IT ISSN 0391 - 9838

GEOGRAFIA FISICA e DINAMICA QUATERNARIA

Bollettino del Comitato Glaciologico Italiano - ser. 3

An international Journal published under the auspices of the
Rivista internazionale pubblicata sotto gli auspici di

Associazione Italiana di Geografia Fisica e Geomorfologia
and (e) Consiglio Nazionale delle Ricerche (CNR)

recognized by the (*riconosciuta da*)

International Association of Geomorphologists (IAG)

volume 43 (1)
2020

COMITATO GLACIOLOGICO ITALIANO - TORINO
2020

GEOGRAFIA FISICA E DINAMICA QUATERNARIA

A journal published by the Comitato Glaciologico Italiano, under the auspices of the Associazione Italiana di Geografia Fisica e Geomorfologia and the Consiglio Nazionale delle Ricerche of Italy. Founded in 1978, it is the continuation of the «Bollettino del Comitato Glaciologico Italiano». It publishes original papers, short communications, news and book reviews of Physical Geography, Glaciology, Geomorphology and Quaternary Geology. The journal furthermore publishes the annual reports on italian glaciers, the official transactions of the Comitato Glaciologico Italiano and the Newsletters of the Intemational Association of Geomorphologists. Special issues, named «Geografia Fisica e Dinamica Quaternaria - Supplementi», collecting papers on specific themes, proceedings of meetings or symposia, regional studies, are also published, starting from 1988. The language of the journal is English, but papers can be written in other main scientific languages.

Rivista edita dal Comitato Glaciologico Italiano, sotto gli auspici dell'Associazione Italiana di Geografia Fisica e Geomorfologia e del Consiglio Nazionale delle Ricerche. Fondata nel 1978, è la continuazione del «Bollettino del Comitato Glaciologico Italiano». La rivista pubblica memorie e note originali, recensioni, corrispondenze e notiziari di Geografia Fisica, Glaciologia, Geomorfologia e Geologia del Quaternario, oltre agli Atti ufficiali del C.G.I., le Newsletters della I.A.G. e le relazioni delle campagne glaciologiche annuali. Dal 1988 vengono pubblicati anche volumi tematici, che raccolgono lavori su argomenti specifici, atti di congressi e simposi, monografie regionali sotto la denominazione «Geografia Fisica e Dinamica Quaternaria - Supplementi». La lingua usata dalla rivista è l'Inglese, ma gli articoli possono essere scritti anche nelle altre principali lingue scientifiche.

Editor Emeritus (*Direttore Emerito*)
P.R. FEDERICI
Dipartimento di Scienze della Terra, Via S. Maria 53 - 56126 Pisa - Italia - Tel. 0502215700

Editor in Chief (*Direttore*)
C. BARONI
Dipartimento di Scienze della Terra, Via S. Maria 53 - 56126 Pisa - Italia - Tel 0502215731

Vice Editor (*Vice Direttore*)
A. RIBOLINI
Dipartimento di Scienze della Terra, Via S. Maria 53 - 56126 Pisa - Italia - Tel 0502215769

INDEXED/ABSTRACTED IN: Bibliography & Index of Geology (GeoRef); GeoArchive (Geosystem); GEOBASE (Elsevier); *Geographical Abstract*: *Physical Geography* (Elsevier); GeoRef; Geotitles (Geosystem); Hydrotitles and Hydrology Infobase (Geosystem); Referativnyi Zhurnal.
Geografia Fisica e Dinamica Quaternaria has been included in the Thomson ISI database beginning with volume 30 (1) 2007 and now appears in the Web of Science, including the Science Citation Index Expanded (SCIE), as well as the ISI Alerting Services.

HOME PAGE: http://gfdq.glaciologia.it/ - CONTACT: gfdq@dst.unipi.it

Printed with the financial support from (pubblicazione realizzata con il contributo finanziario di):

- Comitato Glaciologico Italiano
- Associazione Italiana di Geografia Fisica e Geomorfologia
- Ministero dell'Istruzione, Università e Ricerca
- Consiglio Nazionale delle Ricerche
- Club Alpino Italiano

Comitato Glaciologico Italiano
President (*Presidente*) M. FREZZOTTI

Geogr. Fis. Dinam. Quat.
43 (2020). 3-13, 10 figg.

DOI 10.4461/ GFDQ.2020.43.1

SIMONE RACANO [1], GIANDOMENICO FUBELLI [2*], ERNESTO CENTAMORE [3],
MAURO BONASERA [2] & FRANCESCO DRAMIS [4]

GEOMORPHOLOGICAL DETECTION OF SURFACE EFFECTS INDUCED BY ACTIVE BLIND THRUSTS IN THE SOUTHERN ABRUZZI PERI-ADRIATIC BELT (CENTRAL ITALY)

ABSTRACT: RACANO S., FUBELLI G., CENTAMORE E., BONASERA M. & DRAMIS F., *Geomorphological detection of surface effects induced by active blind thrusts in the southern Abruzzi peri-Adriatic belt (Central Italy).* (IT ISSN 0391-9838, 2020).

In clayey-sandy regions, deformed geomorphological features, such as river channels and terraces, may represent valuable indicators of ongoing tectonic activity. In this perspective, geomorphometric indexes have been developed, among which the SL and k_{sn} indexes seem to be the most efficient to detect tectonically-induced stream anomalies. In the present study, we used these indexes to investigate the possible activity of the easternmost fold-and-thrust system of the Apennine orogen, mostly buried under a thick sequence of post- orogenic, clayey-sandy marine deposits, in a sector of Abruzzi located between the Maiella piedmont and the Adriatic coast. Whereas most authors consider these structures tectonically inactive, several others argue that they still undergo compression. In particular, we used the SL and k_{sn} indexes to identify surface deformations possibly induced by the ongoing activity of the buried structures. Moreover, based on geological-geomorphological field survey, supported by remote sensing and spatial data handling (TINITALY Digital Elevation Model, and the MATLAB® and QGis software products), we surveyed the tread profiles of river terraces in selected valley sectors. The investigation results agree in confirming the ongoing activity of the buried structures as well as the noteworthy effectiveness of the methods applied.

KEY WORDS: Morphotectonics, Active tectonics, Fluvial terraces, Hack (SL) index, k_{sn} index; Blind thrust, Apennine orogen, peri-Adriatic belt.

RIASSUNTO: RACANO S., FUBELLI G., CENTAMORE E., BONASERA M. & DRAMIS F., *Individuazione geomorfologica degli effetti superficiali indotti da* thrust *ciechi attivi nella fascia peri-adriatica degli Abruzzi meridionali (Italia Centrale).* (IT ISSN 0391-9838, 2020).

Nelle regioni a substrato sabbioso-argilloso la deformazione di forme fluviali quali i canali e i terrazzi può fornire preziose informazioni sulla presenza di attività tettonica. In questa prospettiva, sono stati sviluppati diversi indici geo-morfometrici, tra i quali il rapporto tra gradiente/lunghezza del canale (indice SL) e l'indice normalizzato del gradiente fluviale (indice k_{sn}) sembrano essere i più efficienti per rilevare anomalie idrografiche indotte dalla tettonica. Nel presente studio, abbiamo usato questi indici per evidenziare la possibile attività del sistema più orientale di pieghe e sovrascorrimenti dell'orogene appenninico, sepolto sotto una spessa sequenza di depositi marini argillosi-sabbiosi in un settore degli Abruzzi posto tra la zona pedemontana della Maiella e la costa adriatica. Mentre la maggior parte degli autori considera queste strutture tettonicamente inattive, molti altri sostengono che siano ancora sottoposte a compressione. Abbiamo usato gli indici SL e ksn per identificare deformazioni superficiali possibilmente indotte dall'attività delle strutture sepolte. Inoltre, sulla base dell'indagine geologica-geomorfologica sul campo, supportata dal modello digitale di elevazione TINITALY e dai prodotti software MATLAB® e QGis, abbiamo esaminato i profili longitudinali dei terrazzi fluviali in alcuni settori della valli principali. I risultati della ricerca concordano nel confermare l'attività delle strutture sepolte oltre alla notevole efficacia dei metodi applicati.

TERMINI CHIAVE: Morfotettonica, Tettonica attiva, Terrazzi fluviali, Indice di Hack (SL), Indice k_{sn}, Sovrascorrimenti ciechi, Orogene appenninico, Fascia periadriatica.

INTRODUCTION

In clayey-sandy regions, where significant lithological discontinuities are absent, deformed geomorphic features such as river channels and terraces may represent valuable indicators of ongoing tectonic activity (Hack, 1973; Keller & *alii*, 2000; Burbank & Anderson, 2001; Pazzaglia & Brandon, 2001; Tucker & Whipple, 2002).

In this perspective, several geomorphometric indexes have been utilized, among which the *stream length-gradient index* (SL) and the *normalized channel steepness index* (k_{sn}) are considered to be most efficient for detecting anomalies on stream-profiles possibly related to tectonically-induced ground deformation (Burbank & Anderson, 2001; Keller & Pinter, 2002).

---

[1] *GFZ German Research Centre for Geosciences - Potsdam, Germany.*
[2] *Dipartimento di Scienze della Terra - University of Torino, Italy.*
[3] *Dipartimento di Scienze della Terra - La Sapienza University of Rome, Italy.*
[4] *Dipartimento di Scienze - Roma Tre University, Italy.*

* *Corresponding author: G. Fubelli (giandomenico.fubelli@unito.it)*

We warmly thank Laurie Kurilla for the revision of the English text in the manuscript.

