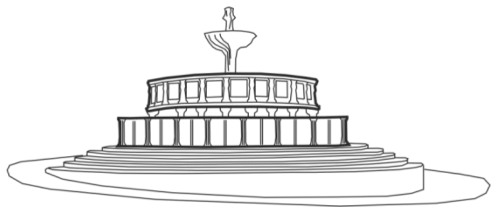
TOOLS, DATA AND MODELS FOR 3D SEISMOTECTONICS: THE ITALIAN OVER TIME LABORATORY

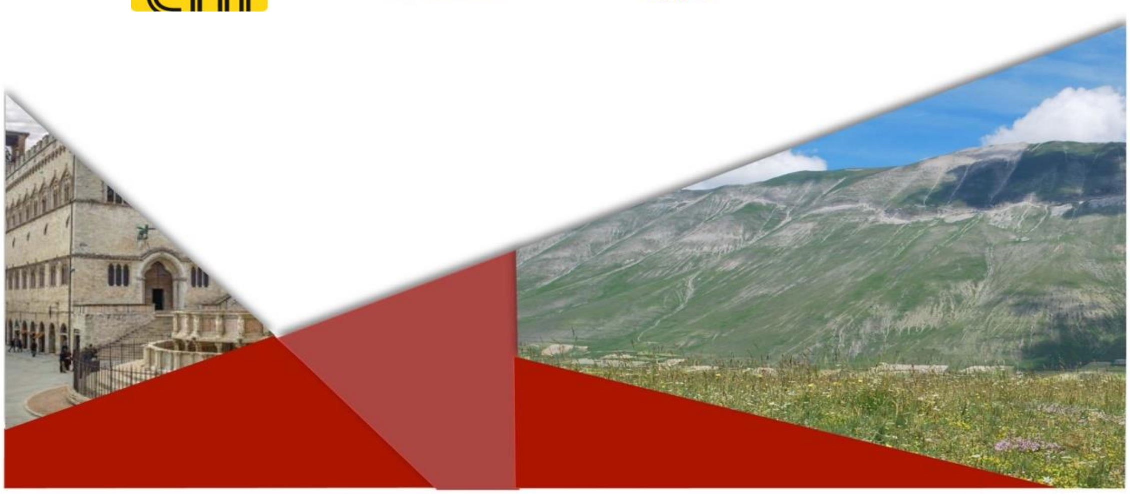
A CRUST INTERDISCIPLINARY WORKSHOP
IN MEMORY OF GIAMPAOLO PIALLI

DIPARTIMENTO
DI FISICA E GEOLOGIA



Perugia, 9-10 July 2019

Abstracts



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The Workshop was hosted by the Department of Agricultural, Food and Environmental Sciences of the University of Perugia.

A seimotectonic journey through Italy dedicated to the memory of Giampaolo Pialli

G. Lavecchia

CRUST, DiSPUTer, University "G. d'Annunzio" Chieti – Pescara

My scientific journey through Italy, in between structural geology and seismology, started 40 years ago, exactly on the 19th of September 1979, with the Norcia normal fault earthquake (Central Apennines, Italy). The day of the earthquake, I was in its epicentral area, mapping the Sibillini thrust, but soon my interest turned on to the interlink among long term, active and seismogenic deformation and between outcropping faults and deep seismicity. Together with Giampaolo Pialli, I started to study the geometry, kinematics and dynamics of the Umbria-Marche Apennines in a seismotectonic and multi-scale perspective. It was soon evident that the structural approach to seismotectonics was a powerful instrument not only for identifying and understanding reliable earthquake-fault associations, but also for constraining the geometry of crustal structures at depth, and for a better understanding of regional geology and geological processes. That earthquake was the first beginning of the not yet ended Central Apennines mega-seismic sequence. In forty years, the Norcia earthquake was followed by the Gubbio 1984, Barrea 1984, Colfiorito 1997, L'Aquila 2009 and Central Italy 2016-17 moderate extensional seismic events (Mw 5.5 to 6.5), distributed along strike across the Apennine mountain belt for a length of about 350 km. The methodological approach to the structural interpretation of these events, and of all the other ones occurred in the rest of Italy, has progressively improved over time and has been enriched by new knowledges and investigative approaches.

The availability of sophisticated software that allow to process a large number of data and to build in 3D the geometry and kinematics of deformed bodies represents one of the instruments to better constrain complex fault patterns and seismogenic patches. As in the case of the balanced section revolution in the Eighties, it is a must to recall that the 3D modelling only does allow to reconstruct plausible geometric configurations that well interconnect neighbouring structures, but the reliability of the interpretation just relays on the good quality of the input data. During the introductive talk at the CRUST workshop in memory of Pialli, I will show some stages of my seismotectonic journey across Italy. My present global point of view on the complex multilayer crust-scale seismotectonic pattern of Italy, also relevant for geodynamic interpretations, has been developed with many colleagues and, in particular, in the last fifteen years, in narrow contact with Francesco Brozzetti and with Rita de Nardis. In the future, I auspicate that our data and ideas may be further developed and shared with the CRUST community, which I am proud to lead. CRUST stays for "Centro InteRUniversitario per l'Analisi SismoTettonica Tridimensionale con Applicazioni Territoriali" and now involves 12 research groups from 12 Italian Universities, from Sicily to Lombardia. CRUST main aim is to contribute to form a new generation of "seismotectonics", a partially new professional and scientific figure meant as an expert with transversal competences between structural geology, quantitative morphotectonics, seismology and geophysics and capable of fully manage and extrapolate geological and seismological data, at local and regional scales.

I am sure that Giampaolo would have liked a lot CRUST people ..and viceversa!

Oral Session 1

Natural and anthropogenic seismicity for seismotectonic purposes

Chairperson: R. Scarpa

On the Italian seismicity

C. Doglioni

INGV, Istituto Nazionale di Geofisica e Vulcanologia

Italian seismicity is the by-product of its geodinamics and lithospheric rheology. Alps and Apennines are two belts associated to subduction zones where the slab hinge is either converging (Alps) or diverging (Apennines) relative to the upper plate. These opposed settings provide profound differences on the structural grains and in the seismotectonic settings. GPS data confirm the geological record, quantifying with great accuracy the strain rates, which are in the order of about 2-3 mm/yr convergence in the central-eastern Alps, 3-5 mm extension along the Apennines belt and at least 2 mm/yr contraction along the accretionary prism front. Active contractional movements are mostly concentrated in areas of lower lithostatic load both in Alps and Apennines fronts, whereas extensional tectonics is widespread all over the Italian peninsula. This phenomenology is related to the different energy accumulated in contractional and extensional tectonic settings, i.e., elastic and gravitational.

From seismic sequences to Near Fault Observatories: the relevance of continuous and high resolution monitoring of the seismic activity.

L. Chiaraluce

INGV- Istituto Nazionale di Geofisica e Vulcanologia

Seismologists would like to be able to detect every single earthquake occurring in a seismically active region, to properly identify earthquake-generating processes. Recently, thanks to methodological advances in computational capability as well earthquake detection and characterization algorithms, has become possible to hunt for loads of tiny events within continuous waveform archives; procedures which have significantly sharpened our view of geological structures. But still, stations density is one of the key ingredient for all kind of detection framework allowing effective improvements in seismological research.

The deployment of tens of 3-components seismic stations together with state-of-art detection procedures, allowed to reach a mean magnitude of completeness Mc (the magnitude above which all events are detected by the network) for the 2016 Central Italy seismic sequence, of ~ML 0.5, corresponding to almost 500 thousands of events in 1 year, and thank to the augmented detection power of The Altotiberina Near Fault Observatory (TABOO) seismic network, 4,000 events every year are located along an individual fault segment during an inter-seismic period.

We investigate fault geometry and seismicity pattern evolution during multi-scale seismic sequences, derived from high resolutions earthquakes catalogues, to identify and describe earthquakes preparatory and evolutionary phase. The systematic analysis of these phenomena, crossed with long lasting multidisciplinary (e.g. geodetic and geochemical) time series, may drive us to a better understanding of the physical/chemical processes, such as fluid migration, elastic strain build-up and accelerating crustal deformation episodes, responsible for earthquakes generation.

Seismic scattering and absorption imaging in the Pollino range

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2. Johannes Gutenberg University of Mainz, Germany
3. Università della Calabria
4. Istituto Nazionale di Geofisica e Vulcanologia

Regions of slow strain along the Apennines chain are often characterized by earthquake sequences without a clear mainshock - aftershock evolution, sometimes showing migration of the sources along complex fault patterns. An example of such seismic behavior is the Pollino range, which was recently affected by a swarm of thousands of earthquakes lasting for more than four years. We analyzed seismic recordings from the 2010-2014 Pollino swarm to separate and map seismic scattering and absorption at different frequencies in the epicentral area and surroundings. S-peak delay time and late coda-wave attenuation methods were applied to investigate seismic scattering and absorpion, respectively.

High-scattering and high-absorption anomalies (1.5-6 Hz) have been interpreted as representative of fluid-filled fracture networks extending from SE to NW. This frequency-dependent pattern fits well the epicentral areas of medium magnitude earthquakes occurred during the last five centuries. High-scattering and low-absorption area suggest that NW fracture propagation ends where carbonates of the Lucanian Apennines begin. At higher frequency (12 Hz) the anomalies widen SW, marking the faults active during the recent Pollino swarms analyzed in this work. Our results suggest that fracture healing has closed small-scale fractures across the SE fault structures. On the contrary, a system of small fluid-filled connected fractures is relevant across the recently-active NW faults. Our results confirm the previously-postulated change in earthquake migration as due to fluid propagation in connected fracture networks. Once blocked in the NW direction, these fractures opened across the SW faults, thus favoring the nucleation of the Pollino swarm.

Discriminating between natural vs induced seismicity from long-term deformation history of intraplate faults

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To assess whether recent seismicity is induced by human activity or is of natural origin, we analyze fault displacements on high-resolution seismic reflection profiles for two regions in the central United States (CUS): the Fort Worth Basin (FWB) of Texas, and the northern Mississippi embayment (NME). Since 2009 earthquake activity in the CUS has increased dramatically, and numerous publications suggest that this increase is primarily due to induced earthquakes caused by deep-well injection of wastewater, both flowback water from hydrofracturing operations and produced water accompanying hydrocarbon production.

Alternatively, some argue that these earthquakes are natural, and that the seismicity increase is a normal variation that occurs over millions of years. Our analysis shows that within the NME, faults deform both Quaternary alluvium and underlying sediments dating from Paleozoic through Tertiary, with displacement increasing with geologic unit age, documenting a long history of natural activity. In the FWB, a region of ongoing wastewater injection, basement faults show deformation of the Proterozoic and Paleozoic units, but little or no deformation of younger strata. Specifically, vertical displacements in the post-Pennsylvanian formations, if any, are below the resolution (~15 m) of the seismic data, far less than expected had these faults accumulated deformation over millions of years. Our results support the assertion that recent FWB earthquakes are of induced origin; this conclusion is entirely independent of analyses correlating seismicity and wastewater injection practices. To our knowledge this is the first study to discriminate natural and induced seismicity using classical structural geology analysis techniques.

Spatiotemporal distribution of natural and anthropogenic seismicity in the Val d'Agri basin (Southern Apennines, Italy).

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INGV- Istituto Nazionale di Geofisica e Vulcanologia, Rome

The Val d'Agri (VA) basin in the southern Apennines is one of the regions in the central Mediterranean with highest seismogenic potential (M7+ earthquake in 1857). In the past forty years, the VA only experienced weak background seismicity (ML<3.2), which coexists with two well-documented cases of anthropogenic seismicity. The first case is related to the operation of the largest onshore oilfield in Europe, hosted in a high productive reservoir formed by naturally fractured, low-porosity carbonates. Since 2006, co-produced saltwater is re-injected at 3 km depth in the Costa Molina 2 (CM2) well located within a marginal portion of the carbonate reservoir, producing microseismicity (ML<2). The second case of anthropogenic seismicity includes M3+ swarms probably associated to the seasonal water-level oscillation (up to 40 m) in the medium-size Pertusillo water reservoir (PWR). In this work, we show a comprehensive analysis of the spatiotemporal seismicity distribution in the VA, by using data collected during 2001-2014 by three different permanent and temporary networks. Seismicity data are used to compute highprecision seismicity locations by integrating cross-correlation and double-difference methods and to reconstruct the detailed three-dimensional Vp and Vp/Vs tomography structure. The properties of the carbonate reservoir (rock fracturing, pore fluid pressure) and inherited faults control the occurrence and spatiotemporal distribution of seismicity. The CM2 wastewater-injection seismicity suggests the channeling of pore pressure perturbations within high permeable fault zone, while the PWR-seismicity might be related to poroelastic deformation processes within the fractured water-bearing carbonates in response to the seasonal loading of the PWR.

Oral Session 2

Geophysical and geological modelling in seismotectonic analysis

Chairperson: F. Pazzaglia

Imaging crustal architecture and modelling its dynamics with seismic attenuation imaging

L. De Siena

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Over the last 15 years, seismic attenuation imaging has grown as a novel take on the description of the 3D geometry of magmatic systems. The technique works at best where velocity tomography loses reliability, as it uses increased 3D heterogeneity as a source of illumination. Here, I will discuss the application of the technique to seisogenic faults at all crustal scales, from rock sample to regional. The technique uses acoustic emissions from seismic events induced by deformation to depict shear zones and deformation-induced structural features in Westerly Granite, linking seismic attenuation attributes to scale-dependent fracturing. When brought to the field, the technique is able to highlight the progressive shift of seismogenic faults from SE-to-NE across the Pollino fault network (Italy), the wider structure of the Thyrrenian Sea, the deep crustal architecture of and crust-mantle interaction under the Vrancea region (Romania), and the link between deep subduction and geomorphological expression at Mount St. Helens volcano (Cascadian Arc, US). Over the following years, the technique will likely become a state-of-the-art tool in the understanding of active tectonics.

A time dependent model of elastic stress in the Central Apennines, Italy

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Seismicity in the Central Apennines is characterized by normal faulting with dip NE-SW near 45°. If the stress at the hypocenter of the 2016 Norcia (Mw=6.5) and 2009 L'Aquila (Mw=6.3 on the Paganica fault) earthquakes originated only from stress transfer from previous historical events, the orientation of the principal stress axes would have been inconsistent with the observed tensional regime. The additional contribution of a regional stress is thus required, but GNSS geodesy provides only stress rates. We empirically estimate a time multiplier for the regional stress rate, computed with a dense GNSS network, such that the principal stress axes resulting from the sum of the stress transferred by previous events and the regional stress rate multiplied by the empirical temporal scale are consistent with normal faulting, both at the L'Aquila and Norcia hypocenters.

Based on a Catalogue of 36 events of magnitude larger than 5.6 we estimate the total Coulomb stress at depths and along planes parallel to those of L'Aquila and Norcia. We provide evidence of an asymmetry of the Coulomb stress leading to a stress concentration near the hypocenter of the two events just prior of the 2009 and 2016 earthquakes. This stress anomaly disappeared after the two events. Similar stress patterns are observed for earlier events which took place in 1461 at L'Aquila, 1703 on the Montereale plain and in 1703 at Norcia/Valnerina. The 1997 sequence of Colfiorito exhibits a similar, anisotropic Coulomb stress pattern. Other areas with a similar stress anisotropy could be seismic gaps.

