits and the absence of river terraces, coupled with the more intense historical seismicity, suggest that differences exist in the basin bounding normal fault rates in creating hanging-wall subsidence.

Role of pre-existing topography

The superposition of different tectonic environments results in significant differences in the evolution of topography, and the corresponding pattern of the drainage network (Mazzanti and Trevisan, 1978). In our study area, the Miocene collisional tectonic phase produced a topography characterized by mountains separated by valleys that coincided with the axial culminations of anticlines and synclines, which controlled the position of the main divides and rivers. The reconstruction of the palaeo-Menotre River flowing to the S is an example of a river which flew according to the geometry of the contractional ridges, following a valley formed in a thrust-related syncline (Fig. 9) Along with these major topographic features, several transverse drainages developed as a result of simple antecedence (Burbank et al. 1996) or a combination of antecedence and superposition (Mazzanti and Trevisan, 1978; Alvarez, 1999).

The pre-existing drainage pattern was inherited by the younger drainage network that developed starting from the onset of Quaternary extension. The effect of the extensional tectonics was to produce or to enhance new depocenters where the rivers discharged their sediments, and to form new high areas at the footwall of the normal faults, causing river headward erosion. Where headward erosion reached a previously low topographic area (e.g., a pre-existing valley), the drainage area increased suddenly through the capture of pre-existing catchments. This is the case of the Attone River (Fig. 2, and river n° 18 in Fig. 6). As a result, some catchment is anomalously large with respect to the size (area) of its alluvial fan. Differences in river erosion and catchment areas can also be due to the different erodibility of the rocks in the catchments. However, in the study area we observe similar anomalies in terms of erosion and alluvial fans catchment areas for rivers draining different lithology domains like carbonate rocks, siliciclastic deposits and continental units. On these bases, we suggest that some of the data scatter in a fan area – contributing area plots are due to tectonic effects, which in turn induced river piracy.

We observe the same pattern in many alluvial fans. Matching geomorphological observations with the plot of the fan area – catchment area, we find that with respect to the average, the fans that were captured lay above the regression line, and the catchments that captured other streams lay below the regression line (Fig. 7a). As an example, the fans n. 4, 5, 6 are 7 are too large for their current contributing area and are expected to deliver less sediments than they did in the past. Part of their contributing areas were captured by the Topino (n. 2) and of the Menotre (n. 3) rivers, which, on the contrary, are expected to deliver more sediments than they did before capture.

A model for alluvial-fan growth in an active extensional setting

In continental environments, the development of alluvial-fan successions, their shape and size, and the variability of their architecture are controlled by the tectonics of the basin margins, and the climate influence on denudation and discharge of water and sediments (Blum and Törnqvist, 2000; Gibling et al. 2011). The distribution of the fan areas versus their catchments is linear in log-log plots, and most Authors relate the data scatter to the different tectonic environment (extensional, compressional) and sediment discharge related to climate (latitude and relief) (Guzzetti et al. 1997; Mather et al. 2000; Viseras et al. 2003; Harvey, 2002, Harvey et al., 2005).

We point out that the regression fittings average empirical data which can mask very different conditions. Our results suggest that part of the data-scatter may be related to the dynamic evolution of the fans, affected by catchment piracy operated by rivers at the expenses of nearby rivers. As shown in Fig. 7, we find that fans of capturing rivers are systematically below the regression line, whereas fans of captured rivers are above the regression line, as a result of river captures. Basing on geomorphological analysis (Fig. 6), we are able to distinguish data which are clearly related to stream piracy effects with a consequent significant difference in the meaning of the fan and catchment areas.

Based on our data and observations, we propose a model of alluvial-fan growth in active extensional settings as described in Fig. 10. Let us consider a continental extensional basin where a series of alluvial-fans draining the footwall of basin-bounding normal faults. The increase in activity of one fault of the fault system increases the subsidence of the hanging-wall block, and promotes headward erosion at the fault footwall, with a consequent enlargement of the catchment size (Fig. 10, stage a). As the process continues, headward erosion can become so strong to break the threshold with a bordering catchment, capturing part of the neighbouring catchment (Fig. 10, stage b). The capturing river increases the size of the catchment but the inherited alluvial fan exhibits a small area, compared to the size of the (enlarged) catchment. At the same time, the captured river has a fan too large compared to the (reduced) catchment. The capturing river will tend to deliver more sediments, increasing the size of the alluvial fan in response to the enlarged catchment area (Fig. 10, stage c). We suggest that the growth/abandonment of fans is similar to the well-established growth of faults populations, where the growth of nearby fault segments occurs at the expenses of smaller faults, the offset of which is included into the capturing growing fault (Kim and Sanderson, 2005).

Our data indicate a strong correspondence between the most active faults and stream catchments piracy at the footwall of the normal faults. In the study area, the enhanced faults activity is further reflected by the active subsidence of the Foligno valley.

Since there is nothing peculiar or unique in the fans and faults in the investigated area, we hypothesize that similar processes occur in similar extensional settings. We conclude that part of the data scatter commonly observed in fan-area plots may be related to catchments piracy induced by active tectonics.

Conclusions

We identify the Montefalco ridge in the Northern Apennines as a fossil alluvial-fan which was dissected by the activation of the NE-dipping Montefalco fault system after Early Middle-Pleistocene. The Montefalco fan abandonment at the normal faults footwall created a drainage inversion in which the former river deposit is presently uplifted above the present-day alluvial plain. The present-day alluvial plain is undergoing active subsidence, triggering strong headward erosion of the rivers draining into it.

We suggest that a change of relative subsidence controlled by the normal faults activity occurred between the Late Pleistocene and the Holocene. Such distribution positively correlates with the distribution of the historical seismicity.

The river-long profiles draining the Montefalco hill reveal a strong correspondence between knick-points and the mapped faults. In addition, a knick-point along the Mauro stream in correspondence of the normal fault closest to the Foligno Valley (Fig. 8c) indicates that the fault displaces a present-day alluvial fan, suggesting that the fault system is active also during the Holocene. This is also in agreement with the thickening of the alluvial deposits towards the NE-dipping normal fault observed in the seismic profiles.

Tectonically induced headward erosion caused streams piracy and capture affecting the dimension of the present-day alluvial fans contributing areas. We plot the alluvial fans areas vs their contributing areas and find that the data-points follow a regression line in log-log plot similar to other authors' data-sets. The comparison of the data distribution with the geomorphological information regarding the river inversions and captures shows that the rivers which caused piracy at the expenses of other streams have got anomalous large catchments with respect to their fans dimension and are located below the regression line. These rivers (capturing) are expected to grow in the size of their fans to equilibrate their contributing areas. As opposed, the fans of captured rivers are located above the regression line. Due to the reduction of the size of their catchment area, the captured river is expected to deliver a reduced amount of sediments to their fans, with the consequent decrease of the fan growth rate.

We propose a model of alluvial fans growth in active extensional settings in which the capture of the nearby contributing areas can produce anomalous large values of contributing areas with respect to the corresponding fan, which has not yet had enough time to re-equilibrate its volume. The process affects the data-scatter distribution in the alluvial fans areas/catchment relationships in the study area, and we suggest that the same may occur in similar extensional settings worldwide. We conclude that stream piracy processes are sensitive to local rate of tectonic deformation and can contribute to highlight the increase of activity of individual fault segments in tectonically active areas, benefiting seismic hazard assessments.

We point out that integrated approaches investigating both the geological record and the morphotectonics of Quaternary basins, compared with present-day drainage networks, allow to bridge long-term deformation rates with geodetic rates of deformation, and can help understand the steadiness/unsteadiness of faults behaviour, unravelling the areas which have experienced a very recent tectonic perturbation.

