FROM 1997 TO 2016:

THREE DESTRUCTIVE EARTHQUAKES

ALONG THE CENTRAL APENNINE FAULT SYSTEM, ITALY

Program and Abstracts

International Field Trip

July 19th - 22nd 2017

Patronage to:

Coverpage:

Upper Left) Falling houses of the Costa village (MC) during the mainshock of the Mw = 6.0 1997 Umbria - Marche Earthquake. Upper Right) Faulted water pipeline at Paganica during the mainshock of the Mw = 6.3 2009 L'Aquila Earthquake. Bottom) Panoramic view of the western slope of Monte Vettore. Here is shown the scarp related to the causative fault of the Mw = 6.5 earthquake during the 2016 Amatrice - Norcia - Visso seismic sequence.

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PROGRAM

<u>19th JULY 2017</u>

***Location*: UNICAM Campus, Via A. D'Accorso, Camerino (MC).**

14:30 - Reception and Packet Pick Up

15:00 - Welcoming Remarks and Introduction to the International Field Trip (Flavio Corradini, Dean of the University of Camerino; Carlo Doglioni, President of INGV; Emanuele Tondi, Head of the Geology Division, UNICAM)

15:30 - The Apennines in the framework of the Mediterranean area (Massimiliano Barchi, UNIPG and Giusy Lavecchia, UNICH, on behalf of the Organizing Committee)

16:00 - Seismicity, GPS and INSAR data of the 1997 Umbria-Marche, 2009 L'Aquila and 2016 Amatrice-Visso-Norcia earthquakes (Lauro Chiaraluce, Stefano Salvi, Roberto Devoti, INGV)

17:30 - Coffee break

17:45 - Active faults and coseismic surface effects in the epicentral areas of the 1997 Umbria-Marche, 2009 L'Aquila and 2016 Amatrice-Visso-Norcia earthquakes (Eutizio Vittori, ISPRA and Paolo Marco de Martini, INGV, on behalf of the Organizing Committee)

18:45 - Open discussion (moderated by the Organizing Committee)

19:00 - Open Poster Session with appetizers and wine

20:30 - Social Dinner in the University Campus

<u>20th JULY 2017</u>

Field trip to the epicentral area of 1997 Umbria-Marche earthquake

Field trip leaders, on behalf of the Organizing Committee: *Anna Maria Blumetti (ISPRA), Paolo Galli (DPC), Alessandro Maria Michetti (INSUBRIA), Emanuele Tondi (UNICAM), Eutizio Vittori (ISPRA)*

8:30 - Departure from University Campus to Colfiorito area

Stop 1: The Church of Santa Maria in Plestia: panoramic view and introduction to the geology of the area

Stop 2: Faento Montain: the Colfiorito Border Fault scarp

Light lunch

Stop 3: Swamp of Colfiorito: morphological evidences of active tectonics and related karsic processes

Stop 4: RED ZONE of the Camerino city: observation of damaged buildings related to the 2016 Amatrice, Visso and Norcia earthquake.

19:00 - University Campus: INQUA Business Meeting (Open to all interested participants) Discussion of paleoseismic projects developed by INQUA

INQUA meeting in New Zealand (November) TERPRO Commission

20:30 - Dinner at Villa Fornari

21st JULY 2017

Field Trip to the epicentral area of 2016 Amatrice, Visso and Norcia earthquake

Field trip leaders, on behalf of the Organizing Committee: *Francesco Brozzetti (UNICH), Francesca Cinti (INGV), Paolo Galli (DPC), Franz Livio (INSUBRIA), Paolo Marco De Martini (INGV), Gilberto Pambianchi (UNICAM), Pietropaolo Pierantoni (UNICAM), Alberto Pizzi (UNICH)*

8:00 - Departure from University Campus in Camerino to Monte Vettore area

Stop 1: Forca Canapine: panoramic view and introduction to the geology of the Monte Vettore area

Stop 2: Pian Perduto: visit to the paleoseismological trench sites at Fonte San Lorenzo

Light lunch

Stop 3: Forca di Presta: visit to the paleoseismological trench site and walk along the "Cordone del Vettore" fault scarp

Stop 4: Colli Alti e Bassi (optional): free face observation along a bedrock fault scarp

Stop 5: Capanna Ghezzi (optional): coseismic rupture on soil

20:30 - Dinner at Hotel Fiordigigli in Assergi, L'Aquila (http://www.fiordigigli.com/)

22nd JULY 2017

Field Trip to the epicentral area of 2009 L'Aquila earthquake

Field trip leaders, on behalf of the Organizing Committee: *Anna Maria Blumetti (ISPRA), Paolo Boncio (UNICH), Luca Guerrieri (ISPRA), Alberto Pizzi (UNICH)*

8:00 - Departure from Hotel Fiordigigli in Assergi to L'Aquila

Stop 1: Highway L'Aquila east exit: panoramic view and introduction to the geology of the area

Stop 2: Paganica area: coseismic rupture of the water pipeline of Paganica

Stop 3: L'Aquila city center: view of the damage of Piazza Duomo, microzonation and reconstruction projects of the L'Aquila city center

Stop 4: Road towards Passo delle Capannelle: the Assergi Fault

Lunch at Hotel Fiordigigli, Roundtable open discussion (moderated by the Organizing Committee)

17:00 - Program ends

ABSTRACTS

FAULTS PARAMETERS CHARACTERIZATION FOR SEISMIC SOURCES MAPPING: PRINCIPLE AND CASE OF STUDIES

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The seismotectonic zonation is prerequisite for any regional seismic hazard assessment. An appropriate dentification of tectonic structures improves the seismic sources characterization, in termes of location, magnitude and recurrence.

The principle of zonation is established on basis of neotectonics deformation evidences and seismicity. It consists of delimiting the area subject to earthquakes into seismoectonic provinces. *Zone I* corresponds to the geological province which reveals a Quaternary deformation; consequently, the zone may be include all active faults identified (observable hidden) to date. *Zone II* corresponds to the province that reveals a Neogene deformation and diffuse seismicity. *Zone III* corresponds to the geological province which reveals an uplift of its old massifs and low seismicity.