Rheological modelling as a contribution for the seismotectonics of the Aegean Region

M. Maggini, R. Caputo

University of Ferrara, CRUST-UR UniFe

We reconstructed a rheological model for the (western) Aegean Region, starting from 1D rheological profiles areally interpolated in order to obtain a three-dimensional picture. We realized the rheological profiles on the basis of literature data and geological considerations for selecting the values of the input parameters in the constitutive equations. Our main objectives are to: i) present the rheological properties of the lithosphere across the Western Hellenides along multiple transects, obtained from the interpolation of closely spaced and well-calibrated 1D rheological profiles; ii) highlight the possible different rheological behaviour in continental collision and subduction zone settings and finally iii) determine the depth to the brittle-ductile transition and hence the thickness of the seismogenic layer.

The comparison between continental collision and oceanic subduction settings emphasizes the following differences and peculiarities: i) the interposition of a relatively thin ductile layer within the continental underlying plate (collisional setting); ii) a generally much thinner brittle layer in the back-arc region for both collisional and subduction settings (15-20 and 9-17 km, respectively); iii) the presence in the back-arc area of the continental collision of a deeper (35-45 km) brittle body representing a seismogenic potential for the area. The obtained depths of the shallowest BDT were thus used to better constrain the geometrical parameters of the seismogenic sources taken from GreDaSS database and compared with the depth distribution of relocated seismic sequences.

The role of gravity modeling in seismotectonics analysis

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4. Department of Biology, Ecology and Earth Sciences, University of Calabria

The integration of surface geological investigations with geophysical techniques is useful to characterize systems of active faults, whose anatomy is often complex. Integration of different geophysical methods has a key-role in yielding information on the underground geometry of the systems.

We use an integrated analysis of geo-structural, seismological and gravimetric data and focus on the identification and geometrical description of faults, with associated density contrast, both at the surface and at depth. At the surface, this task is accomplished by a Multiscale Derivative Analysis (MDA) of the Bouguer anomaly map and by the integration of the MDA maps with the epicentral distribution and all the available geological information. The characterization of fault structures at depth is instead performed by the combination of the Depth from Extreme Points (DEXP) gravity imaging method with the hypocentral sections.

Our multi-parametric approach was effectively applied to different seismically active regions of the Central Apennines, such as the area hit by the 2016-2017 Amatrice-Visso-Norcia seismic sequence (Central Italy) and the area of San Giuliano di Puglia (Southern Italy), struck by a moderate earthquake in October 2002.

The role of near-surface lithology in relation with fault tip propagation: a case-study using trishear inverse modeling

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The assessment of potential for surface faulting has gained an increasing interest in recent years, due to strong earthquakes that caused complex ruptures of the ground surface.

Here, we show a kinematic inverse modelling of a break-through fault propagation fold outcropping at Monte Netto hill (Capriano del Colle, BS, Northern Italy). The ca. 6 m-thick fault zone, cutting through a fluvial and overlying syn-growth loess-paleosol sequence, is composed by tens of discrete closely spaced reverse dip-slip fault planes.

Trishear kinematic restoration of the break-through thrust allowed to perform a grid search over the parameters regulating fault growth (slip, trishear angle, ramp angle, tip line position and propagation/slip ratio - P/S) and to successively check the obtained results with the geological likelihood of the restored models. Our results indicate that the total slip of 13 m cumulated through a two-stage evolution: firstly, the fault propagated quite quickly through deeper stratigraphic units (PS = 7) and then, during its latest evolution, slowed down to P/S close to 3.

Stratigraphic data show that at the site a 50 m-thick sequence of channel *facies* alluvial deposits is present at depth, overlaid by clay-rich silts and sands. We thus interpret the modelled switch in the P/S value during fault growth as due to underlying stratigraphy.

Vertical and lateral changes of lithological units would thus result in derived changes in the potential for surface faulting across the same tectonic structures, with relevant implications in the fault displacement hazard assessment.

Oral Session 3

Active faulting and seismic ruptures

Chairperson: M. Mattei

Sharpening our view of active faulting processes with high resolution topography

R. Arrowsmith

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Earthquake-related displacements of topography and subsequent surface process responses have meters of magnitude typically and occur across fault zones 10s to 1000s of meters wide and as much as 100s of km long. Given these spatial constraints, it is essential to have the right capability to measure the resultant features at the appropriate fine scale. High resolution topography samples the ground surface at least once per square meter and has decimeter local or preferably global accuracy. Analyses of high resolution topography in the study of active faulting can be divided into 4 classes: fault zone mapping, reconstructing surface deformation including offset, investigating geomorphic responses to active deformation, and differencing of repeat surveys for both fault and ground failure characterization.

Active tectonics and surface faulting in central Italy: stress reorientation, blind normal faults, and the march of a continental divide above an active, low-angle

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We seek to combine tectonic geomorphology, structural geology, and cyclostratigraphy, with novel application of anisotropy of magnetic susceptibility (AMS) rock fabrics to test contrasting geometries and kinematics of seismogenic faults with little to no surface expression in central Italy. Here, the Alto-Tiberina fault offers a natural laboratory to study kinematics at the orogen scale for a demonstrably slipping, low-angle detachment. The western flank of the Umbrian-Marche (UM) ridge is extending, leading to high angle, seismogenic normal faults that rupture the surface. In contrast, faults do not obviously rupture the surface directly east of the UM ridge, where nevertheless, large, destructive, historic earthquakes are well documented. The faults here may be blind normal, reactivated, inverted thrusts, or strike-slip faults. We endeavor to test contrasting hypotheses that predict fault type arising in response to (1) principal stress reorientation, or (2) nascent blind normal faults cutting upsection from the detachment. In either case, the faults and earthquakes directly east of the UM ridge would be predicted to deform the land surface in different ways, resulting in a testable instrumental (GPS) and geomorphic geodetic strain field. Geomorphic documentation of that strain hinges on the construction of age models and deformation rates of syntectonic geomorphic and stratigraphic markers using numeric ages, paleomagnetics, and astrochronology. In addition, AMS rock fabric inversion and mesoscopic fault population analyses are well-suited for application along a central Apennine transect stretching from Monte Conero, through the UM ridge. These proposed studies provide a broad platform for geologic and geophysical collaboration

Geometries and kinematics of the coseismic ruptures

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The documentation of earthquake-induced surface ruptures is the basis for the identification of seismogenic structures and represent an important step to define fault scaling relationships used for assessing the recurrence intervals and magnitude of earthquakes.
Surface ruptures display key structural relationships that are the essential tools for extrapolating and constraining the depth of the fault plane from a kinematic point of view. Structural relations such as fracture length and distributions, fault offsets, shear zone width, links between geometries along the fault strands provide insight into mechanics of earthquake rupture. These parameters are the input for any seismic-hazard analysis, engineering design criteria, and studies of fault rupture dynamics. The extension and distribution of the coseismic fault slip in the near-surface give insight into the initiation, propagation, and cessation of dynamic ruptures and the structural evolution of the faults.

The distribution and internal configuration of the rupture zones often display complex structure comprising two or more anastomosing, synthetic slip-surfaces. Looking in three dimensions the degree of complexity is seen to vary, and parts of a rupture zone with multiple slip-surfaces can alternate with parts with a single surface. These ruptures typically show multiple overlapping scarps that can be divided into kinematic sets that occur throughout the width of the pre-existing fault zones. The spatial variation records the evolution of the fault zone with more complex structures arising from several processes including a linkage between different rupture segments which shows to be a common fault growth mechanism.

Pliocene-Quaternary fault kinematics in the Larderello geothermal area (Italy): insights for the interpretation of the Present stress field

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In geothermal areas the evaluation of the active stress field from local earthquakes is generally contradictory, mainly suggesting normal to strike-slip tectonic regime. This feature has been investigated in the Larderello geothermal area comparing information from field data and available focal mechanisms from the area of the Pliocene-Pleistocene Lago Basin, where the most effective exploitation is today run. The methodology is based on the classical approach of structural geology, inversion of kinematic data from slip-fault surfaces and comparison with published focal mechanisms of local earthquakes. The analysed dataset is from Pliocene-Quaternary faults. The results indicate strong similarities in the orientation of the main stress axes as obtained from paleo-stress analysis and double couple focal mechanisms solution, thus suggesting the maintenance of the same stress field through time, under the regional NE-oriented stretching direction. In this context, the analysed structures are explained as part of the deformation developed within a NE-oriented transfer zone, affecting the study area.

The development of the tectonic depression, giving rise to the Lago Basin, is therefore explained as a pull-apart basin.The transfer zone is characterized by the coeval activity of left-lateral oblique to strike slip NE-trending faults and by NW-trending normal faults, thus indicating a key for the understanding of the different focal mechanisms from local earthquakes. Moreover, field data analysis suggests that both the NE- and NW-trending faults can be reactivated as normal faults dominantly, indicating that vertical movements took place. Focal mechanisms from local seismic events confirm this occurrence. It is therefore concluded that the vertical movement is active when uplift, reasonably induced by heat flow, is much effective than crustal stretching. Finally, considering the reaction between orientation of stress axes and permeability, the competition between stretching and uplift, favoring the switch of the local intermediate axis from vertical to horizontal along the NW-trending faults, contributes to channel deep geothermal fluids toward lateral structural traps.

Speleoseismological constraints on ground shaking threshold and seismogenic sources in the Pollino range (Calabria, Southern Italy)

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Speleoseismological research carried out in the Pollino Range (Calabria, Southern Italy), an area of alleged seismic gap in the active extensional belt running along the Southern Apennines, has placed constraints on the recurrence of M>6 earthquakes, on the expected ground shaking threshold, and on definition of seismogenic sources in the region. Radiometric (U-Th, AMS-14C and bulk-14C) dating of pre- and post-deformation layers from collapsed or tilted cave speleothems indicates that six speleoseismic events have occurred in the area during the last ~42 ka, with a mean recurrence of ~5.6 ka.

Based on the in-situ measured geometry and laboratory determined mechanical properties of speleothems and using an ad hoc seismogenic source model for northern Calabria which involved both normal and strike-slip faults, we evaluate the seismic hazard at the cave sites. The numerical models to compute the ground horizontal acceleration threshold for speleothem failure was tested against intact and currently growing stalactites. The inferred age of these stalactites calibrated using established average speleothem growth rates of 0.3-1.2 cm/ka, ranges from ~0.7 to ~10 ka, with most of them younger than ~5.6 ka.

Results show that the ~0.8-1.0 g PGA threshold estimated for collapsed speleothems every 5.6 ka was achieved during strong (M>6) and close (epicentral distance<12 km) earthquakes. Considering a mean speleoseismic event recurrence of 5.6 ka and that no speleo-seismic shaking has occurred in the last 5.5 ka, the probability of occurrence of a M>6 event in the area in the next few centuries is quite high.

Active faulting offshore Southeast Sicily: implication for seismogenic sources

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The Ionian Sea and Eastern Sicily, as part of the Africa-Eurasia collisional system, are considered potential sources of big earthquakes and tsunamis. This study focuses on the seismotectonic of northern segment of the Malta Escarpment, a 300-km long, NNW-SSE trending, submarine faults system extending from the eastern Sicily margin to the Medina seamounts. Geo-structural interpretation on high-resolution seismic lines and bathymetric data (CIRCEE, in October 2013 and M86/2 in December 2011–January 2012) confirms the occurrence of an array of E-dipping, 60-km long, extensional (or oblique?) faults that has deformed the continental slope between Catania and Syracuse. Near-fault growth strata clearly show a Quaternary syn-sedimentary activity for most of the detected faults (especially for those in the near-offshore) testified by sedimentary packages progressively thinning away from the fault trace. However, another set of faults has deformed the continental rise and consists of opposite-dipping normal faults forming up to 4-km wide graben structure.

The western side of the graben is controlled by an active fault, which has clearly displaced the seafloor. Time/depth conversion performed according to previously adopted velocity models revealed that the sea-bottom is displaced of about 4 m and, according to empirical scaling relationship, offset (assumed as coseismic) and fault length (60 km) are consistent with a M>7 earthquake. Further elaborations such as 3D modelling of the active structure(s), slip-tendency analysis on modelled fault planes, and synthetic tsunami model should provide valid constraints on identifying seismogenic sources for large earthquakes in the area.

Oral Session 4

Active tectonics and seismotectonics: case studies from Italy

Chairperson: R. Arrowsmith

Seismic expression of seismogenic faults: experiences from the Central Italy normal faults.

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This presentation is aimed to recall the milestones of a 25 years long research activity, performed by the Perugia GSG (Geologia Strutturale & Geofisica) Reasearch Group, formerly led by Giampaolo Pialli, focused on the study of the seismogenic faults of Central Italy (and also of other areas in Italy and abroad), using seismic reflection data, mostly provided by Agip/Eni. The story started in the 1990's with the NVR CROP03 project and is still on-going, with an integrated project, aimed to study the seismogenic faults, responsible of the 2016-2017 seismic sequence of Central Italy. The interpretation of vintage seismic profiles, acquired by oil industry in seismically active regions, gives significant contributes to seismotectonic research, despite some limitations, due to their variable quality/resolution and to the fact that their trace and acquisition was not specifically designed for the study of the faults. An important task, performed though a stable collaboration with INGV researchers, is the opportunity of comparing the subsurface geological setting, reconstructed though the interpretation of active seismic data, with the "passive" seismological data (e.g. focal mechanisms seismicity distribution). A provisional appraisal of this long-lasting and always stimulating research includes the following issues:

a) Reliable and detailed tracing of the Quaternary faults is often hampered by the generally low quality of the seismic data (especially where carbonate rocks are exposed at the surface) and by the lack of 3D data-sets.

b) Remarkable exceptions regard the Altotiberina fault and the Gubbio fault, whose 3D geometry and displacement has been reconstructed thanks to the availability of a relatively dense network of 2D good-quality profiles.

c) Seismic profiles provided unprecedented information about the internal geometry of the basins (e.g. high Tiber Valley, Umbria Valley, Norcia) developed in the hangingwall of the Quaternary faults, and so indirectly constrain fault geometry and activity.

d) Seismic data give new and in some cases detailed information about the geological setting at depth, promoting important considerations about the rheology of the rocks involved in the faulting process and their attitude to exert a control on the location and distribution of the observed seismicity.

A new seismic imaging of the Messina Strait and seismotectonic implications

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Since the December, 28 1908 disastrous event (M 7.1) in the Messina Strait, which caused more than one hundred thousand victims, several workers have attempted to define the location, geometry and kinematics of the seismogenic fault. Based mostly on available geodetic levelling data, many fault models have been proposed, spanning from E-dipping, low-angle (Sicilian side) to W-dipping, high-angle (Calabria side) extensional faults. However, an exhaustive tectonic model of the Messina strait area together with a reliable faults pattern and depth-architecture are still lacking, due to the unavailability of good geophysical data in the offshore sector. Here we present the preliminary results of a geo-structural interpretation performed over a dense grid of high-resolution, multichannel seismic lines recorded across the Messina Strait. Seismo-stratigrahic interpretation allows to unravel that the shallow portion of the Messina Strait has been shaped lastly by an array of extensional structures forming overall an asymmetric SSW-NNE trending graben structure. On The E-side of the strait, picked faults well correlate with the on-land Armo and Reggio Calabria faults whereas to the west, the graben is limited by another extensional fault, running along the axial zone of the Strait and following the rectilinear western flank of the Messina Canyon. Moreover, the W-fault has clearly controlled sedimentation during the Quaternary. It is noteworthy that, at this preliminary stage, none of the recognized faults (onshore + offshore) have the potentiality of generating M>7 earthquake although calculated pseudo-focal mechanism is consistent with the December, 28, 1908 event. Nevertheless, 3D-positioning of relocated earthquakes in the area appear to suggest the detected faults as the upper crustal expression of possible larger structures at depth.