Acknowledgments

We thank the Editor, P. Hughes, for editorial assistance and two anonymous reviewers for their constructive and helpful comments.

Funding information

This work was supported by Fondazione Cassa di Risparmio di Perugia, project code 2012.0242021 (grant to F. Mirabella), the Department of Physics and Geology, University of Perugia (grant to F. Mirabella), the IRPI-CNR (project M3RIGEL, 2016-18), and the Umbria Region under contract POR-FESR 861.2012.

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Figure captions

Fig. 1. (a) Location map of the study area. The map shows the position of the historical seismicity (M≥5), of the main normal faults and the position of the present-day alluvial-fans and alluvial deposits. The map also reports a sketch of the underlying geology. **(b)** Study area within the main normal faults alignment from Spoleto to the SE to Sansepolcro to the NW.

Fig. 2. (**a**) Geological sketch of the area across the Bastardo and Foligno valleys. The sketch is oriented SW-NE and is redrawn from- and integrated with- the map after Bucci et al. (2016a). The map reports the traces of the high resolution seismic reflection profiles (Fig.5a, b) and the trace of the integrated geological cross-section (A-A', Fig.5c). (**b**) Sketch of the stratigraphic relationships within the area. See text for stratigraphy details.

Fig. 3. (**a**) View towards the East of the Foligno fan from the Montefalco hill. The rose-diagram reports the palaeo-currents indicators of the Montefalco alluvial fan. The diagram is the sum (red line) of the data (n = 34) acquired by Regione Umbria (2014) (blue line) and of the data (n = 32) within this work (green line). Inset a) also reports the position of the outcrops of insets 3c and 3d.

(**b**) Example of embricate clasts in the Montefalco Unit composed of organised in layers. The stereographic projection reports the poles (n = 28) of bedding layers (yellow), the dip direction (blue) of embricate planes (n = 32), and the computed flow direction (blue arrow).

(**c**) Well cemented embricate clasts of the Montefalco Unit. The position of the outcrop is Fig. 3a). (**d**) Outcrop of the Montefalco Unit at Foligno (outcrop position in Fig. 3a). Here, the facies is more proximal than at Montefalco (Figs. 3b and 3c).

Fig. 4. (**a**) View towards the South of the Montefalco hill, showing the sub-horizontal beds (yellow) and the morphological evidence of the NE-dipping normal faults. The stereo-plot is the stereographic projection (Schmidt net, lower hemisphere) of the mapped normal faults (n = 7) and the resulting

stresses analysis. (**b**) Outcrop of a normal fault (position in a) within the continental sequence and fault kinematics. (**c**) View of the western part of the Bastardo valley (filled by the Colle del Marchese Unit – CU, and the Bevagna Unit - BU), at the contact with the Mt. Martani ridge (shaped on the Bedrock). The stereographic projection (Schmidt net, lower hemisphere) reports poles to planes (n = 27) of the Giano dell'Umbria Fault system and the resulting average dip and kinematics (red arrow). (**d**) Geometry and kinematics of one of the faults of the Giano dell'Umbria fault System (position in c)

Fig. 5. (**a-b**) High resolution seismic reflection profiles (trace in figure 2a) showing the depth geometry of the Bevagna Unit, of the normal faults bordering the eastern flank of the Montefalco hill and the thickness of the alluvial deposits. (**a**) Shows the difference in seismic facies between the bedrock at the normal faults footwall and the layered continental sequence made of sands and clays. (**b**) SW-tilt of the Bevagna Unit and alluvial deposits thickening towards the SW. (**c**) Geological cross-section (trace in figure 2) across the Foligno valley which integrates the surface geology and the seismic profiles of a) and b). The SW part of the section is extrapolated to depth of the basis of a) and b), the NE part of the section is extrapolated to depth on the basis of previous work (Barchi et al., 1991). The section reaches the outcrop of the Montefalco Unit near Foligno (locality "I Cappuccini", Fig.2a).

Fig. 6. Geomorphological map of the study area. The map is oriented E-W and shows the evidences of drainage perturbation on both the western and eastern reliefs induced by the increase in subsidence of the Foligno valley. The numbers refer to the drainage areas of specific rivers which captured of were captured by a nearby river. The numbers are the same as those in figure 7. We mapped the geomorphological anomalies related to the migration of the watershed, hanging palaeo-valleys, anomalous confluences and the direction of the palaeo-rivers for the most significant rivers in the study area. See text for description and discussion.

Fig. 7. (**a**) Log-Log plot of the alluvial fans areas towards basins areas of the study area. The regression line was obtained through a logarithmic space quantile regression, applied to the 50th (dotted thick line) 5th, and 95th percentiles (grey shaded area) of the distribution. The data distribution is self-similar (equation of the type $A_F = q * A_B^n$). (**b**) Distribution of the alluvial fans (points in Figure 7a) related to capturing and captured rivers. In both figures, red and black numbered circles represent the alluvial fans related to rivers clearly perturbed by the Foligno valley subsidence which induced captures and drainage inversions (Figure 6).

Fig. 8. (**a**) stream-long profiles of the Mauro, La Fornace and La Torre streams plotted together with the downstream variation in slope % (dH/dL, where H is elevation and L is distance). The symbols (diamond, circle, triangle, square and star) represent the correspondence between stream knick-points and mapped normal faults. (**b**) map location (inset of in Fig. 2) of the streams shown in a) on the NE-flank of the Montefalco hill. (**c**) drape of an aerial photograph on a 10m resolution DEM (TIN-Italy - Tarquini et al., 2007). We used a three-times vertical exaggeration to mimic the vertical exaggeration of the stereoscopic images. The image was drawn by using the QGIS2threejs plugin of QGIS (QGIS Development Team, 2018). On the image, the trace of the normal fault affecting the Holocene alluvial fans is evidenced with the white arrows.

