Fluid diffusion and seismic clusters identification: results on the seismicity of Molise (southern Italy) in 2018

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1. ABSTRACT

The identification of clusters is crucial for the statistical analysis of seismicity and the forecasting of earthquakes, **because discrepancies in the methods used to identify clusters can lead to inconsistent results**. In this work, the seismic activity in **Molise**, southern Italy, from April to November 2018 is analyzed as a case study. The focus is on **how such discrepancies can affect forecasting algorithms** such as NExt STrOng Related Earthquake (NESTORE), which are designed to forecast strong aftershocks following a first strong event.

A detailed analysis was performed using an improved template matching catalog and a comparative evaluation of clustering methods, including **window-based** analysis techniques, **Nearest Neighbor**, and **fractal dimension**. Probabilistic information was integrated through the **Epidemic Type Aftershock Sequence (ETAS) model**.

Significant differences in cluster definition required further analysis, including **principal component analysis (PCA)** and **ETAS modeling**, to investigate spatiotemporal seismic patterns. The main results show an **upward migration of seismicity**, an **extended duration of the sequence** and **relative quiescence between stronger events**, all suggesting fluid-driven mechanisms. These observations suggest that the **presence of fluids plays a crucial role in the sequence dynamics and the discrepancies between clustering methods.**

The study highlights the importance of **refining approaches to cluster identification, incorporating physical and geological factors**, and encourages **further investigation** of **anomalous seismic sequences** such as the **2018 seismic cluster in Molise**. The results also highlight **the influence of fluids on seismicity in the Apennines** and call for advanced analytical methods to improve the accuracy of strong events forecasting.