Early-Middle Pleistocene extensional faulting in the Amatrice Basin (central Apennines, Italy) at the hanging wall of the seismogenic structures

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The Amatrice Basin is an intermountain morphostructural depression of the central Apennines (Italy) that hosted large amount of the epicentral distribution activated during the 2016-2017 seismic sequence. The basin rests on the hanging wall of the Gorzano-Laga Fault, a major NW-SE-striking extensional fault that is part of the complex seismogenic fault array. While structures and kinematics have been previously documented for the Gorzano-Laga Fault, no details on kinematics, styles of deformation, and time of activity have been yet provided for the fault systems resting within the Amatrice Basin.

This work deals with the mechanisms of nucleation and development of the Amatrice Fault System (AFS), a ~10 km-long fault system located in the depocentre of the Amatrice Basin. Our multidisciplinary approach combines geological-structural investigations with geochronological (230Th/234U, Uranium-series disequilibrium) and geochemical (δ13C and δ18O stable isotope) analyses on selected carbonate structures (calcite-filled veins and calcite fibres on fault surfaces). Our results are used to address the spatial-temporal evolution of the AFS in a complex mechanism of growth and link of isolated segments, likely assisted by fluid migration and calcite mineralisation. The stale isotope compositions and the geochronological dating attest for a meteoric water ingress through and along the AFS extensional faults in the Early-Middle Pleistocene. The AFS constrains the long-term history of the extensional tectonics regime in the Amatrice Basin, providing useful correlation with the activity of the basin-bounding Gorzano-Laga Fault.

The Campotosto relay-growing fault zone in between the 2009 and 2016–2017 seismic sequences of central Italy: implications for seismic hazard analysis

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The Campotosto area is considered a seismic gap after the seismic events that affected the Central Appenines in the last 20 years. This has important implications for seismic hazard assessment in central Italy, as the area is characterized by the occurrence of the NW-SE striking Mt. Gorzano normal fault, considered active and able to generate an earthquake of maximum magnitude Mw 6.5-7.0.

In this study, we carried out an integrated field and seismological analysis of the Mt. Gorzano fault. Displacement-length ratios for the whole Mt. Gorzano fault are significantly larger with respect to commonly described values from normal faults worldwide. Furthermore, slip rates calculated by assuming a late Quaternary activity for this fault are unrealistically high (reaching several cm/y). These features, together with field evidence of buttressing of the hanging-wall succession against the fault, as well as the thicker Miocene turbiditic Laga Formation in the hanging wall with respect to the footwall, are consistent with the fact that the Mt. Gorzano fault is offset by a Mio-Pliocene thrust, i.e. it represents a pre-thrusting synsedimentary Miocene normal fault.

The hypocenter clusters of the 2009 and 2017 earthquake sequences in the study area occur at depths in excess of 7 km, which suggests the occurrence of a deep structure, interpreted as a relay-growing fault zone in between the seismogenic faults responsible for the L'Aquila 2009 and Amatrice-Visso-Norcia 2016 earthquakes. This active and seismogenic structure, not necessarily connected with the superficial Mt. Gorzano fault, controls the seismic hazard of the Campotosto area.

Active tectonics in the Santa Eufemia Gulf revealed by ultra-high-resolution seismic reflection

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An ultra-high-resolution seismic reflection grid was acquired in the Sant'Eufemia Gulf (Tyrrhenian side of the Calabrian Arc, Italy) in the frame of the EPAF Project (Earthquake Potential of Active Faults using offshore Geological and Morphological Indicators). The purpose of the seismic investigation was to trace the geometry of active faults using innovative technology for the offshore imaging of seismic stratigraphy and tectonic structures, with a horizontal and vertical resolution at decimetric scale. The location of the Mw 7.0 Calabria centrale earthquake falls within our study area. This destructive event, which was followed by a tsunami, is among the largest recorded in the Italian seismic catalogues. Although early investigation tentatively identified its causative fault, the *regional processes* active in the Santa Eufemia Gulf, related to the oblique subduction of the Adriatic-Ionian plate, and the 3D pattern of active faults are still poorly understood and not completely reconstructed yet. Here, we present the preliminary results of a multi-scale study that characterises in detail the Quaternary stratigraphy and active *tectonic* structures of the study area, and documents the geometry and the Late Miocene to Recent kinematics of a strike-slip fault zone, named Santa Eufemia fault system. The data acquired are used to reconstruct the Late Quaternary activity of this fault system quantitatively and to characterise its related hazard.

Long-living seismogenic faults system in the Val d'Elsa Basin (southern Tuscany) and their role in controlling the local seismicity

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We describe the seismotectonic setting of a southern Tuscany sector (Valdelsa Basin, Italy) where fault systems, active since Neogene, are generating low-magnitude earthquakes, and where the occurrence of active faults was formerly undocumented.

Our study is based on the integration of different datasets and fieldwork analyses: i) reconstruction of the stratigraphic and structural setting of the northern-central portion of the basin through fieldwork; ii) analyses of aerial and satellite images; iii) kinematic analyses on exposed faults; iv) interpretation of reflection seismic profiles and borehole logs acquired for hydrocarbons exploration by AGIP during the 1980's; v) reprocessing of the seismological data set of seismic events recorded by INGV network. The main results allow us to conclude that the Castelfiorentino and Certaldo earthquakes, M=3.9 (2016-10-25) and M=3.4 (2014-08-09) respectively, and their associated minor shocks, are associated with a NE-trending faults system, orthogonal with respect to the main NW-SE trend of the Valdelsa Basin. We discuss the role of these faults in controlling the earthquakes, their detection by means of subsurface data and possible correlation with geomorphological observations, also framing their evolution in the Neogene-Quaternary tectonic setting of the inner Northern Apennines.

Oral Session 5

Laboratory approaches and 3D fault models

Chairperson: M.B. Magnani

The Northern Apennines as a key-area to study the mechanics of low-angle normal faults: what we have done in the last 20 years following Pialli's suggestions.

C. Collettini

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The 23 December 1998, Giampaolo Pialli brought me to visit the Zuccale low-angle normal fault, LANF, in the Elba island. Inspired from that field trip we started a 20 years long research to address the mechanical paradox of LANF, mainly focusing on the Northern Apennines of Italy. Here, in the active (3 mm/yr) extending area geophysical data define a regional LANF characterized by locked and creeping (1.7 mm/yr) portions with interspersed microseismicity (about 3 events per day, ML < 2.3). In the hanging-wall block high angle normal faults host the larger earthquakes and accommodate extension in a stress field characterized by a vertical S1. Field and microstructural studies along the Zuccale LANF show that fluid-assisted deformation promoted dissolution of strong minerals and precipitation of phyllosilicates. Laboratory friction experiments on these phyllosilicates show that they are weak and velocity strengthening.

The low friction coefficient of the phyllosilicates coupled with fluid overpressure can explain movements on LANF and the velocity strengthening behaviour of the phyllosilicates implies fault creep and therefore can be used to explain the absence of moderate-to-large earthquakes on LANF on the seismological records.

Although the above conditions can be invoked to explain some aspects of LANF mechanics, they do not represent the solution of the LANF paradox since: a) a widespread development of phyllosilicates does not seem to be a common feature in plenty of exhumed LANF and b) most LANF initiated as gently dipping structures. These two points highlight an important gap of knowledge in fault mechanics.

How sismotectonic analog modelling can contribute improving megathrust hazard assessment

F. Corbi

Università di Roma Tre, CRUST

Subduction zones are complex dynamic systems hosting two of the most dangerous geo-hazards: mega-earthquakes and tsunamis. Despite the growing spatio-temporal density of geophysical observations at subduction zones, our understanding of the megathrust earthquake cycle continues to be limited by a series of factors. Among the others the short observation time compared to mega-earthquake recurrence and the partial spatial coverage of geodetic data. Here, I contribute to improving this understanding by simulating dozens of seismic cycles in a laboratory-scale analogue model of subduction. The model creates analog earthquakes of magnitude Mw 6.2–8.3, with a coefficient of variation in recurrence intervals of 0.5, similar to real subduction zones. Using a digital image correlation technique, I measure coseismic and interseismic deformation with high accuracy (few tens of m µm) and resolution (few mm). This is equivalent to having a very dense geodetic network homogeneously distributed over the whole margin, including the generally offshore seismogenic zone. I show that such large dataset provides an unique opportunity to investigate two important subjects in the frame of subduction zones seismic hazard assessment: a) how to profit of a dense geodetic network to predict the time and size of megathrust earthquakes using machine learning; and b) how to capture the maximum details of slip distribution using the minimum number of geodetic data.

Geological 3D modeling in a seismic country: lessons learned and step forwards.

C. D'Ambrogi

Servizio Geologico d'Italia - ISPRA, Rome

In a country characterized by high geological complexity, and affected by natural hazards, the Servizio Geologico d'Italia completed several 3D models to answer the need for a better knowledge of subsurface geology. Since 2000 these activities are part of "GeoIT3D - 3D modeling and visualization of geological data" institutional framework, and received funds from EU research projects (i.e. GeoMol, GeoERA "HotLime" and "HIKE") or the support from national programs (e.g. DPC-INGV projects).

Geological 3D models of large areas have been built, or are under construction; they focus on a comprehensive 3D geology as mandatory input for the definition of the geometry and relations between faults, and for the characterization of active faults and seismogenic sources.

These 3D models extend to a depth of up to 20 km, by integrating surface data with seismic reflection profiles, deep wells, and other geophysical data.

In order to maximize the surface and subsurface information, SGI devoted significant efforts to the design of specific workflows for i) the 3D model building, ii) the 3D velocity model calculation and the Time-Depth conversion, and iii) the quantitative analysis, with special focus on the characterization of faults activity. These activities demonstrate the full applicability of the designed workflow and tools to obtain comprehensive and coherent models as a basic input for seismotectonics.

The next steps of SGI 3D modeling activities will be the definition of national standards for production, exchange, and dissemination, and the long-term completion of an Italian Bedrock and Quaternary 3D model.

Three-dimensional anatomy of an active seismic source: kinematic complexity and structural inheritance constrained by field observations and present-day seismic activity (Central Apennines, Italy)

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In recent years, high-resolution geophysics imaged with unprecedented spatial resolution the geometry and velocity structure of seismogenic faults. Nevertheless, fundamental questions about the origin of geometrical and kinematic complexities associated to seismic faulting remain open.

We addressed these topics by characterizing the internal structure of the Vado di Corno Fault Zone, an active seismogenic normal fault cutting carbonates in Central Italy and comparing it with present-day seismicity of the area. The exhumed fault footwall block was mapped along strike combining field structural and photogrammetric surveys in a 3D model. Three main structural units were recognized: a cataclastic fault core (CU ~20-100 m thick), a fractured damage zone (DZ ~ 300 m thick), and a breccia body (BU ≥ 20 m thick). The CU is affected by in-situ shattering and extreme, possibly co-seismic, shear strain localization on discrete fault surfaces. The BU is an inherited low-angle thrust zone with pervasive veining and secondary dolomitization, striking subparallel to the active normal fault. The CU cuts through thrust flats within the BU, while normal to oblique inversion occurs on large-scale frontal and lateral ramps.

A comparable structural setting was imaged westward during the 2009 L'Aquila seismic sequence. Here at ~2 km depth in equivalent lithologies, earthquake hypocentres illuminated a master normal fault cutting through a ~10 km long flat structure with lateral ramps. This geometry suggests the superposition of normal seismic faulting on inherited compressional structures which may be a common feature controlling the shallow architecture of active seismic sources in the region.

Immersive Virtual Reality as a novel tool for active tectonic and volcano-tectonic studies: key examples from Iceland and Santorini

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In the present work we present a novel approach to study active tectonic and volcano-tectonic features. It is very common that field geologists are often unable to access key outcrops because of their location in remote or dangerous areas and associated hard logistic conditions. The Aerial Structure from Motion resulted in a helpful technique that allows a very high- detailed 3D model reconstruction of relevant outcrops, providing also the possibility to cover very wide areas and to overcome several difficulties in sites investigation. In fact, this approach is nowadays widely used in Earth and Environmental Sciences, but we think that an advancement in the exploration of 3D reconstructed environments as well as in data collection from 3D models is mandatory. This is why we introduced the use of immersive virtual reality (VR) for studying volcano-tectonic features such as normal faults, extensional fractures, dykes and volcanic vents. The key areas we have chosen as test sites are the active Northern Volcanic Zone of Iceland (NVZ), where several outcrops have been reconstructed in the framework of the Italian Argo3D project (http://argo3d.unimib.it/), and Santorini Caldera Wall (SCW) where the survey has been carried out during the 2018 Santorini Summer school within the framework of 3DTeLC Erasmus+ projects (https://sites.google.com/port.ac.uk/3dtelc/). The tools for field data collection in VR have been tailored in the framework of both Argo3D and 3DTeLC Erasmus+ projects. The NVZ experienced fracturing, volcanic unrest and eruptions in both Holocene and historical times; the SCW is affected by several huge dykes that are inaccessible on foot. In both cases, the reconstructed ambient were explored using different VR modalities: on foot, as is often the case during field activity, moving like a drone, above and around the target, as well as flying like an airplane. Thanks to these modalities of exploration we were capable of better understanding the geometry of dykes and extension fractures, scoria cones and normal faults. We systematically measured, using VR, dykes attitude and thickness, the opening direction and the amount of dilation along the extensional fractures, the direction of magma-feeding fractures underlying cones and volcanic vents, as well as the amount of vertical offset along normal faults. Thanks to the use of the VR we collected thousands of data and we were capable of defining the Holocene spreading vector direction and the stretch ratio in the NVZ as well as to fully define the geometry of dykes intruded the SCW, providing a more complete picture of the deformation processes that have been taking place in these areas.

Poster Session

Prospecting of tectonic indications near a supposed active zone in Setif region – Eastern Algeria

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The purpose of this present work is to discuss the neotectonic indications around supposed active faults in one region of Algerian Maghrebides. In fact, the majority of earthquakes in the wholly active domain of the Northern Algeria, are not related to cartographical faults or are not associated to knowning faults excepted for two or three examples.

For seismic hazard assessment, at the scale of Sétif region, two distinct seismotectonic zones may be proposed; the northern zone corresponds to Babors chain characterized by frequent seismicity with moderate magnitudes, and the southern zone corresponding to the high plains with low seismicity.

The mean of this work is to describe neotectonic structures affecting Pliocene and sometimes quaternary deposits. These structures are observed around regional tectonic context characterized by slow crustal deformations and by weak seismicity for quite short periods.

Insights on the subsurface geology of the central Apennines by the use of 3D geological models

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Understanding structural processes relevant to human problems often relies on interpretations of sub-surface geology that can be subjective, so this presentation demonstrates that a formal work flow for 3D visualization can remove subjectivity and hence decrease uncertainty. The use of 3D geological model is very common in different fields of the hydrocarbon exploration and petroleum modelling. During the last years this approach has been also applied in geological studies in order to better visualize the geometry of the subsurface geological structures. Particularly useful may be the use of 3D geological model in seismotectonic studies for the reconstruction of 3D geometry of the seismogenic faults and their interactions with inherited structures. In this work we present two 3D geological models realized starting from different types of dataset obtained in a seismic area of the central Apennines (Italy). The first case study is located in the area of the Mt. Vettore area, interested by the last 2016-2017 seismic sequence. Here we use detailed geological maps of the area and a grid of 14 geological cross-sections in order to reconstruct the main tectonic and stratigraphic surfaces of the area: The M. Sibillini thrust, top Maiolica formation and the main seismogenic faults. This model was very useful to calculate the throw distribution of the main seimsogenic faults and to understand the cross-cutting relationships with the inherited compressive structures. The second model is located in the Acquasanta anticline and involves a larger area than the previous case. This model was realized starting from a grid of seismic profiles provided from Eni s.p.a. We reconstructed three surfaces: top Carbonate sequence, top Evaporites sequence and the basal thrust. This model was useful to understand the geometry of the basal thrust and to define the geometry and the evolution of the Acquasanta anticline, as well as the relationship with the seismogenic Gorzano faults.