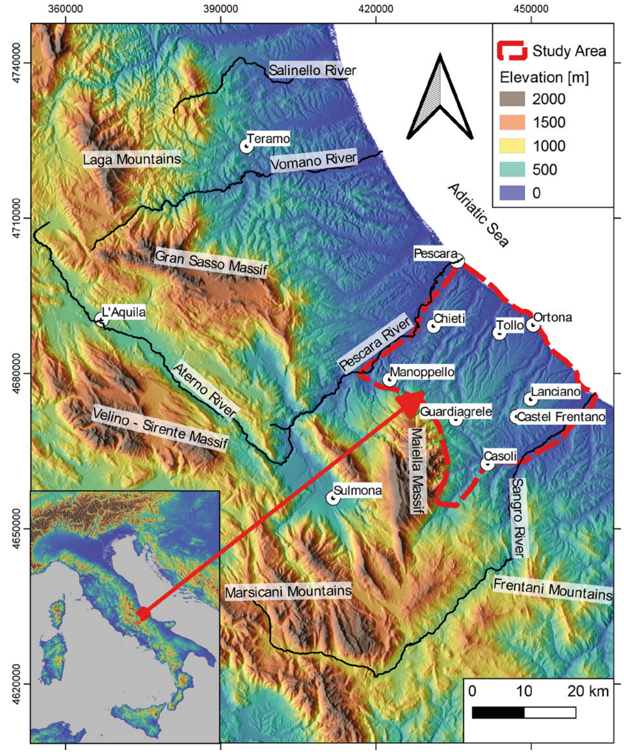

FIG. 1 - Location map of the investigated area.

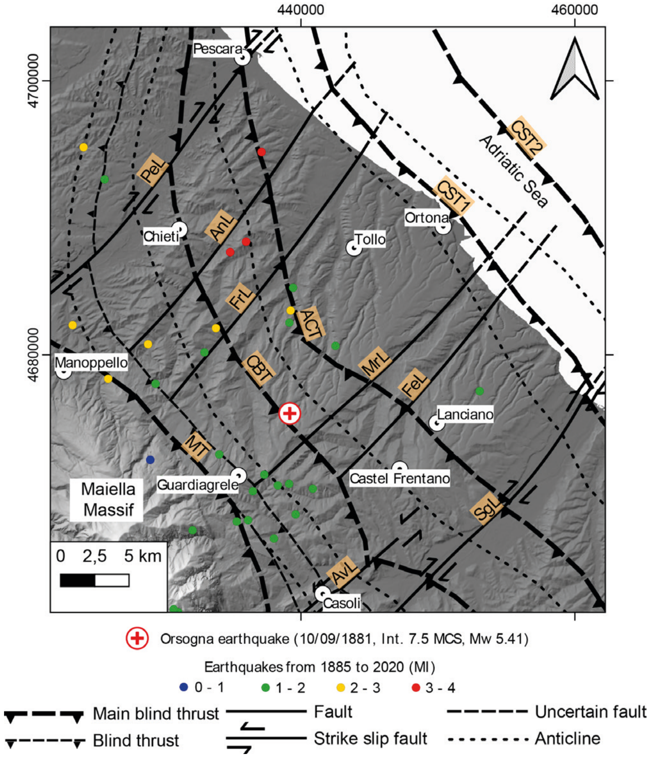

FIG. 3 - Synthetic reconstruction of the buried compressive structures that dislocate the carbonate substratum (based on the interpretation of oil companies data and the hypocenters of earthquakes recorded from 1985 to 2020). MT (Maiella Thrust); CBT (Casoli-Bomba Thrust); ACT (Abruzzo Citeriore Thrust); CST1-2 (Coastal Thrusts 1-2); PeL (Pescara Line); AnL (Alento Line); FrL (Foro Line); MrL (Moro Line); FeL (Feltrino Line); AvL (Aventino Line); SgL (Sangro Line).

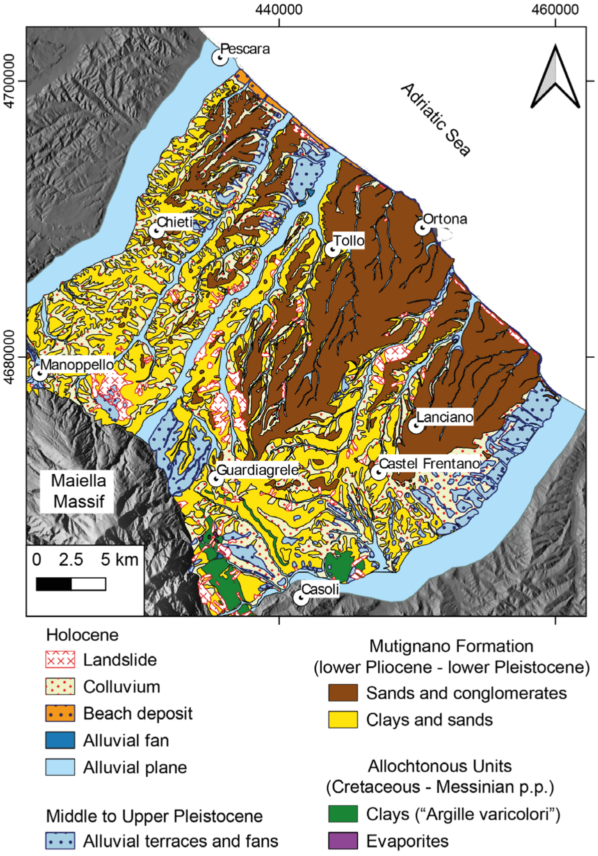

FIG. 2 - Geological sketch of the investigated area.

The stream length-gradient (SL) index (Hack, 1973) is defined by the equation:

$$SL = (\Delta H/\Delta L)\cdot L_r$$

where ΔH is the difference of altitude between two points of the stream channel, ΔL is the distance between the same points, and Lr is the total length of the stream. It relates the total stream power at a particular channel reach with the stream capacity to transport sediments and erode its bed. By applying the above relation to the long profile of a graded stream, it is possible to highlight knickpoints that, in the absence of litho-structural discontinuities or natural/man-made disturbances, may be related to tectonically-induced ground deformation (Molin & *alii*, 2004; Zovoili & Koukouvelas, 2004; Troiani & Della Seta, 2008; Di Naccio & *alii*, 2013).

The normalized channel steepness (k_{sn}) index (Flint, 1974; Wobus & *alii*, 2006; Kirby & Whipple, 2012) describes channel steepness as defined by the equation:

$$k_{sn} = A^{-\theta}S$$

where A is the upstream drainage area, S is the channel slope and θ represents the concavity of the river channel profile. Both k_{sn} and θ can be easily estimated by linear regression of log S and log A (Kirby & Whipple, 2012). With concave river channel profiles, θ values are positive, generally ranging between 0.3 to 0.6 (Tucker & Whipple, 2002); negative θ values are typical of convex profiles (Wobus & *alii*, 2006) where in lithologically homogeneous areas, may represent transient channel deformations induced by active tectonics (Hoke & *alii*, 2007).

In the present study, we used the SL and k_{sn} indexes to investigate the possible activity of the easternmost fold-and-thrust system of the Apennine orogen, mostly buried under a thick sequence of post-orogenic, clayey-sandy marine deposits (Bigi & *alii*, 1992), in a sector of the southern Abruzzi peri-Adriatic belt located between the Pescara River to the north, the Sangro River to the south, and the eastern Maiella piedmont to the west (fig. 1).

To further verify the possible occurrence of tectonically-induced surface ruptures/deformations in the study area during the recent Quaternary times, we also investigated the longitudinal profiles of river terrace staircases along selected valley reaches crossing the blind thrust culminations (Keller & *alii*, 2000; Lavé & Avouac, 2000; Thompson & *alii*, 2002; Formento-Trigilio & *alii*, 2003; Ishiyama & *alii,* 2004; Scharer & *alii*, 2006; Amos & *alii*, 2007; Picotti & Pazzaglia, 2008).

The last shortening phases of the Abruzzi sector of the Apennine orogen are commonly constrained to the Middle-Upper Pliocene/Lower Pleistocene *p.p.* (Casnedi, 1991; Crescenti & *alii*, 2004 and references therein). However, ongoing activity of the buried structures seems to be indicated by the faintly visible N-S Casoli-Bomba anticline in the westernmost part of the study area, which involves Lower Pleistocene sequences (Parotto & *alii*, 2003; Cosentino & *alii*, 2010), the finding of recent fault displacements in the eastern side of the Maiella Massif (Sauro & Zampieri, 2004), and the occurrence of low-to-intermediate magnitude earthquakes both in the study area and in the contiguous Adriatic offshore (Bonazzi del Poggetto & *alii*, 2009; Camassi & *alii*, 2011; INGV, 2019).

GEOLOGY AND GEOMORPHOLOGY OF THE STUDY AREA

Structural geology and stratigraphy

The southern Abruzzi peri-Adriatic belt (fig. 2) is characterized by a more than 3 km thick sequence of siliciclastic, transgressive-regressive sedimentary units ranging in age from the Lower Pliocene to the Middle Pleistocene *p.p.* (Casnedi, 1991; Bigi & *alii*, 1997a, b; Scisciani, 2009; Pieruccini & *alii*, 2017). The uppermost unit, *Mutignano Formation,* consisting of 200-300 m of thick clayey-sandy sediments with minor conglomerate intercalations, widely outcrops in the study area.

