Diffusion processes in minor normal faulting seismic sequences monitored by the Alto Tiberina Near Fault Observatory (Northern Apennines, Italy)

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1. Introduction

The effect of pore-fluid flow in triggering seismicity has long been suggested (Nur, 1972), and specific characteristics and patterns related to fluid-driven seismic activity have been highlighted both in aftershocks (Noir et al., 1997), swarm like sequences (Ross et al., 2021) as well as in induced seismicity episodes (Talwani, 1984).

Extensional seismic sequences occurred along the Apennines (Italy) during the last decades have shown multiple indications of fluids and earthquakes interactions (e.g. Colfiorito 1997: Miller et al. (2004) and Antonioli et al. (2005); L'Aquila 2009: Di Luccio et al. (2010), Lucente et al. (2010), Terakawa et al. (2010); 2016-2017 Central Italy: Chiarabba et al.(2018), Malagnini (2022).

We analyzed two small but prolific sequences occurred nearby **Città di Castello (CdC)** and **Pietralunga** (see boxes in map).

The **Northern Apennines** are a perfect place to investigate the evolution of minor extensional seismic sequences and the effects of fluids on seismogenesis because of:

1) the **presence of a known source of CO_2** at depth (Chiodini et al., 2004);

2) the geologic and tectonic setting favoring **fluid overpressure** (Trippetta et al., 2013) directly measured in boreholes (Santo Stefano and San Donato, reported on map) and

3) a **dense seismic network** pertaining to the Altotiberina Near Fault Obserfvatory (TABOO NFO, Chiaraluce et al. 2014).

Following the approach proposed by Shapiro et al. (1997, 2003) **we tested the hypothesis of the presence of a triggering front due to an evolving pore-pressure diffusion process.**