We demonstrate that the use of 3D geological model is one of the powerful approaches to understand the subsurface geometry and the geological evolution of complex area, such us the Apennines. The proposed geological models may contribute to a better definition of the active faults segmentation, and thus of the related seismic hazard.

The 1983 Borah Peak earthquake (M_w7.3, I_o IX MCS) (USA): new evidence from surface rupture and 3D fault segmentation patterns from high-resolution topography and field observations along the Lost River fault

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The Lost River Fault (LRF; northern Basin and Range, USA) is composed of six segments and of a large number of multi-scale en-echelon SW- to SSW dipping normal and normal oblique traces. The 120 km long fault trace lends itself well to the careful study of the segmentation pattern. Two NNW-SSE trending segments, known as Warm Spring (WSS) and Thousand Spring (TSS), failed in the 1983 Borah Peak earthquake (Mw7.3), the largest historic event in Idaho and one of the largest in the Basin and Range. After 35 years, spectacular co-seismic fault scarps with vertical displacement up to ~2.7 meters are still well evident and outcrop for a length of ~37 km. Consistent with focal mechanisms of the mainshock field evidences show a normal-sinistral kinematics along a southwest dipping plane (Crone and Machette, 1984).

Structural field work was carried out along the entire Lost River Fault in spring 2019: mapping fault traces and characterizing fault zone structure. Along the 1983 earthquake epicentral area we examined the surface ruptures. Long-term and coseismic fault/slip data were acquired using FieldMove on an iPad for digital field mapping. UAV overflights produced high resolution imaging to construct topographic and orthophoto maps and 3D models. These allowed us to constrain the surface fault trace geometry, to highlight extremely complex coseismic rupture patterns along TSS and WSS, and to systematically extrapolate the height of the fault scarps, generating profiles of slip along strike. Further analysis of the high-resolution images indicates piercing points that will be used as displacement vectors for paleostress analysis.

Latest Quaternary tectonic activity in the Bagno Vignoni-Valdorcia area (inner Northern Apennines, Italy) recorded by travertine deposits

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Studying travertine deposits and the network of banded calcite veins, forming their roots in the substratum, can place important constraints on neotectonic activity and the seismotectonic settings of geothermal areas. We present the results of integrated studies of a geothermal area located in the inner Northern Apennines (Bagno Vignoni area, Italy), where low magnitude (M<4) seismicity suggests the occurrence of active faults, but information on the age of faults and seismotectonic setting is lacking. The study area is characterised by thermal springs (T<50°C) and travertine deposits exposed in some saw-cut walls of abandoned quarries. We investigate the relationships between faults and the travertine deposits, in order to reconstruct the syn-sedimentary tectonic activity and the age of faulting, by combining analyses of: i) geological setting and structural/kinematic analyses of faults; ii) travertine morpho-structural and architectural setting; iii) travertine facies; iv) U-Th radiometric, stable- and clumped isotopes of travertine and banded calcite veins. The results highlight a wide brittle shear zone (>3 km) formed by NE- and NW-trending faults systems, characterised by oblique-slip to normal kinematics, respectively; these faults are associated with extensional tectonics affecting the inner Northern Apennines since the Middle Miocene. U-Th dating of travertine and banded calcite veins indicates that faulting is still active. Fault activity renews the permeability of the damaged rock volumes, enhancing the hydrothermal fluid circulation started during the middle Pleistocene. The hydrothermal fluids have not changed their δ18O composition and temperature through time. Our findings define the seismo-tectonic setting of this sector of the inner Northern Apennines, demonstrating more broadly the utility of travertine deposits in reconstructing the neotectonics in geothermal areas.

Present Day Geokinematics of Central Europe

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A new set of rigorously computed velocities of GNSS sites of the CEGRN network in Central Europe provides an invaluable data set for the investigation of present day crustal deformation at the continental scale. We present six velocity profiles covering structural features of Central Eastern Europe and at the same time well populated by GNSS sites, to minimize interpolation errors. One N-S profile samples the extensional stretching of the crust in the Balkan Aegean region, three E-W profiles sample the part of Central Europe north of the Black Sea, one profile SW NE crosses the Trans European Suture Zone. A sixth profile outlines the shear deformation associated with the eastward extrusion of the Eastern Alps towards the Pannonian Basin.

Analytical modelling of the first and last profiles, for which there is a significant deformation, provides quantitative constraints on the relation between back arc retreat and extensional deformation in the continental crust (Aegean-Balkan profile), and model parameters such as the locking depth of faults accommodating the lateral extrusion of the Eastern Alps. For the four remaining profiles, across the TESZ and the Central Europe through the Carpathians, we report a westward velocity East of the TESZ and Carpathians. The velocities appear to drop West of these structures, suggesting that in a conventional 'European fixed' reference frame the East European Craton is generating a small compressional strain in a nearly E-W direction.

Seismological and statistical trends in Central Apennines (Italy) before and during the Amatrice-Norcia sequence

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The Amatrice-Norcia seismic sequence began in August 2016 with a first major earthquake of Mw 6.0, followed by two strong events (Mw 5.4 and 5.9) and a mainshock of Mw 6.5 at the end of October 2016. Areas involved in the sequence are located in Northern-Central Apennines, Italy. The target of this work is to determine how statistical parameters, especially the b¬-value from Gutenberg-Richter law, possibly act as stress indicators before and during the different phases of the seismic crisis and how they interact with the fault systems. A seismic dataset was composed from earthquakes located in the sector of Central Apennines struck by the sequence and selected during a time period from August 2009 to December 2017; after that, in properly chosen areas, a series of cross-sections were plotted featuring variable width. The re-localization of the selected earthquakes allowed good definition of the fault geometries along these sections; at the same time, we compared the enlightened fault structures to b-value plots, which were calculated for several time windows of variable length.

Reconciling sinuosity changes in ancient Mississippi River meanders in the context of Late-Pleistocene and Holocene active faults

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Numerous studies have documented changes in alluvial stream sinuosity in response to crustal deformation; however, few examples quantitatively link sinuosity amplitude/wavelength with fault slip rate. The Fisk (1944) maps recording the Holocene channel planforms of the Mississippi River along with high-resolution seismic reflection imaging of faults that offset late Pleistocene/Holocene alluvium beneath the Mississippi floodplain provide a unique opportunity to quantitatively explore functional relationships between fault slip and meander sinuosity. Here we present (1) a python-based code that objectively quantifies river sinuosity and (2) results from ten digitized Mississippi River thalwegs spanning the Holocene. We geometrically transformed the channel and evenly sampled the planform to apply a Fast Fourier Transform (FFT) and identify frequencies at which the river meanders. We hypothesize that a sinuosity 'signature' with a spectral peak at a specific frequency will occur in regions where long-term crustal deformation has caused a local change in slope.

The FFT data is displayed on an 'evolutionary spectrogram' to spatially locate the frequencies at which spectral power occurs along the channel. Our results show two regions of significant spectral power co-located with neotectonic faults (White River and Arkansas River fault zones) imaged by high-resolution seismic reflection data. The long-term record of Holocene channel planforms enables us to reconstruct the temporal evolution of sinuosity, and regions with persistent power suggest a long-term influence of crustal deformation related to the neotectonics faults. Our ultimate goal is to quantify the change in sinuosity to identify locations of neotectonic faults and constrain slip rates.

New mapping techniques for structural-geologist using Drone and Tablet: an application to the coseismic effects of 30 october 2016 Central Italy earthquake (Mw 6.5)

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In the last decades, the traditional techniques of geological mapping have been integrated by the use of several types of instruments as tablet, with dedicated softwares, and drones. The latter have become widely available in structural geology and, being a remote sensing technique, they offers multiple advantages compared to the traditional fieldwork. They enable the reconstruction of three dimensional models of inaccessible outcrops, and to explore in detail areas surveyed with this new techniques. Here we report on the fieldwork during which the technologies adopted were an useful tools to reduce sensibly the working time and to collect massive datasets. During the 2016 Central Italy seismic sequence after the Mw 6.5 (October, 30) earthquake, we performed a detailed survey of the cosesimic features through the digital field mapping application "FieldMove", developed by Midland Valley. We mapped a huge number of data during the survey along the "Colli Alti e Bassi" fault trace, and in the Castelluccio di Norcia plain on the "Prate Pala Fault", both structures re-activated during the Mw 6.5 earthquake.
Our mapping techniques allowed a great speed of acquisition combined with the good quality of the collected data.

Certain difficulties occurred during the post-processing phase, which is very hard to manage due to the amount of acquired data. In the study case, these problems were overcome by using specific photogrammetry software for professional drone-based mapping and the softwares ArcView GIS, Move 2018 and Agisoft - Cloud Compare, installed on very high performing hardwares.

3D Fault geometry from field and seismological data: the seismogenic fault system in the Mt. Pollino area (Calabria-Lucania boundary, southern Italy)

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We present an integration of a structural geological mapping, performed on the Quaternary and active normal faults of the Pollino area with a high-quality dataset of re-located earthquakes. From 2010 to 2014, this area was affected by long lasting seismic activity characterized by three major events which occurred in May 2012 (Mw 4.2), October 2012 (Mw 5.0) and June 2014 (Mw 4.0) and by 3156 other earthquakes with 1<Mw<3.7. Structural-geological Fieldwork aided by morpho-structural and remote sensing analyses, led to define the geometry, the kinematics, the cross-cutting relationships and the slip rates of the inferred active fault segments within and near the epicentral area.

Geological data allowed us to reconstruct an asymmetric extensional fault system characterized by low-angle, E and NNE-dipping faults, and high-angle, SW- to WSW-dipping antithetic faults. The 3D geometry of the faults at depth was constrained using high-resolution hypocenter distributions, after an accurate selection and re-location performed by HypoDD method. The overall system fits well with the deformation field obtained from focal mechanisms and geodetic data.

Comparing the fault pattern with the time-space evolution of the Pollino seismic activity, we identified the main WSW-dipping seismogenic sources activated during the sequence and assessed their seismogenic potential.

Active deformations at rift-transform fault intersections: the case of the Theistareykir Rift (Northern Iceland)

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The aim of this work is to contribute to delineate the active deformations at the intersections between rifts and transform zones, using Northern Iceland as a key site, where the Grimsey and Husavik transform faults connect with the Theistareykir Fissure Swarm (ThFS). We studied in great detail 4415 structures belonging to the ThFS, considering both extensional fractures and normal faults, in order to define the structural-geological setting of the area, and to identify how the intersection with the transform zones influences rift kinematics.

We carried out detailed geological-structural field surveys, integrated with the use of UAVs (Unmanned Aerial Vehicles) and the Structure from Motion (SfM) technique. Extensional fracture strikes and opening directions are coherent with the regional tectonic setting and spreading direction in the southern part of the rift; instead, the range of fracture strikes and opening directions increases in the northern part, especially in correspondence with the rift-transform junctions. Here the rift structures assume a sigmoidal pattern, with strike-slip component of motions mainly linked to block rotation. In regards to normal faults, they have a preferential westward dip in the central part of the rift, while they show a preferential eastward dip in the southern sector; this change occurs abruptly, and it could be due to the presence of a WNW-striking blind fault that acts as a transfer structure.

Focal Mechanisms for middle-crust to upper mantle earthquakes beneath Central-Eastern Italy: implication for geodynamic context

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This work has the purpose to reconstruct the geometry, the kinematics and the deformation pattern of the principal seismogenic domains of Central-Eastern Italy by using well-relocated earthquakes and a new large dataset of focal mechanisms. This reconstruction was possible thanks to a dense seismometric network in Central Italy composed by 103 stations managed by the INGV – Ancona. Specifically, we used 141965 earthquakes occurred from 2009 to 2017, with $0.5 \leq ML \leq 4.8$, and 254 new focal mechanisms, integrated with 63 focal solutions retrieved from catalogues and detailed papers for the time period 1967-to-2009. The huge number of high-quality hypocentral data and of focal solutions well constrained at depth allowed us to define detailed 3D geometries starting from 72 radial cross-section, with a half-width of 2.5 km and to ascertain a good correspondence between the identified seismogenic volumes and the associated kinematics.

In particular, it was possible to unveil two well distinct lithospheric-scale compressional shear zones, one corresponding to the already known Adriatic Basal Thrust (ABT) and the other to an underlying discontinuity, developed at middle crust-upper mantle depth and here referred to as Incipient Thrust (IT). A detailed 3D kinematic fault model was built for both the ABT and the IT and the corresponding multilayer lithospheric-scale strain pattern was defined.

Such findings did allow to renegotiate the geodynamic context of the Apennine fold-and-thrust system at the light of new constraints.

Background seismicity vs earthquake clustering: quantitative analyses of case studies in central Italy for seismotectonics purposes.

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The Central Apennines of Italy are a high seismic-risk zone and experience destructive earthquakes both in historical and in instrumental time. The sector that extends in between the Irpinia 1980 (Mw 6.9) and the Accumoli-Visso-Norcia 2016 (Mw 6.5) seismic sequences was struck by eleven events among the largest historical-early instrumental earthquakes (MW ≥ 6.5) of the Italian territory since 1349. On the contrary, if we exclude the Barrea seismic sequence occurred in 1984 (Mw 5.9), the instrumental catalogue shows that this area is predominantly characterized by a low level of seismicity, relatively stable in the size and time domains, and by low energy seismic clustering. A quantitative analysis of the seismicity occurring from 1985 to 2018 (0.0 ≤ ML ≤ 5.0) allowed the declustering of the earthquake catalogue, the separation of the background seismicity and the identification of a set of 45 spatio-temporal clusters.

The resulting background seismicity (6196 events, 0.0≤ML≤4.1) is characterized by a b value of 0.96 ± 0.4, a magnitude of completeness of 1.4 and it is strictly controlled by known fault patterns. The earthquake clustering accounts for a non-negligible (45%) part of the total seismicity recorded in the study area. It was further divided in 4 seismic sequences and 41 swarms. We observed that the swarms have a typical 2-12 day duration, 2.5-3.0 characteristic magnitude and 1.2 km/d migration rate. They can be constituted by mono and/or polyphase episodes; they do not show a spatial complementarity and they are often spatially overlaid. The swarm focal mechanisms and the depth of foci well correlate with the active normal fault systems and mark the fault segmentation pattern.

Slipping zones associated with seismic faults and gravitational slope deformations in carbonate-built rocks (Central Apennines, Italy)

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Carbonate-built rocks of the Central Italian Apennines are cut by sharp slip surfaces bounding less than few cm-thick slipping zones surrounded by cm to hundreds meter-thick damage zones. Recent paleo-seismological, geological and geomorphological observations pointed out that the principal slipping zones (PSZs) may accommodate either large landslides (Deep-Seated Gravitational Slope Deformation, DGSD) and seismic or aseismic crustal scale fault deformation (normal faults, NF), characterized by different geological hazards.

Depending if associated to DGSD or NF, the PSZs (1) reach down-dip depths of 100-1000 meters (DGSD) or 3-10 km (NF), (2) formed at ambient temperatures of 0-30 °C (DGSD) or 0-250°C (NF) and pressures of < 20 MPa (DGSD) or < 200 MPa (NF) and accommodate slip rates usually < 10-3 m/s (DGSD) or up to ~1 m/s (NF). Such large differences in loading conditions should result in the formation of distinctive secondary fault/fracture networks in the damage zones recognizable at the outcrop scale and in peculiar microstructures in the slipping zones.

This study aims at identifying the geological structures and deformation mechanisms associated to both DSGD and NF by (1) conducting extensive field surveys, (2) investigating in the laboratory the origin of the slipping zones under controlled deformation conditions and (3) performing microstructural studies on natural and experimental PSZs.