These deposits, emplaced in association with the growth of the outer Apennine ridges, cover Upper Miocene evaporitic and clastic sediments overlying platform carbonates (*Apulian Domain*; Patacca & *alii*, 2008). The latter units crop out in the Maiella Massif but, in the study area, are only known from deep boreholes drilled for oil exploration at depths ranging between -100 m in the western sector and -4000 m in the Adriatic offshore (Bigi & *alii*, 1992). The Upper Miocene sediments are also observable in drill cores but crop out locally in the eroded core of the Casoli-Bomba anticline (Cosentino & *alii*, 2010). East of this structure, no clear surficial evidence of compressive tectonics is recognized.

Bounded by the Aventino and Sangro rivers to the north and south and by Maiella Massif and Guardiagrele to the west and east, the Molisano outcrops, a gravitational tectonic melange of Argille Varicolori (varicolored clays), pelagic limestones, and flysch, Cretaceous to Messinian *p.p.* in age (Patacca & *alii*, 1993; Corrado & *alii*, 1998). These deposits crop out in the Sangro River basin, in correspondence to the Casoli-Bomba structure to the east. They are only recognizable in borehole logs at ca. -2200 m below the ground surface. South of the Sangro River, Middle Pliocene - Lower Pleistocene siliciclastic marine deposits unconformably overlay the allochthonous nappe (Crostella, 1967).

Valuable information concerning the deep-seated bedrock stratigraphy and the buried structures of the peri-Adriatic belt is provided by the geophysical/geognostic investigations carried out by oil companies whose results, in case of ceased research licenses, are freely available and downloadable at http://unmig.sviluppoeconomico.gov.it/videpi/videpi.asp, the website of the Italian Ministry of Economic Development: Villamagna, Montedison (1977/1985), https://www.videpi.com/videpi/cessati/fascicolo.asp?titolo=898; Montenerodomo, Total Mineraria (1988/1991), http://www.videpi.com/videpi/cessati/fascicolo.asp?titolo=555; and Palombaro (Anschutz Italiana Petroli 1998/2003), http://www.videpi.com/videpi /cessati/fascicolo.asp?titolo=617.

Since the last stages of the Early Pleistocene, the Italian peninsula has been involved in a large-scale arching (Demangeot, 1965; Dramis, 1992; D'Agostino & *alii*, 2001; Bartolini & *alii*, 2003), reaching its maximum values (1500-2000 m) in the Apennine ridge. According to D'Agostino & *alii* (2001), the uplift has been induced by the eastward migration of a long wavelength bending that involved the entire Italian peninsula, possibly in relation to the retreat of the Adriatic subduction zone (Doglioni & *alii*, 1999, Sallustri Galli & *alii*, 2002). Other authors (Locardi & Nicolich, 1992; Luongo, 1992; Centamore & Nisio, 2003) interpret the uplift as bulging due to the rising of the lithospheric mantle in the Tyrrhenian side of Italy. Due to this event, the peri-Adriatic post-orogenic sequence rose as a NE dipping monocline with very low attitudes close to the coast (where the sequence top reaches ca. 100 m a.s.l.) and progressively steeper and higher westward (Dramis, 1992). The uplift has continued till recent Quaternary times as indicated by the longitudinal convergence of alluvial terraces in the SW-NE river valleys (Urbano & *alii*, 2017).

The area is crossed by SW-NE lineaments interpreted by several authors (e.g., D'Alessandro & *alii*, 2008; Della Seta & *alii*, 2008; Centamore & *alii*, 2012) as transverse faults (fig. 4). According to Bigi & *alii* (1997a, b), these faults have acted as tear faults during the building phases of the Apennine playing a significant role in the evolution of the peri-Adriatic basin. More recently, following the general uplift of the area, they were reactivated as normal faults bordering differentially raised blocks (Della Seta & *alii*, 2008; Centamore & *alii*, 2012).

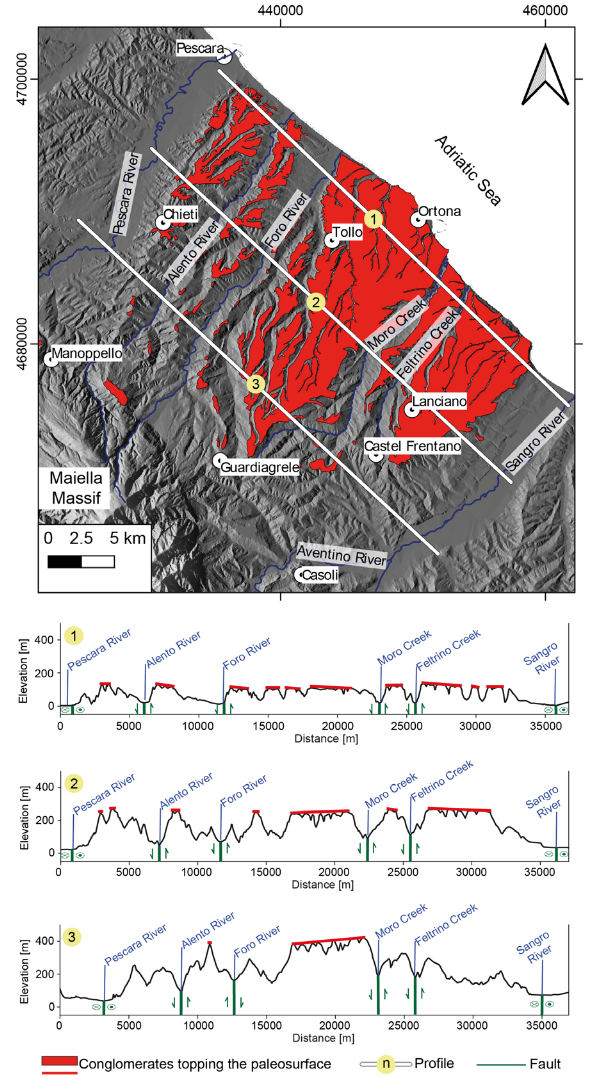

FIG. 4 - Topographic profiles across the Middle Pleistocene paleosurface in the study area: the lowermost profile 3 clearly shows the displacements caused by the transversal faults; the effects of faulting are also shown in the upper profiles 2 and 1 together with those produced by fluvial erosion.

As mentioned in the introduction, the study area is affected by recurrent seismic events, even if of low or moderate intensity (Bonazzi del Poggetto & *alii*, 2009; Camassi & *alii*, 2011). The most important historical event recognized in the area is that of Orsogna (10 September 1881; I = 7.5; Mw = 5.41), which was followed by the one (15 February 1982; I = 7; Mw = 5.26) which occurred, a little more to the north, in the surroundings of Chieti (Savarese & *alii*, 2011; INGV, 2020). Figure 3 shows the epicentral area of the 1881 earthquake and the spatial distribution of the epicenters of the earthquakes that occurred in the area between 1985 and 2020 (from the list of Italian earthquakes of the National Institute of Geophysics and Volcanology (http:// terremoti.ingv.it/).

Geomorphology

The landscape of the study area is characterized by a hilly relief whose altitude gradually decreases from the Maiella piedmont to the Adriatic coast. On top of the hills, remnants of a wide pediment (first described as "Villafrachian Planation Surface" by Demangeot, 1965) covered by conglomerates, gently dip eastward. The final stages of this surface, formed by running waters since the first emersion of the eastern Apennine piedmont, are presently referred to Middle Pleistocene because of its connection with "Crotonian" (ancient Middle Pleistocene) marine-continental deposits (comparable with the top surface deposits of the Mutignano Formation; Bigi & *alii*, 1997a; Centamore & Nisio, 2003) in the Marche peri-Adriatic belt (Coltorti & *alii*, 1991; Dramis, 1992).

The main rivers show a general north-east trend (Urbano & *alii*, 2017) even when they follow SW-NE faults (Centamore & *alii*, 2012). Minor valleys, river captures, and beheaded watercourses have developed along NW-SE, NNW-SSE, and WNW-ESE lineaments (D'Alessandro & *alii*, 2008; Del Monte & *alii*, 1996; Della Seta & *alii*, 2008; Urbano & *alii*, 2017).

The transverse profiles of the main river valleys are typically asymmetric with steep to sub- vertical right-bank (southern) slopes and low-angle left-bank (northern) slopes. This asymmetry could be the effect of differential uplift with increasing values from north to south. Due to the same event and process, the river terraces are almost exclusively found on their left bank (Del Monte & *alii*, 1996).

In the study area, up to five levels of fluvial terraces are present ranging in age from the Middle Pleistocene (the age of the Mutignano Formation top surface in which the entire terrace staircase is entrenched) to the Holocene: T1, T2 - Middle Pleistocene; T3 - Late Middle Pleistocene; T4 - Upper Pleistocene; T5 - Holocene (D'Alessandro & *alii*, 2008; Urbano & *alii*, 2017; Miccadei & *alii*, 2018).

As in other sectors of the Apennines and the peri-Adriatic belt, these are "climatic" terraces formed by the interaction between climate changes and regional uplift. Riverbed aggradation occurred in the "glacial" stages of the Middle-Late Pleistocene due to the enormous amount of frost-shattered debris supplied by the bare slopes. In the subsequent interglacial stages, the streams, less charged with debris, incised the previous alluvium and underlying bedrock, due to the increased gradients induced by the uplift (Demangeot, 1965; Ciccacci & *alii*, 1985; Della Seta & *alii*, 2008; Nesci & *alii*, 2012). Their ages are constrained by radiocarbon dating, archaeological findings, pedo-stratigraphic observations, and interfingering with periglacial deposits (Alessio & *alii*, 1979; Alessio & *alii*, 1987; Coltorti & Dramis, 1987; Calderoni & *alii*, 1991; Calderoni & *alii*, 2010).

