TALKS:

Seismicity/attenuation/seismic velocity changes at Clear Lake volcanic field, Long-valley caldera, Lassen volcanic center, California

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Abstract

In California, there are several hazardous volcanoes that are designated as “High Threat volcanoes” by the U.S. Geological Survey. Such volcanoes include Clear Lake Volcanic Field (CLVF), Long-Valley Volcanic Region(LVVR), and Lassen Volcanic Center (LVC) that are located in northern California, and their tectonic and volcanic seismicity have been monitored by arrays of seismic stations as parts of Northern California Seismic System (NCSS). We present results from three projects for these volcanoes.

Deep long-period earthquakes (DLPEs) are commonly observed at volcanics areas. Interpretations of DLPEs include the resonance of fluid-filled cracks and nonlinear fluid flow along conduits with irregular geometry, which may lead to using these events as indicators for a volcanic system that is evolving towards eruption. The CLVF is seismically active and over the years DLPEs have been detected. To improvise the DLPE catalog at the CLVF, a template match analysis was applied to continuous recording from the late 1993 through the end of 2023 with 81 template DLPEs listed in the NCSS catalog. Over 1500 additional DLPEs are detected. We also characterized the source process of the largest DLPEs (M=2.93) that show a very clear long-period resonance at 0.3 to 0.4 Hz following the direct S arrival and its duration is about 30 seconds. We applied a time dependent moment tensor inversion in which a sequence of point-sources with independent moment tensors is simultaneously solved for. F-test suggests that an isotropic component is required to explain observed seismic data, and the most striking observation from our inversion is the oscillatory behavior of the isotropic moment between volume increase and decrease, which suggests fluid mechanism would be important in this DLPE.

Seismic attenuation is an important property of seismic wave propagation, and its relationship to the thermal state of the rocks has been used to identify subsurface features related to deep magma reservoirs at volcanoes. To evaluate the attenuation stricture at the LVVR, we applied a coda-based approach to estimate spatial variations of intrinsic and scattering attenuation assuming a diffusion model. In a higher frequency range (> 20 Hz), we identify high intrinsic and high scattering attenuation anomalies in the fluid-rich western and eastern areas of the caldera. By comparing spatial variation of other geophysical images (magnetotellurics and seismic velocity tomography), we attribute these attenuation anomalies to be related to a hydrothermal origin. High intrinsic attenuation to the west of the Hartley Springs Fault may be produced by the magmatic system that produced the Inyo Craters.

Time-lapse monitoring of seismic velocity at volcanic areas can provide unique insight into the properties of hydrothermal and magmatic fluids and their temporal variability. We established a quasi real-time velocity monitoring system by using seismic interferometry with ambient noise to explore the temporal evolution of velocity in the LVC. Our monitoring system finds temporal variability of seismic velocity in response to stress changes imparted by an earthquake and by seasonal environmental changes. Dynamic stress changes from a magnitude 5.7 local earthquake induced a 0.1% velocity reduction at a depth of about 1 km. The seismic velocity susceptibility defined as ratio of seismic velocity change to dynamic stress change is estimated to be about 0.006 MPa-1, which suggests the Lassen hydrothermal system is marked by high-pressurized hydrothermal fluid. By combining geodetic measurements, our observation shows that the long-term seismic velocity fluctuation closely tracks snow-induced vertical deformation without time delay, which is most consistent with an hydrologic load model (either elastic or poroelastic response) in which surface loading drives hydrothermal fluid diffusion that leads to an increase of opening of cracks and subsequently reductions of seismic velocity. We infer that heated-hydrothermal fluid in a vapor-dominated zone at a depth of 2-4 km range is responsible for the long-term variation in seismic velocity.