The geometrical parameters of each active fault (length, width, dip and depth) are integrated in the empirical formulas to estimate the maximum magnitude of credible earthquake designated by MCE (Wells & Coppersmith). And also, to calculate the peak ground acceleration PGA.

LARGE LANDSLIDES AND DEEP SEATED GRAVITATIONAL SLOPE DEFORMATION TRIGGERED BY THE 2016-2017 CENTRAL ITALY SEISMIC CRISIS: FIRST EVIDENCES FROM THE MOUNT VETTORE - MT BOVE EPICENTRAL AREA

Domenico Aringoli[*1], Piero Farabollini[1], Marco Materazzi[1], Gilberto Pambianchi[1] & Gianni Scalella[2]

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On August 24th 2016 a Mw=6.0 earthquake gave rise to a catastrophic seismic crisis over a large area located among the Lazio, Marche, Abruzzi and Umbria regions (Central Italy) which caused human casualties and severe damages to buildings and infrastructures (Aringoli et al., 2016).

The epicentre of the first main shock was located a few kilometers north of the village of Accumoli (Rieti) and was followed by thousands of aftershocks, which are continuing to shake the area since that time.

With regard to the seismic sequence started on 24 August, more than 1200 earthquakes with magnitude greater than 3 Mw were recorded in the first six months that affected a large area over a thousand km2, extending from Amatrice to Camerino. During this period seven earthquakes with magnitude greater than 5 Mw have been recorded.

Immediately after the mainshocks, an in depth geomorphological survey has been focused on co-seismic and post seismic effects, the latter related to the seismic shaking (e.g. landslides and fracturing in soil and rock).

This paper brings data on superficial effects and some preliminary considerations about the interaction and possible relationship between surface faulting and the occurrence of large landslides and Deep-Seated Gravitational Slope Deformation (*DSGSD's*) along the alignment of the main active faults.

TOWARDS A UNIFIED AND WORLDWIDE DATABASE OF SURFACE RUPTURES (SURE) FOR THE FAULT DISPLACEMENT HAZARD ANALYSES

Stéphane Baize[*1], Oona Scotti[1] and the SURE working group

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Assessing Fault Displacement Hazard is based on empirical relationships predicting on-fault and off-fault surface rupture, these equations being derived from earthquake data. The regressions that are used so far are based on sparsely populated datasets, including a limited number of mainly pre-2000 events. A common effort has started in 2015 to constitute a worldwide and unified database (SUrface Rupture due to Earthquakes) to further improve hazard assessments. This database will update existing databases that relate earthquake magnitude to surface faulting. Since 2015, two workshops have been organized to start discussions on how to build such a database: it was decided that, together with existing datasets, the future database will include 1) recent cases which deformation have been captured and measured with modern techniques (InSAR, LiDAR, Optical correlation, etc), 2) new parameters which are relevant to properly describe the rupture (such as surficial geology, width of deformation band, description of structural complexity of rupture, etc).

The first step that is presently ongoing has consisted in merging the existing Japanase and USA databases into the SURE structure, which includes the "earthquake table", "fault section table" and obviously "observation point table". The next steps will consist in incorporating well-known earthquake cases described in literature. A preliminary search in the USGS earthquake database provided a catalog of ≈130 M6+ onshore epicenters since 2000, most of which have occurred in Asia and very few having reported surface rupture information. We already anticipate that recent events in Oceania (e.g. 2016 Kaikoura in New Zealand and 2016 Petermann Range in Australia), Europe (2009 L'Aquila and 2016 Norcia in Italy), Northern America (2010 El Mayor-Cucapah and 2014 Napa) or Asia (2008 Wenchuan and 2016 Kumamoto) will become good candidates to populate the new database, with their numerous field and remote sensing data. A special attention will be paid to the M6.5 Norcia earthquake which rupture has been extensively mapped and measured by an international team (Open EMERGEO). Observations were compiled in a homogenous way, providing a unique dataset and opening a promising perspective on future cooperation at the Euro-Mediterranean scale to study future cases. With the International Field Trip in Central Italy, we aim to exchange with geologists and hazard community on the Surface Rupture Database and its relevance to contribute to hazard analyses.

This work, performed in the framework of INQUA and IAEA activities, is presently sponsored by IRSN. The following persons have so far provided their data to the SURE database: Johann Champenois, Francesca Cinti and Luca Guerrieri, Timothy Dawson, Yann Klinger, James McCalpin, Koji Okumura, Pilar Villamor, Makoto Takao, Riccardo Civico and the Open EMERGEO team.

We plan to finalize the first version by the end of 2017 and publish the data in open access files. If you are interested to participate or to obtain the first version of the database, please contact stephane.baize@irsn.fr

COSEISMIC RUPTURES RELATED TO THE 2016 CENTRAL ITALY EARTHQUAKE SEQUENCE IN THE NORTHERN TERMINATION OF THE MT. VETTORE - MT. BOVE FAULT SYSTEM

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The 2016 Central Italy earthquake sequence, consisted of three main shocks and thousands of secondary events, produced significant surface ruptures along the SW-dipping normal fault system associated with the Mt. Gorzano-Mt. Vettore-Mt. Bove alignment. The mapping and characterisation of the distribution of coseismic ruptures is an essential tool to determine the movement along pre-identified/inferred faults and to better understanding the ground response. For this reason, several teams of geologists from different research institutes and universities undertook systematic field surveys since after the first seismic event.

The intention of this study is to determine the presence and the character of coseismic features at the northernmost termination of the Mt. Vettore-Mt. Bove fault system (VBFS), nearby the highly damaged village of Ussita. The methodology consisted on selecting, in the available geological map, the faults oriented NNW-SSE (mostly parallel to the VBFS), which were more prone to be activated. Once in the field, a detailed measurement of the surface ruptures (orientation, length, opening, vertical throw) was performed. Coseismic ruptures associated with primary and secondary effects were observed between the localities of Frontignano and Cupi.