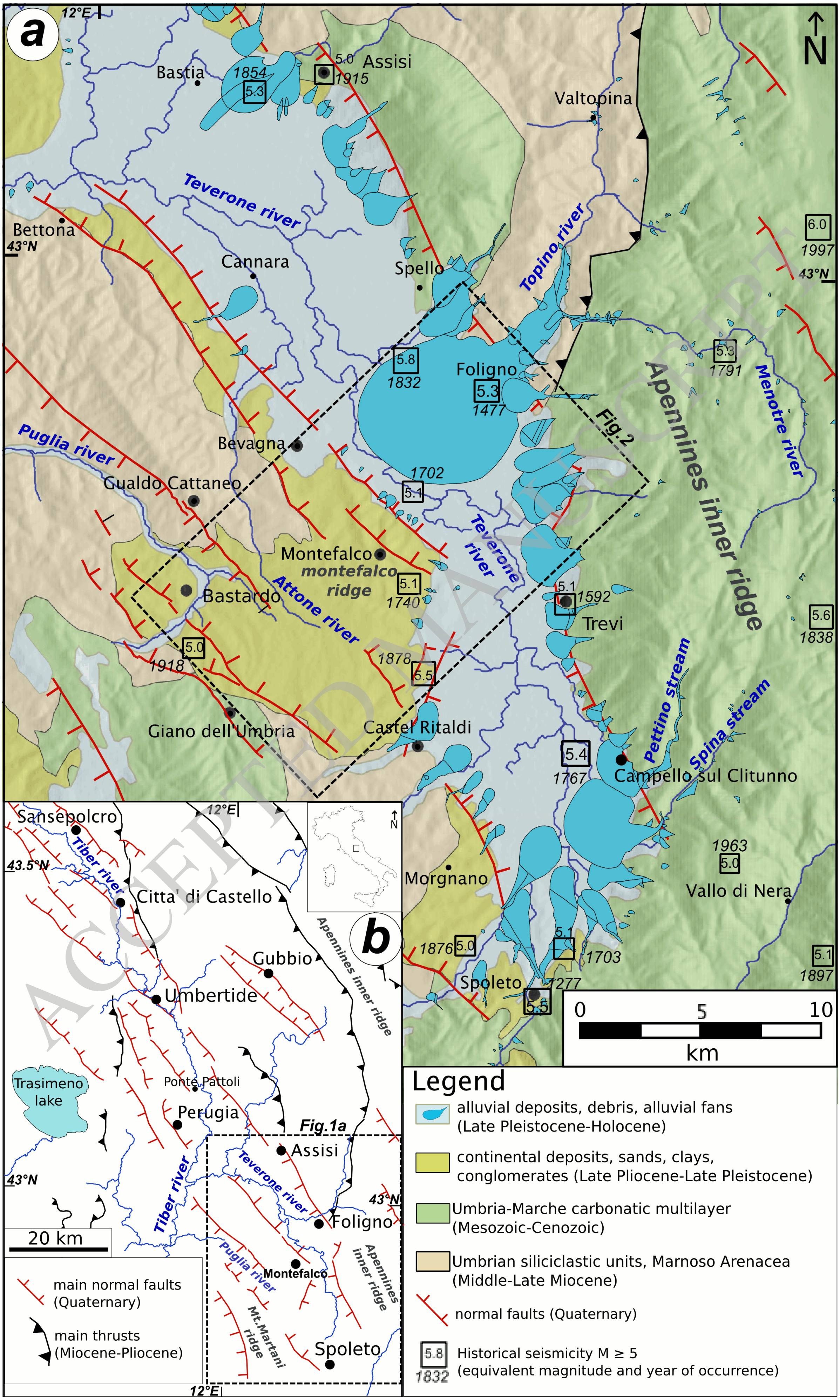
Fig. 9. Tectono-sedimentary evolution of the study area. (**a**) Early-Middle Pleistocene, initial formation of the continental basin. (**b**) Middle-Late Pleistocene, the increase in activity of the Montefalco east-dipping fault downthrows the Foligno valley and uplifts the Montefalco fan (**c**) Upper Pleistocene-Holocene, further downthrowing of the Foligno valley and strong -stream headward erosion. See test for details.

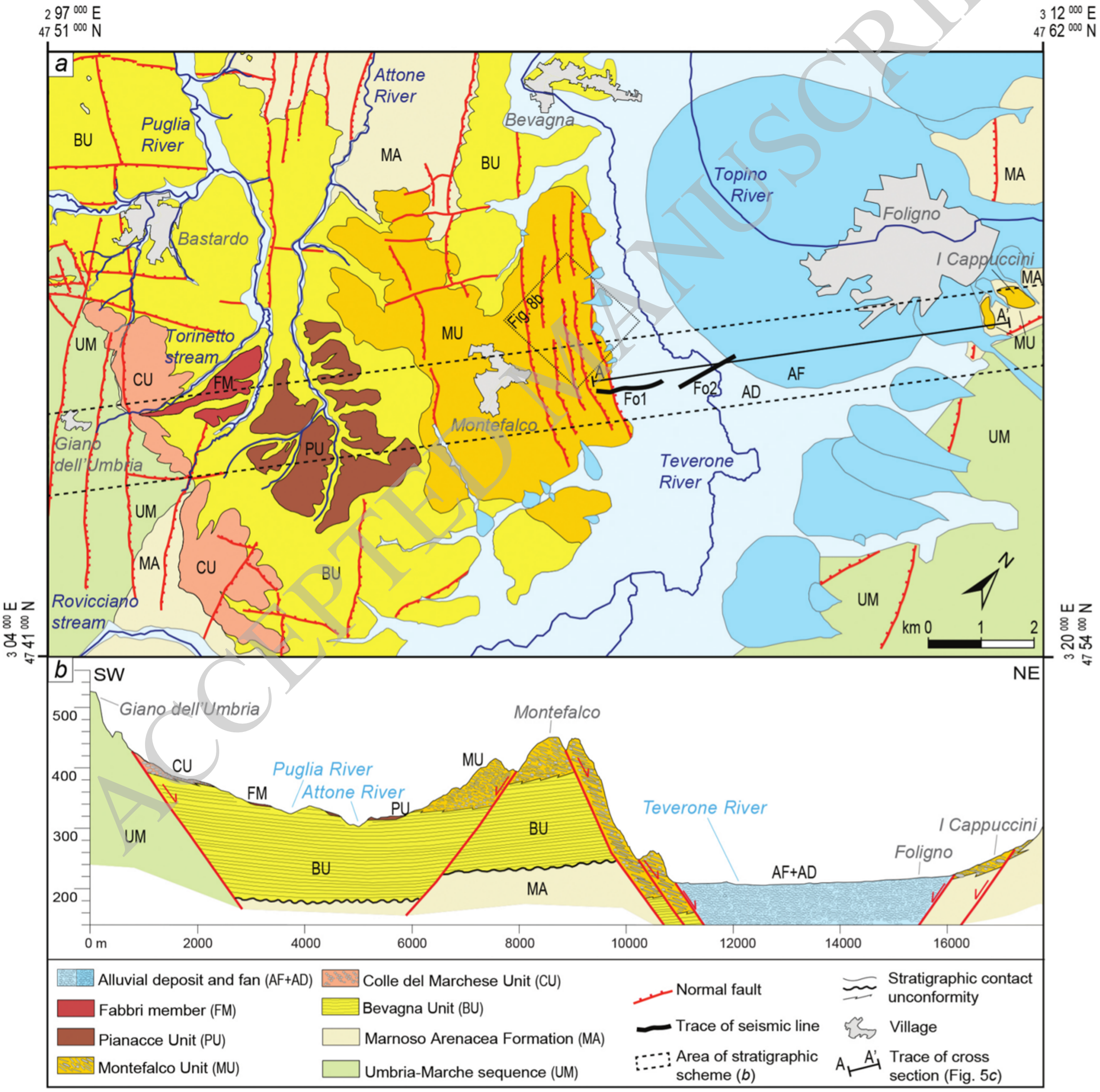
Fig. 10. Conceptual sketch of the growth of a set of alluvial fans in an actively subsiding basin where one or more fault segments are more active than others. Increase of tectonic subsidence triggers headward erosion and drainage capture of neighboring rivers. See text for explanation.