Monitoring the fluid content in the shallow crust through seismic noise interferometry and geodesy

L. Zaccarelli, A. Almagro Vidal, E. Mandler, F. Pintori, E. Serpelloni

Abstract

Ambient seismic noise cross-correlations have been proven to be a useful tool for reconstructing the elastic characteristics of the medium and tracking their temporal variations. We present a few case studies (from the Alps to the Apennines) of a long time series (~10 years) of seismic velocity variations undergone by the superficial crustal layers (a few km of depth), and its comparison with the time series computed for the total water storage variations and the ground deformation of the same area. The main feature that emerges, independently of the tectonic and geological setting of the area under study, is the very good agreement between velocity variations, total water storage and ground deformation time series. Surprisingly the influence of the water content is visible also at a few km depth (without any delay). Thus it becomes important to remove this effect on the velocity variation time series in order to explore minor sources of seismic velocity variations. We test some methodology for doing this operation and we discuss the possible interpretation of the residuals. Also considering possible implications for real time noise-based monitoring application.

Wet-quakes: the case study of the 2012 Emilia seismic sequence, Italy.

F. P. Lucente & P. De Gori (INGV)

Abstract

In May 2012, two major earthquakes struck Northern Italy, causing tens of casualties and widespread damage. These earthquakes occurred nine days apart (May 20th Mw 6.0 and May 29th Mw 5.8) on contiguous thrust faults and were the main shocks of a seismic sequence lasted until the end of June. Seismicity spread over a 50-km wide, roughly E–W trending region, counting thousands of aftershocks with at least six with ML ≥ 5.0 (Govoni et al.2014). Aftershock decay rate and Vp/Vs changes along the fault system suggests that a fluid-diffusion process drove the seismicity and the activation of the second main shock (Pezzo et al., 2018). Taking advantage of the approach recently proposed by De Gori et al. (2023) we compute the source parameters for the entire aftershocks sequence. The analysis of the spatio-temporal distribution of the aftershocks source parameters in the rock volume hosting the two ruptured faults sheds light on some new details about the interaction between fluid-diffusion processes and seismogenesis.

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Detecting fluids signature in seismogenic processes.

Chiaraluce L. and M. Cocco

Abstract

In the last 20 years, three moderate seismic sequences (Colfiorito 1997 – M_W 6.0; L'Aquila 2009 M_W 6.1 and Amatrice 2016-2017 M_W 6.5) occurred in between the northern and central Apennines of Italy, activating a NW-trending, 130km long and contiguous normal fault system composed by a set of 12-18 km fault segments rupturing the first 10 kilometres of the upper crust.

Such a fault system is located south of the Alto Tiberina fault (ATF) a 60km long active low-angle normal fault (LANF; mean dip 20°) that is the target of the Alto Tiberina Near Fault Observatory (TABOO-NFO), a state-of-art permanent research infrastructure based on a dense network of multidisciplinary sensors.

By means of high-resolution earthquakes catalogues, we reconstructed the anatomy of the entire fault systems showing heterogeneity of rupture histories and complex faults geometry raising questions not only on our understanding of long-term segmentation, strain partitioning and dynamic control of coseismic ruptures, but also on possible hints of fluids involvement in the preparation and onset of the main seismogenic episode. Small and moderate seismic sequences resolved at high spatial resolution, display in fact relevant similarities as well as fundamental differences in the larger events preparatory phase and seismicity pattern evolution.

We observed nearby sequences experiencing foreshocks activity occurring along structural discontinuities between main faults [1997 Colfiorito] and along main fault plane [2009 L'Aquila]. These sequences lasting for months, marked the onset of large variations in elastic properties of the crustal source volumes modelled in terms of dilatancy and diffusion processes, corroborating the hypothesis that fluids play a key role in the nucleation process of extensional faults as testified by main fault planes sometimes activated before the occurrence of the largest event on the fault plane itself. Differently the 2016-2017 seismic sequence did not show any standard foreshocks activity, while it seems to be loaded by strain partitioning affected by a mid-crustal layer characterized by seismic activity showing changes in the rate of earthquake production during the months before the sequence onset and during the aftershock sequence.

In this context, TABOO-NFO gives us an exceptional opportunity to explore processes driving the activation of a complex fault system composed by multiscale fault segments (from hundreds of meters to kilometres) embedded in diverse hosting lithologies, activated through the occurrence of earthquake sequences or background seismicity.