Preliminary optical and electron microscope investigations of natural PSZs showed microstructures dominated by protocataclastic fabrics in the DGSD and cataclastic to ultracataclastic fabrics in the NF, including both stylolites and foam-like structures associated to pressure-solution and sintering processes, respectively.

Seismic attributes, an innovative tool for seismotectonic research: results from the epicentral area of the 2016 Norcia Mw 6.5 earthquake (Central Italy)

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The Seismic Attribute Analysis is a well-known and powerful technique mainly used by the Oil and Gas industry. It is still not commonly used in the seismotectonic research. In this work, we have analyzed three 2D seismic data crossing the two Quaternary basins of Norcia and Castelluccio di Norcia. This area was struck during the 2016-2017 by a long seismic sequence, culminated with a destructive mainshock of Mw= 6.5 (30th October 2016).

After testing several types of seismic attributes, we have extracted the best images obtained by the application of amplitude and phase-based attributes. As results, we have considerably enhanced the overall interpretability of such seismic lines. We have imaged a strong deep reflector (range of 3-4 s, TWT), the result of a high acoustic impedance contrast. It corresponds to a threshold in depth for the seismicity, therefore suggesting important rheological implications. In addition, we have obtained a good match between the location of the seismogenic faults mapped at surface and their improved geophysical signature at depth. We have highlighted the main complex fault zones of the area and displayed for the first time clear evidence of the antithetic fault in the Norcia Basin.This new approach allowed us to extract additional information from vintage 2D seismic lines, representing a promising tool for the geoscientists to study complex and seismically active areas.

Ambient vibration measurements to reveal the deep architecture of the Norcia basin in Central Italy

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During the 2016-2017, a long seismic sequence struck Central Italy, involving four regions and causing important damages and victims in inhabited areas such as Norcia and Amatrice towns. Norcia is a historical town situated in an extensional inter-montane basin, and an MCS intensity level of 7.5 was estimated after the 30 October 2016 Mw 6.5 event. However, it was evident that different zones of the basin responded differently to the shaking. Its geological architecture has surely played an important role in affecting the seismic response.

In this study, we have integrated literature geological and geophysical data with new ambient noise measurements (53 single station and 4 bidimensional arrays), recently collected at the Norcia basin, in order to shed light on its deep structure. The HVSR analysis displayed a variable pattern of “fundamental frequency” (F0) across the basin, with a clear difference between the northern and southern sectors. The lowest F0 (0.6-0.9 Hz, high amplitude and narrow peaks) were recorded at the northwestern sector. After defining a preliminary velocity model, we extrapolated the average thickness of the deposits. We have therefore depicted a possible variable interface between the infilling Quaternary units and the rigid calcareous bedrock. A clear increase in the thickness of the deposits can be inferred in the northern area from E to W, reaching a maximum thickness (ca. 250-300 m) in the area known as “Le Marcite”. A lower thickness seems to characterize the southern part of the basin. Such results will bring onto a better understanding of the 3D deep structure of the Norcia basin, possibly establishing also a link with the seismic response of the entire area.

Hidden geometries reconstruction and site effects estimation: first results from geophysical investigations in the Valle Umbra basin (central Italy)

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The Valle Umbra is a NW-SE 20 km long and 10 km wide Quaternary alluvial basin located in the internal sector of the active extensional tectonic Apennine chain, central Italy.

This area historically suffered major earthquakes such as in 1832 (ME=6.3; I0=X) and 1854 (Me=5.6; I=VIII). It was marginally affected by the Colfiorito earthquake (M 6.0; September 1997) and more recently suffered from damages to buildings caused by the 2016-2018 Amatrice-Visso-Norcia seismic sequence.

This work is about the application of geophysical techniques aimed at the reconstruction of the hidden structures of the Valle Umbra basin (central Italy). We decided to perform a single station ambient noise campaign to investigate the subsoil and try to identify and distinguish the different geological units and retrieve their trend in the subsoil all along the valley. From the results of HVNSR analysis we could identify the main impedance contrast on the subsoil due to the superimposition of lithological layers with different density and velocity of propagation of seismic waves.

Additional constraints for the site effects estimation come from results of spectral ratios techniques applied on a dataset of earthquakes acquired by the accelerometric station IT.CSA of the national civil protection located in the middle of the valley and from the shear wave velocity profile retrieved for the seismic characterization of the site.

Seismicity observed in the Mt. Amiata Geothermal Area

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The crustal volume beneath Mt. Amiata is characterized by a high geothermal gradient, which makes the area particularly suitable for geothermal exploitation. Seismicity in the Tuscan Geothermal Areas is generally observed within the upper crust and is confined in depth by the K-horizon, a strong seismic reflector located in between 4-8 km b.s.l., often interpreted as the 400°C isotherme. The overlaying structure presents permeable layers of highly fractured volcanic rocks, saturated with hot water and steam. Geothermal exploitation from these layers started in the 1960's. Since then, shallow earthquakes have been occasionally observed close to the geothermal wells, and the question is whether these event are of natural origin or related to the exploitation of heat. To monitor the seismic activity inside the geothermal field of Mt. Amiata, we installed in 2015 a dedicated 8-station seismic network in the vicinity of the productive geothermal power plants for a 3-years recording period. The main challenges of our experiment are to automatically detect and locate the local microseismicity, trying to discriminate from natural seismicity those events caused by human operations. We use a waveform based detector to quickly scan the large dataset and automatically detect weak events in the target volume, providing also preliminary event locations, which are then refined in a second step, using standard and waveform based techniques. For hypocenters located close to the geothermal power plants, at a similar depth as the production level (3500 m b.s.l.), it remains very challenging to discriminate between natural and anthropogenic events.

First results of CISA, the new Central Italy Seismic Array

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During the last decades, seismic monitoring experienced important advances by introducing small aperture arrays and dense seismic networks equipped with high-dynamic-range instrumentation. This new recording reality allowed to lower significantly the monitoring threshold, to identify in quasi real time active seismo-tectonic structures and to reveal information about the seismic source and its rupture dynamics. The application of array techniques, as beamforming and f-k analysis use the coherence properties of the recorded wavefield for increasing the S/N-ratio, to determine back-azimuth and apparent velocity of the incoming wavefield and to automatically locate the seismic events of small magnitudes. We realized the first permanent small aperture array installation in Italy, called CISA (Central Italy Seismic Array) composed of 9 three-component seismic sensors installed at interstation distances from 100 - 500m and a maximal extension of 1000m. CISA's circular configuration and its geographical position is aimed to monitor the microseismicity of Central Italy at a local and regional range, including the epicentral area of the 2016/17 seismic sequence, as well as the geothermal areas in the western sector.

CISA's challenges are to decrease the detection threshold of the microseismicity, to identify active faults in Umbria by analysis of the microseismicity and to study in detail the rupture dynamics of moderate earthquakes, by using source scan algorithm. Seismic data are transmitted in real-time to the data center of SARA-electronic (Perugia) by ordinary 4G-LTE router and then forwarded to the observatories of Arezzo and Munich by using seedlink protocol.

Testing Late Quaternary tectonics in low-rate contractional settings – preliminary outcomes from fluvial network analysis along the Southern Apennine Outer compressional Front (SAOF)

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The Apennine compressional Outer Front (AOF) is clearly seismogenic in northern- and central Italy, and along the Maghrebian chain in Sicily. This seismogenic setting is supported by geodetic data revealing evidence of active shortening, at low rates (0.2–0.8 mm/y), as well as by available focal mechanisms. On the other hand, the AOF is often considered inactive in southern Italy (SAOF) where it is buried under Plio-Quaternary foredeep successions, and relevant instrumental seismicity with compressive kinematics is lacking.

Following some recent literature reporting Late Quaternary regional uplift affecting marine terraces (Gulf of Taranto-southern Italy), as well geological/ morphotectonic evidence and macroseismic data analyses supporting the existence of active compressive structures in the Maiella Mt-Abruzzo foothill areas (central-southern Italy), we tested the hypothesis of Late Quaternary deformation along the SAOF.

Considering the favorable setting of the drainage system (with respect to the SAOF) in the southern Abruzzi and Molise regions, we here investigated the transient response that fluvial networks could exhibit as consequence of active processes (active folding, uplift) and related base-level changes. Knick-point detection over along-river longitudinal profiles, along with more advanced metrics (x-z profiles, normalized steepness index maps) were compared with the geological, lithological and structural features known for the area. Geomorphic indexes seem to suggest significant tectonic signals along the Adriatic piedmont sector, between the rivers Pescara and Saccione. Preliminary results will be shown and discussed in terms of fluvial landscape response in low deformation rate areas, and to comparison to adjacent and/or similar settings.

Surface faulting in-depth: the Central Italy 2016-2017 seismic sequence

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Moderate to strong seismic events are commonly accompanied by surface faulting phenomena, that are nowadays captured by a number of independent means, from space to field surveys to geophysical investigations. Modern technologies unveil the high degree of complexity of surface faulting spatial pattern, providing results not achievable only few years ago. The 2016-2017 Central Italy seismic sequence was characterized by unforeseen features, such as the repeated rupture of Mt. Vettore Fault within few months (24th August and 30th October 2016), the role of barriers to rupture propagation and the amount of distributed faulting. Taking into account all these features and assure comparability between modern events and paleoseismological investigations is a challenge for the scientific community, but is also the key for targeted mitigation and the development of integrated tools for a better seismic risk assessment.

Controls of diagenesis on petrophysical properties of carbonate fault rocks

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Many seismically active regions on Earth are characterized by thick sequences of carbonates. Their investigation in terms of fault zone architecture, cataclastic micro-mechanisms, and fault rock petrophysical properties is fundamental to decipher the physical, chemical and mechanical processes that take place during seismogenesis. On this regard, this work focuses on large-scale, seismically active extensional fault zones cropping out along the axial sector of the central and southern Apennines. All study fault zones were exhumed from depths <1.5 km during Plio-Quaternary times, and crosscut tight carbonates. Their fault cores include both grain- and matrix-supported fault rocks, and 10s of cm-thick cemented fault rocks that localize along the main slip surfaces. Results of petrophysical and ultrasonic analyses show that all grain-supported fault rocks are made up of soft pores, which form amounts of connected porosity of ca. 6%, and permeability of ca. 3 mD. The matrix-supported fault rocks exhibit different pore geometries according to the host rock mineralogy. In fact, dolomite-rich fault rocks include soft pores, which constitute amounts of connected porosity of ca. 10%, and permeability 5 mD; the calcite-rich fault rocks, due to pervasive cementation, are made up of stiff, subspherical, isolated pores, which form amounts of connected porosity down to ca. 3%, and permeability down to 10-3 mD. The role of cementation is hence key to modify the petrophysical properties of carbonate fault rocks. Pervasive euhedral calcite cement precipitation occurs in a vadose environment during interseismic periods, whereas coseismic fibrous cements precipitate at greater depths in a phreatic environment.

Late Pleistocene to Recent shortening rates in the broken foreland of NW Argentina: new observations from the intermontane Cafayate Valley, 26° S lat.

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In thick-skinned broken forelands, localized uplifts typically occur in areas where retroarc convergence is mainly accommodated along re-activated high-angle structures. This reactivation typically occurs in a highly disparate manner, in time and in space (Strecker et al; 2012). These features also characterize the foreland of the Central Andes of NW Argentina. In this study, we evaluate how Quaternary deformation in the broken foreland is accommodated on millennial time scales. We assess the late Pleistocene to Recent tectonic evolution with special emphasis on shortening rates in the Cafayate intermontane basin of the Eastern Cordillera and compare them with the GPS surface velocity field.

Our new structural data shows that the Quaternary deformation in the Cafayate basin is mainly located inside the valley rather than along the principal range-bounding faults that delimit the basin. We infer that faults and associated folds are linked with a thin-skinned detachment horizon in the Quaternary valley fill. The strike and vergence of the Quaternary faults are very similar to the basin-bounding structures. Shortening rates based on dated lacustrine and alluvial-fan sediments range from 0.5 to 5.66 mm/yr. The obtained velocity field profile for NW Argentina reveals that velocities decrease gradually from west to east. Taken together, our Quaternary shortening rates spanning different time scales suggest that deformation in the Eastern Cordillera is accommodated by widely distributed faults with variable shortening rates, pointing to strain release through numerous minor structures.

Coseismic scratches along Mount Vettore Fault System (2016 central Italy earthquake). Implications on offset components and fault-block motion

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Structural analyses were performed along the rejuvenated, carbonate fault planes of the Mount Vettore fault system, responsible in 2016 for a Mw 6.6 earthquake accompanied by 30-km-long surface faulting. We focused on scratches, a peculiar coseismic abrasion feature rarely analyzed in structural geology, mainly because of its ephemeral nature. The comparison between structural data, coseismic slip vector and focal mechanisms make it possible to define that coseismic scratches are valuable kinematic indicators. The direct link between coseismic scratches and the other kinematic indicators allowed to identify two kinematic phases, not visible only through striae analysis. The presence of two kinematic phases produced by a single event rises a problem concerning the motion components acting on the fault blocks. Two components have been identified, one of which can be linked to the release of the Apennine tensional stress, and a second one linked to passive gravity-driven rebalancing. The passive rebalancing is induced by the different accumulation of vertical displacement on the different fault segments. In this case, the fault of Mount Vettore has accumulated a greater vertical slip from the nearby fault of Mount Porche, thus creating the necessity for the hanging-wall block of Mount Porche to accommodate the difference in displacement.

Structural architecture and damage zones in relay zones of normal fault systems: the Vecchiano (Pisa) case study and experimental modelling

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Segmentation along strike is a common feature for all kind of faults, particularly in extensional regime. The step zones, known as relay zones, usually show a complex overall structural architecture with large damage zones.

Object of our study was the structural and morpho-structural analysis of the Vecchiano (Pisa) normal faults system, where a wide exhumed damage zone has been associated with a step between two normal faults bordering to the E the Viareggio basin, a major Neogene extensional basin of the internal Apennines. After an original fieldwork synthesized in a 1:10000 geological and structural map, a photointerpretation has been conducted using a high-resolution dataset (including LiDAR images, ortophoto, DTM). Structural architecture of the system and the segmentation pattern along strike at the mesoscale has been defined associated with the first order features of the basin. Results have been quantitatively analyzed in 2D and 3D to draw up a fault scarps database.

Analogue modelling represented the counterpart of the previous analysis. A series of experiments in extensional tectonic setting have been realized to implement the knowledge about the evolution of deformational structures in relay zones. The starting setup provided a basal plastic film modelled with two steps of variable dimensions, acting as a velocity discontinuity on a brittle behaving sand layer. They represent inherited structures influencing the extensional process.

Analogies between the study case of Vecchiano and our experimental studies provided fundamental insights on the kinematics and tectonic significance of the deformation pattern in relay zones of extensional fault systems.

Seismic reflection profiles and geological cross-sections across the area of the 2016-2017 seismic sequence: comparison with seismological data

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From 24th August 2016 a strong seismic sequence, with nine mainshocks of Mw>5.0 struck the Amatrice-Norcia area. It was triggered by the reactivation of a complex NNW-SSE trending, WSW-dipping, Pliocene – Quaternary normal fault system crosscutting the Umbria-Marche fold-and-thrust belt. By interpolating surface geology data with available seismic reflection profiles, we prepared four integrated geological cross-sections, trending WSW-ENE (i.e. orthogonal to the major active normal faults), in correspondence of the four strongest events (24th August 2016 with Mw= 6.0, 26th October 2016 with Mw= 5.9, 30th October 2016 with Mw= 6.5, 18th January 2017 with Mw= 5.4). Re-located seismicity was also plotted along the sections, in order to discuss the relationships between geology and seismicity distribution, which clearly follows the geometries of the active geological structures. The mechanical stratigraphy of the region plays a major role in controlling the thickness of the seismogenic layer: in our sections, seismicity is confined within the sedimentary sequences, not penetrating the underlying basement at depth, and propagating up to the surface only in the areas where the Carbonates outcrop.