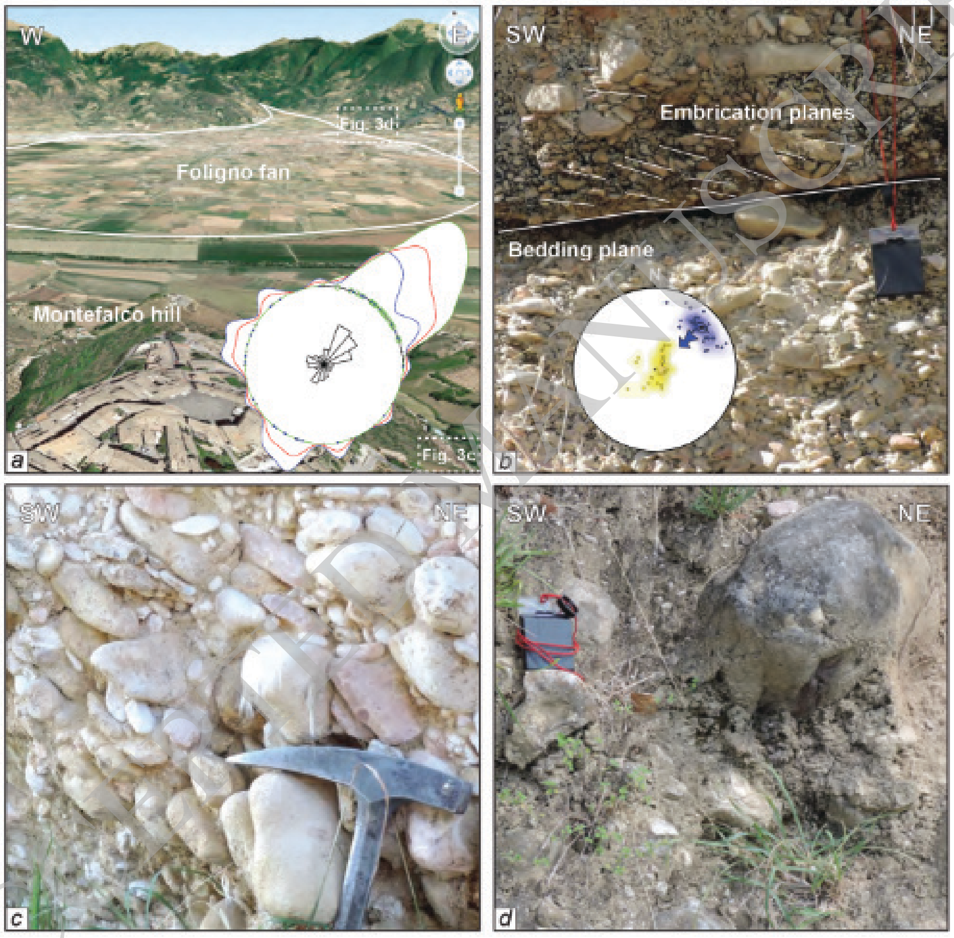
Table caption

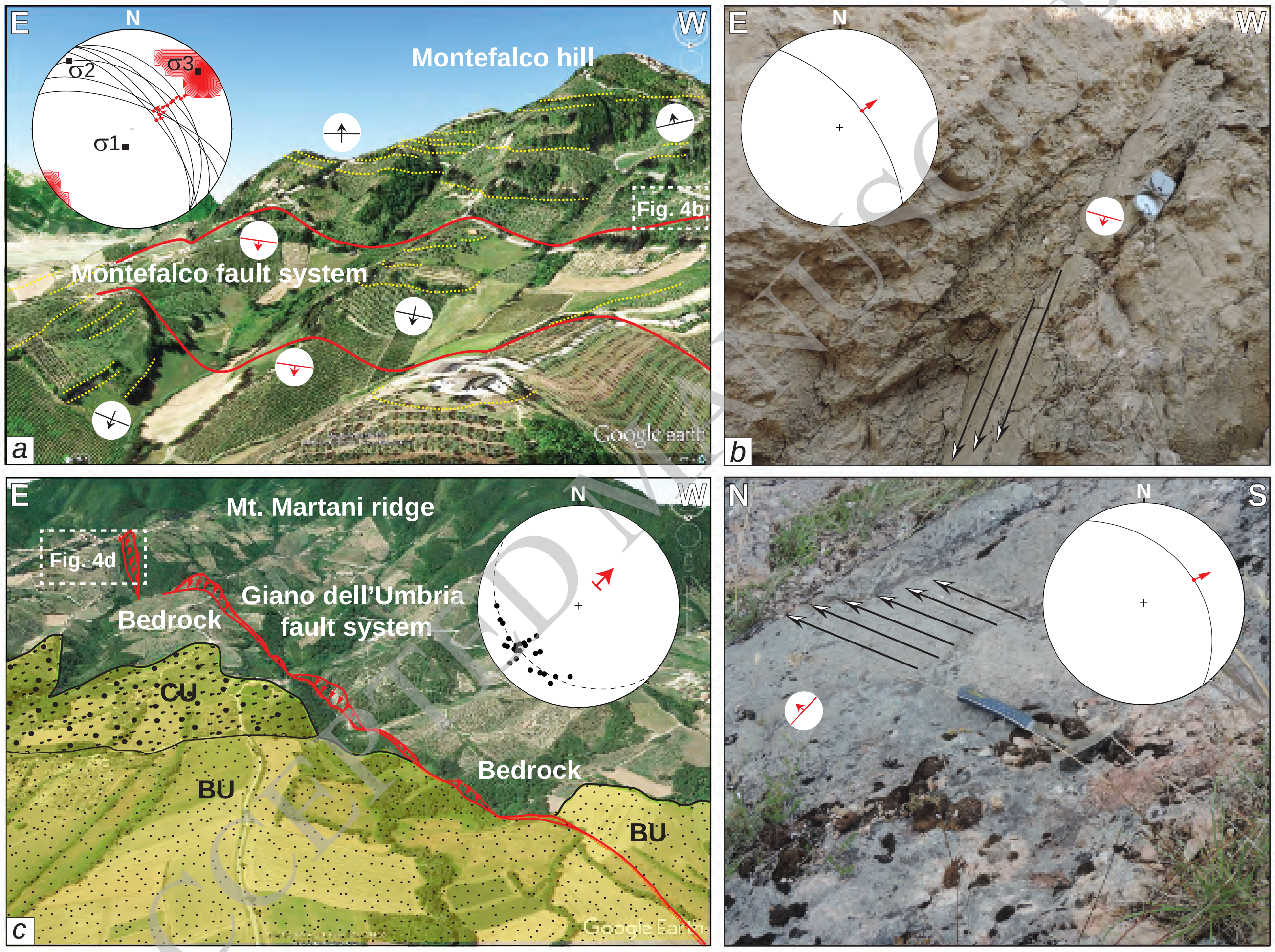
Table 1. Stratigraphical, depositional and tectonic features of the continental deposits of the study area. See text for details.