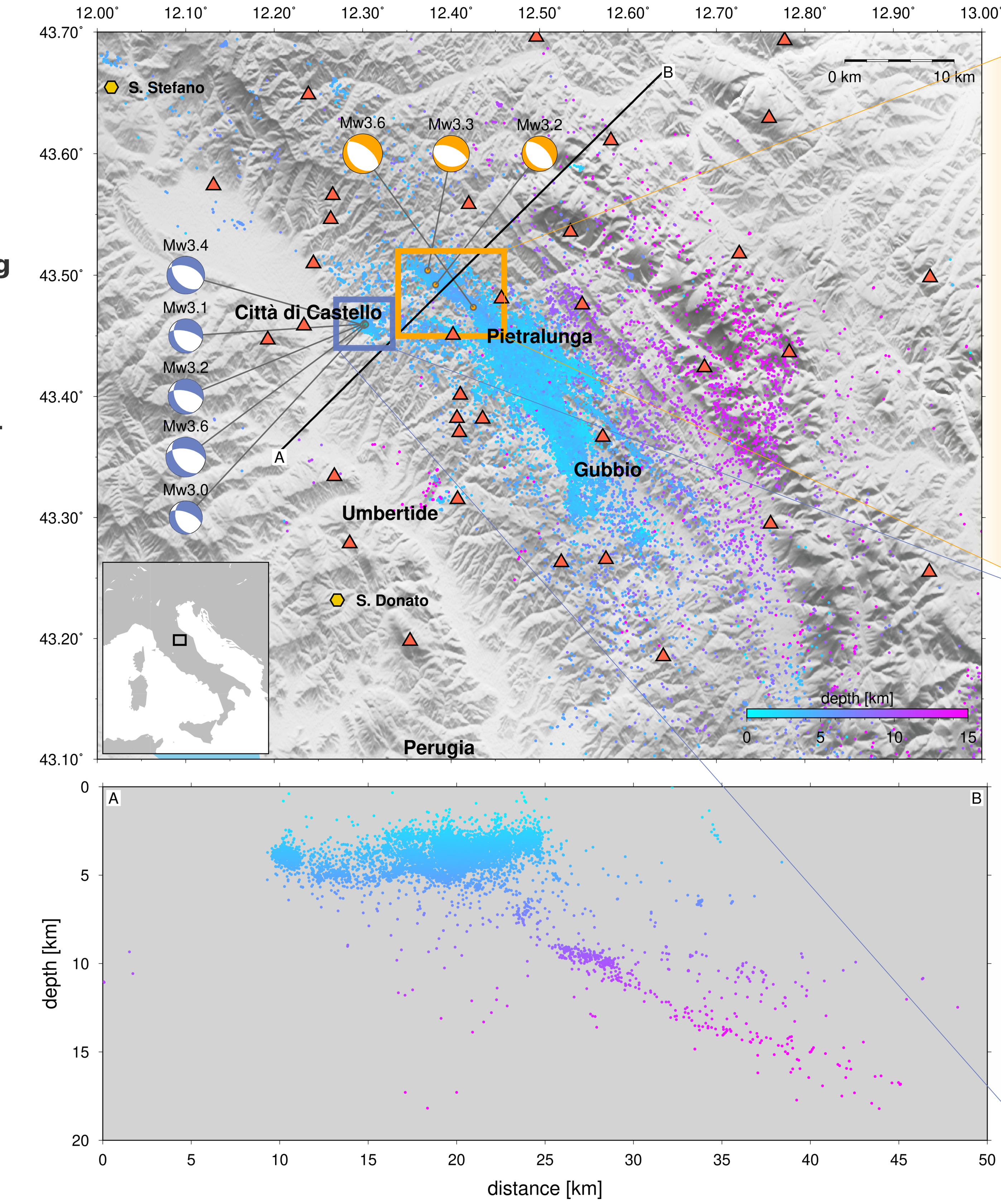
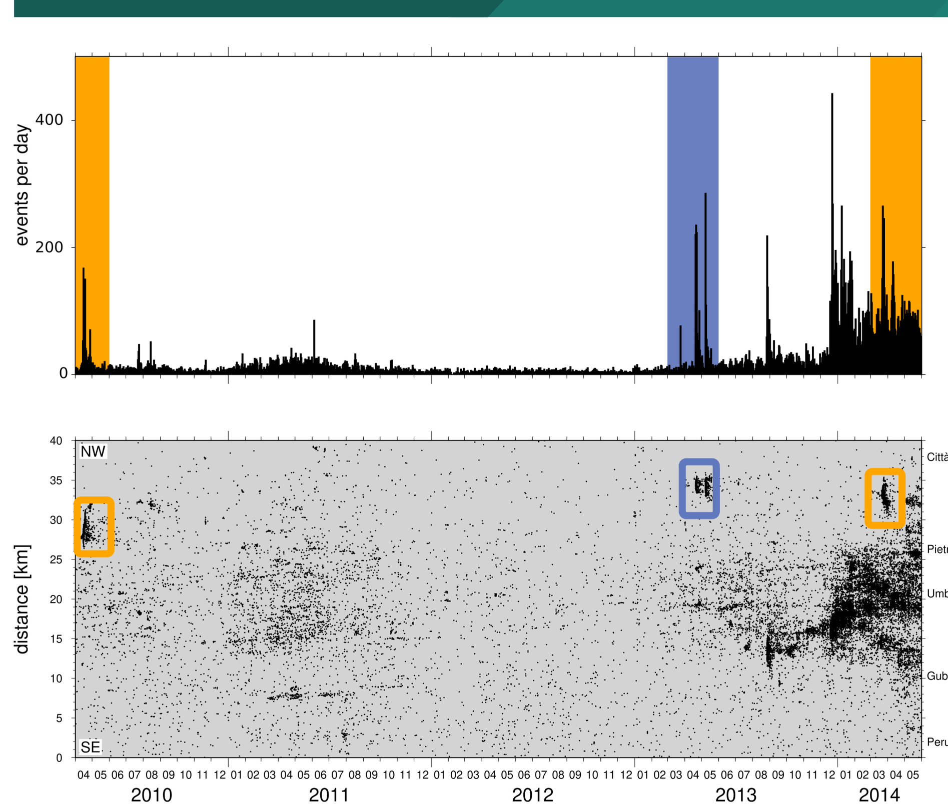


Figure 1. Top: map of the study area (events from Valoroso et al., 2017). Città di Castello and Pietralunga areas are marked respectively by purple and orange rectangles. Red triangles represent seismic stations. Yellow hexagons mark boreholes where overpressure have been measured. Bottom: cross section (width=20 km) highlighting the high seismic activity at shallow depths (<7 km) and the ATF visible at higher depths, dipping toward NE.