Preliminary results based on the observations collected so far in this area, show that significant primary surface ruptures (>100m long and <60cm splay) are recorded in the Frontignano area, whereas these tend to decrease (<20m long and <15cm splay) toward the northern sector of the study area, precisely near the locality of Vallestretta, about the 2 km north from Ussita. The latter are the last surface ruptured ascribable to fault reactivation and inferred to belong to the related VBFS. Despite a considerable seismic activity that interested the contiguous area at the north of the field study, between the villages of Fiordimonte and Muccia, coseismic surface ruptures were not evident beyond the locality of Cupi.

METHODOLOGY FOR EARTHQUAKE RUPTURE RATE ESTIMATES OF FAULT NETWORKS: EXAMPLES FOR THE WESTERN CORINTH RIFT, GREECE

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Modelling the seismic potential of active faults is a fundamental step of probabilistic seismic hazard assessment (PSHA). An accurate estimation of the rate of earthquakes on the faults is necessary in order to obtain the probability of exceedance of a given ground motion. Most PSHA studies consider faults as independent structures and neglect the possibility of multiple faults or fault segments rupturing simultaneously (Fault to Fault -FtF- ruptures). The latest Californian model (UCERF-3) takes into account this possibility by considering a system level approach rather than an individual fault level approach using the geological , seismological and geodetical information to invert the earthquake rates. In many places of the world seismological and geodetical information along fault networks are often not well constrained. There is therefore a need to propose a methodology relying only on geological information to compute earthquake rate of the faults in the network. In this methodology, similarly to UCERF-3, a simple distance criteria is used to define FtF ruptures and consider single faults or FtF ruptures as an aleatory uncertainty. Rates of earthquakes on faults are then computed following two constraints: the magnitude frequency distribution (MFD) of earthquakes in the fault system as a whole must follow an imposed shape and the rate of earthquakes on each fault is determined by the specific slip-rate of each segment depending on the possible FtF ruptures. The modelled earthquake rates are then confronted to the available independent data (geodetical, seismological and paleoseismological data) in order to weigh different hypothesis explored in a logic tree.

The methodology is tested on the Western Corinth Rift, Greece (WCR) where recent advancements have been made in the understanding of the geological slip rates of the complex network of normal faults which are accommodating the ~15 mm/yr North-South extension. Modelling results show that geological, seismological extension rates and paleoseismological rates of earthquakes cannot be reconciled with only single fault rupture scenarios and require hypothesising a large spectrum of possible FtF rupture sets. Furthermore, in order to fit the imposed regional Gutenberg-Richter MFD target, some of the slip along certain faults needs to be accommodated either with interseismic creep or as post-seismic processes. Furthermore, individual fault's MFDs differ depending on the position of each fault in the system and the possible FtF ruptures associated with the fault. Finally, a comparison of modelled earthquake rupture rates with those deduced from the regional and local earthquake catalogue statistics and local paleosismological data indicates a better fit with the FtF rupture set constructed with a distance criteria based on a 5 km rather than 3 km, suggesting, a high connectivity of faults in the WCR fault system.

Surface ruptures following the 30 October 2016 Mw 6.5 Norcia earthquake, central Italy

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We present a 1:25,000 scale map of the coseismic surface ruptures following the 30 October 2016 M_w 6.5 Norcia normal faulting earthquake, central Italy. Detailed rupture mapping is based on almost 11,000 oblique photographs taken from helicopter flights, with derived Structure-from-Motion photogrammetry, that has been verified and integrated with field data (7000 measurements). Thanks to the common efforts of the Open EMERGEO Working Group (130 people, 25 research institutions and universities from Europe) we were able to document a complex surface faulting pattern with an average strike of 155° (primarily down to the SW) along about 28 km of the active Mt. Vettore - Mt. Bove fault system. Geometric and kinematic characteristics of the rupture were observed and recorded along closely-spaced, parallel or subparallel, overlapping or step-like synthetic and antithetic fault splays of the activated fault systems, comprising a total surface rupture length of approximately 45 km when all ruptures were considered.

STRUCTURAL ARCHITECTURE AND PETROPHYSICAL PROPERTIES OF THE CATACLASTIC ROCKS ALONG THE MONTE MARINE EXTENSIONAL FAULT ZONE, CENTRAL APENNINES (ITALY)

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The Monte Marine Fault Zone (MMFZ) is an extensional seismogenic fault zone located to the Northwest of the L'Aquila town. The MMFZ strikes NW-SE and is one of the many fault segments constituting the wide array of fault systems responsible for the recent earthquake sequences occurred in the Central Apennines (Campotosto 2017, Amatrice 2016). The exposed fault zone, which is likely composed by two near parallel, hard-linked fault strands, crops out continuously for 6.5 km, from the village of Barete (to the Northwest) to the village of Arischia (to the Southeast). The MMFZ is structurally complex and characterized by a well-developed fault core formed by several meters-thick carbonate gouges and breccias, and by a hundreds of meters thick fractured damage zone. Both fault core and damage zone contain minor, synthetic and antithetic extensional faults. Despite some limitations due to vegetation, the fault architecture can be mapped in detail, thanks to the presence of quarries, road cuts and of some accessible valleys cutting the fault zone perpendicular to the orientation of the master slip surface.

With this contribution, we present the preliminary results of the study of the Northwest sector of the MMFZ, where we have investigated the microstructural fabric, deformation mechanisms, and grain size and shape evolution of the fault core rocks, across a ~ 20 m wide transect.

The main fault surface outcrops discontinuously to the East of the village of Barete and consists of a very smooth surface with an average orientation of 217/64. This surface is surrounded by loose micro-breccia and gouge that contain clasts of different grain size and shape. Based on this evidence, we have divided the tens of meters wide fault core in three main cataclastic facies: Facies 1: fault gouge composed by loose material with clasts <0.063 mm floating into a very comminuted matrix; Facies 2: breccia composed by loose material with clasts <2 mm; Facies 3: breccia composed by loose material with clasts >2mm and <20-30 mm. All these fault rocks are partially cemented or re-cemented and locally display carbonate concretions elongated in the fault dip direction. Near the contact between fault core and damage zone, Facies 3 is typically characterized by intensely fractured rocks with few matrix and very angular clasts of 20-30 mm in diameter. Such transitional facies has the diagnostic feature of a proto-cataclasite.