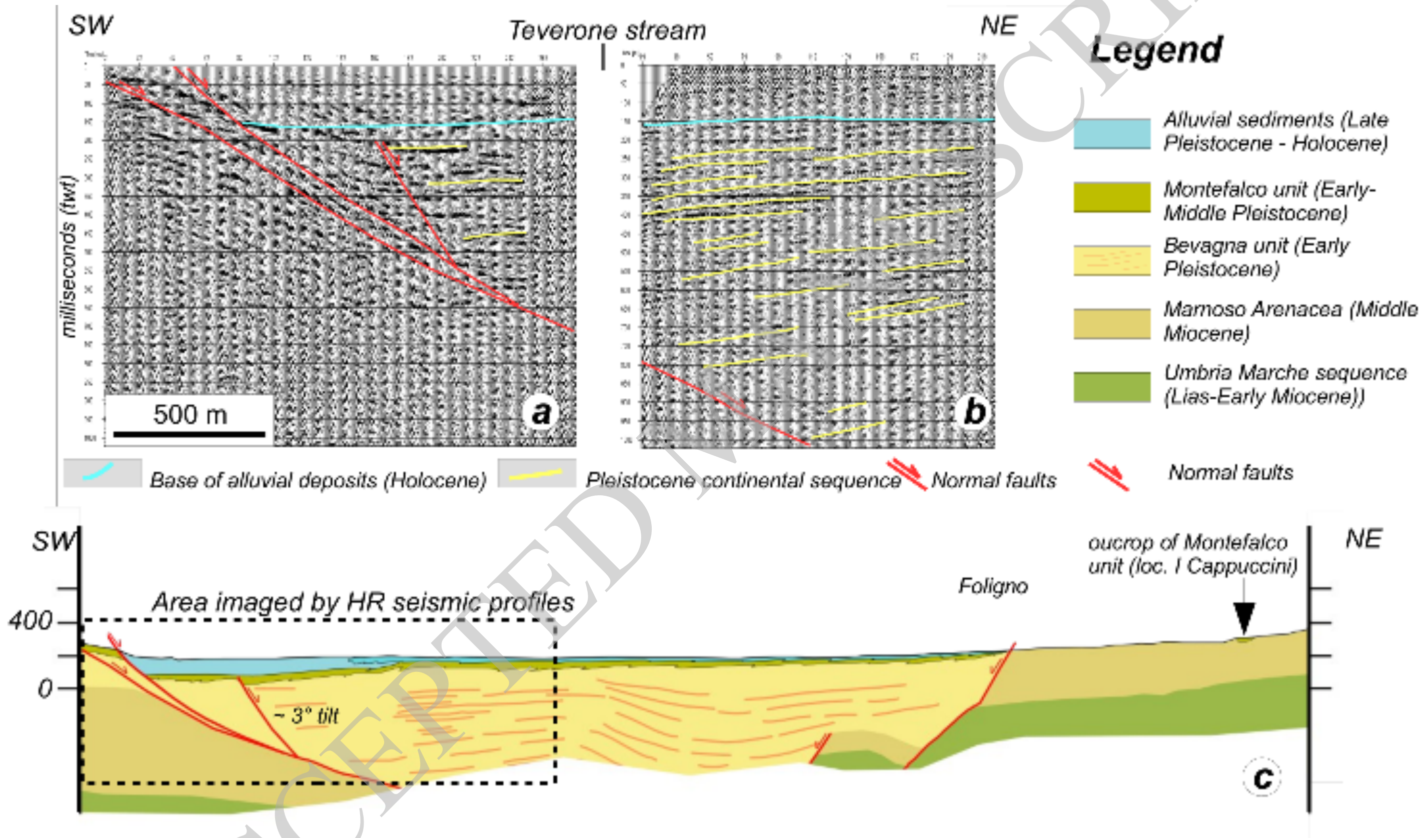
Lithostratigraphic Unit	*Stratigraphic feature*	*Depositional environment*	*Age*	*Evidences of tectonic activity*
Alluvial deposits (AD)	Fine-grained floodplain sediments made of gray and yellowish clays and sandy clays	Floodplain	Late Pleistocene -Holocene	Thickening at the fault hanging-wall at the base of the E slope of the Montefalco Hill
Alluvial fans (AF)	Coarse-grained fan-shape debris deposits in a silt and subordinately clay matrix	Alluvial, fluvial	Late Pleistocene -Holocene	Fans aligned at the hanging-wall of the Foligno Valley bounding faults
Pianacce Unit (PU)	Brown and subordinately red clay and silty clay whith sporadic carbonate clasts	Palustrine, locally connected to distal part of alluvial fan environment	Middle - Late Pleistocene	The deposit is present only in the Bastardo valley with no direct evidence of faulting
Colle del Marchese Unit (CU)	Conglomerate and gravel made up of clasts of mesozoic-cenozoic carbonates, in a silt and subordinately clay matrix	Poor rounding of pebbles indicates a fluvial depositional environment proximal to the origin	Early-Middle Pleistocene	Faulted deposits at the hanging-wall of the Giano dell'Umbria fault System (Mt. Martani ridge)
Montefalco Unit (MU)	Conglomerate and gravel made up of rounded locally sub-angular and rarely flat pebbles and cobbles in a sand or silt matrix. Clasts are Mesozoic-Cenosoic carbonates and subordinately sandstones of E-NE origin.	Gravel bar deposition alternated to sandy and silty layers suggests a braided pattern in the middle and distal part of alluvial fan environment	Early-Middle Pleistocene	i) Faulted deposits ii) Evidence of fault escarpment locally marked by triangular facets iii) Deposit uplifted at the footwall of the active fault system bounding SW the Foligno Valley
Bevagna Unit (BU)	Grey and yellow clay, sandy-clay with minor conglomerate lenses. Lignite layers are present locally.	Fine sediment related to floodplain, lacustrine or shallow lake environment	Early Pleistocene	(7) Faulted deposits (8) Inclined and tilted bedding related to fault activity