The Holocene terrace has a different origin, being mostly related first to river bed aggradation induced by widespread anthropic deforestation and agricultural works carried out in ancient times and then to stream incision resulting from more recent reforestation and hydraulic settlement of slopes (Coltorti & *alii*, 1991; Cilla & *alii*, 1996).

Near the river mouths, the post-glacial eustatic deposits overlap with the climatic terrace treads. Given the relatively slow uplift rates of the coastline (considering the elevation of ca. 100 m a.s.l. attained by the "Crotonian" top surface of the Mutignano Formation), the eustatic coastal plain transitions to the last climatic terrace tread without any significant discontinuity (Coltorti & *alii*, 1991; Calderoni & *alii*, 2010; Nesci & *alii*, 2012).

MATERIALS AND METHODS

Initially, based on 1:25,000 scale geological maps produced by one of the authors (Centamore, unpublished), we performed a detailed geomorphological field/airphoto survey of the study area hydrographic network (drainage channel orientation, river beds, fluvial terraces, and limbs of summit flat surfaces) to detect anomalies that could be related to tectonically-induced surface deformation.

Moreover, to outline the deep-seated geo-structural setting of the investigated area, we interpreted the borehole data and seismic sections provided by oil companies ceased licenses.

Then, we calculated the Hack (SL - Slope-Length) index and the normalized channel steepness index (k_{sn}) for all the main rivers of the study area.

We performed the SL index analysis along the longitudinal profiles of rivers, extracted by the 10 m TINITALY Digital Elevation Model (Tarquini & *alii*, 2007, 2012) using the MATLAB® software Topotoolbox (https://topotoolbox.wordpress.com/; Schwanghart & Kuhn, 2010; Schwanghart & Scherler, 2014). We calculated the index values extracting the stream channels from a minimum drainage area of $500\ m^2$ and for a ΔL of 250 m (in agreement with Pérez-Peña & alii, 2009, for a DEM with a resolution of 10 m/px). The data were interpolated in QGis by Inverse Distance Weighting (IDW) to obtain a distribution map of SL over the study area.

Following Wobus & alii (2006), we calculated the normalized channel steepness index (k_{sn}) from the investigated drainage system using a reference θ of 0.46, estimated by a slope-area plot of the entire investigated drainage network. Finally, to obtain the normalized steepness index map, we interpolated the results by the IDW function.

We analyzed the longitudinal profiles of the river terrace treads along four valley reaches where these landforms are better preserved and less discontinuous: the Aventino River valley from 400 m a.s.l. to the confluence with the Sangro River (90 m a.s.l.); the Sangro River valley from the confluence with the Aventino River and the Adriatic Sea; the Alento River valley over the last 17 km to the sea; and the Foro River valley over the last 9,5 km to the sea. We performed this analysis using the 10 m TINITALY Digital Elevation Model and the QGis software. For the same valley reaches, we also traced profiles of different length and width along the left side divides, topped by patches of the Middle Pleistocene planation surface. The resulting data were checked in the field by a detailed geological-geomorphological survey.

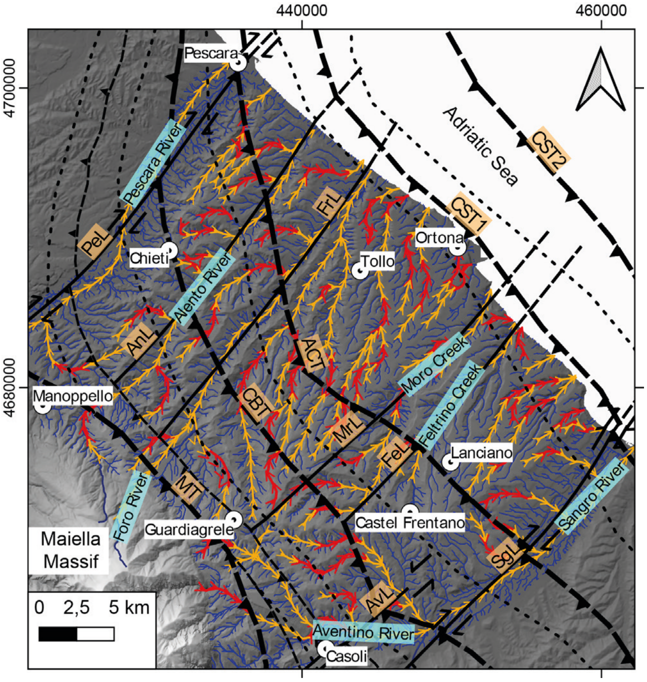

FIG. 5 - Stream channels inferred by Topotoolbox for a minimum drainage area of 0.5 km2 (in blue); drainage network main directions (in orange) between the Pescara and Sangro rivers with channel diversions (in red) from the regional SW-NE slope direction. For the other symbols, see fig. 4.

RESULTS AND DISCUSSION

Deep-seated structures

Through the interpretation of borehole data and seismic sections from the ceased oil research licenses, we recognized, three main blind thrusts from the Maiella piedmont to the Adriatic coast, buried under the Upper Pliocene-Middle Pleistocene post-orogenic stratigraphic sequence and roughly aligned according the Apennine direction (fig. 3): the inner structure (Casoli-Bomba Thrust - CBT), outcropping in part to form the Casoli-Bomba anticline; the intermediate structure (Abruzzo Citeriore Thrust - ACT; already described by De Nardis & *alii*, 2011) buried under 2500 m of sediments; and the deeper coastal structure (Coastal Thrust 1 - CST1). Another blind thrust (Coastal Thrust 2 - CST2), parallel to CTS1, was located in the Adriatic offshore.

The oil research data also highlighted deep-seated dextral strike-slip faults that dislocate the blind thrusts (fig. 3). These buried faults roughly coincide with the Pescara River valley (Pescara Line - PeL) to the north and the Aventine and Sangro valleys (Aventino Line - AvL; Sangro Line - SgL) to the south; minor buried faults follow the Moro, Foro, Feltrino and Alento rivers (Moro Line - MrL; Foro Line - FrL; Feltrino Line - FrL; Alento Line - AnL).

The geomorphological analysis of the study area highlights the surface activity of these faults that have visibly displaced the Middle Pleistocene paleosurface (fig. 4).

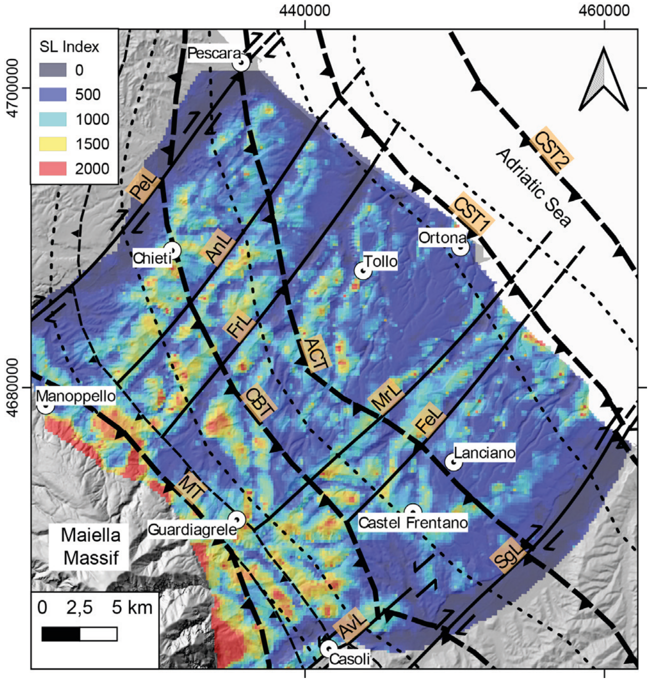

FIG. 6 - SL (Hack) Index distribution map. The SL Index is calculated with MATLAB® using Topotoolbox, for a minimum drainage area of 0.5 km², the values were interpolated with the IDW function (Inverse Distance Weighting) using QGis. For the other symbols, see fig. 4.

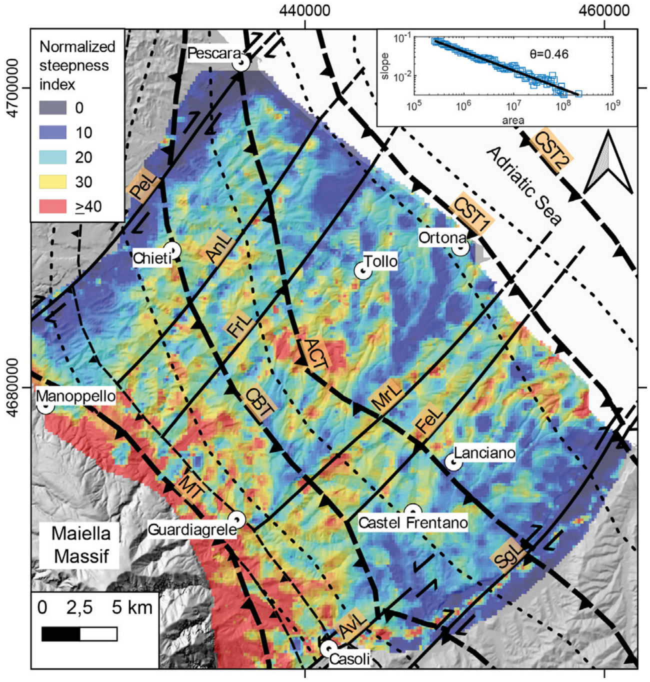

FIG. 7 - Map of channel steepness indexes (k_{sn}) that are normalized to a reference concavity (θ_{ref}) of 0.46 throughout the study area basins, calculated using Topotoolbox with the same minimum drainage area of SL Index and then interpolated by the IDW function in QGis. In both pictures, the distribution of the indexes predominantly follows the trend of the buried structures. For the other symbols, see fig. 4.