Crustal thickness estimates beneath four seismic stations in Ethiopia inferred from p-wave receiver function studies

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Moho depths beneath four stations of the Ethiopian Seismic Station Network (ESSN) are estimated from P-wave receiver functions (RF). We used high quality seismic data recorded at ANKE (Ankober), DILA (Dilla), HARA (Harar) and SEME (Semera) stations for earthquakes located at epicentral distances ranging from 30 to 100° with magnitude mb ≥ 5.5. We applied a frequency domain deconvolution technique to remove source and propagation path effects from the earthquakes waveforms to make the RFs dependent only on the structure beneath the seismic stations. The minimum number of teleseismic earthquakes used is 14 for HARA while the maximum is 39 for SEME station. A linearized-iterative inversion is applied on the generated radial component of the receiver functions to obtain P-wave velocity models beneath the stations.

We achieved a reasonably good fit between the observed and synthetic RFs, which demonstrated the high quality of the inversion process. From the obtained models we estimated Moho depths of 26 ± 2 km for SEME, 36 ± 2 km for DILA, 38 ± 2 km for HARA and 42 ± 1.7 km for ANKE. The lowest Moho depth is observed at Semera station which implies a thinned crust while the highest crustal thickness is observed at Ankober, which lies along the North western plateau margin. Our results agree with previous observations which strengthen the hypothesis that Moho depths estimated for stations that lie within the rift and rift margins are lower than those located in the plateaus. Our RFs inversions show a low velocity gradient at about 16 km depth at Semera station, interpreted as evidence for lower crustal storage of partial melt.

The origin of the endoreic basins, the case of the Fucino basin (central Apennine)

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The relationships between sedimentation, erosion and crustal extension has been recently addressed on several studies but still few of them have been able to document the feedback between faulting and sedimentary loading. However, in particular when considering internally drained basins (endoreic), the load of sediment might highly influence the dynamic of the faults surrounding the basin. Here, we explore this problem in the Fucino basin.

The Fucino basin, located in Central Apennine (Italy) represents a remarkable case study for is large dimension, unsmoothed shape, significant sediment thickness (almost 1 km) and its endorheic nature. We performed a detailed structural analysis along the main faults surrounding the basin to unravel their slip kinematic and geometry. The distribution of slip-vectors, derived from accurate measurements of the slickenlines, suggests two families of direction. Both in the southern or northern structures of the Fucino basin, cross-cut relationships of the striations indicate a recent swing toward the core of the basin, where the sediments are thicker and subsidence is major. Adopting an isostatic model, we reconstruct the expected influence of sedimentation on fault slip. Our results indicate that almost 30% of the fault offset is related to the sediment loading.

Our results show that the relationships among faulting and sedimentation can be particularly relevant. Overall, our results suggest that the load of the sediments in internally drainage system can increase the slip on the structures and re-organized the kinematics of faults surrounding the basin producing a feedback between faulting and sedimentation.

3D gravity inversion across the Central and Northern Apennines

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In this work, the crustal volume struck by the 2016-2017 seismic sequence in Central and Northern Apennines is investigated using 3D inversion of the observed Bouguer anomaly. In order to focus on the area encompassing the two mainshocks of the sequence, we perform a regional signal removal on the data as a pre-processing step.

This residual dataset is then inverted in 3D to model density contrasts at depth, performing a series of inversions to test different geological scenarios. Starting with unconstrained geometries and density contrasts, we then introduce some geological knowledge with basement and turbidites geometries retrieved from the most recent geological and geophysical models in the area. With the aim of investigating the geometries and densities of the basement and the upper carbonates, evaporites and turbidites, we also test the hypothesis of a phyllitic low-density layer in the upper basement. Finally, we compare our modeling results to the spatial distribution at depth of major seismic events during the 2016-2017 period.

Tectonic activity and palaeoseismicity reconstruction: implications from texture, geochemistry and development of banded calcite veins in travertine depositional systems.

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Fissure ridges-type travertine deposits are morpho-tectonic structures useful for reconstructing age, geometry and kinematics of active faults, potentially hazardous. We compared different latest Quaternary banded calcite veins, from two areas of the inner Northern Apennines (Southern Tuscany, Italy): Bagno Vignoni and Iano areas, located to the north of Monte Amiata and north-east of Larderello geothermal areas, respectively. Bagno Vignoni banded calcite veins belong to a veins network corresponding with a hypogenetic conduit system (i.e. shallow root of a hydrothermal system). Vein structure shows double textures characterized by the alternation of blocky and elongate-blocky crystals types. Iano banded calcite veins formed within the central fracture of the main fissure ridge-type deposit and therefore, correspond to a subaerial system feeding thermal springs. Vein structure is characterized by bands made of elongate-blocky crystals.
After studying the geometry and kinematic of the faults along which the banded calcite veins developed, we analyzed: i) the geometry of the bands crystals by optical microscope; ii) their mineralogical composition through micro-Raman and electronic microscope analyses and X-Ray diffractometry; iii) the δ13C and δ18O stable isotope geochemistry, in order to better understand their development mechanism.

The results highlight that the crystals type geometries together with the different isotope signals can be the outcome of a prevailing factor (such as temperature, CO_2 degassing rate, fluid permanence into the conduits), suggesting alternation between period of tectonic activity and quiescence. The absence of blocky crystals can be explained as a consequence of: (i) absence of fluid into the conduit during CO_2 degassing and/or (ii) constant CO_2 exchange with the atmosphere. To conclude, we documented two different textures, reasonably related to tectonic-driven crack episodes and, consequent filling, occurred in different structural levels.

Flexural-slip and fold growing in the Tabas (central Iran) active folding deduced by AMS and structural analyses.

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An integrated AMS and structural study was carried out in order to reconstruct the geometry of the Tabas fold system and the tectonic evolution of this sector of Central Iran. Fifteen sites in the Neogene Upper Red Formation were sampled for AMS investigation. A mesoscopic structural analyses in the Tabas Neogene fold system was carried out with the aim to describe the geometry of the folds and of the associated brittle deformation to define the mechanism that drove the kinematic evolution of the thrust related fold system. In the Tabas area, AMS analysis shows a magnetic foliation parallel to the bedding plane, reflecting the diagenetic to post-diagenetic compaction processes. In some other cases the magnetic foliation is sub-vertical and not related to bedding, suggesting a tectonic overprint. At the same time, the maximum susceptibility (Kmax) direction and the intermediate susceptibility (Kint) direction axes are well clustered, with a mean NNW-SSE trend for Kmax direction (magnetic lineation), suggesting a tectonic origin of the magnetic lineation. In particular, the magnetic lineation is well defined in most of the analysed sites and correlates with the main tectonic elements recognized in the study area. In fact, the magnetic lineation shows a N-S to NW-SE orientation in all the analysed sites, which corresponds, at the site scale, to the main fold-axis orientation. The magnetic lineation is also orthogonal to the main slip direction (N70◦E) deduced by slickenside orientation on the thrust fault planes soon after the 1978 Tabas earthquake.

Quaternary drainage inversion driven by progressive extension in central Umbria, Italy.

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Modification of rivers and their drainage basins is a poorly understood process associated with tectonically and/or climatically induced erosion, that strongly influence paleogeography, sediment budgets, and provenance. Such events may represents the geomorphological response to variation in rate, style, and locus of tectonic deformation, hence their identification and investigation is a key issue in active tectonic studies.

We identify six orders of fluvial terraces and erosional surfaces associated with the evolution of the Puglia River, a tributary of the Tiber River, in central Umbria, Italy. Investigation of the highest terraces and erosional surfaces demonstrates southeastward flow of the Puglia River, until at least the middle Pleistocene, before reversal, erosion of the Ponte di Ferro Canyon, and deposition of the lowest terraces. Additional sedimentological evidences, including pebble imbrications, composition, dimension and roundness, confirm that the Puglia River reversed its course to northwestward flow in the recent geological past.

Basing on an update geological survey, we document the structural control operated by low and high angle normal faults on the geometry of the ancestral Puglia River Basin and propose that the drainage inversion was driven by progressive extension, consisting with an eastward migration of fault activity. River reversal likely followed stream capture in response to enhanced fluvial erosion and uplift of the Puglia River basin, at the footwall of a NE dipping active normal fault. Future dating of the river terraces, will allow determine the timing of the inversion of the Puglia River, and will help to constraint the space-time changes of fault activity.

Maps of the coseismic ruptures of the 2016 earthquakes in the Sibillini mountains (Central Italy)

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A significant sequence of earthquakes occurred in the Sibillini Mountains in Central Italy in the second half of 2016. On August 24th, Mw 6.1 earthquake struck the area between the town of Amatrice (Rieti Province) and Arquata del Tronto (Ascoli Piceno Province). Several ground ruptures along different strands of SW dipping extensional faults occurred over a distance of more than 20 km, throughout the morphologically complex landscape of the Sibillini Mountains chain and the Laga massif. The October 26th Mw 6.0 earthquake was centered in the Visso area (Macerata Province), approximately 30 km northwest of the previous event. On October 30th, an Mw 6.5 event occurred near Norcia (Perugia Province), in an area located between the epicenters of the former earthquakes. This event reactivated existing ground ruptures and produced further rupturing over a larger area extending for more than 30 km.

Structural rupture maps (clouds, orthophotos, DSM), derived from low altitude flights and ground-based reconnaissance of the different strands of the surface ruptures, are produced. The digital images have been processed using SfM algorithms obtaining 3D clouds of more than 3*107 points for each area. These point clouds permitted to generate a fully rendered 3D terrain model making the extraction of the fractures geometries possible. These maps at scales finer than 1:500, documented the complex distribution of all fractures from few cms of vertical offset. Moreover, maps of the ruptures of the August 24th earthquake can be compared with larger ruptures of the main event of October 30th.

The seismogenic source of the 2018 December 26th earthquake (Mt. Etna, Italy): a shear zone in the unstable eastern flank of the volcano

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The 2018 December 26th earthquake (M = 4.8) at the south-eastern slope of Mt. Etna provides new insights for improving the knowledge of the kinematics of the eastern flank of the volcano. The earthquake was preceded by a seismic swarm on the upper southern-western sector of the volcano and by a short eruptive event in the summit area. The associated crustal deformation triggered seismic reactivation of tectonic structures in the eastern flank of the volcano. In fact, the seismogenic source has been localized in one of the segments cutting the south-eastern slope the volcanic edifice, the NW-SE trending Fiandaca Fault, one of the most active shear zones belonging to the upslope extension of the Timpe fault system.

This large event was followed by the reactivation on 2019 January 9th (M = 4.1) of the WNW-ESE trending Pernicana Fault. In the last centuries, all these faults have been the source of very shallow, low magnitude, but destructive earthquakes. In order to determine the response of the unstable eastern flank of Mt. Etna to the volcano-tectonic events, we applied a multidisciplinary approach based on: i) analysis of historical and instrumental seismicity; ii) mapping of coseismic fracturing, iii) analysis of GPS and InSAR data. In particular, the field survey supported by the interferometric data provided a new scenario of the rupture framework. The results are fundamental for reconstructing a kinematic model and for new considerations about the geological hazard in one of the most urbanized areas of the volcano.

Lo sviluppo delle microzonazioni sismiche in Umbria

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In Umbria various seismic microzonation actions have been done over 38 years at the turn of 2 millennia. The evolutionary path made since 1980 was important and was as follows. 1980, 1997, 1998, 1999, 2000, 2006, 2008, 2013, 2014, 2018 (detailed seismic microzonation investigations were carried out at the same time in a very large number of municipalities of 4 regions, according to timelines and uniform procedures in a short time; general criteria have been defined and approved for the use of the results of the level 3 seismic microzonation studies for the reconstruction in the territories affected by the seismic events). Not all actions have completely reached the conclusion and others are underway. We have moved from a degree of qualitative knowledge to an ever-increasing amount of detail. All the results have been made available online, even when possible, as open data and this has greatly facilitated the application of the results also because the Umbria Region has made their use mandatory.

In conclusion, the execution of studies and applications of the achieved knowledge applied to the reconstruction has allowed to decrease from 1 to 3 degrees the macroseismic intensity.

La rappresentatività geologica

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Detailed information about geology, hydrogeology and seismic hazard issues for Umbria region are contained in a spatial database available as open data format (shapefile or KMZ) and distributed under the regional open data portal called Open Data Umbria where 251 datasets have been produced by Umbria Region until now and most of them are made by Geological Survey. Geological Survey of Regione Umbria carried out a 20 years program to produce 276 geological maps at 1:10.000 reference scale with an accurate geological model of the regional surface and providing millions of geological data. The key word is the characteristic index of the single geologic unit. Characteristic index calculates the ratio between the surface of the geologic units compared to their thickness. Thickness value for each geologic unit is intended to be based on rank level and calculated as weighted average of the thickness for each geologic unit.

Imaging of the 2010-2014 structures in the Pollino area from relative locations of microearthquakes

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Small-to-moderate earthquakes of the most intense period of the 2010-2014 Pollino seismic sequence, from November 2011 to March 2012 and from September 2012 to May 2013, have been analyzed with the aim of imaging and characterizing with high accuracy the fault structures responsible for the swarm. Clusters of events of similar waveforms, likely produced by the same fault patch, have been identified through a cross-correlation analysis and relocated using a methodology based on the computation of travel time difference at any stations with respect to the reference event. For each cluster the best fit plane of hypocenters has been compared with the fault plane obtained from the focal mechanisms computed for individual earthquakes of the cluster. Additionally relative location of each cluster has been performed to improve the fault imaging and compared with their absolute locations.

Results show that clustered events of the first period were likely produced by a 2x3 km2 normal fault, located at depth between 4.5 and 7 km, characterized by a strike NW-SE, dip around 35-45 degrees and deepening SW, toward the Tyrrhenian sea. The analysis of the second period of seismicity shows that the rupture developed toward south, following the above-mentioned fault. It is also evident the rupture of a sub-parallel fault with similar features, as confirmed by focal mechanisms.

Active normal faulting in the Garfagnana and Lunigiana basins. New data from Lidar image analysis and field mapping.

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The Garfagnana and Lunigiana basins are bounded to the east and to the west by normal fault systems and were the site of the most destructive seismic event ever recorded in the Northern Apennine (the 1920 MW = 6.5) and of other devastating events (e.g. the earthquake of 1834 Mw~5.9, 1837 Mw~5.9 and the 1481 Mw~5,6). At a large scale, the eastern fault systems maintain a continuity between the two basins whereas the western systems are separated by a right-lateral transfer zone known as North Apuan Fault zone. The relationships between the fault systems (master fault vs antithetic fault) in both basins along with their overall geometry and seismogenic role is still matter of debate.

A new mapping of the already known and newly detected active faults and minor connecting structures in the basins was performed integrating all the available geological data with and an extensive field work and image analysis from LiDAR data.

Field evidences of quaternary faulting combined with quantitative geomorphology elaborations allowed to make preliminary estimations of slip rates for the main fault systems located on both sides of the basin and on the main transfer zone. The geomorphological and structural features revealed by LiDAR analysis and the field structural analyses shed light on the overall architecture and kinematic history of the recognized fault systems allowing to speculate about their structural role and seismogenic potential.