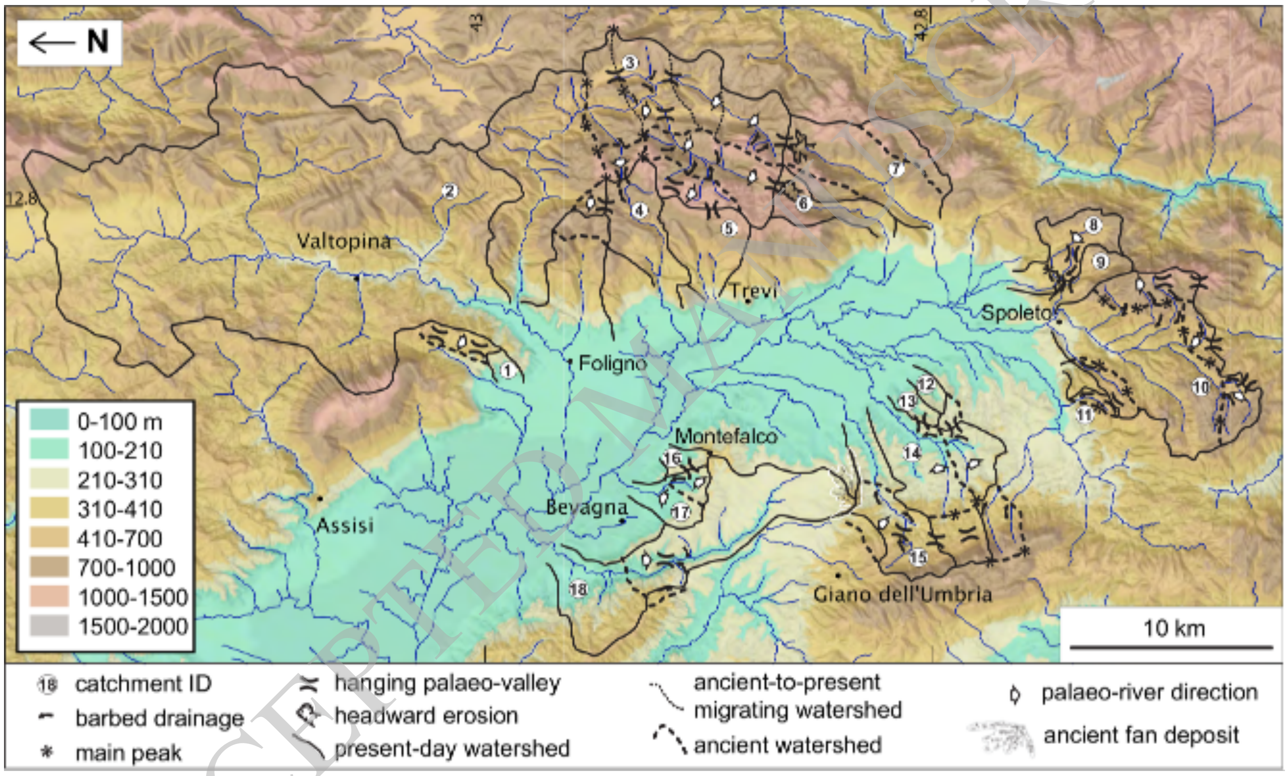

a
12°E
N
Assisi
5.0
1915
Bastia
1854
5.3
Valtopina
Teverone river
Bettona
43°N
Cannara
Spello
Topino river
6.0
1997
43°N
5.8
1832
Foligno
5.3
1477
5.3
1791
Menotre river
Fig.2
Apennines inner ridge
Puglia river
Bevagna
1702
5.1
Gualdo Cattaneo
Teverone river
Montefalco
montefalco ridge
5.1
1740
5.1
1592
Bastardo
Attone river
Trevi
5.6
1838
5.0
1918
1878
5.5
Pettino stream
Spina stream
Giano dell'Umbria
Castel Ritaldi
5.4
1767
Campello sul Clitunno
1963
5.0
Morgnano
Vallo di Nera
5.1
1703
1876
5.0
5.1
1897
Spoleto
1277
5.5
0
5
10
km
b
Sansepolcro
12°E
43.5°N
Tiber river
Citta' di Castello
N
Apennines inner ridge
Gubbio
Umbertide
Trasimeno lake
Ponte Pattoli
Perugia
Fig.1a
Assisi
43°N
Tiber river
Teverone river
43°N
Foligno
20 km
Puglia river
Montefalco
Apennines inner ridge
Mt.Martani ridge
Spoleto
12°E
main normal faults (Quaternary)
main thrusts (Miocene-Pliocene)
Legend
alluvial deposits, debris, alluvial fans (Late Pleistocene-Holocene)
continental deposits, sands, clays, conglomerates (Late Pliocene-Late Pleistocene)
Umbria-Marche carbonatic multilayer (Mesozoic-Cenozoic)
Umbrian siliciclastic units, Marnoso Arenacea (Middle-Late Miocene)
normal faults (Quaternary)
5.8
1832
Historical seismicity M ≥ 5 (equivalent magnitude and year of occurrence)

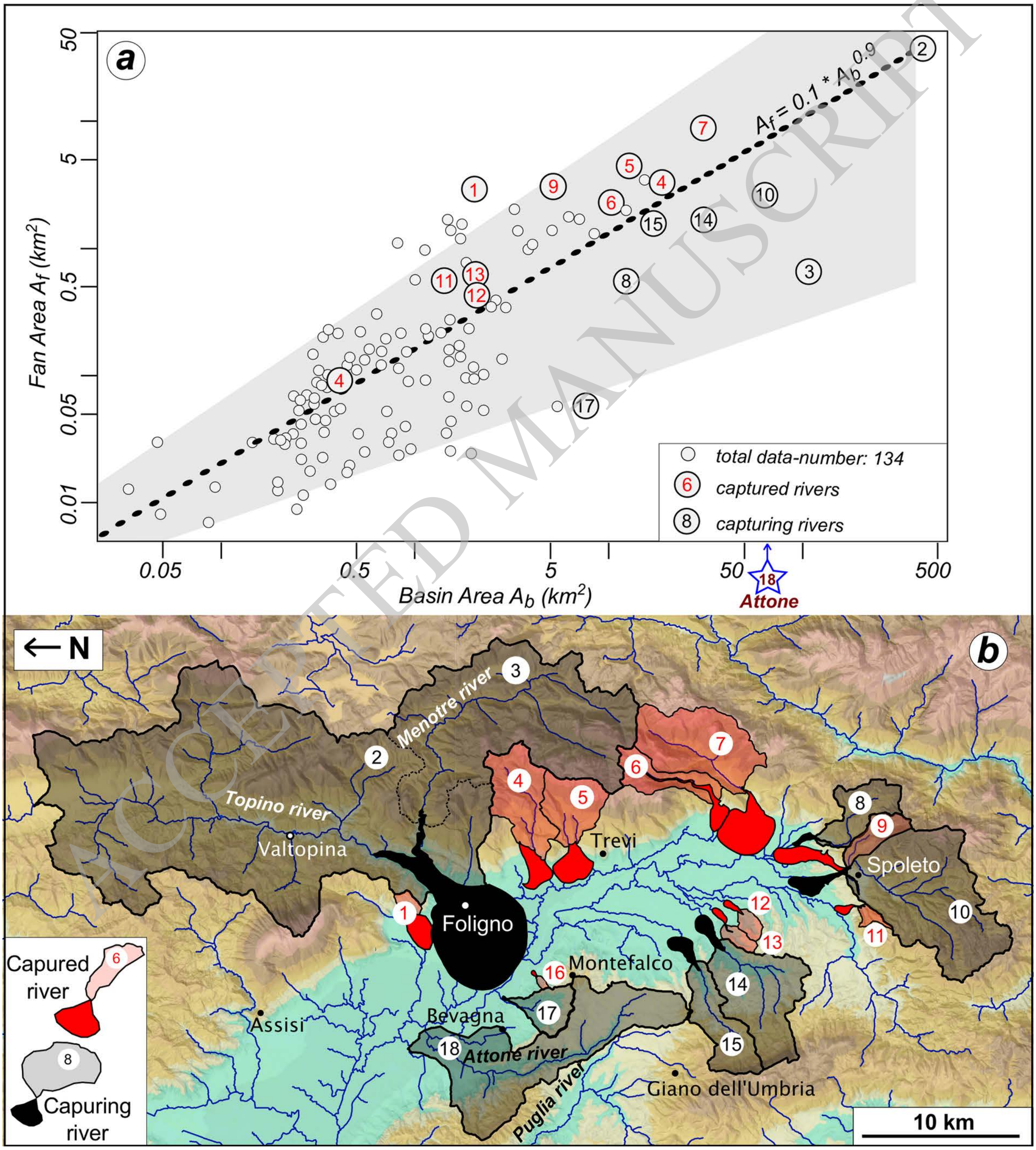

2 97 000 E
47 51 000 N
3 12 000 E
47 62 000 N
3 04 000 E
47 41 000 N
3 20 000 E
47 54 000 N
a
Attone River
Puglia River
Bevagna
Bastardo
Topino River
Foligno
I Cappuccini
Torinetto stream
Giano dell'Umbria
Montefalco
Teverone River
Rovicciano stream
Fig 8b
BU
MA
UM
CU
FM
PU
MU
AF
AD
A
A'
Fo1
Fo2
N
km 0 1 2
b
SW
NE
Giano dell'Umbria
Montefalco
Puglia River
Attone River
Teverone River
I Cappuccini
Foligno
AF+AD
500
400
300
200
0 m
2000
4000
6000
8000
10000
12000
14000
16000
Alluvial deposit and fan (AF+AD)
Fabbri member (FM)
Pianacce Unit (PU)
Montefalco Unit (MU)
Colle del Marchese Unit (CU)
Bevagna Unit (BU)
Marnoso Arenacea Formation (MA)
Umbria-Marche sequence (UM)
Normal fault
Trace of seismic line
Area of stratigraphic scheme (b)
Stratigraphic contact unconformity
Village
Trace of cross section (Fig. 5c)