Drainage pattern

In the study area, from the Maiella piedmont to the Adriatic coast, the general pattern of stream courses does not match the regional slope trend. As already observed by Del Monte & *alii* (1996), most watercourses flowing from the Apennine ridge to the Adriatic Sea present anomalous diversions, sometimes very abrupt, with angles close to 90° (fig. 5).

The drainage pattern anomalies, in particular, the occurrence of abrupt diversions of river channels, could indicate the growth of topographic highs capable of diverting the course of channeled flowing water. This does not happen to the major rivers (Pescara, Foro and Sangro rivers) which, due to their higher erosional power, are less affected by ground deformations being capable of crossing them by antecedence. In the southern margin of the Po Plain, Burrato & *alii* (2003) observed that river channel diversion above the axis of buried compressive structures related their formation to ongoing tectonic activity.

Particularly significant among others are the stream diversions close to the coast. To the north, in the area around the towns of Tollo and Ortona, the river channels abruptly deviate from the consequent SW-NE trend turning counterclockwise, and to the south they turn clockwise. This behavior indicates the growth of a topographic high corresponding to a culmination of the CST1 buried structure.

Hack (SL) Index

The distribution of the SL index in the investigated area (fig. 6) shows that the highest values (up to SL > 1000) are mostly clustered in the eastern piedmont of the Maiella Massif and across the buried anticlines and thrust fronts. Field inspection showed that man-made constructions across the rivers (e.g., bridges, dams, industrial plants) or landslides from the clayey-sandy valley slopes might have influenced only a few of the increased SL values.

The increased values of the Hack (SL) index across the buried compressive structures are indicators of the occurrence of growing topographic highs likely related to persistent tectonic deformation, as recognized by other authors in the northern sector (Romagna, Marche) of the peri-Adriatic belt (Lavecchia & *alii*, 2015). There are, in fact, no widespread lithological contrasts that could induce the formation of knickpoints. The only stiff/soft bedrock contacts in the investigated area are those related to the transition between the Pleistocene clays and the Mutignano Formation conglomerates (see fig. 2); however the latter, for the most part, are presently incised by the rivers down to the underlying clays; furthermore, the harder bedrock would be downstream of the contact, thus making knickpoint formation impossible. The inability of the weak clayey bedrock to maintain small height differences over a long time would exclude the persistence of tectonically-induced knickpoints in the river channels if not related to ongoing ground deformation and the presence of mountainward migrating knickpoints induced by base-level changes.

The increased values of the Hack Index in the Maiella piedmont may be due to the swollen character of the river beds fed by debris flows and alluvial fan deposition from the steep slopes of the massif. An alternative explanation would imply a possible recent reactivation of the Maiella thrust as supported by Sauro & Zampieri (2004) mainly based on geomorphological considerations. This massif, however, does not fall within the study area and its morphotectonic evolution will be the subject of a forthcoming study.

Normalized Channel Steepness (k_{sn}) Index

The k_{sn} values, as shown in fig. 7, reach their highest values in the eastern Maiella piedmont and across the buried structures. High values of the index occur in the central part of the study area between Tollo, Lanciano, Castelfrentano, and Guardiagrele. As reported by Dey & *alii* (2016) for the southern Sub-Himalaya chain, the increase in k_{sn} observed across channels that cut buried structures may indicate ongoing tectonic activity.

In general, as observed by Castillo & *alii* (2014) in western Mexico, the increased values that characterize the central part of the study area may indicate higher uplift rates (Castillo & *alii*, 2014; Cyr & *alii*, 2014) due to higher deformation rates affecting the buried structures in this sector.

The high values of the k_{sn} Index in the Maiella piedmont may relate to the recurrence of debris flows and alluvial fan deposition in the headwater channels, without considering the previously mentioned hypothesis (Sauro & Zampieri, 2004) of possible reactivation of the Maiella thrust.

Longitudinal profiles of river terraces

We reconstructed the longitudinal profiles of river terraces nested in four selected valley reaches based on the distribution of the terrace tread strips of different orders (fig. 8). In all four cases, the profiles present showy irregularities where the rivers cross the buried structures. The left divide swath profiles also show comparable irregularities. We have tried to explain these irregularities although the scarcity of geological field data, due to the homogeneous clayey-sandy substrate, makes the interpretations rather uncertain.

Aventino River valley. The investigated sector of the Aventino River valley lies in the Maiella Massif eastern piedmont, across the Casoli-Bomba (CBT) structure. It comprises all five orders of terraces, although T1 and T2 are poorly present. The analysis of terrace longitudinal profiles (fig. 9a-up) shows a clear deformation of T3 and T4 giving rise to a depression with the maximum depth at ca. 6100 m from the graph origin, across the CBT axis; no deformation is visible in the T5 longitudinal profile. At the same distance from the origin, left divide swath profile presents a comparable depression (fig. 9a-down). These features could indicate a growing extrados graben induced by ongoing deformation of the buried structure whose effects are not yet detectable in the T5 longitudinal profile.

Alento River valley. The investigated sector of the Alento River valley crosses the ACT and. the CST1 in the northern part of the study area. In the left side of the diagram, where the river crosses the ACT, T2 and T3 show convex longitudinal profiles; to the east, across the CST1, the profiles are interrupted by steps degrading to the Adriatic coast (fig. 9b-up). A step down is visible also in the left divide longitudinal profile, in the right side of the diagram while, its upstream sector does not follow the trend of terraces likely due to erosion (fig. 9b-down). The above features could be related to the continuing activity of both the ACT and CST1 blind structures. The step-like features in the right sector of the profiles could be interpreted as an effect of deep-seated growing extrados faults.

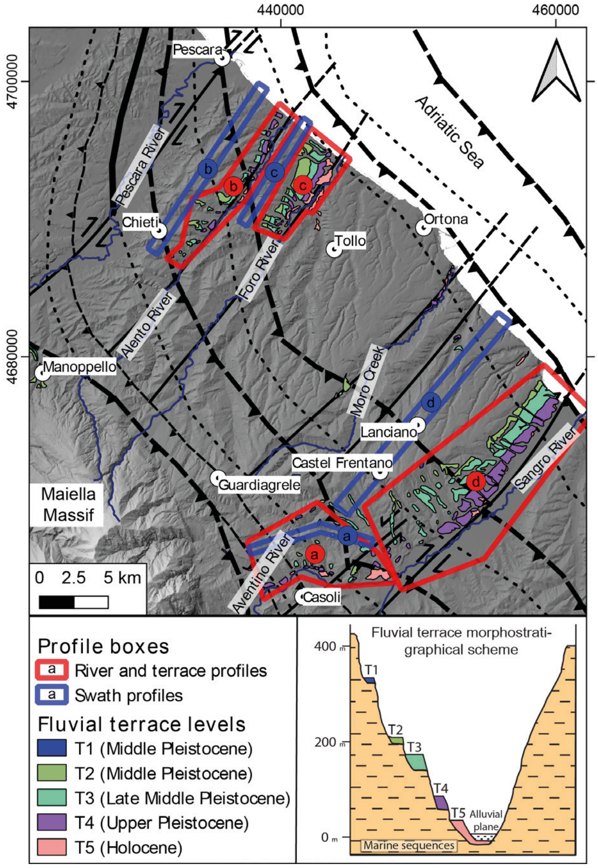

FIG. 8 - Morphostratigraphical scheme and map of the investigated river terraces. Red polygons delineate the analyzed river terrace longitudinal profiles. Blue polygons indicate the swath profile traces of the analyzed catchment divides. The swath profiles' widths are 1.5 km for a, 2 km for b, 1.5 km for c, and 5.5 km for d. For the other symbols, see fig. 4.

Foro River valley. The investigated sector of the Foro River valley includes four well- developed orders of terraces (from T2 to T5). The longitudinal profiles of the upper terraces show evidence of irregularity between 2300 and 4750 m from the origin and near the coast, where T2 and T3 are uplifted acquiring an upstream declining trend (fig. 9c-up). The swath profile of the left divide (fig. 9c-down) shows evidence of uplifting near the coast. The left side profile trend could be interpreted as related to growing extrados faults induced by ongoing activity of the ACT blind structure; both the uplift and tilting at the left edge of the terrace profiles could be related to the growth of the CST1.