2. Data analysis

Waveforms picking: **Phasenet** Zhu et al., 2019 → Association: **REAL** Zhang et al., 2019 → Absolute location: **NonLinLoc** Lomax et al., 2014 → Quality selection: Michele et al., 2019 → Relative location: **HypoDD** Waldhauser et al., 2000



The analysis of spatiotemporal earthquakes patterns requires 1) a large number of events and 2) robust hypocentral locations. Therefore **we generated a new earthquakes catalog** for both sequences leveraging on the detection capabilities of a **deep neural network picking algorithm** (PhaseNet) that we tested and applied on the continuous waveforms (selected time windows highlighted in Fig. 2). In order to detect the microseismicity of the area as comprehensively as possible, we relaxed the conditions for event declaration in the association step (e.g. minimum number of phases: 3P+2S).

We computed absolute locations with NLLoc using a 1D velocity model of the area (Carannante et al., 2013) and static station corrections (Bagh, p.c.). This resulted in 160k events.

The uncertainty estimators from NLLoc output are gathered to compute a quality factor for each event, following Michele et al. (2019).

Only high quality events from CdC and Pietralunga sequences are selected and finally **relocated with HypoDD**.

Figure 2. Events per day (top) and space-time distribution of seismicity (bottom) in the TABOO area. Città di Castello and Pietralunga sequences are highlighted in purple and orange.