Fault activation from up close

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Abstract

Our understanding of earthquake rupture processes is generally limited by the resolution of available observations. In all but exceptional cases, earthquake observations are made at comparatively large distances from the rupture itself, which puts a limit on what spatial scales can be resolved. At the same time, it is clear that small scale processes may play a crucial, if not dominant, role for various seismogenic processes, including rupture nucleation, co-seismic weakening and stress re-distribution.

The Fault Activation and Earthquake Rupture ('FEAR') project aims at collecting and interpreting a multitude of earthquake-relevant observations from directly on and around the process zone of an induced earthquake. To this end, we attempt to activate a natural granitic fault zone in the BedrettoLab, at a depth of ~1km, after instrumenting the fault zone with a multi-domain and multi-scale monitoring system. The goal is to observe and study earthquake rupture phenomena in a natural setting, from unusually close distance.

In this talk, we outline the project status, the science goals, the plans for the main experiments (scheduled for the years 2024 - 2026), and present first high resolution observations from a successful, recently conducted test experiment.

* *FEAR Science Team: Alberto Ceccato, Alexis Shakas, Anne Obermann, Antonio Pio Rinaldi, Aurora Lambiase, Cara Magnabosco, Carolina Giorgetti, Chiara Cornelio, Claudio Madonna, Daniel Escallon, Elias Heimisson, Giuseppe Volpe, Pooya Hamdi, Hansruedi Maurer, Kadek Palgunadi, Kai Broeker, Kathrin Behnen, Linus Villiger, Lu Tian, Marco Scuderi, Maria Mesimeri, Marian Hertrich, Mariano Supino, Marie Violay, Martin Mai, Martina Rosskopf, Miriam Schwarz, Nima Gholizadeh, Peter Achtziger, Julian Osten, Stefano Aretusini, Victor Clasen, Zhe Wang*

The impact of tectonic structures on the 3D scattering imaging of the Central Italy Seismic Sequence

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Abstract

The Amatrice (Mw 6.0) - Visso (Mw 5.9) - Norcia (Mw 6.5) seismic sequence (hereafter AVN) struck the Central Apennines (Italy) in a period of 6-7 months during 2016-2017, and it has been widely associated with fluid migration in the normal faults network. The behaviour of fluids in the crust is fundamental to understanding earthquake occurrence and stress interaction. Analysing seismic attenuation and its different mechanisms can give information about material properties and the presence of fluids and fracturing in the medium.

Here, we present the results in 2D and 3D of the scattering and absorption contribution to the total attenuation of coda waves, at different frequency bands. We investigated the variation of attenuation using two datasets, the first considering a pre-sequence phase (March 2013-August 2016) and the second comprising the Amatrice-Visso-Norcia sequence. The subdivision of the seismic sequence can highlight changes in attenuation in space and time, allowing us to interpret the fracturing development and fluid migration in the seismogenic zone.

We applied peak delay as a proxy of seismic scattering, both in 2D and 3D, while we mapped the absorption using a tomographic inversion of coda wave attenuation (coda Q) in 2D.

The results of the 2D mapping of peak-delay time and coda attenuation tomography indicated a substantial control on the scattering of seismic waves by structural (e.g., Monti Sibillini thrust) and lithological (e.g., Umbria- Marche and Lazio-Abruzzi geological domains) features, showing a clear difference between the sequences, with an increment in attenuation in space and time. We associated this with the deep migration of CO_2-bearing fluids across the seismogenic zone during the seismic sequence in the fault network following the mainshock progression from south to north.

As the 2D, the 3D results show strong changes between the pre-sequence and the sequence, where we can identify an increase of scattering with time after the mainshocks.

Substantial variations in scattering are observed in the hanging wall of the Monti Sibillini thrust, which acts as a rheological barrier between high and low scattering zones, and in the Triassic deposits layer. Here, low scattering during the pre-sequence phase is replaced by high scattering

during the mainshocks, suggesting an increment of pore pressure, associated with fluids in this geological formation. The subsequent release of these fluids might have triggered the mainshocks of the seismic sequence, leading to an increase in fracturing, as indicated by high scattering anomalies. These findings shed new light on the significance of considering thrust systems within the tectonic framework of Central Italy.