2. MOLISE 2018 SEISMICITY

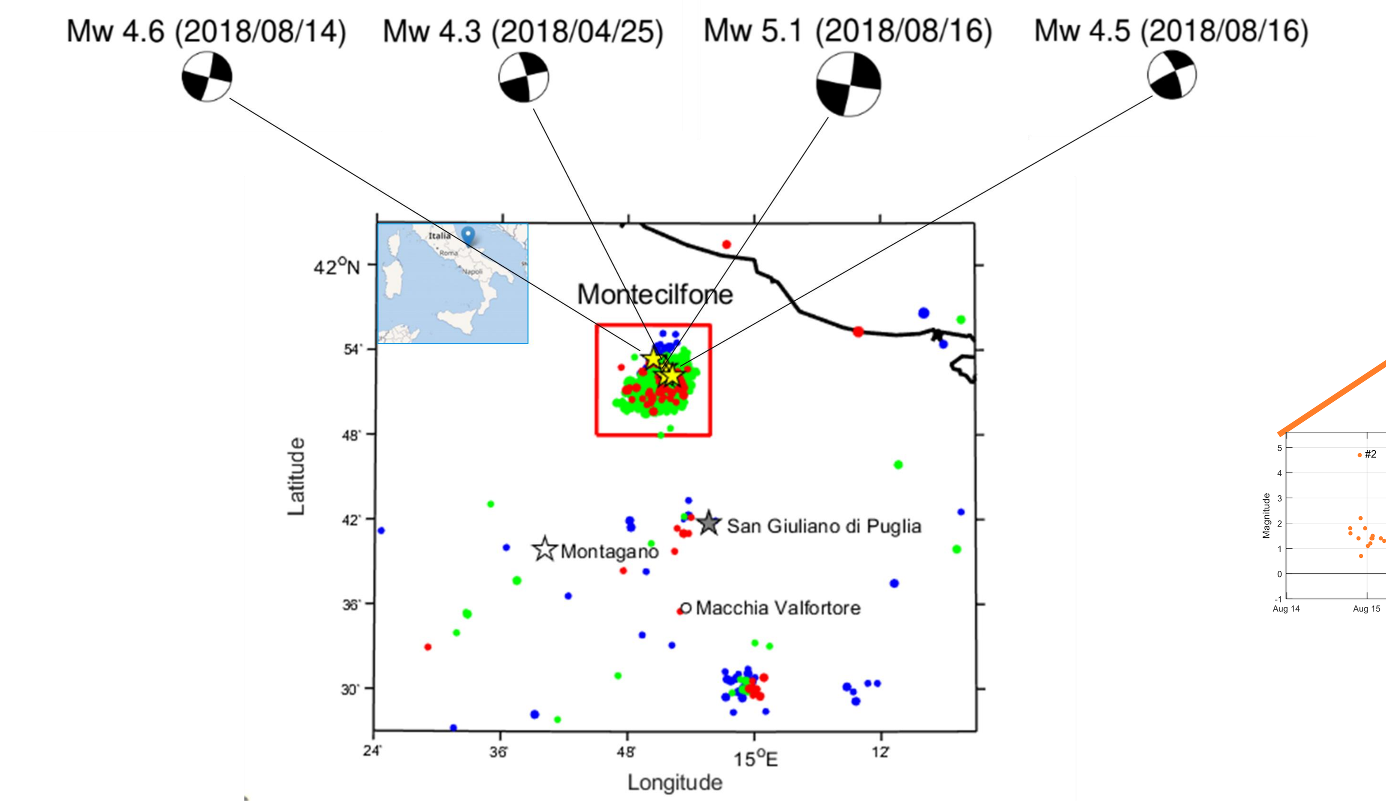


Fig. 1: Seismicity map. Colored dots: events April-November 2018. Blue: April–July; green: August–September; red: October–November. White dot: 2022 event. Stars: events with magnitude >4; yellow: Montecilfone events of Table 1; gray: San Giuliano di Puglia 2002; white: Montagano 2023. Red square: Montecilfone cluster in space. Insert: the position of the study area in Italy. Upper part: focal mechanisms (beachballs) of the earthquakes in Table 1; size of the beachballs proportional to the magnitude.

The seismicity of 2018 (see Fig.1) occurred **slightly to the north of the San Giuliano di Puglia 2002** seismic activity, (mainshock magnitude Mw=6.0 on October 31).
Both sequences involved a **right-lateral strike-slip motion**, which is possibly due to the reactivation of pre-existing roughly E-W oriented faults (Di Luccio et al., 2005).