3. Results

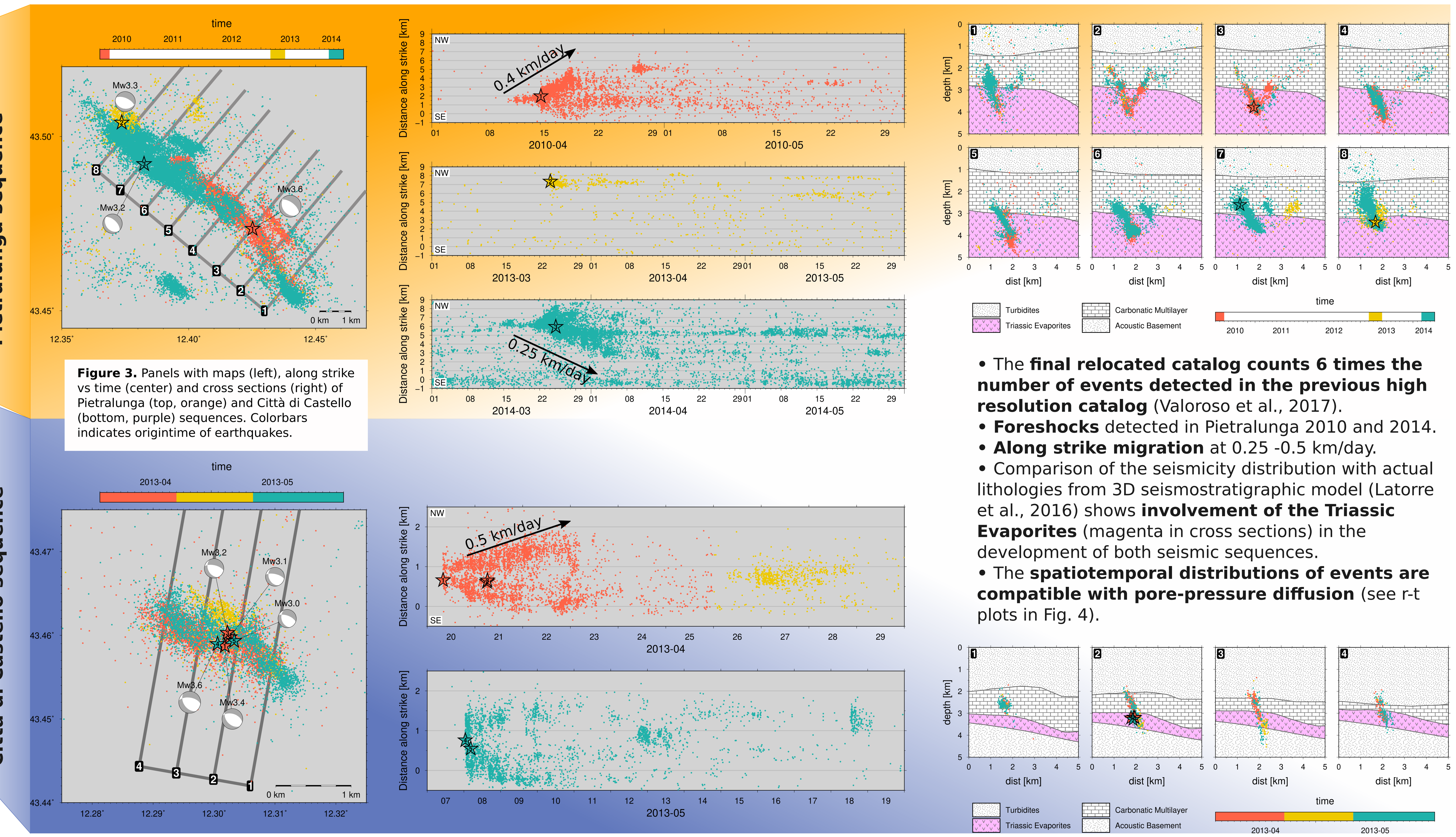


Figure 3. Panels with maps (left), along strike vs time (center) and cross sections (right) of Pietralunga (top, orange) and Città di Castello (bottom, purple) sequences. Colorbars indicates origintime of earthquakes.

- The **final relocated catalog counts 6 times the number of events detected in the previous high resolution catalog** (Valoroso et al., 2017).
- **Foreshocks** detected in Pietralunga 2010 and 2014.
- **Along strike migration** at 0.25 -0.5 km/day.
- Comparison of the seismicity distribution with actual lithologies from 3D seismostratigraphic model (Latorre et al., 2016) shows **involvement of the Triassic Evaporites** (magenta in cross sections) in the development of both seismic sequences.
- The **spatiotemporal distributions of events are compatible with pore-pressure diffusion** (see r-t plots in Fig. 4).

4. Conclusions

- We observe **diffusive processes in both Città di Castello and Pietralunga extensional seismic sequences**, with hydraulic diffusivity estimates (1-2 m^2s^{-1}) lying well within the 0.1-10 m^2s^{-1} interval, commonly observed for induced and natural earthquakes (Talwani, 1984).
- **Strong lithological control on earthquakes distribution**: low permeability Triassic Evaporites seem to be able to promote earthquake nucleation as a response to development of (CO_2 rich) fluid overpressure (Collettini et al., 2009; De Paola et al., 2009).
- Small sequences show along strike seismicity migration and multi-segments ruptures similar to large extensional sequences (e.g. Colfiorito 1997 L'Aquila 2009, Central Italy 2016).