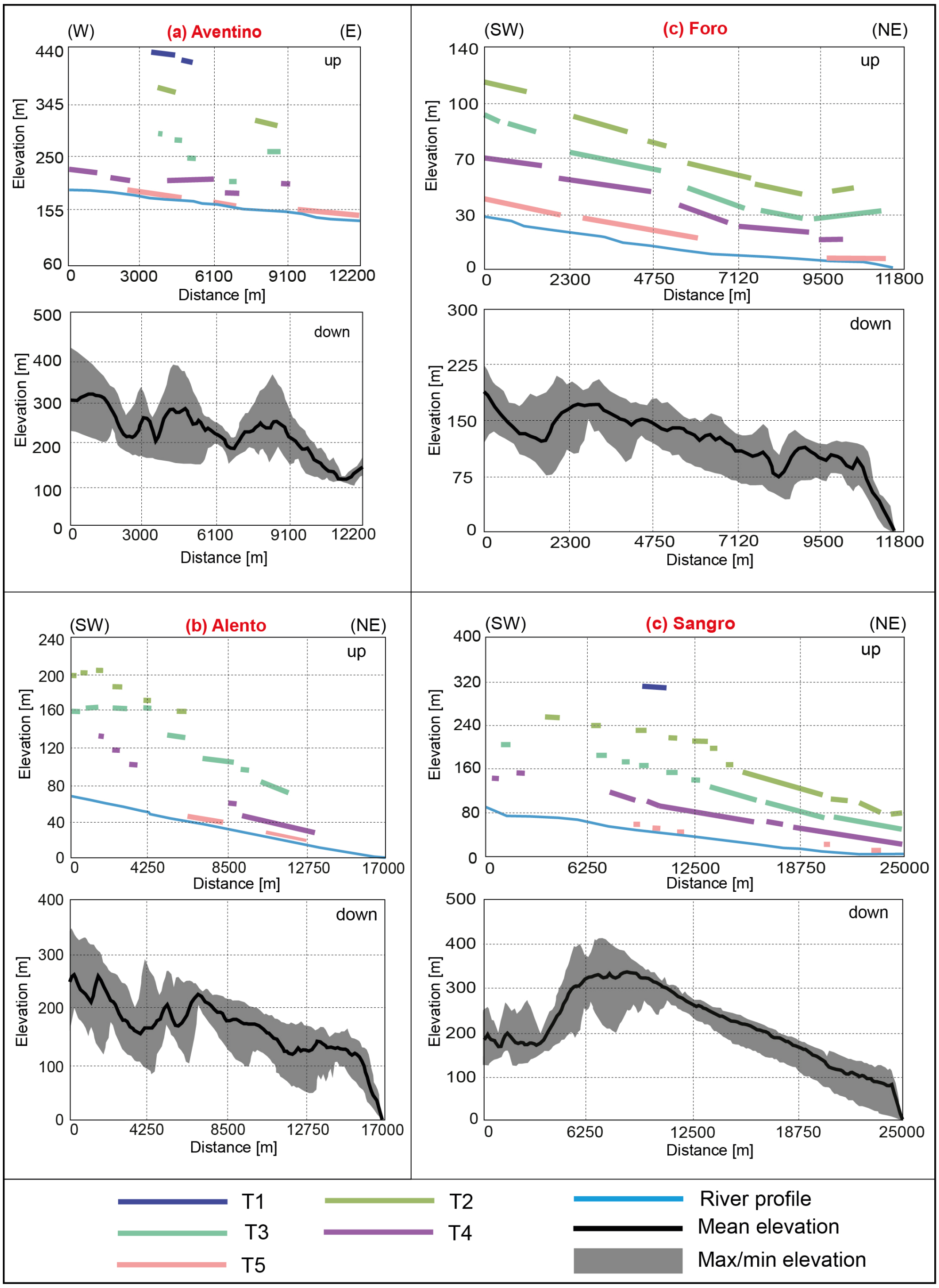

FIG. 9 - (a-b-c-d up) Longitudinal profiles of river channel and terraces in the investigated valley reaches; (a-b-c-d down) swath profiles taken along the left side divides of the investigated reaches of river valleys. The grey color in the swath profiles indicates the area between the minimum and maximum heights in the profile trace; the black line indicates the mean elevation.

Sangro River valley. The investigated reach the of the Sangro River valley crosses the entire peri-Adriatic belt from the external edge of the Maiella piedmont and the Adriatic coast. In this valley reach all the terrace orders are well developed, with the exception of T1 which is only represented by a small strip. T2 and T3 show irregularities of longitudinal profile just after 12,500 m and between 18,750 m and 25,000 m from the diagram origin (fig. 9d-up); T4 shows limited irregularities between 12,500 m and 18,750 m. No irregularities are clearly visible in the T5 longitudinal profile. The swath profile of the left divide (fig. 9d-down) shows a step downstream between 18,750 m and 25,000 m. In the left sector of the diagram, the divide elevation drops down due to erosion of the top planation surface. The irregularities affecting the longitudinal profiles of the T2 and T3 river terraces (at 12,500 m) could be explained as related to a growing extrados normal fault affecting the blind ACT structure, and a growing reverse fault (at 18,500 m) in correspondence with the CST1 front. A reverse fault affecting the Upper Pleistocene (T4) terrace was observed in an abandoned gravel quarry, close to the inferred reverse fault (fig. 10a). Another geological evidence of recent tec-

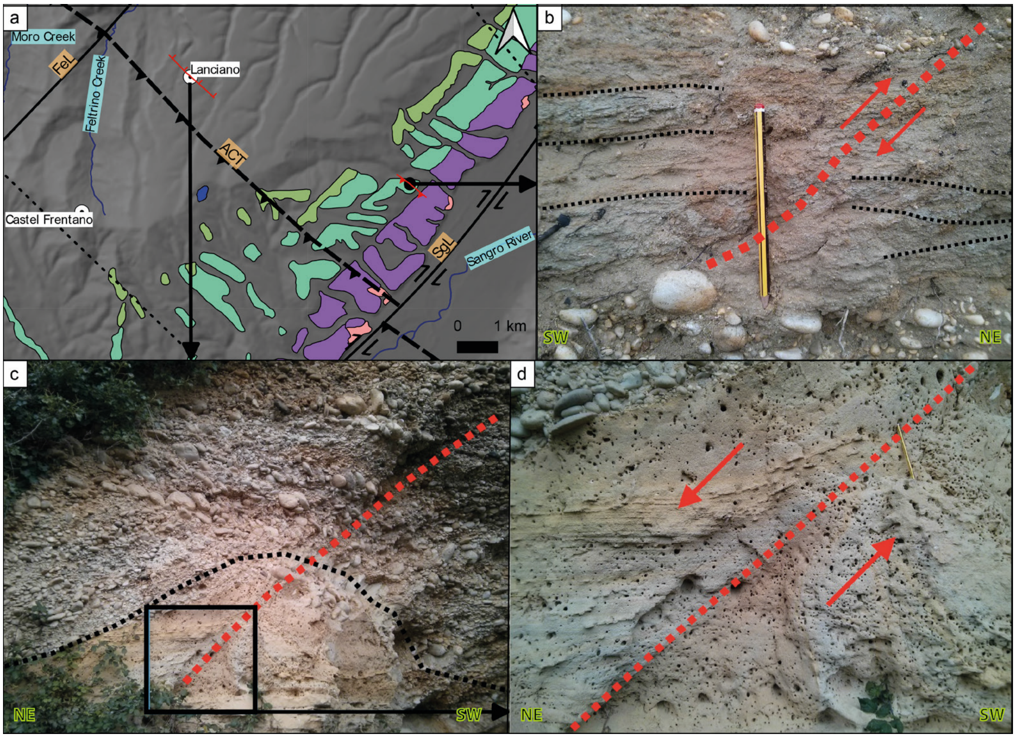

FIG. 10 - Field indicators of Late Quaternary faulting in the study area, in red the faults found on the field (a); (b) reverse fault in the T3 alluvial deposits; (c) normal fault in Quaternary delta conglomerates (above the dotted black line) and marine sands near the Lanciano Railway Station; (d) detail of the normal fault from the square in c.

tonic activity may be seen near the Lanciano Railway Station, where a normal fault dislocates Quaternary marine deposits (fig. 10b).

Notwithstanding the uncertain tectonic interpretation of the river terrace longitudinal-profiles and valley divide swath profiles in the selected valley reaches, the observed indicate that compressive activity has continued to characterize the evolution of the buried structures since the Middle Pleistocene. These findings are consistent with the results obtained by the drainage pattern analysis and the spatial distribution of the Hack (SL) and k_{sn} indexes in the study area.

CONCLUSION

The results of this research indicate with a reasonable probability that the investigated sector of the peri-Adriatic belt is currently subject to surface contraction induced by the ongoing activity of blind thrusts buried under a more than 4000 m thick cover of Pliocene-Quaternary deposits, a process that likely characterizes the whole easternmost sector of the Apennine orogen.

They also confirm the effectiveness of SL and ksn indexes and longitudinal profile analysis of river terrace treads as powerful tools for demonstrating ongoing tectonic deformation of deep-seated structures in tectonically-affected areas where surface deformations are not easily visible.

This methodology can be applied to every area suspected to be affected by the activity of deep-seated, blind thrust systems to account for and locate the deep sources of earthquakes in view of assessing the local seismic hazard (Vannoli & *alii*, 2004; Burrato & *alii*, 2012).

REFERENCES

ALESSIO M., ALLEGRI M., COLTORTI M., CORTESI C., DEIANA G. & DRAMIS F. (1979) - *Depositi tardowurmiani nell'alto bacino dell'Esino (Appennino Marchigiano). Datazione al* ^{14}*C.* Geografia Fisica e Dinamica Quaternaria, 2, 203-204.

ALESSIO M., ALLEGRI L., AZZI C., CALDERONI G., CORTESI C., IMPROTA S., NESCI O., PETRONE V. & SAVELLI D. (1987) - *Successioni alluvionali terrazzate nel medio bacino del Metauro (Appennino Marchigiano). Datazione con il* ^{14}*C.* Geografia Fisica e Dinamica Quaternaria, 10, 307-312.