3D MULTI-SCALE VELOCITY STRUCTURE OF AN ACTIVE SEISMOGENIC NORMAL FAULT ZONE (CENTRAL APENNINES, ITALY)

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The characterization of physical properties of fault zones (e.g., ultrasonic velocities, elastic moduli, porosity and fracture intensity of the fault zone rocks) is a relevant topic in reservoir geology (exploration and exploitation) and fault mechanics, for the modelling of both long-term quasi-static and fast dynamic fault zone evolution with time.

Here we characterized the shallow subsurface velocity-elastic structure of the active Vado di Corno normal fault zone (Campo Imperatore, Central Apennines, Italy) which is up to > 300 m thick. Based on a detailed structural mapping of the fault footwall block covering a ~ 2 km long fault segment, four main structural units separated by principal fault strands were recognized: (i) cataclastic unit, (ii) breccia unit, (iii) high-strain damage zone, (iv) low-strain damage zone. The single units were systematically sampled along a transect (~ 200 m) orthogonal to the average strike of the fault and characterized in the laboratory in terms of petrophysical properties (i.e., V_p, V_s, static and dynamic elastic moduli, porosity). The cataclastic and breccia units (V_p = 4.68±0.43 kms^{-1}, V_s = 2.68±0.24 kms^{-1}) were significantly "slower" compared to the damage zone units (V_p = 5.43±0.53 kms^{-1}, V_s = 3.20±0.29 kms^{-1}). A general negative correlation between ultrasonic velocity and porosity values was reported. Moreover three dimensional acoustic anisotropy was quantified within the different units with respect to the mapped fault strands, and related to the deformation fabrics (i.e., open fractures, veins) observed at the sample scale.

A V_p - V_s seismic refraction tomography was then performed in the field along a profile (~ 90 m) across the fault zone. The tomographic results clearly illuminated fault-bounded rock bodies characterized by different velocities (i.e., elastic properties) and geometries which match with the ones deduced from the structural analysis of the fault zone exposures.

Fracture intensity measurements (both at the sample and outcrop scale) were performed to investigate the scaling relation between laboratory and field measurements. These results were then coupled with ultrasonic velocity vs. confining pressure (0-30 MPa) profiles measured in the laboratory to extrapolate the subsurface velocity structure of the fault zone to larger depths (up to ~ 1 km). The final dataset of physical properties was used to build a three dimensional velocity-elastic model of the Vado di Corno fault zone based on the fault zone structure inferred from the mapping.

This type of studies are extremely relevant to better understand the petrophysical evolution and geophysical expression of active fault zones during the seismic cycle and represent the base for modern and robust fault mechanics models developed both in quasi-static or dynamic rupture scenarios.

FAULT DISPLACEMENT HAZARD ASSESSMENT FOR NUCLEAR INSTALLATIONS BASED ON IAEA SAFETY STANDARDS

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In the IAEA Safety Standard NS-R-3(rev.1), surface fault displacement hazard assessment (FDHA) is required for the siting of nuclear installations. If any capable faults exist in the candidate site, IAEA recommends the consideration of alternative sites. However, due to the progress in palaeoseismological investigations, capable faults may be found in existing site. In such a case, IAEA recommends in SSG-9 to evaluate the safety using probabilistic FDHA (PFDHA), which is an empirical approach based on still quite limited database. Therefore a basic and crucial improvement is to increase the database. In 2015, IAEA produced a TecDoc-1767 on Palaeoseismology as a reference for the identification of capable faults. Another IAEA Safety Report 85 on ground motion simulation based on fault rupture modelling provides an annex introducing recent PFDHAs and fault displacement simulation methodologies. The IAEA expanded the project of FDHA for the probabilistic approach and the physics based fault rupture modelling. The first approach needs a refinement of the empirical methods by building a world wide database, and the second approach needs to shift from kinematic to the dynamic scheme. Both approaches can complement each other, since simulated displacement can fill the gap of a sparse database and geological observations can be useful to calibrate the simulations. The IAEA already supported a workshop in October 2015 to discuss the existing databases with the aim of creating a common worldwide database. A consensus of a unified database was reached. The next milestone is to fill the database with as many fault rupture data sets as possible. Another IAEA work group had a WS in November 2015 to discuss the state-of-the-art PFDHA as well as simulation methodologies. Two groups jointed a consultancy meeting in February 2016, shared information, identified issues, discussed goals and outputs, and scheduled future meetings. In line with the agreement between two groups, the structure of the work group was discussed and nominated external experts from the Member States during the consultancy meeting in Menlo Park, USA in December 2016 and decided to produce a TecDoc on PFDHA. In May 2017 in Vienna, all nominated external experts and work group members gathered and consolidated the table of the contents of the TecDoc and scheduling. This task will be support by External Events Section/NSNI, IAEA ExtraBudgetary Project (EESS-EBP).

BEHAVIOR OF THE BEAR RIVER FAULT - A NEW NORMAL FAULT ON THE EASTERN MARGIN OF THE BASIN AND RANGE, U.S.A.

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Interpretation of paleoseismic results from three sites on the Bear River fault (BRF) in Wyoming and Utah substantiates the conclusion of an earlier study (West, 1993) that the fault, which appears to have formed along a thrust ramp in the Sevier orogenic belt, first ruptured to the surface in the late Holocene. Our results provide evidence and additional age control for two previously identified large earthquakes (~ 4500 and 3000 yr B.P.) and for a newly recognized earthquake that occurred c. 200-300 yr B.P. (after development of a topsoil above a deposit with a date of A.D. 1630 and before the beginning of the historical period in 1850). Cumulatively, these earthquakes produced about 6-10 m of net vertical displacement on a zone 40-km long and up to 5 km wide wide. The complexity and evolution of rupture at the south end the fault, mapped in detail using airborne lidar imagery, is strongly influenced by preexisting structure. The rapid flurry of strain release and high slip rate (~2 mm/yr) on the nascent BRF make it one of the most active normal faults in the Basin and Range. These observations from a region of low crustal extension (<1 mm/yr relative to North America) have implications for the mechanics, evolution and strain-release behavior of immature faults. Also, the sudden initiation of faulting in an area of no prior late Cenozoic extension has implications for the size of background earthquakes (M>7) that should be considered for seismic hazard analysis.