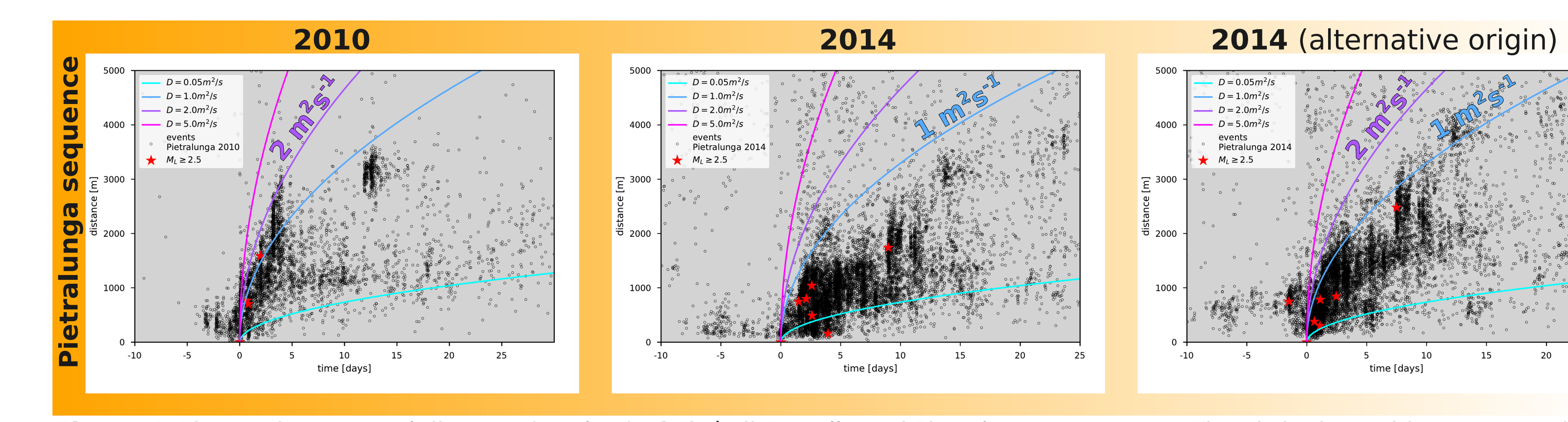
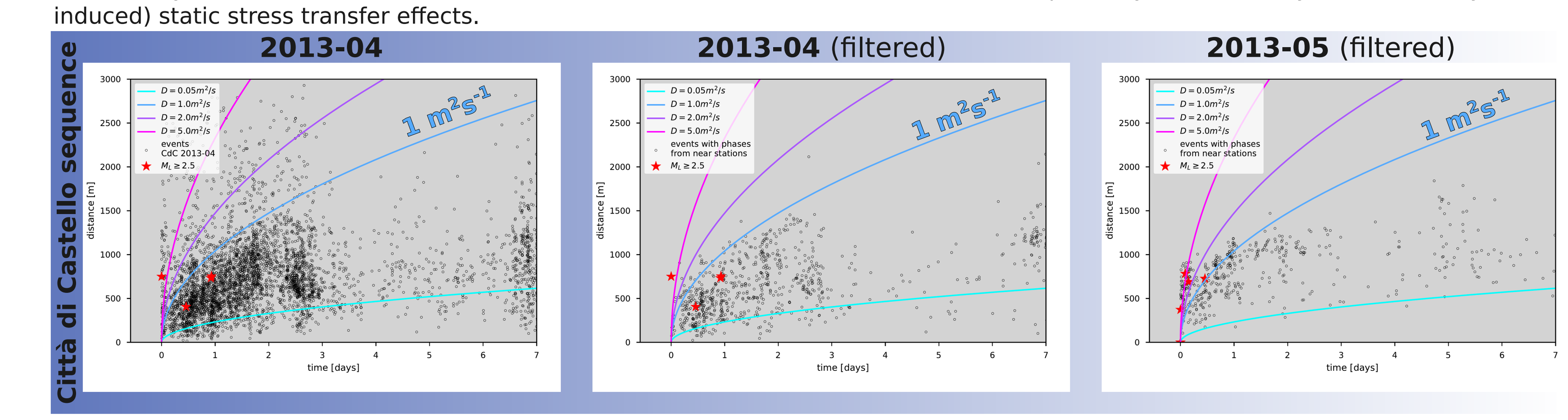


Figure 4. Time vs hypocentral distance (r-t plots) of Città di Castello and Pietralunga sequences. Time is in days with respect to the start of diffusive process. Pore-pressure diffusion curves calculated for different diffusivity values are reported with different colors. Since Pietralunga 2014 shows a swarmlike behavior, we tested different events with $M_L \geq 2.5$ as the origin of the diffusive process: events at 2014-03-21T04:41:02 and 2014-03-22T16:23:19 (alternative origin). The diffusive pattern is evidenced in both cases, with the only difference being a slight change in the diffusivity value.

In CdC 2013-04 and 2013-05 the diffusive pattern is outlined more precisely when considering only events with phases recorded at nearest stations (filtered version), despite the lower number of events considered. In CdC 2013-05 the diffusive pattern becomes clearer only after the first hours from the mainshock, where the distribution of events is probably dominated by (co-seismically induced) static stress transfer effects.



5. Ongoing work

- Expand the catalog including waveforms from 2010 to 2023.
- Train PhaseNet on local waveforms and use this model for phase detection and polarity estimation.
- Update each step of the workflow.
- Further explore the link between seismicity and hosting lithology.
- Systematic search of repeaters and in-depth analysis of foreshock sequences.

References

Carannante, S., G. Monachesi, M. Cattaneo, A. Amato, and C. Chiarabba. 2013. "Deep Structure and Tectonics of the Northern-Central Apennines as Seen by Regional-Scale Tomography and 3-D Located Earthquakes." Journal of Geophysical Research: Solid Earth 118 (10): 5391–5403.