POSTERS:

Hydrologically-related strain reveals non-linear elasticity and promote earthquake triggerring along the Irpinia Fault (Italy).

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Abstract

The pore-fluid pressure diffusion is commonly interrogated as the mechanism by which fluids can influence seismic failure. However, hydrological masses can also operate inducing significant deformation with a subsequent weakening of the materials and modulation of the seismicity, without the need for direct pore pressure diffusion (as observed in D'Agostino et al., 2018). In this perspective, the continuous monitoring of the elastic properties of rocks can offer insights into the physical processes concurring in the seismic failure. Here we present a quasi-static pump-probe experiment to quantify the non-linear response of crustal rocks to hydrological forcing associated with phases of recharge/discharge of karst aquifers near the Irpinia Fault System (IFS, Southern Italy) and investigate its role in the seismic cycle. Charge/discharge phases of the karst aquifers in the Apennines cause significant seasonal and multi-annual strain transients (Silverii et al, 2019), that modulate the secular, tectonic deformation (~3 mm/yr extension across the Apennines). It has been previously observed that these seasonal and multi-annual transients correlate with the seismicity rate (D'Agostino et al, 2018) and seismic velocity variations (Poli et al., 2020). Recent studies (Silverii et al., 2016; D'Agostino et al., 2018) have shown the high sensitivity of the IFS to hydrological stresses reflected in a complex, time-dependent response of deformation and seismicity. Here we compared continuous 14-years-long time series of discharge, geodetic strain, seismic-velocity variations and seismicity rate. Seasonal horizontal strains associated with the discharge and recharge of karst aquifers are used as the "pump", while the seismic velocity

variations, computed using empirical Green's functions reconstructed by autocorrelation on the continuous time series of ambient noise, represent the “probe”. We analyzed two different sites (co-located GPS and seismic stations), near and afar the IFS. We found that velocity variations are significant (~0.2%) nearby IFS rather than far away from it. We found earthquakes preferentially occur during maximum hydrological loading periods, revealing that hydrologically-induced deformation and subsequent deterioration of elastic properties govern the earthquake triggering. At the time of the maximum peak of the discharge spring, representing a proxy of the hydraulic head, the seismic wave velocity is minimum, and the dilation of the crust is maximum and related to the opening of the pre-existing cracks’ system. The background microseismicity occurrence is favored by the hydrologically-related dilatation, superimposed on the ongoing tectonic extension. From the comparison between hydrological strain variations and velocity changes, we estimate a strain sensitivity of velocity change of $\sim - 10^3$, typical for worn crustal material and in good agreement with laboratory experiments. This non-linear elasticity regime suggests the presence of a multi-fractured and damaged crust subject to periodic seasonal phases of weakening/healing, potentially affecting earthquake nucleation processes in one of the most earthquake-prone areas in Italy.

Seismic attenuation and stress on the San Andreas Fault at Parkfield: are we critical yet?

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Abstract

The Parkfield transitional segment of the San Andreas Fault (SAF) is characterised by the production of frequent quasi-periodical M6 events that break the very same asperity. The last Parkfield mainshock occurred on September 28th, 2004, 38 years after the 1966 earthquake, and after the segment showed a ~22 years average recurrence time. The main reason for the much longer interevent period between the last two earthquakes is thought to be the reduction of the Coulomb stress from the M6.5 Coalinga earthquake of May 2nd, 1983, and the M6 Nuñez events of June 11th and July 22nd, 1983.

Plausibly, the transitional segment of the SAF at Parkfield is now in the late part of its seismic cycle and current observations may all be relative to a state of stress close to criticality. However, the behavior of the attenuation parameter in the last few years seems substantially different from the one that characterised the years prior to the 2004 mainshock. A few questions arise: (i) Does a detectable preparation phase for the Parkfield mainshocks exist, and is it the same for all events?