COSEISMIC THROW VARIATION ACROSS ALONG-STRIKE BENDS ON ACTIVE FAULTS: IMPLICATIONS FOR DISPLACEMENT/LENGTH SCALING OF SEISMIC RUPTURE

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We suggest that fault bends play a key role in explaining the scatter seen in maximum offset vs fault length relationships shown in existing fault scaling relationships. Primary detailed field measurements of the fault geometry and coseismic throw in the 2016-2017 central Italy earthquake sequence, together with observations of other large historical normal-faulting earthquakes within the literature, provide multiple examples where coseismic throw increases across bends in the strike of faults. We can quantify the expected change in throw across a bend by applying the "geometry-dependent throw-rate theory" (Faure Walker et al., 2015) to a single rupture, based on conservation of the strain-rate across the variable fault geometry.

We measured the geometry and kinematics of earthquake surface ruptures for the 24th August and 30th October 2016 earthquakes (Mw 6.0, Mw 6.5) in central Italy, collecting measurements of strike, slip vector azimuth, plunge of the slip vector, displacement, heave and throw. Following the 24th August event, we covered the total extension of the coseismic surface ruptures, with measurements taken every 2-10 m along strike. Following the 30th October event, we focused on constraining the large coseismic throws evident around a prominent along-strike fault bend, present in the southern part of the Mt. Vettore fault, collecting measurements every 10-50 m along strike, and characterizing the surface ruptures across the along strike fault bend and on the fault segments either side along strike.

Both datasets show that although the slip-vector azimuth and the coseismic heave vary by <10-20% across the bend, yet the coseismic dmax increases by a factor of x2-3 where the strike of the host fault changes by ~30º and the dip increases by 20-25º. We explain the large increase of throw using calculations that relate it to strain-rate conservation across the varying geometry and kinematics of the host fault. This calculation predicts large variations in throw given changes in the strike and dip of the fault in the fault bend. This is consistent with the large increase of throws on fault bends we have observed on other historical large-offset normal faulting earthquakes, which ruptured across along-strike fault bends (e.g. 1887, Sonora earthquake, Mw 7.5 (Suter, 2015); 1981, Corinth earthquake, Mw 6.7-6.4 (Jackson et al., 1982; Morewood & Roberts, 2001); 1983, Borah Peak earthquake, Mw 7.3 (Crone et al., 1987)). The application of the same calculations can explain the large increase of throws across fault bends also for these other examples. The largest offsets, observed across fault bends, including those associated with the 30th October Mw 6.5 earthquake and with the other historical earthquakes, are always larger than the maximum displacement predicted by Wells & Coppersmith, 1994, *Dmax*/fault length scaling relationship. We use these findings to suggest that the varying geometry of faults, represent one of the possible causes of the scatter of values in *Dmax*/fault length scaling relationships. Hence, along-strike fault bends should be considered when scaling relationships are used to infer stress drop variability for earthquakes or maximum magnitudes from vertical offsets in palaeoseismic datasets.

INTEGRATING GEODETIC AND GEOLOGIC ESTIMATES OF SLIP RATE ON THE CARBONERAS FAULT IN THE BETICS, SPAIN

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For the last decade, we have been studying in detail the tectonic activity of the Carboneras fault in the SE Betics in southern Spain. Specifically, we quantify the geodetic and geologic slip rates for the on-land section of the fault, as well as trying to get some further insight on the state of locking of the fault. Continuous and campaign GPS observations conducted by the UB group during the last decade, illustrate that the Carboneras fault is continuing its tectonic activity, which is expressed mainly as a left-lateral strike slip motion of 1.3±0.2 mm/yr (Echeverria et al., 2015). To reveal how the deformation is partitioned between different structures, 3 new continuous GPS points are being established along the fault-perpendicular profile. In addition, since summer 2016, we have conducted surveys of the nearby CuaTeNeo and IGN Regente points. We have also established and measured several new geodetic points near the fault, with the aim of increasing the spatial coverage of the observations. This geodetic, short-term, slip rate is in surprising good agreement with the geologic slip rate estimates based on paleoseismic studies, which indicate a minimum strike-slip rate of 1.31 mm/yr and dip-slip rate of 0.05 mm/yr since 110.3 ka (Moreno et al., 2015). To increase the paleoseismic event database, 6 new sites have been identified along the fault, where further paleoseismic trenching surveys will be performed within the coming year or two. These new data, combined with the findings of the recent geomorphological study of river offsets (Ferrater, 2016) and new GPS observations, should significantly improve the reliability of the existent deformation data. Ultimately, we hope that our results will contribute to better understanding of the seismic hazard posed by the Carboneras fault in the SE Betics.

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TESTING PFDHA FOR DISTRIBUTED FAULTS DURING NORMAL FAULTING EVENTS: PROBABILITY OF OCCURENCE AS DERIVED FROM THE 30th OCT. 2016 EVENT (Mw 6.5).

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Recent advancements in earthquake surveying show that distributed faulting (DF) is a typical mechanism for moderate to strong earthquakes (e.g., L'Aquila 2009; Napa Valley 2014; Kaikoura 2016; Kumamoto 2016). The Mw 6.5, 30 October 2016 event confirms this behavior, having generated surface faulting along a plethora of fault strands, resulting in a total of 43 km of mapped surface ruptures (Open EMERGEO Working Group, 2017, in submission to *Scientific Data*). The main fault trace includes the Monte Vettore – Monte Bove segments and ruptured almost continuously for a length of ca. 20-25 km.
We analyzed the available database (Open Emergeo data) exploring the probability of occurrence of distributed faulting as a function of distance from the main fault (commonly referred to as Probabilistic Fault Displacement Hazard Assessment – PFDHA; e.g., ANSI/ANS-2.30, 2015), using the methodology proposed by Youngs et al. (2003). We found that the probability of DF occurrence is higher than expected from empirical regressions based on normal faults database (Youngs et al., 2003). This is particularly true in the far-field (i.e., commonly more than ca. 5 km) and agrees with the results previously obtained, with a similar approach, for the 2009 L'Aquila event (Mw 6.3) by Livio et al. (2016).