Probabilistic fault displacement hazard maps for thrust faults - modelling based on new empirical regressions for distributed faulting

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Probabilistic fault displacement hazard analysis (PFDHA) is used for characterizing the expected fault rupture hazard and the amount and distribution of co-seismic fault displacement. The approach was seen incomplete especially regarding the distributed faulting (DR) in thrust faulting environments. This work creates a probabilistic model for predicting the surface fault displacement in thrust faulting environments. The analysis is based on the empirical database gathered from 11 historical thrust earthquakes, which is used in the analysis of the spatial distribution of DR and establishing the attenuation relationships to the amount of dislocation for the increasing distance from the principal fault (PF). The general methodology follows the one of the traditional PFDHA, but especially for the analysis of the distributed fault rupturing several methodological adjustments were done for obtaining a statistically robust model that could be used for prediction purposes. The model utilizes the surface geometry of the chosen fault, the parameters derived from the calculation of the probability of the occurrence, and the expected amount of surface faulting. It computes the probability of DR exceeding a certain displacement level, or the amount of the DR displacement with a given probability. The model is applied to the Suasselkä post-glacial fault (Finland) for a scenario where the fault ruptures for its total length (Mw ~7.0), and the probability of surface displacement is analysed in the surroundings of the fault. The model created here can be applied to any well-known mapped thrust fault with relatively simple geometry.

Seismogenic stress constraints to geodynamic modeling of Southern Italy

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We have selected from official catalogs and the literature the focal mechanisms estimated by waveform inversion methods for shallow earthquakes that occurred in the last 40 years in Southern Italy and surroundings. The compiled database is characterized by fault parameter errors not larger than ca. 10-15°, suitable for good quality seismogenic stress inversion. We have performed stress inversion on subsets of this database partitioned according to spatial grouping of earthquakes, focal depth, mechanism homogeneity and magnitude, with the main purpose of detecting the space variation of stress on local to regional scale and inferring geodynamic features of the study region.

The application of different stress inversion methods and comparison of the respective results have allowed to evaluate the effects of different assumptions on stress field estimates. We also explored the possibility of distinguishing the different tectonic engines acting in selected sectors by simulation tests. The stress orientations obtained for several sectors of the central Mediterranean region have been commented in the light of knowledge existing on geometry and kinematics of microplates and tectonic units in this part of the Africa-Europe plate boundary.

Reproduced coseismic ground deformation through numerical modeling: a sensitivity analysis on geological and rheological parameters.

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Determining the relationships between seismic fault slip and surface deformation is relevant for several issues, as seismotectonic studies or seismic hazard assessment. Surface deformation is commonly detected through remote sensing and is often used to infer the slip distribution on geologically reliable fault surfaces. In this modelling workflow a number of parameters must be known and assumptions are often required.

In this work, starting from a well-known case study (2009 L'Aquila sequence), we analyzed how geological and rheological parameters could affect the coseismic surface deformation. Different fault geometries were reconstructed using aftershocks distribution and coseismic ruptures, and then were tested using boundary elements numerical models in order to run a sensitivity analysis on two rheological parameters: stress drop and stiffness.

The results of the numerical models obtained by varying fault geometry, stiffness and stress drop were compared with the satellite observed deformation (Envisat, descending orbit). Modeling outputs change considerably both in terms of distribution and amount of subsidence.

These results help to understand and better constraining the geometry of the fault responsible for the surface deformation and the value of stress drop and stiffness associated with the L'Aquila seismic sequence. The fault geometry is the main factor that controls the surface deformation, suggesting that a reliable and accurate 3D geological reconstruction is by far the most important input data.

Relationships between geological long-term and coseismic surface slip distributions of the 2016-2017 earthquake rupture (central Italy): hints for fault system behaviour and interactions

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During the 2016–2017 central Italy seismic sequence, the 30 October, Mw 6.5 Norcia earthquake produced a 28-30 km-long, impressive surface ruptures belonging to the NW-trending Mt. Vettore-Mt. Bove normal fault system (VBFS). To detect possible segmentation patterns or hints on the fault system growth and to evidence the contribution of the last seismic event to the cumulative net throw, long-term, geological and geomorphological throw distribution (T-x diagram) of the VBFS were reconstructed by reviewing published geological maps, collecting new field data and constructing 23 spaced geological cross sections. We produced single and aggregate geological T-x diagram of the VBFS splays excluding the pre-orogenic tectonics.

A displacement/length relationship is calculated in order to test the scaling relationship with those from other worldwide and national study cases. Then, we compared the geological and morphological throws, in order to verify how the cumulative deformation of multiple earthquakes built the Quaternary landscape. Moreover, we discuss the fit between the aggregate T-x diagram with the co-seismic data at the surface (from both near-fault surface ruptures and far-field DInSAR dislocation model) and at depth (from strong motion models). The observed asymmetric T-x diagram is discussed in term of possible interaction between the VBFS and the nearby Laga Mountain Fault System. As key area, we also estimated in detail and with quantitative approach the morphologic throw of the bedrock fault scarp of the Cordone del Vettore (CDV) splay, to reconstruct the post-LGM fault slip and to provide insight into the slip rate and average recurrence interval.

Active tectonics in NW-Sicily detected through morphometric and geodetic analyses

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Landscapes are sensitive recorders of tectonic forcings. Hence, their quantitative analysis represents a powerful tool to detect active tectonics processes in areas that show no clear evidence of surficial faulting. The goal of this research is to detect active deformation processes, through morphometric and geodetic analyses, in a selected area of the NW-Sicily. Low relief, erodible rocks which alternate with carbonatic ridges and low deformation rate characterised the investigated area. GPS measurements highlight a shortening rate of 0.47 mm/yr between the permanent stations of Palermo and Termini Imerese in a NW-SE direction. The topographic relief, geology and geomorphic indexes describing the geometry of four different river basin (respectively Oreto, Eleuterio, Milicia and S.Leonardo) were analysed to depict the topographic response to this stress regime. Outcomes from analyses of basins asymmetry, relief distribution and hypsometry highlighted anomalies in river network geometries and relief distribution.

Most of them were detected in the area of the Milicia basin and its surroundings that is set almost entirely on easily erodible rocks; in particular, the Milicia trunk stream is horizontally shifted of roughly 1/3 of its length and flow at a higher altitude than its second order stem. Also, swath profile analyses and field surveys allowed the detection of asymmetric valleys and unpaired terraces suggesting differential vertical movements. The achieved results integrated with seismicity catalogues and a subsurface 3D geological model allowed us to produce a morphotectonic evolution model that can provide information to the understanding of the active tectonic processes in the area.

Shear wave splitting evidence and relations with stress field and main fault from the "Amatrice-Visso-Norcia Seismic Sequence"

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We present the largest dataset of anisotropic high-quality parameters (~12000) for the Amatrice-Visso-Norcia seismic sequence to understand the physical mechanisms causing crustal anisotropy and its relation with crustal deformation, stress field, fluids and earthquakes.

We performed shear wave splitting analysis on ~40000 aftershocks recorded at 31 seismic stations during the first six months of the sequence starting from August 24th 2016 Mw 6.0 Amatrice mainshock. Automatic and manual-revised P- and S- picking and high-precision locations are used to delineate the fracturing pattern and spatio-temporal variations in the anisotropic parameters: fast direction polarization (φ) and delay time (δt). The mean fast direction strikes N146°, parallel to the extensional Quaternary fault systems, and to the NE-SW local active extension as proposed by the Extensive Dilatancy Anisotropy model. Locally φ directions outline the pattern of micro and mesoscale structures that we relate to structural-controlled anisotropy. Temporal variations of anisotropic parameters allowed us to deduce stress-induced and pervasive fluid-filled stress-aligned crack systems as the prevalent anisotropic mechanisms.

Higher δt (~0.096 s) and higher anisotropy percentage (> 1.5%-2.0%) are found at the boundaries and in the hanging-wall of the activated fault system, where heavily fractured carbonates are present. These fault network along with the lithological heterogeneities may act as a structural barrier along which fluids are channeled and trapped, thus causing over-pressured fluid zones. Observations of shear-wave splitting during a seismic sequence suggest that the time-delays of split shear- waves monitor the buildup of stress before earthquakes and the stress release as earthquakes occur.

Transpressive tectonic activity along the borgo Faris-Cividale fault (NE- Italy)

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Borgo Faris-Cividale fault (BFCF) belongs to the strike slip fault-system that characterizes NE-Friuli and W-Slovenia. In the present NNW-SSE to NNE-SSW oriented accumulating strain, with velocities of about 2-3 mm/yr, they act as right lateral transpressive faults giving rise to historical and instrumental strong earthquakes (1511: Mw: 6.3; 1998: Mw 5.8; 2004: Mw 5.5).

In particular, BFCF borders the Julian Prealps, running from Nimis to Cividale for about 25 km. It is about N130 striking, but it presents two active WNW-ESE striking, SW-verging reverse splays (Colle Villano thrust and Cividale thrust).

Morphotectonic, structural, geophysical and paleoseismological investigation along this tectonic association showed evidence of recent deformation (until historical). In particular:

- Morpho-structural analyses indicated drainage anomalies and suspended terraces along the fault trace;

- mesostructural analyses (kinematic indicators) on the fault plane showed two superimposed tectonic phases: the first (probably Pliocene in age; sigma 1 NW-SE) indicates left lateral movement; the second, linked to the Quaternary tectonic activity with sigma 1 about N-S, indicates right lateral movement.

- The Plio-Quaternary Natisone conglomerates are frequently characterized by contractional features (pitted pebbles and striae), consistent with the Pliocene and Quaternary main stress axes (sigma 1).

- Analyses of seismic industrial lines (ENI) indicate a complex structural association between strike slip faults and reverse ones with transpressive component.

- Paleoseismological studies (trenches) demonstrated tectonic activity during Holocene and historical times. Widespread paleo-liquefactions were identified along the fault trace.

3D geometry of the buried quaternary faults in the NE-Friuli plain

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Interpretation of seismic lines, gently supplied by ENI, implemented with well logs, seismicity and morphotectonic data allowed us to reconstruct the 3D-geometry of the active buried faults of the NE-sector of the LGM Friuli plain. The study area corresponds to the junction zone between the SW-verging External Dinarides and the S-verging eastern Southalpine Chain. Starting from Late Cretaceous three main compressional tectonic phases involved the area:

- NE-SW late Cretaceous-Paleogene Dinaric phase;
- NNW-SSE Neogene Neoalpine phase;
- late Miocene-to-Present phase, with a repeatedly oscillating NNW-SSE to NW-SE $\sigma 1$.

At present, the inversion of focal mechanisms of the main seismic events, in good agreement with geodetic data, reveals that the about N-S accumulating slip is partitioned between two deformational systems:

- middle-to-low angle E-W/ENE-WSW and WNW-ESE reverse structures (central-western Friuli compressional domain);
- NW-SE trending strike-slip/transpressive structures (NE Friuli-western Slovenia transcurrent domain).

Historical seismicity shows that at least 3 Mw>6 events struck the area in 1348 (Mw 6.63), 1511 (Mw6.32), 1976 (Mw 6.45) (Rovida et al, 2016). Nevertheless, the seismogenic role of the tectonic structures isn’t yet completely clear. In this study, by means of 3DMove software, we present the 3D-geometry of the main faults. By merging these new data with morphotectonic evidence and recent seismicity, estimation of minimum activity rates and seismogenic potential of the Quaternary faults were performed. Two main Quaternary faults were detected: Pozzuolo and Udine-Buttrio thrusts. They both show evidence of Quaternary activity with minimum throw rate of the order of 0.12-0.13mm/yr and an estimated Mmax~6.

References

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Geological/seismological data to infer a fault model for the south-eastern Sicily 1693 earthquakes.

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Our study deals with the south-eastern Sicily 1693 main-shocks (9 and 11 January, Mw≈6.1 and Mw≈7.3, respectively). Although they have been largely studied, robust and commonly accepted seismogenic sources are still missing. We performed a revision of the macroseismic data of the 1693 shocks and remodelled seismic sources. The detailed mapping of seismogeological effects shows that the most numerous and relevant ones occurred between Noto and Catania, suggesting that the sources of the 1693 earthquakes are located in this area.

In the area of maximum damage and seismogeological effects, we mapped three fault systems: the reverse NNE-SSW Palazzolo-Villasmundo Fault System (PVFS), the normal NW-SE Augusta-Floridia Fault System (AFFS) and the almost N-S West Canicattini-Villasmundo Fault System (WCFS). Through a geomorphological and morphometric investigation, we observed that these faults are active. The coexistence of local extensional and contractional stress-fields suggests the presence of a deeper-seated N-S left lateral transtensional fault. WCFS can be the expression at surface of this fault; PVFS can be the associated reverse faults, responsible of upthrust blocks; AFFS are the associated normal faults, causing strike-slip basins.

WCFS lies across the remodelled seismogenic sources and it matches with a present day alignment of earthquakes with focal mechanisms showing prevalently left lateral movement on almost N-S fault planes. Considering the possible WCFS rupture length in depth, it is compatible with earthquakes of Mw ≈ 7.1, therefore it can be the source responsible of the 1693 earthquakes.

Geometry and evolution of the Middle Aterno Quaternary basin and relationship with the 2009 L'Aquila earthquake causative fault system (Abruzzi Apennines, Italy)

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On April 6, 2009, a Mw 6.1 devastating earthquake, struck the Middle Aterno Valley (MAV) (Abruzzi Apennines, Italy) due to the activation of a poorly known normal fault system. In order to image the subsurface 3-D geometry of the MAV and to reconstruct the long-term, tectono-sedimentary evolution of the basin, we successfully integrated geophysical investigations (deep ERT profiles, time domain electromagnetic soundings and single-station ambient vibration surveys), structural analysis of the fault population and reconstruction of the relationships with the Quaternary continental deposits. A polyphasic evolution of the MAV is dominated by a ~E-W and ~N-S-trending strike slip fault system, reactivated with dip-slip kinematics during the Pliocene-Early Pleistocene, and by a dip-slip, NW-striking fault system starting from the late Early Pleistocene. The ~E-W and ~N-S fault system is responsible of the physiography of the Early Pleistocene basin: controlled the triangular-shaped sedimentary traps, produced intra-basin bedrock highs and significant syn-tectonic deposition, causing variable thickness (up to 500-600 m) and hiatuses of the continental infill. The NW-striking fault system activity, through linkage of NW-strands into longer splays and migration toward the leading Paganica-San Demetrio fault segment, disrupted the irregular early Quaternary basin and controlled the Middle Pleistocene–Holocene alluvial deposition. Notably, two major elements of the ~E-W and ~N-S-striking faults act as transfer to the nearby stepping active fault systems or form the boundaries, as geometric complexities, that limit the Paganica-San Demetrio fault segment overall length to 19 ± 3 km. The resulting size of the leading fault segment is coherent with the extent of the 6 April 2009 L'Aquila earthquake causative fault.

Comparing coseismic slip with cumulative displacements at various time scales on the mt. Vettore- mt. Bove fault system after the 2016 central italy earthquakes: insights into growth and segmentation processes of an active extensional system.

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Understanding how a fault system evolves in time and space is a fundamental task for seismic hazard assessment because it helps to individuate how and where coseismic surface rupturing can likely occur. As a case study, we analyse the Mt.Vettore-Mt. Bove Normal Fault System in the central Apennines, which broke during three major earthquakes (Mw6.0, Mw5.9, and Mw6.5) in 2016, associated with clear coseismic ruptures.

We compare data at short (coseismic), mid (morphological) and long (geological) term for reconstructing how the system evolves over time.