AMOS C.B., BURBANK D.W., NOBES D.C. & READ S.A.L. (2007) - *Geomorphic constraints on listric thrust faulting: Implications for active deformation in the Mackenzie Basin, South Island, New Zealand.* Journal of Geophysical Research, Solid Earth, 112, B03S11.

BARTOLINI C., D'AGOSTINO N. & DRAMIS F. (2003) - *Topography, exhumation, and drainage network evolution of the Apennines.* Episodes, 23 (3), 212-217.

BIGI G., COLI M., COSENTINO D., PAROTTO M., PRATURLON A., SARTORI R., SCANDONE P. & TURCO E. (1992) - *Structural Model of Italy, Scale 1:500.000, Sheet 4.* C.N.R., Progetto Finalizzato Geodinamica, S.EL CA., Firenze.

BIGI S., CALAMITA F. & CENTAMORE E. (1997a) - *Caratteristiche geologico-strutturali dell'area abruzzese ad oriente del Gran Sasso.* Studi Geologici Camerti, Volume Speciale 1995/2, 67-76.

BIGI S., CENTAMORE E. & NISIO S. (1997b) - *Elementi di tettonica quaternaria nell'area pedeappenninica marchigiano-abruzzese.* Il Quaternario, Italian Journal of Quaternary Sciences, 10 (2), 359-362.

BONAZZI DEL POGGETO P.L., LUDOVICO N. & FLARÀ N. (2009) - *Terremoti nelle terre d'Abruzzo. Storia di uomini e di eroi.* AUPI, 3, 1-48.

BURBANK D.W. & ANDERSON R.S. (2001) - *Tectonic Geomorphology.* Blackwell Scientific, Oxford, 274 pp.

BURRATO P., CIUCCI F. & VALENSISE G. (2003) - *An inventory of river anomalies in the Po Plain, Northern Italy: evidence for active blind thrust faulting.* Annals of Geophysics, 46 (5), 865-882.

Burrato P., Vannoli P., Fracassi U., Basili R. & Valensise G. (2012) - *Is blind faulting truly invisible? Tectonic-controlled drainage evolution in the epicentral area of the May 2012, Emilia-Romagna earthquake sequence (northern Italy).* Annals of Geophysics, 55 (4), 525-531.

Calderoni G., Della Seta M., Fredi P., Lupia Palmieri E., Nesci O., Savelli D. & Troiani F. (2010) - *Late Quaternary geomorphologic evolution of the Adriatic coast reach encompassing the Metauro, Cesano and Misa river mouths (Northern Marche, Italy).* GeoActa, Special Publication, 3, 49-64.

Calderoni G., Nesci O. & Savelli D. (1991) - *Terrace fluvial deposits from the middle basin of Cesano River (northern Marche Apennines): reconnaissance study and radiometric constraints on their age.* Geografia Fisica e Dinamica Quaternaria, 14, 201-207.

Camassi R., Castelli V., Molin D., Bernardini F., Caracciolo C.H., Ercolani E. & Postpischl L. (2011) - *Materiali per un catalogo dei terremoti italiani: eventi sconosciuti, rivalutati o riscoperti.* Quaderni di Geofisica, 96, 50 pp.

Casnedi R. (1991) - *L'avanfossa abruzzese fra i fiumi Vomano e Pescara nel Pliocene inferiore: rapporti fra sedimentazione e tettonica.* Studi Geologici Camerti, Volume Speciale 1991/2, 375-379.

Castillo M., Muñoz-Salinas E. & Ferrari L. (2014) - *Response of a landscape to tectonics using channel steepness indexes (k_{sn}) and OSL: A case of study from the Jalisco Block, Western Mexico.* Geomorphology, 221, 204-214.

Centamore E., Dramis F. & Fubelli G. (2012) - *Plio-Pleistocene tectonics in the Marche- Abruzzi peri-Adriatic belt.* Rendiconti Online della Società Geologica Italiana, 21, 69-70.

Centamore E. & Nisio S. (2003) - *Effects of uplift and tilting in the Central-Northern Apennines (Italy).* Quaternary International, 101-102, 93-101.

Ciccacci S., D'Alessandro L., Dramis F., Fredi P. & Pambianchi G. (1985) - *Geomorphological and neotectonic evolution of the Umbria-Marche ridge, northern sector.* Studi Geologici Camerti, 10, 7-15.

Cilla G., Coltorti M., Farabollini P., Dramis F., Gentili B. & Pambianchi G. (1996) - *Fluvial sedimentation during the early Holocene in the Marchean valleys (Central Italy).* Il Quaternario, Italian Journal of Quaternary Sciences, 9 (2), 459-464.

Coltorti M., Consoli M., Dramis F., Gentili B. & Pambianchi G. (1991) - *Evoluzione geomorfologica delle piane alluvionali delle Marche centro-meridionali.* Geografia Fisica e Dinamica Quaternaria, 14 (1), 87-100.

Coltorti M. & Dramis F. (1987) - *The significance of stratified slope waste deposits in the Quaternary of Umbria-Marche Apennines (Central Italy).* Zeitschrift für Geomorphologie, N.F., Supplement Band, 71, 59-70.

Corrado S., Di Bucci D., Naso G., Giampaolo C. & Adattet T. (1998) - *Application of organic matter and clay mineral studies to the tectonic history of the Abruzzo - Molise - Sannio area, Central Apennines, Italy.* Tectonophysics, 285 (1), 167-182.

Cosentino D., Cipollari P., Marsili P. & Scrocca D. (2010) - *Geology of the central Apennines: A regional review.* Journal of the Virtual Explorer, Electronic Edition, 36 (11), 1-37.

Crescenti U., Umilia M.L. & Rusciadelli G. (2004) - *Stratigraphic and tectonic evolution of the Pliocene Abruzzi basin (Central Apennines, Italy).* Bollettino Società Geologica Italiana, 123, 163-173.

Crostella A. (1967) - *Osservazioni sul Pliocene degli Abruzzi settentrionali: la trasgressione del Pliocene medio-superiore.* Bollettino Società Geologica Italiana, 90 (1), 3-21.

D'Agostino N., Dramis F., Funiciello R. & Jackson J.A. (2001) - *Interactions between mantle upwelling, drainage evolution and active normal faulting: An example from the central Apennines (Italy).* Geophysical Journal International, 147, 475-497.

D'Alessandro L., Miccadei E. & Piacentini T. (2008) - *Morphotectonic study of the lower Sangro River valley (Abruzzi, Central Italy).* Geomorphology, 102, 145-158.

Della Seta M., Del Monte M., Fredi P., Miccadei E., Nesci O., Pambianchi G., Piacentini T. & Troiani F. (2008) - *Morphotectonic evolution of the Adriatic piedmont of the Apennines: An advancement in the knowledge of the Marche-Abruzzo border area.* Geomorphology, 102, 119-129.

Del Monte M., Di Bucci D. & Trigari A. (1996) - *Assetto morfotettonico della regione compresa tra la Maiella e il mare Adriatico (Appennino abruzzese).* Memorie della Società Geologica Italiana, 51, 419-430.

Demangeot J. (1965) - *Géomorphologie des Abruzzes Adriatiques.* Mémoires et Documents CNRS, Paris, 403 pp.

De Nardis R., Garbin M., Lavecchia G., Pace B., Peruzza L., Priolo E., Romanelli M., Romano M.A., Visini F. & Vuan A. (2011) - *A temporary seismic monitoring of the Sulmona area (Abruzzo, Italy) for seismotectonic purposes.* Bollettino di Geofisica Teorica ed Applicata, 52 (4), 651-666.

Dey S., Thiede R.C., Schildgen T.F., Wittmann H., Bookhagen B., Scherler D. & Strecker M.R. (2016) - *Holocene internal shortening within the northwest Sub-Himalaya: out-of- sequence faulting of the Jwalamukhi Thrust, India.* Tectonics, 35 (11), 2677-2697.

Di Naccio D., Boncio P., Brozzetti F., Pazzaglia F.J. & Lavecchia G. (2013) - *Morphotectonic analysis of the Lunigiana and Garfagnana grabens (northern Apennines, Italy): implications for active normal faulting.* Geomorphology, 20, 293-311.

Doglioni C., Gueguen E., Harabaglia P. & Mongelli F. (1999) - *On the origin of W -directed subduction zones and applications to the western Mediterranean.* Geological Society London Special Publications, 156, 541-561.

Dramis F. (1992) - *Il ruolo dei sollevamenti tettonici a largo raggio nella genesi del rilievo appenninico.* Studi Geologici Camerti, Volume Speciale 1992/1, 9-15.

Flint J.J. (1974) - *Stream gradient as a function of order, magnitude, and discharge.* Water Resources Research, 10 (5), 969-973.

Formento-Trigilio M.L., Burbank D.W., Nicol A., Shulmeister J. & Rieser U. (2003) - *River response to an active fold-and-thrust belt in a convergent margin setting, North Island, New Zealand.* Geomorphology, 49 (1-2), 125-152.

Hack J.T. (1973) - *Stream-profile analysis and stream-gradient index.* U.S. Geological Survey Journal of Research, 1 (4), 421-429.

Hoke G.D., Isacks B.L., Jordan T.E., Blanco N., Tomlinson A.J. & Ramezani J. (2007) - *Geomorphic evidence for post-10 Ma uplift of the western flank of the central Andes 18°30'-22°S.* Tectonics, 26, TC5021.