The probability of distributed faulting for the 2016 event peaks at 1-2 km from the main fault strand and then decreases with distance. In the far-field, minor peaks in DF occurrence are recognized at 7-8 and 10-11 km from the main fault in the hangingwall sector; these ranges correspond to the location of mapped antithetic fault strands. We suggest that the structural control on the occurrence of distributed faulting has to be taken into account in the PFDHA for distributed faulting, as an appropriate weighting parameter (Gürpinar et al., 2017).

Despite its striking role in terms of earthquake-related damage, DF is often overlooked in seismic hazard assessment practice, possibly due to a lack of analyzed case histories; the investigation of the 30 October 2016 Central Italy earthquake, together with other recent events will contribute to the implementation of better strategies for managing seismic risk. In this sense, we believe that the 2016 Central Italy can act as a reference case history for DF investigation, due to the availability of detailed pre-event information (i.e., geological and structural maps) and post-seismic surveys on multiple fault strands achieved through field- and remote-based techniques.

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NEW PALEOSEISMOLOGICAL DATA ON CARBONERAS FAULT (SE IBERIA): PRELIMINARY RESULTS ON TOSTANA SITE

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The Eastern Betics Shear Zone (EBSZ), in SE Iberia, is a slow deformation zone with low seismicity. The lack of moderate-large earthquakes in historical times forces us to include paleoseismological records to better assess the seismic hazard. The last studies on Carboneras Fault (CF) showed that this 150 km long (100 km off-shore, 50 km on-shore) left-lateral strike-slip fault has a ca. 1.3 mm/yr slip rate. However, this velocity only to some segment or trace of the fault, and there is still a lack of data on the different segments.

On the 12 km long La Serrata Range the CF forms a contractional duplex. In this work, we are studying, for the first time, the southeastern mountain front by means of geomorphological and paleoseismological methods. Through the analyses of the landforms observed on a 0.5 m resolution DEM and field survey, an *a priori* late Pleistocene alluvial fan, at the base of Cerro Tostana, was selected to carry out the paleoseismological trenching.

Seven trenches were dug onto the apex zone of the alluvial fan. Two of them were perpendicular and the other five, parallel to the fault. The stratigraphy is complex and difficult to define in some points. It consists of an alternation of limestone gravels and silty layers, crossed by fine angular gravel channels. All of them are from the same source area.

The perpendicular trenches, T1 and T4, aimed to cross the fault and locate it. These two trenches showed evidences for at least 4 paleo-earthquake events on the sedimentary record. The youngest event reaches the Present-day soil. The parallel trenches crossed three well defined channels and at least four stratigraphic units correlative between the trenches. The channels are offset, and show different stratigraphical positions, evidencing greater offsets in the older channels. This suggests that this fault had a continuous activity during the last 100 Ka at least.

Trench-slicing between trenches T6 and T7, towards the fault plane, is planned to finely measure the offset of the channels. Future work implies the radiocarbon dating of 60 samples collected along the trenches, mainly consisting of mollusk shells and charcoals. Relative dating of the mollusk shells by means of amino acid racemization will also be achieved in the next steps.

COULOMB STRESS TRANSFER BEFORE, DURING AND AFTER THE 2016 – 2017 A.D. EARTHQUAKE SEQUENCE

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Coulomb stress changes from 1349 A.D. to the present day have been calculated on all faults in the central Italian Apennines, including stress changes from the 1997 A.D., 2009 A.D. and 2016 - 2017 A.D. earthquake sequences. These Coulomb stress changes are calculated for faults with strike-variable geometry (as observed from bedrock scarps throughout the Apennines, following the approach of Mildon et al. [2016]). The interseismic loading of the brittle faults is calculated from Holocene slip rates on discrete shear zones (following the method of Wedmore et al. [2017]). In particular we focus of the faults the ruptured in the 2016 – 2017 A.D. sequence, the Mt. Vettore and Laga faults. We take account of the long elapsed time on the Mt. Vettore fault (from palaeoseismology, Galadini and Galli [2003]). The coseismic stress changes from historical and palaeoseismic events are calculated. Then the coseismic and interseismic Coulomb stress changes are summed together over time. The cumulative Coulomb stress present on the Mt. Vettore and Laga fault is calculated, prior to the 2016 – 2017 A.D. sequence. The stress is heterogeneous across the fault planes, and it is suggested that this controlled the extent and timing of the three mainshocks of the sequence (24th August Mw=6.0, 26th October Mw=5.9 and 30th October Mw=6.5) by the presence of stress barriers (regions of negative Coulomb stress) at the limits of the first two mainshock ruptures. The coseismic Coulomb stress changes on the Mt. Vettore fault from the two most recent events, 1997 A.D. and 2009 A.D., are considered, as well as other nearby large events from the historical record. We show that the coseismic stress changes induced by the recent earthquakes are negligible when compared to the stress induced by other historical earthquakes and the interseismic loading. Therefore the concept of a "seismic gap" between the 1997 A.D. and 2009 A.D. epicentral areas is perhaps correct, but oversimplified. This highlights the importance of considering 1.) the full historical record, 2.) the importance of elapsed time and 3.) the importance of including the strike-variable fault geometry when calculating Coulomb stress changes. This work has been published in Mildon et al. [2017].

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ACTIVE FAULTS IN THE INNER NORTHERN APENNINES: A MULTIDISCIPLINARY REAPPRAISAL

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The recent seismic events in Garfagnana (January 2013 Mw 4.8) and Lunigiana (June 2013 Mw 5.1) have drawn new attention by the geological community on the seismotectonic problems of the internal segment of the northern Apennines, its seismogenic sources and related surface expressions, i.e. active faults. The long term to recent geological evolution of the Apennines has been characterized by contractional tectonics in the foreland, accompanied by extensional structures in the internal domain (Elter et al., 1975; Meletti et al., 2000; Carminati and Doglioni, 2012). This kinematic setting is still active today as documented by the crustal deformation given by GPS analysis (Bennett et al., 2012; Faccenna et al., 2014) and seismological data (INGV). Within this tectonic frame our work focuses on a revision of geological, geomorphological, geodetic, and seismological (instrumental and historical) data, with the aim to present a reappraisal of active faults of the internal Apennines North of the Arno river. We present a revision of the structural and morphological characteristics of the active fault systems, as well as the kinematics and strain rate estimates. They represent a new frame for an improvement of the current Ithaca (ISPRA) as well as DISS (INGV) catalogues with some utilities for the MS local projects. Finally, this work allows a better understanding of the seismotectonics of a region which in 1920 hosted the Fivizzano EQ, with an estimated Mw 6.5 similar to the main shock of the 2016 Central Italy seismic sequence.