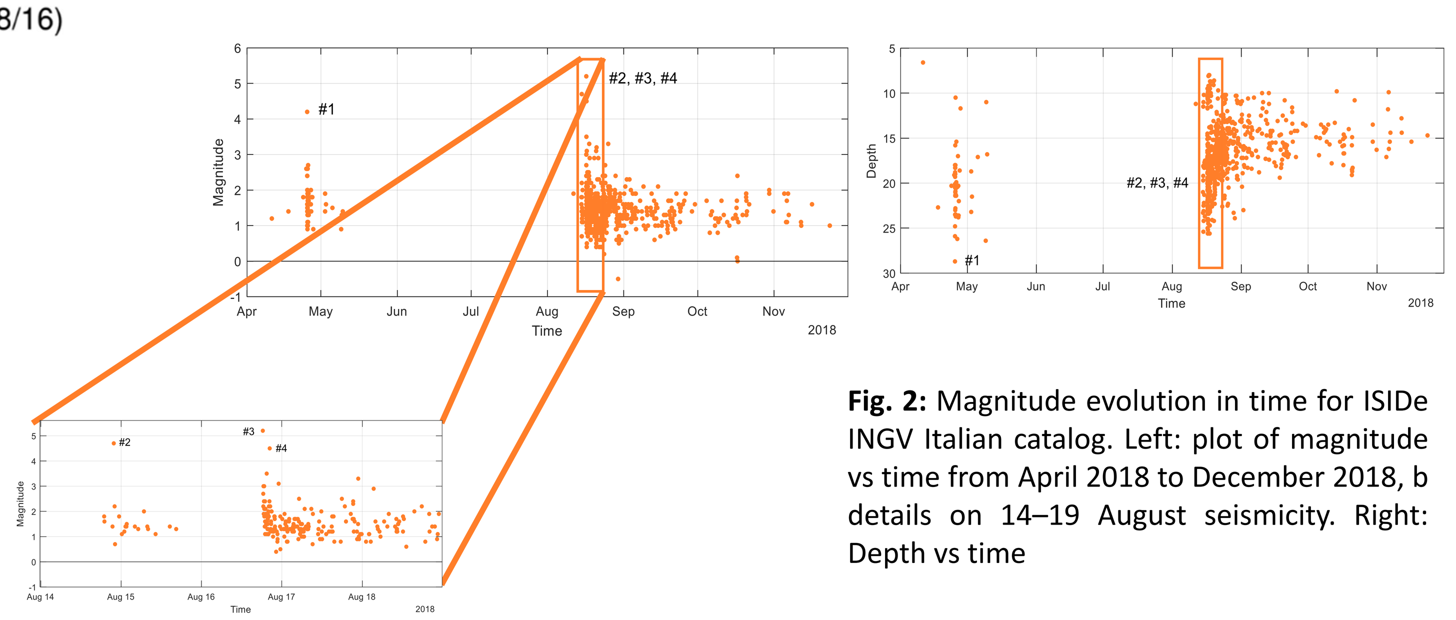


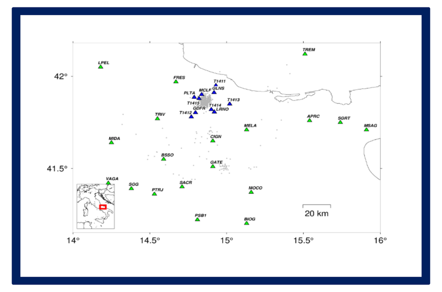
Fig. 2: Magnitude evolution in time for ISIDe INGV Italian catalog. Left: plot of magnitude vs time from April 2018 to December 2018, b details on 14–19 August seismicity. Right: Depth vs time

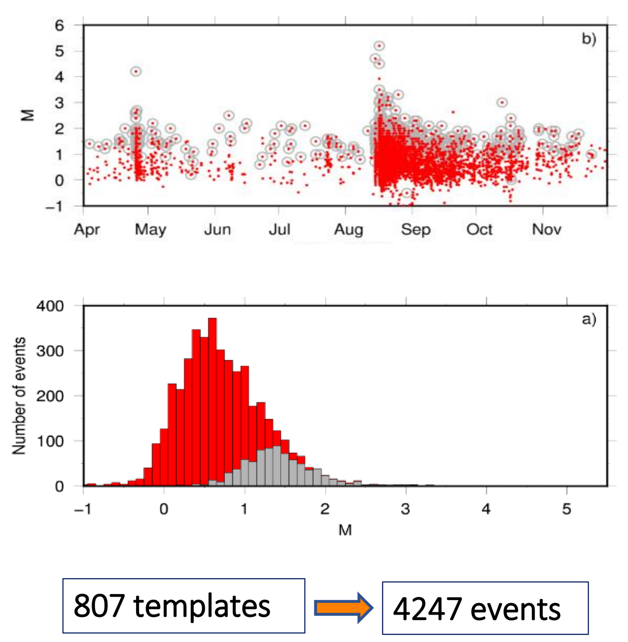
A **marked decrease of seismicity** has been observed between event 1 and 2 and event 2 and 3, even if the events are very close in space.

#	Date	Time	Lat	Lon	Depth	ML	Mw
1	2018/04/25	09:48:41	41.88	14.86	29	4.2	4.3
2	2018/08/14	21:48:31	41.89	14.84	19	4.7	4.6
3	2018/08/16	18:19:05	41.87	14.86	20	5.2	5.1
4	2018/08/16	20:22:34	41.87	14.87	22	4.5	4.4