INGV - Istituto Nazionale di Geofisica e Vulcanologia (2019). *Catalogo Parametrico dei Terremoti Italiani CPTI15° v2.0.* http://emidius.mi.ingv.it/CPTI15-DBMI15/

Ishiyama T., Mueller K., Togo M., Okada A. & Takemura K. (2004) - *Geomorphology, kinematic history, and earthquake behavior of the active Kuwana wedge thrust anticline, central Japan.* Journal of Geophysical Research: Solid Earth, 109 (B12), B12408.

Keller E.A. & Pinter N. (2002) - *Active Tectonics, Earthquake Uplift and Landscape, 2nd Edition.* Prentice Hall, Upper Saddle River, 362 pp.

Keller E.A., Seaver D.B., Laduzinsky D.L., Johnson D.L. & Ku T.L. (2000) - *Tectonic geomorphology of active folding over buried reverse faults: San Emigdio Mountain front, southern San Joaquin Valley, California.* GSA Bulletin, 112 (1), 86-97.

Kirby E. & Whipple K.X. (2012) - *Expression of active tectonics in erosional landscapes.* Journal of Structural Geology, 44, 54-75.

LAVÉ J. & AVOUAC J.P. (2000) - *Active folding of fluvial terraces across the Siwaliks Hills, Himalayas of central Nepal.* Journal of Geophysical Research, Solid Earth, 105 (B3), 5735-5770.

LAVECCHIA G., DE NARDIS R., DI NACCIO D., FERRARINI F., CIRILLO D. & BROZZETTI F. (2015) - *Active compression in Eastern Abruzzo (central Italy): evidences from geological morphotectonic and macroseismic data analyses.* Rendiconti Online Società Geologica Italiana, 36 (Suppl. 1), 45.

LOCARDI E. & NICOLICH R. (1992) - *Geodinamica del Tirreno e dell'Appennino centro- meridionale: la nuova carta della Moho.* Memorie della Società Geologica Italiana, 41, 121-140.

LUONGO G. (1992). *Tettonica globale dell'Italia meridionale: subduzione o bending?* Memorie della Società Geologica Italiana, 41, 159-163.

MICCADEI E., CARABELLA C., PAGLIA G. & PIACENTINI T., (2018) - *Paleo-drainage network, morphotectonics, and fluvial terraces: Clues from the Verde Stream in the middle Sangro River (Central Italy).* Geosciences, 8 (9), 337.

MOLIN P., PAZZAGLIA F.J. & DRAMIS F. (2004) - *Geomorphic expression of active tectonics in a rapidly-deforming forearc, Sila Massif, Calabria, Southern Italy.* American Journal of Science, 304, 559-589.

NESCI O., SAVELLI D. & TROIANI F. (2012) - *Types and development of stream terraces in the Marche Apennines (central Italy): a review and remarks on recent appraisals.* Géo- Morphologie, 18 (2), 215-238.

PAROTTO M., CAVINATO G.P., MICCADEI E. & TOZZI M. (2003) - *La linea CROP 11: Appennino Centrale.* Memorie Descrittive della Carta Geologica d'Italia, 62, 145-154.

PATACCA E., SARTORI R. & SCANDONE P. (1993) - *Tyrrhenian basin and Apennines. Kinematic evolution and related dynamic constraints.* In: BOSCHI E., MANTOVANI E. & MORELLI A. (Eds.), Recent Evolution and Seismicity of the Mediterranean Region, NATO ASI Series C (Mathematical and Physical Sciences), vol. 402, Springer, Dordrecht, pp. 161-171.

PATACCA E., SCANDONE P., DI LUZIO E., CAVINATO G.P. & PAROTTO M. (2008) - *Structural architecture of the central Apennines: Interpretation of the CROP 11 seismic profile from the Adriatic coast to the orographic divide.* Tectonics, 27, TC3006.

PAZZAGLIA F.J. & BRANDON T.M. (2001) - *A fluvial record of long-term steady-state uplift and erosion across the Cascadia Forearc High, Western Washington State.* American Journal of Geoscience, 301, 385-431.

PÈREZ-PEÑA J.V., AZAÑON J.M., AZOR A., DELGADO J., GONZÁLEZ-LODEIRO F. (2009) - *Spatial analysis of stream power using GIS: SLk anomaly maps.* Earth Surface Processes and Landforms, 34,16-25.

PICOTTI V. & PAZZAGLIA F.J. (2008) - *A new active tectonic model for the construction of the Northern Apennines mountain front near Bologna (Italy).* Journal of Geophysical Research, Solid Earth, 113 (B8), B08412.

PIERUCCINI P., DI CELMA C., DI RITA F., MAGRI D., CARNEVALE G., FARABOLLINI P., RAGAINI L. & CAFFAU M. (2017) - *Sedimentology, faunal content and pollen record of Middle Pleistocene palustrine and lagoonal sediments from the Peri-Adriatic basin, Abruzzi, eastern central Italy.* Quaternary Research, 83 (3), 359-372

SALLUSTRI GALLI C., TORRINI A., DOGLIONI C. & SCROCCA D. (2002) - *Divide and highest mountains vs subduction in the Apennines.* Studi Geologici Camerti, Nuova Serie, 1, 143-153.

SAURO U. & ZAMPIERI D. (2004) - *Evidenze morfologiche di tettonica recente sul margine orientale della Maiella (Appennino centrale).* Il Quaternario, Italian Journal of Quaternary Sciences, 17, 3-9.

SAVARESE F., TERTULLIANI A. & GALADINI F. (2011) - *Le fonti sul terremoto del 10 settembre 1881 in provincia di Chieti: revisione critica e nuove conoscenze.* Bollettino della Deputazione Abruzzese di Storia Patria, 102, 155-179.

SCHARER K.M., BURBANK D.W., CHEN J. & WELDON R.J. (2006) - *Kinematic models of fluvial terraces over active detachment folds: Constraints on the growth mechanism of the Kashi-Atushi fold system, Chinese Tian Shan.* GSA Bulletin, 118 (7-8), 1006-1021.

SCHWANGHART W. & KUHN N.J. (2010) - *TopoToolbox: A set of Matlab functions for topographic analysis.* Environmental Modelling & Software, 25, 770-781.

SCHWANGHART W. & SCHERLER D. (2014) - *TopoToolbox 2 - MATLAB-based software for topographic analysis and modeling in Earth surface sciences.* Earth Surface Dynamics, 2, 1-7.

SCISCIANI V. (2009) - *Styles of positive inversion tectonics in the Central Apennines and in the Adriatic foreland: Implications for the evolution of the Apennine chain (Italy).* Journal of Structural Geology, 31, 1276-1294.

TARQUINI S., ISOLAI., FAVALLI, M., MAZZARINI F., BISSON M., PARESCHI M.T. & BOSCHI E. (2007) - *TINITALY/01: a new Triangular Irregular Network of Italy.* Annals of Geophysics, 50, 407-425.

TARQUINI S., VINCI S., FAVALLI M., DOUMAZ F., FORNACIAI A. & NANNIPIERI L. (2012) - *Release of a 10-m-resolution DEM for the Italian territory: comparison with global-coverage DEMs and anaglyph-mode exploration via the web.* Computers & Geosciences, 38, 168-170.

THOMPSON S.C., WELDON R.J., RUBIN C.M., ABDRAKHMATOV K., MOLNAR P. & BERGER G.W. (2002) - *Late Quaternary slip rates across the central Tien Shan, Kyrgyzstan, central Asia.* Journal of Geophysical Research, Solid Earth, 107 (B9), 2203.

TROIANI F. & DELLA SETA M. (2008) - *The use of the Stream Length-Gradient Index in morphotectonic analysis of small catchments: A case study from central Italy.* Geomorphology, 102, 159-168.

TUCKER G.E. & WHIPPLE K.X. (2002) - *Topographic outcomes predicted by stream erosion models: Sensitivity analysis and intermodel comparison.* Journal of Geophysical Research, Solid Earth, 107 (B9), 2179.

URBANO T., PIACENTINI T. & BUCCOLINI M. (2017) - *Morphotectonics of the Pescara River basin (Central Italy).* Journal of Maps, 13 (2), 511-520.

VANNOLI P., BASILI R. & VALENSISE G. (2004) - *New geomorphic evidence for anticlinal growth driven by blind-thrust faulting along the northern Marche coastal belt (central Italy).* Journal of Seismology, 8 (3), 297-312.

WOBUS C., WHIPPLE K.X., KIRBY E., SNYDER N., JOHNSON J., SPYROPOLOU K., CROSBY B. & SHEEHAN D. (2006) - *Tectonics from topography: procedures, promise, and pitfalls.* In: WILLETT S.D., HOVIUS N., BRANDON M.T. & FISHER D.M. (Eds.), Tectonics, Climate and Landscape Evolution, Geological Society of America Special Paper, 398, pp. 55-74.

ZOVOILI E., KONSTANTINIDI E. & KOUKOUVELAS I. (2004) - *Tectonic geomorphology of escarpments: the cases of Komptotades and Nea Anchialos faults.* Bulletin of the Geological Society of Greece, 36 (4), 1716-1725.

(Ms. received 22 April 2020, accepted 3 September 2020)

Edizioni ETS
Palazzo Roncioni - Lungarno Mediceo, 16, I-56127 Pisa
info@edizioniets.com - www.edizioniets.com
Finito di stampare nel mese di dicembre 2020