THE LATEST EARTHQUAKES IN CENTRAL ITALY - PS-InSAR TIME SERIES OF ANALYSIS OF PRE- TO CO-SEISMIC DEFORMATION.

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In this study it's been applied the PSInSAR technique (Ferretti et alii, 2001).
The PSInSAR data cover a 20 year long time span, which encompasses both the pre-seismic and co-seismic phases.
They consist, moreover, of time series datasets (TS) of ERS (1992 - 2000) and ENVISAT missions (2002 - 2010), both ascending and descending orbits, that have been obtained by the Piano Straordinario di Telerilevamento Office (Ministero dell'Ambiente).

The PSInSAR data deformation scenario, on a decadal time scale, indicate that, in the study region, the preseismic phase could be characterised by a complex pattern. In particular, they highlight the occurrence of a uplift, in the hanging wall or footwall, predating the earthquake occurrence a few years before; moreover, a reversal of motion (pre-seismic subsidence), could occur less than a year before the main shock.

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HYDROCHEMICAL RESPONSE OF HIGH FLOW SPRINGS FOLLOWING THE CENTRAL ITALY SEISMIC SEQUENCE FROM AUGUST 24, 2016 TO JANUARY 18, 2017, CENTRAL APENNINES.

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Co-seismic hydrochemical response of groundwater springs following strong earthquakes is a significant concern in the Apennines, a region in central Italy characterized by carbonate groundwater systems interacting with active normal faults. We began sampling springs on August 27th to look for a co-seismic response following the August 24, 2016 earthquake that hit Central Italy 8 km northwest of Amatrice. We sampled two high discharge springs from carbonate aquifers in the Rieti area: Peschiera (PES) which feeds the aqueduct of Rome, Santa Susanna (SUS) on the the edge of the Rieti plain, and one medium discharge spring, Vicenna Riara (VIC), from a shallow alluvial aquifer within the Rieti plain, and the high discharge Nerea bottling plant in the Monte Vittore area. Samples collected at PES, SUS and VIC during 2014 and 2015 provide an opportunity for comparison with pre-seismic parameters.

The Rieti springs show that δ^2H_{water} vs. $\delta^{18}O_{water}$ and The $\delta^{34}S$ and $\delta^{18}O$ of sulfate remain relatively stable and plot with previous data, indicating no major change in recharge source. A brief enrichment in $\delta^{18}O_{sulfate}$ at PES after the August earthquake may be related to aeration of groundwater and introduction of atmospheric oxygen. There is $\delta^{13}C$-DIC enrichment at PES following the Aug 24th event and continuing through Oct 30th , whereas SUS shows no enrichment after Aug 24th, but enrichment starts after the October shocks. The source of the enrichment may either be deeply sourced CO_2 gas, released during dilation of specific fault conduits, or deeper circuit fluids that have had greater interaction with the relatively enriched carbonate aquifer. Although PES and SUS are only 10 km apart, they have different recharge areas, with the PES recharge area extending over a larger area and further to the east towards the Aug. 24th epicenter, which may explain the different responses between the August and October shocks.

At Nerea, located near the epicenter of the Oct 26th and 30th shocks, there was a strong response in electrical conductivity (EC) and alkalinity. Trace metals also show a strong response and elevated values persist through the end of November. A weaker response was noted following the Aug 24th shock, but no pre-earthquake data are currently available for comparison. The Rieti Springs show a strong response in physio-chemical and trace element concentrations following the Aug 24th shock, and a weaker response to the October shocks. One possible mechanism explaining the differential response between events is the release of stagnant pore fluids enriched in trace elements due to long residence times in the pore water during shaking. This mechanism accounts for the strong response at both Nerea and Rieti springs to earlier shocks in the sequence. The lack of response of the Rieti springs to the October shocks and Nerea to the January shock may be a function of pore fluid depletion during the earlier quakes. Continued work involves the installation of sensor equipment in wells found in high seismic risk areas to continuously monitor EC, water level, and temperature of both pre- and post-shock effects.

FAULT2SHA – An ESC WORKING GROUP TO BOOST INTEGRATED COLLABORATIONS AROUND FAULT-RELATED SEISMIC HAZARD ISSUES IN EUROPE

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Two major challenges need to be overcome in Europe to reach a unified structural representations of three-dimensional models of active faults and earth structure (velocity, density, attenuation, etc.) for use in fault-system analysis, ground-motion prediction, and hazard assessment: funding and the establishment of highly integrated collaborations between European earthquake science communities. Research funding dedicated to the systematic and continuous identification and characterization of potentially active faults has been and will always be a major challenge in Europe. This has led to a heterogeneous state of knowledge across the continent and the development of quite different representations of faults and methodologies when considering faults in seismic hazard. Thus, if improving the characterization of potentially active sources remains a priority that will depend on each country, boosting integrated collaborations within Europe should be feasible and should be attempted. This is the main focus of FAULT2SHA, an ESC working group that started in 2016 and is planned to last for at least 4 years. Presently the WG has no resources and relies on the support of individual member's institutes for the organization of Workshops and WG activities. The WG is composed of members from numerous European countries (complete list will be available soon on the website site) and is presently organizing itself around specific field laboratories more focused on issues related to field data collection, integration of faults into PSHA studies and physics-based approaches. In the future, depending on the members, additional WG topics could be included involving communities from earthquake source dynamic rupture modeling, statistical seismology, geodynamic, geodetic and strong ground motion modeling.