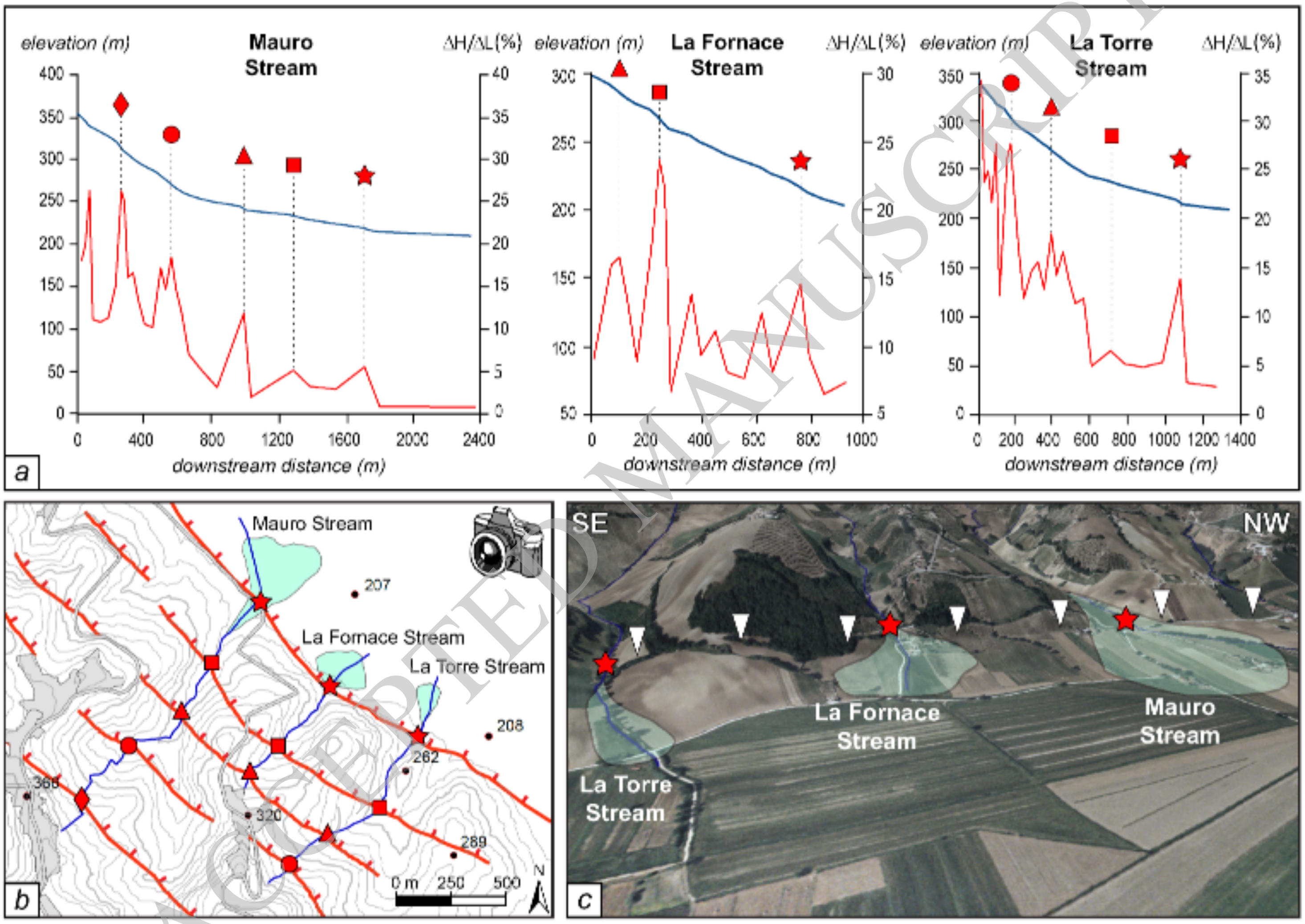

W
Fig. 3d
Foligno fan
Montefalco hill
Fig. 3c
a
SW
NE
Embrication planes
Bedding plane
b
SW
NE
c
SW
NE
d

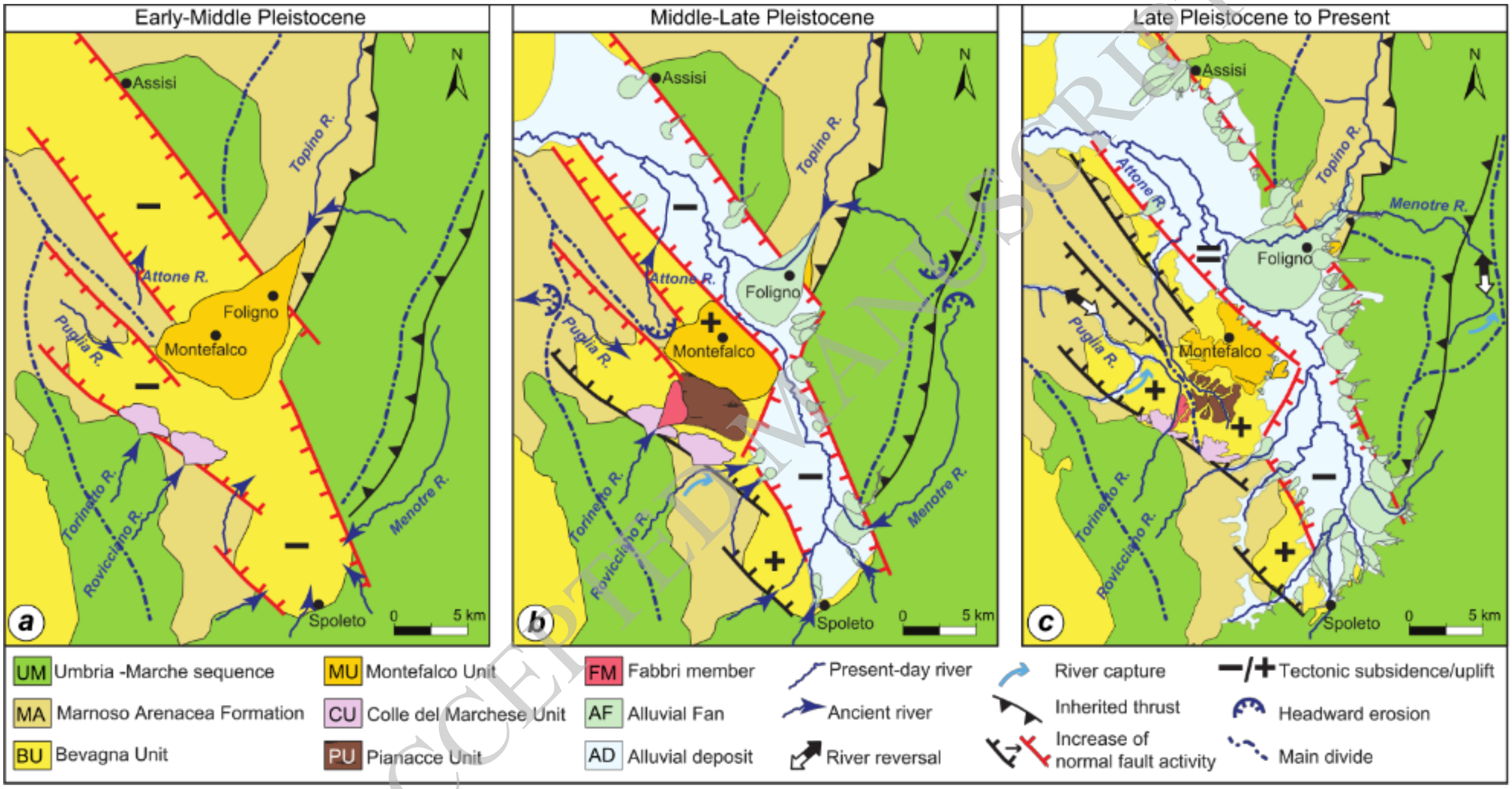

E
N
W
σ2
σ3
σ1
Montefalco hill
Fig. 4b
Montefalco fault system
Google earth
a
E
N
W
b
E
Mt. Martani ridge
N
W
Fig. 4d
Bedrock
Giano dell'Umbria
fault system
CU
BU
Bedrock
BU
Google Earth
c
N
N
S