(ii) How dynamically/kinematically similar are the quasi-periodic occurrences of the Parkfield mainshocks?

(iii) Are some dynamic/kinematic characteristics of the next mainshock predictable from the analysis of current data? (e.g., do we expect the epicenter of the next failure to be co-located to that of 2004?).

(iv) Should we expect the duration of the current interseismic period to be close to the 22-year "undisturbed" average value?

We respond to the questions listed above by analysing the non-geometric attenuation of direct S-waves along the transitional segment of the SAF at Parkfield, in the close vicinity of the fault plane, between January 2001 and November 2023. Of particular interest is the preparatory behavior of the attenuation parameter as the 2004 mainshock approached, on both sides of the SAF. We also show that the non-volcanic tremor activity modulates the seismic attenuation in the area, and possibly the seismicity along the Parkfield fault segment, including the occurrence of the mainshocks.

Heat and Fluid Flow around Faults and Lava Domes in Mono Lake, California

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Abstract

Sublacustrine hydrothermal systems in continental interiors are impacted by coupled tectonic, volcanic, biological, and surface processes. In this study we couple new campaign and time series heat flow measurements with data from seismic and bathymetric surveys to study sublacustrine hydrothermal systems in Mono Lake, California. We collected 62 shallow (<1.5 m penetration) temperature gradient measurements. While temperature fluctuations in the shallow sediments induced by annual lake temperature fluctuations influence the shallow temperature gradients, sublacustrine hydrothermal systems provide large enough heat flow to produce observable anomalies. Temperature gradient measurements exceed seasonal background levels at two locations: (1) Hot Springs Cove southeast of Paoha Island where a lava dome formed approximately 300-350 years BP and (2) South Tufa along a fault mapped onshore and identified offshore through seismic reflection data. Repeat surveys in March 2022 and August 2022 near Hot Springs Cove confirm a temperature gradient anomaly at the bottom of the lake even during summer conditions when lake floor temperature is broadly elevated. High temperature gradients in the lake at Hot Springs Cove and South Tufa are associated with sublacustrine hydrothermal systems. Heat flow and fluid velocities are estimated by numerically solving the unsteady advection-diffusion equation using 20 years of monthly water column temperature measurements to constrain boundary conditions and using lakebed temperature gradient timeseries measurements to estimate thermal diffusivity. In addition, we couple geophysical observations with basin wide non-isothermal hydrogeological modeling to assess the distribution of thermal anomalies under Mono Lake. Our analysis supports the hypothesis that shallow fractured lava domes and fault zones within the Mono Basin form conduits for vertical fluid flow that transport heat and produce fumaroles, hot springs, and sublacustrine hydrothermal systems. Our results provide insights into the near-surface distribution and dynamics of hydrothermal systems in the Mono Basin and their relation to local volcanic and tectonic structures.

Wet-quakes: twenty years of "diffused" seismicity in Italy

F.P Lucente, P. De Gori, L. Malagnini (INGV)

Abstract

Major seismic sequences occurred in Italy in the last three decades can be all classified as cascades of multiple mainshocks. For all these seismic sequences, going from Colfiorito 1997, to L'Aquila 2009, to the Emilia sequence in the 2012, to Amatrice-Visso-Norcia (2016–2017), fluid-diffusion processes have been inferred, and pore pressure pulses have been suggested to play an important role in the fault failure processes, hence in the seismic sequences evolution in space and time (Miller et al., 2004; Chiarabba et al., 2009; Lucente et al., 2010; Malagnini et al., 2012; Malagnini et al., 2022, among many others).

After presenting a non-exhaustive set of results obtained so far on the relationship between fluid diffusion and strong earthquake sequences in Italy, we focus our contribution on the relationships between fluid diffusion and seismic attenuation in the footwall and in the hanging wall of the normal faults responsible of the 2016 seismic sequence of the Central Apennines (Italy). Time histories of seismic attenuation anomalies are calculated for a set of central frequencies in a time window containing the entire multi-mainshock sequence: between January 1st 2016 to February 28th 2017.

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