If you are interested in contributing to the Fault2ha WG discussions, please sign on at the following site: https://sites.google.com/site/linkingfaultpsha/fault2sha-esc-wg

COMPARISON OF EARTHQUAKE SOURCE COMPLEXITY INFERRED FROM SEISMOLOGICAL WAVEFORMS AND GEODETIC SURFACE DISPLACEMENT DATA

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Earthquake rupture processes occur with different degrees of complexity in terms of source segmentation into a discernible number of sub-sources.
We study how segmentation of kinematic source models improves modeled data fit of far-field and near-field observations separately with the aim to find meaningful source model parameterizations. Far-field observations used here are teleseismic waveform data and near-field observations are InSAR static surface displacements derived with
(InSAR) data. The different sensitivity of far-field and near-field data matters in joint optimizations of seismic waveforms and InSAR (Interferometric Synthetic Aperture Radar) surface displacements.

For our analysis we use four real-earthquake data from Central Italy (2009 L'Aquila and 2016 Amatrice earthquakes) and from the Xizang Region (2005 and 2009 Zhongba earthquakes).

The earthquake pairs are closely located, of similar magnitudes and normal-faulting mechanisms to avoid influences of path effects in the source complexity sensitivity analysis. The earthquake source models are optimized by using far-field and near-field displacement data separately. The forward model formulations to predict far-field seismological waveforms are the commonly used Double-Couples (DC). To predict near-field static surface displacements we employ rectangular dislocation models embedded in an elastic half-space. The source optimization schemes for both far- and near-field observations are harmonized by applying the seismological software toolbox pyrocko (http://pyrocko.org). We consider data errors that are correlated in time and space for seismic waveforms and static surface displacement data, respectively, and propagate them in the estimation of source model parameter trade-offs and uncertainties. To infer the rupture segmentation we explore the data-dependent resolvability by applying informational theory in the form of the Akaike Informational Criterion (AIC) and consult the trade-offs of the estimated source model parameters. We further use array beam-forming of long-period seismic waveforms and seismic back-projections to aid the determination of rupture segmentation. From our results so far we conclude that AIC in combination with analysis of source model parameter trade-offs and uncertainties and taking into account moment release functions is a data-driven and objective way to estimate the degree of source model segmentation.

THE SEISMIC CYCLE OF THE CENTRAL APENNINES FAULT SYSTEM (ITALY)

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Tondi and Cello in 2003 analysed the active seismogenic crustal-scale fault system (named the Central Apennines Fault System or CAFS) with the aim of assessing the spatial and temporal characteristics of fault development and related earthquake activity. The CAFS represents the most important tectonic element in central Italy and extend over a large area (more than 100 km long and 40 km wide) from Colfiorito, to the north, to L'Aquila, to the south.

The main results of the work was the reconstruction of the seismic cycle of the entire active fault system for the last thousand years, with the following considerations:

1. The CAFS is a multi-scalar seismogenic fault structure including strike-slip and normal/transtensional active fault segments. The cumulative distribution of the fault lengths within the CAFS is expressed by the relation $N_{(\geq S)}=aS^{-D}$. The value D=1.5 of the exponent of the power law suggests that the system is an immature still-growing fault structure (The exponent of the power law D=1.5 which suggests that the system is an immature still-growing fault structure).

2. The displacement rate of the whole system in the last 700 ka is 1.6 cm/year.

3. The two largest earthquakes recorded within the CAFS (1349–1703 A.D.) account for approximately 90% of the total seismic energy released by the system in the last thousand years.

4. Given the assumption that one thousand years is a time period long enough to characterize the slip pattern of the CAFS, the cumulated coseismic slip patterns can be interpreted in terms of ‘‘time-predictable’’ and ‘‘slip-predictable’’ models, and the average recurrence time for M>6.5 events is about 350 years.

5. The b value of the Gutemberg–Richter relation for CAFS-related earthquakes is 0.8; the magnitude of the maximum expected event coincides with the largest historical event.

6. The exponent of the relation between seismogenic fault length and seismic moment is 2.6; this suggests that most of the seismic events in central Italy can be considered as small earthquakes (with $Mo=L^3$).

After the last seismic sequences generated by some of the active faults belonging to the CAFS (L'aquila earthquake, $Mw_{max}=6.3$ the 6th April 2009; Amatrice-Visso-Norcia earthquake, $Mw_{max}=6.5$ the 30th October 2016), the seismic cycle that was interpreted as ''time-predictable'' and ''slip-predictable'' can be completed, verified and discussed. In particular, with respect to the terms of the resolution of geological analysis for seismic hazard evaluation.

References:

Tondi, E., and Cello, G., 2003. Spatiotemporal Evolution of the Central Apennines Fault System (Italy). Journal of Geodynamics, 36, 113-128.

Near-field fault slip of the 2016 Vettore M6.6 earthquake (Central Italy) measured using low-cost GNSS

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The temporal evolution of slip on surface ruptures during an earthquake is important for assessing fault displacement, defining seismic hazard and for predicting ground motion. However, measurements of near-field surface displacement at high temporal resolution are elusive. We present a novel record of near-field co-seismic displacement, measured with 1-second temporal resolution during the 30 October 2016 M 6.6 Vettore earthquake (Central Italy), using low-cost Global Navigation Satellite System (GNSS) receivers located in the footwall and hanging wall of the Mt. Vettore - Mt. Bove fault system, close to new surface ruptures. We observe a clear temporal and spatial link between our near-field record and InSAR, far-field GPS data, regional measurements from the Italian Strong Motion and National Seismic networks, and field measurements of surface ruptures. Comparison of these datasets illustrates that the observed surface ruptures are the propagation of slip from depth on a surface rupturing (i.e. capable) fault array, as a direct and immediate response to the 30 October earthquake. Large near-field displacement ceased within 6–8 seconds of the origin time, implying that shaking induced gravitational processes were not the primary driving mechanism. We demonstrate that low-cost GNSS is an accurate monitoring tool when installed as custom-made, short-baseline networks.

FROM 1997 TO 2016:

THREE DESTRUCTIVE EARTHQUAKES

ALONG THE CENTRAL APENNINE FAULT SYSTEM, ITALY