Based on high-resolution satellite images, DTMs and original field observations, we identify three types of faults having geological displacement (≥ 50 m). (1) Active faults with 2016 surface ruptures and morphological evidence of activity over the last glacial maximum (i.e. ~18 kyr); (2) Probably active faults only with morphological evidence; (3) faults without morphological and coseismic evidence. We evaluated the geological throw on all fault segments (1, 2 and 3) through seven geological cross-sections. The cumulative offset is assessed on each fault portion exhibiting morphological evidence of activity by topographic profiles extracted from a 2m DEM. Those 102 offset measurements yield the distribution of the post-glacial cumulative throw over the 22 km-long studied portion. In general, distribution of coseismic and morphological displacements show a similar pattern and, to the south, they exhibit a strong correlation.

Recent activity is concentrated on segments that have recorded activity over the last 18 Kyr. Those segments might be more prone to rupture than faults displaying only high geological throw.

Are InSAR data a tool to aid the field geological survey of coseismic ruptures?

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The detection and the structural analysis of surface coseismic ruptures are essential tools for characterizing the seismogenic structures. Sentinel-1 A/B Interferometric Wide (IW) Swath TOPSAR mode offers the possibility of acquiring images with a maximum revisit time of twenty-four days. This huge amount of open data is extremely useful for geohazards monitoring such as earthquakes. Interferograms of a moderate-large earthquake show elastic deformation caused by the principal fault movement. Phase discontinuities appearing on wrapped interferograms or loss-of-coherence areas could represent small ground displacements. However, also phase gradient maps from complex interferograms could be exploited to visualize lineaments. In this work, a comparison between different methods has been made together with an accurate field validation of results. We investigated two case studies. The first is relative to the 2016 Central Italy earthquakes (M=6.1, M=6; M6.5), where the InSAR outcomes relative to the Amatrice event highlight quite accurately the good field documented displacement of extensional faults in the Mt. Vettore – M. Bove area. Here the geological effect of the earthquake is more than 35 km of ground ruptures with a complex surface ruptures pattern composed by subparallel and overlapping synthetic and antithetic fault splays.

The second case is about the Mt. Etna 2018 December 26th earthquake (M=4.8) where ground transtensional ruptures related to the Fiandaca fault are detected. The analysis of the unwrapped phase and the application of edge detector filtering and other discontinuity enhancers permits to identify a complex pattern of ground ruptures.

New findings by recent seismic data and Coulomb stress transfer in the Yellowstone region

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The extremely intense geological activity of the Yellowstone volcanic plateau, western United States, is manifested through diffuse and intense seismicity and movement of magmatic fluids. The area is considered as one of the most active volcanic systems also due to persistent episodes of surficial deformation which testify movement of magma underneath. Nevertheless, no volcanic eruption occurred earlier than 70 ka ago.

Here we analyze both the spatial and temporal evolution of seismicity between 1988 and 2016 and we perform an accurate evaluation of fault kinematics and related state of stress through a new and complete data set of 226 well-constrained, double-couple, focal mechanism solutions (FMS). The majority of the events have normal-faulting and strike-slip faulting solutions, and very rarely, reverse motions. We use earthquake focal mechanism inversion to calculate stress-field solutions for different areas and time periods. We investigate spatial and temporal variations in fault kinematics through the relation with sill intrusion, by calculating Coulomb stress transfer exerted on nodal planes and on mapped Quaternary faults in order to describe the deformation pattern that characterize the different phases of the intrusion of magmatic bodies.

Our results show that the deeper section of the crust, whereas pre-existing fault planes in the upper section are subject to unclamping, thus explaining why magma upwelling has been inhibited despite of extensional tectonics of the area. We present new structural models to explain the deformation pattern before, during and after sills emplacement, thus contributing to a better interpretation of geophysical data in active volcanic zones.

Crustal deformation pattern for the Aegean - Anatolian region from a dense GPS-based velocity field

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The Aegean - Anatolian region, sited in the collision zone between the African, Arabian and Eurasian plates, has been characterized by a long-lasting complex tectonic evolution. The convergence between Africa and Eurasia plates started since Jurassic and leaded to the orogenic systems of the Hellenides; since late Miocene, the Hellenides divided in a northern and a southern segment. The former segment remained trapped into the continental collision with the Apulian foreland; such a collision is currently occurring at rates of 5-10 mm/yr. In the latter segment, a rapid oceanic subduction of the African plate beneath western Turkey and the Aegean region started, leading to the creation of the Hellenic arc subduction zone. Such a rapid subduction, currently occurring at rates of ~40 mm/yr, caused extension of the continental crust and volcanism in the overlying Aegean region.

Here, we present an improved picture of the ongoing crustal deformation field of the Aegean - Anatolian region, based on an extensive combination of novel observations rigorously integrated with published geodetic velocities. In addition, by taking into account the observed horizontal velocity field and associated uncertainties, we estimated the 2D strain-rate field for the whole region. Main results well highlight the right-lateral behavior of the northern Anatolian fault as well as the extensional pattern in central Greece, along the Corinth rift.

Crustal deformation along the Nubia-Iberia plate boundary

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A spatially dense crustal velocity field, based on up to 20 years of GNSS observations at more than 430 sites and extensively covering the Iberian Peninsula and Northern Africa, allows us to provide new insights into the main tectonic processes currently occurring in this area. In particular, we processed all available GPS coming from networks developed for mapping, engineering and cadastre purposes, by using the GAMIT/GLOBK software in order to estimate a consistent set of positions and velocities in an ITRF2008 frame and in a fixed Eurasian reference frame. In order to improve the spatial resolution, we integrated our velocity field with the ones coming from recent literature. Main results allow as to observe a slow large-scale clockwise rotation of the Iberian Peninsula with respect to a local pole located closely to the northwestern sector of the Pyrenean mountain range.

Furthermore, the western Mediterranean basin appears fragmented into independent crustal tectonic blocks, which delimited by inherited lithospheric shear structures and trapped within the Nubia-Eurasia collision, are currently accommodating most of the plate convergence rate. In addition, geodetic velocity along the western Algeria are uniform and collinear to the plate convergence trend, with a sharp gradient at the coast, while in the eastern sector they indicate that deformation involves a broader region. Finally, most of the observed crustal ground deformation can be attributed to processes driven by spatially variable lithospheric plate forces imposed along the Nubia-Eurasia convergence boundary. Nevertheless, the observed deformation field infers very low convergence rates.

Seismic activity in the Marche foothills and Adriatic offshore: modelling from revised deep seismic profiles and seismological data

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In 2016-2017 a seismic sequence (maximum magnitude Mw=6.5) severally affected the Central Italy, for this reason many studies focused on investigating nearby potentially seismic active areas. In particular, this work deals with an investigation of seismogenic faults in the northern part of the outer Marche region affected in the past by several significantly destructive earthquakes: i.e., Fabriano 1741 (Mw= 6.2), Cagli 1781 (Mw= 6.4) and Senigallia 1930 (Mw= 5.8).

In the last three decades, the progress in the geological and geophysical knowledge has been coupled with the increasing availability of digital multi-scale geological datasets. Therefore, nowadays it is possible to build reliable geological models taking into account the distribution of the seismicity in the study area.

The starting point was the collection of the seismic events occurred from 1985 to 2019, with magnitude M≥2 (INGV database) coupled with interpreted seismic sections (SW-NE oriented) and structural maps.

With these input data, a 3D geological model was created by means of Move™ software licenced by Midland Valley Ltd. The hypocentres of seismic events have been compared with deep and shallow geological structures, in order to identify any correlation among them.

It has been observed that seismic events tend to cluster in the proximity of some of the main faults at variable depths particularly approaching the faults affecting the Quaternary-Holocene deposits with an evidence of recent activity.

The present study could be useful for the governance of the territory to the reduction of seismic risks and emergency preparedness.

Seismotectonics of central-western Caucasus, Republic of Georgia

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This work contributes to a better knowledge of potentially seismogenic faults of the Georgia Greater and Lesser Caucasus by evaluating the distribution of earthquake foci, active tectonic stress field, kinematics and geometry of main fault planes. We consider all the information coming from field structural geology, geomorphology, seismological data from historical and instrumental catalogues, seismic reflection sections, as well as new focal mechanism solutions. These data enable recognizing some active ENE-WSW reverse faults in the core of the Greater Caucasus that are parallel to the mountain range. At the southernmost front of the Greater Caucasus, a series of main thrusts dipping towards NNE are active, with tens to hundreds-km-long segments; along this thrust zone, a potentially locked segment is present, about 90 km long. The studied section of the Lesser Caucasus has active structures along the northern front given by south-dipping thrusts, as well as in the central core where strike-slip and oblique faults coexist.

The Transcaucasian depression between the two mountain ranges shows an ongoing inversion tectonics of the central part of the Rioni Basin where active N- to NE-dipping reverse faults are present, accompanied by clear evidence of uplift of a wide area. The data are coherent with a N-S to NNE-SSW contraction of the central-western Greater Caucasus and Lesser Caucasus. Although in general the seismicity decreases westward in terms of number of earthquakes and magnitude, seismological and geological structural data in the Rioni Basin indicate here the presence of an important zone of recent tectonics.

Structural setting and seismotectonics of the Adriatic foreland of the Marche-Romagna Apennines

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The Adriatic Sea constitutes the foreland of the Northern Apennines orogen where a deep Plio-Pleistocene foredeep is located. The chain is the product of a NE verging foreland fold-and-thrust system that migrates progressively since the Oligocene from the innermost Tuscany domains reaching the Adriatic area in the Pliocene. The result is a complex of northwest-southeast-trending anticlines parallel to the coastline, stepped by lateral ramps and strike-slip faults with three important detachment levels located in the Triassic anhydrites, in the Marne a Fucoidi - Scaglia Cinerea formations and the shallower in the Messinian evaporites. Clarify the structural and geological setting of the Romagna-Marche Apennine in the Adriatic off-shore and delineate a seismotectonic framework is the aim of this work. Starting from the geological observations, geophysical data have been used to extrapolate in depth the main structures, verify spatial and temporal relationships and define the deformation style. Some on-offshore seriate geological cross-section has been create integrating geometries, deformation styles and calibrated with stratigraphy derived from wells data. These cross-sections have been balanced and restored in order to get a new 3D structural picture of the area useful to define the seismotectonics of the area. Starting from a new velocity models, earthquake's location has been significantly improved, highlighting the main seismologically active structures.

3D Plio-Pleistocene architecture and evolution of the Po plain/Northern Adriatic foredeep

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The distribution of clastic sediments in foreland basins and the resulting architecture of basin-fill are related to the interplay between tectonics (i.e. changing basin topography and entry-point location) and sedimentation. Through the 3D reconstruction of 6 regional unconformities, we present the preliminary results of the Po Plain and Northern Adriatic Foreland Basin Pliocene-Pleistocene evolution. This study is based on published results from the Venetian Friulian basin and new reconstructions regarding the central Po Plain and the Piemonte region. Isobath and isopach maps were carried out by interpreting a dense network of seismic reflection profiles and correlating more than 250 wells.

Results provide a 3D image of the step-by-step Plio-Pleistocene evolution of the basin and the corresponding sediment dispersal patterns. We found that the basin records the change from a cylindrical to a non-cylindrical foredeep geometry. In the Northern Apennines, the main factors driving the development of a non-cylindrical geometry are the occurrence of inherited inhomogeneities in the footwall block (related to its Mesozoic extensional faulting) and the relative orientation of the inherited lineaments with respect to the direction of tectonic transport. During the late Pliocene-Pleistocene the two directions progressively became close to parallel, and the Northern Apennines system reacted changing from a cylindrical to a non-cylindrical state. These preliminary results still need to be homogenized, refined and made continuous by interpreting further data but yet provide for the first time a detailed 3D reconstruction of the recent tectonic evolution of a key sector of the Italian peninsula.

Seismic velocities of carbonates from the Apennines

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3D crustal model results strongly depend on the applied seismic velocity model. The variation of velocities is severely influenced by lithological differences and by the changing boundary conditions. To this aim we analysed and compared an extensive seismic-wave velocity dataset coming from different acquisition-methodologies such as: sonic log, interval velocities and laboratory experiments that measured velocities on carbonates of the Apennines. We have divided the investigated carbonates into three representative groups such as: massive pure limestone (Calcare Massiccio, CM), layered pure limestone (Maiolica, MA), and layered marly limestone (Calcareous Scaglia, SC). The different acquisition-methodologies give comparable results where the mostly common recorded Vp is 6.1 km/s for CM, 5.7 km/s for MA and 5.8 km/s for SC. We observed that laboratory measurements (performed on relatively small samples) are only sensible to mineralogical variations such as clay content or dolomitization. Laboratory velocities are pressure (depth) independent whilst the depth-influences on sonic and interval velocity decrease from SC (quite influenced) through MA (slightly influenced) to CM (not influenced). Structural position, i.e. the maximum experienced load, exerts a key role in controlling Vp for carbonates in particular for stratified formations whilst a minor role of fracturing is suggested due in particular to the larger velocity observed in the mountain range (fractured), respect to the foreland (unfractured). This difference is of about 1km/s in particular for SC highlighting that detailed velocity models are fundamental to properly define the subsurface geological bodies.

Inside the 2012 Emilia seismic sequence: new evidence from geological-structural modelling and 3D FEM

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The 2012 Emilia sequence (Northern Apennines, Italy) represents one of the largest Italian seismic sequences occurred in a continental compressional tectonic setting. The sequence begins on 20 May 2012 with a Mw 6.1 earthquake, causing casualties and severe damage; nine days later, on 29 May, a Mw 6.0 event occurs about 15 km southwest of the first shock. The existing literature substantially agrees in associating the 20 May earthquake with the Middle Ferrara Thrust, whereas the debate is mostly focused on attributing the 29 May event to the Inner Ferrara Thrust or, rather, to the Mirandola Thrust. In this work, we propose a new 3D reconstruction of the main faults involved during the 2012 Emilia multi-events seismic sequence.

We show that the 20 May and the 29 May events nucleate along the Middle and the Inner segments of the Ferrara Thrust System, respectively, and that these two thrust segments are along strike connected by an up to now unnoticed left-lateral transfer fault. In order to verify our findings and to constrain the best earthquake/fault association, we start our analysis by developing a 3D geological model of the investigated area. Subsequently, we extend our analysis by applying a 3D numerical modelling approach based on the finite elements method, implemented in a structural-mechanic framework; this allows us to simulate the ground deformation patterns retrieved through the RADARSAT-2 DInSAR measurements. Finally, we retrieve the volumetric distribution of the coseismic strain and stress variation, responsible for the observed ground deformation pattern.

Holocene thrusting at Montodine (Cremona Italy): evidence for recent surface faulting

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An intriguing outcrop was exposed along of River Serio, south of Montodine (Cremona Italy), following a severe flooding event in 2008. The outcrop, studied by us during 2009, consists of an alluvial to palustrine sequence formed by well-bedded sandy-clay with compressed peat beds, which are crosscut by a well-defined low-angle reverse fault, displacing the succession up to one meter. The hangingwall is gently folded in an open syncline with a metric wavelength, and shows secondary reverse faults, whereas the footwall is almost undeformed.

^{14}C radiocarbonic ages obtained from the deformed alluvial peat deposits range from about 10 ka to 5ka cal BP for wood fragments stretched within the fault. Subsequent installations of prehistoric Bronze Age pile dwellings on top of the sequence appears to be undisturbed.

In this contribution, we discuss the possible origin of the thrust fault, which can be alternatively ascribed to anthropic, gravitational or tectonic processes. Indeed, other belts of strongly compressed, deformed peat layers of Pleistocene Age were recently exposed after ongoing down cutting along the Adda River bed near Lodi.

Due to the position of the outcrop, laying above the buried thrust front of the North Apennines, we favour a tectonic origin, directly related to surface faulting. Recent earthquakes in the nearby area of Soncino, occurred at the beginning of the XIX century, testify to the seismic activity of the area.

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