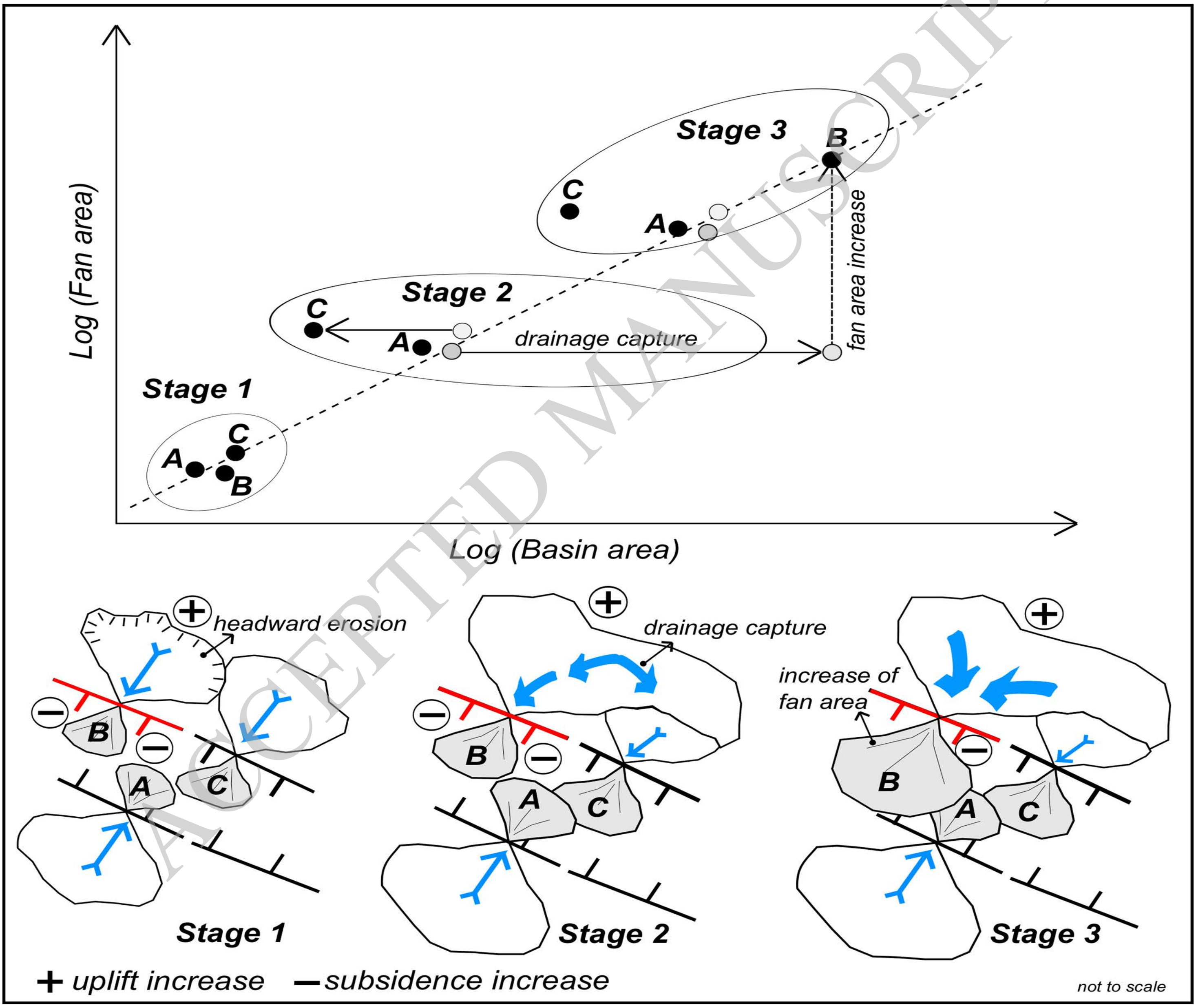

SW
Teverone stream
NE
milliseconds (twt)
500 m
a
b
Legend
Alluvial sediments (Late Pleistocene - Holocene)
Montefalco unit (Early-Middle Pleistocene)
Bevagna unit (Early Pleistocene)
Marnoso Arenacea (Middle Miocene)
Umbria Marche sequence (Lias-Early Miocene))
Base of alluvial deposits (Holocene)
Pleistocene continental sequence
Normal faults
Normal faults
SW
NE
400
0
Area imaged by HR seismic profiles
~ 3° tilt
Foligno
oucrop of Montefalco unit (loc. I Cappuccini)
c


N
43
42.8
12.8
Valtopina
Trevi
Spoleto
Foligno
Montefalco
Bevagna
Assisi
Giano dell'Umbria
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
0-100 m
100-210
210-310
310-410
410-700
700-1000
1000-1500
1500-2000
10 km
catchment ID
barbed drainage
main peak
hanging palaeo-valley
headward erosion
present-day watershed
ancient-to-present migrating watershed
ancient watershed
palaeo-river direction
ancient fan deposit


a
Fan Area A_f (km^2)
50
5
0.5
0.05
0.01
$A_f = 0.1 * A_b^{0.9}$
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
17
total data-number: 134
6 captured rivers
8 capturing rivers
0.05
0.5
5
50
500
Basin Area A_b (km^2)
18
Attone
b
← N
3
Menotre river
2
Topino river
Valtopina
7
6
4
5
Trevi
8
9
Spoleto
10
1
Foligno
12
13
11
16
Montefalco
14
17
Bevagna
Assisi
18
Attone river
15
Puglia river
Giano dell'Umbria
Capured river
6
8
Capuring river
10 km


elevation (m)
Mauro Stream
ΔH/ΔL(%)
400
350
300
250
200
150
100
50
0
40
35
30
25
20
15
10
5
0
0
400
800
1200
1600
2000
2400
downstream distance (m)
elevation (m)
La Fornace Stream
ΔH/ΔL(%)
300
250
200
150
100
50
30
25
20
15
10
5
0
200
400
600
800
1000
downstream distance (m)
elevation (m)
La Torre Stream
ΔH/ΔL(%)
350
300
250
200
150
100
50
0
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
1400
downstream distance (m)
a
Mauro Stream
207
La Fornace Stream
La Torre Stream
208
262
368
320
289
0 m
250
500
N
b
SE
NW
La Fornace Stream
Mauro Stream
La Torre Stream
c


Early-Middle Pleistocene
Middle-Late Pleistocene
Late Pleistocene to Present
a
b
c
N
Assisi
Foligno
Montefalco
Spoleto
Topino R.
Attone R.
Puglia R.
Torinetto R.
Roviccciano R.
Menotre R.
0
5 km
UM Umbria -Marche sequence
MA Marnoso Arenacea Formation
BU Bevagna Unit
MU Montefalco Unit
CU Colle del Marchese Unit
PU Pianacce Unit
FM Fabbri member
AF Alluvial Fan
AD Alluvial deposit
Present-day river
Ancient river
River reversal
River capture
Inherited thrust
Increase of normal fault activity
−/+ Tectonic subsidence/uplift
Headward erosion
Main divide


Log (Fan area)
Log (Basin area)
Stage 1
A
B
C
Stage 2
C
A
drainage capture
Stage 3
C
A
B
fan area increase
headward erosion
drainage capture
increase of fan area
B
A
C
Stage 1
Stage 2
Stage 3
+ uplift increase
— subsidence increase
not to scale