Table 1: The four main events of the seismicity of Molise in 2018

3. TEMPLATE MATCHING





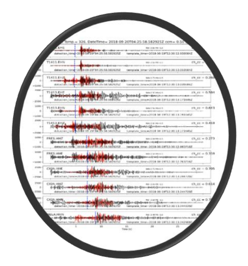
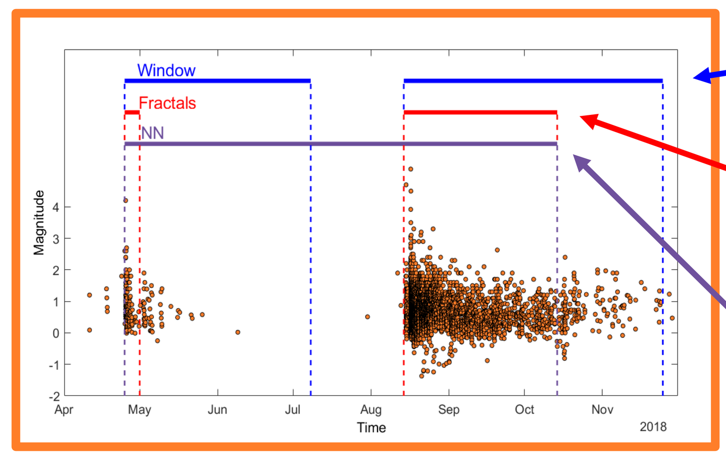
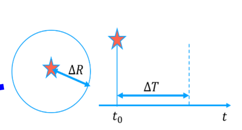


Fig. 3: Map of the 29 seismic stations: green triangles: permanent INGV network; blue triangles: INGV and RAN-DPC stations after Aug 16, 2018. Histograms: magnitude distribution for the original (gray) and augmented (red) catalogs. Time series: magnitude evolution over time.

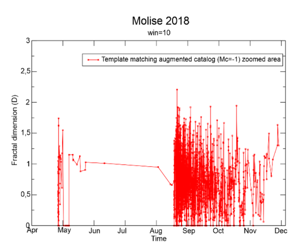
April - November 2018 continuous data. (Vuan et al., 2018, 2020). Original catalog: **ISIDe** (ISIDe Working Group, 2007).

4. CLUSTER DETECTION METHODS

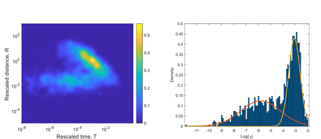




Uhrhammer (1986): space
Lolli & Gasperini (2003): time



Correlation integral on temporal sliding windows of 10 events (Bressan et al. 2017)



Nearest-Neighbour (NN) (Zaliapin et al., 2008). ISIDe catalog long. > 14

Fig.4: Comparison among cluster detection methods

5. NESTORE ANALYSIS

NESTORE – (NExt STrOng Related Earthquake – Gentili et al., 2023) divides the clusters into two classes **depending on the difference Dm between the magnitude of the mainshock and strongest following earthquake** (Type **A: Dm≤1** Type **B: Dm>1**).

NESTORE goal is **type A clusters probabilistic forecasting** based on **features extracted** from seismic catalogues in the first hours/days after the o-mainshock.

On April NESTORE forecasts a Type A cluster but a strong earthquake **happened on August 14 only**.

Was it one only cluster?

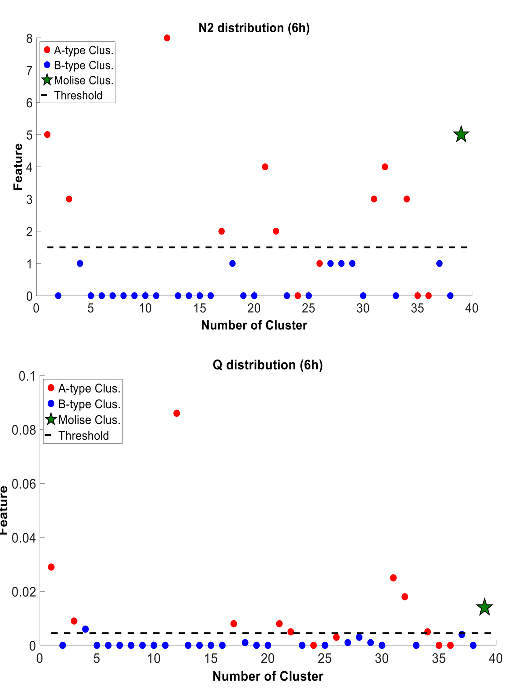
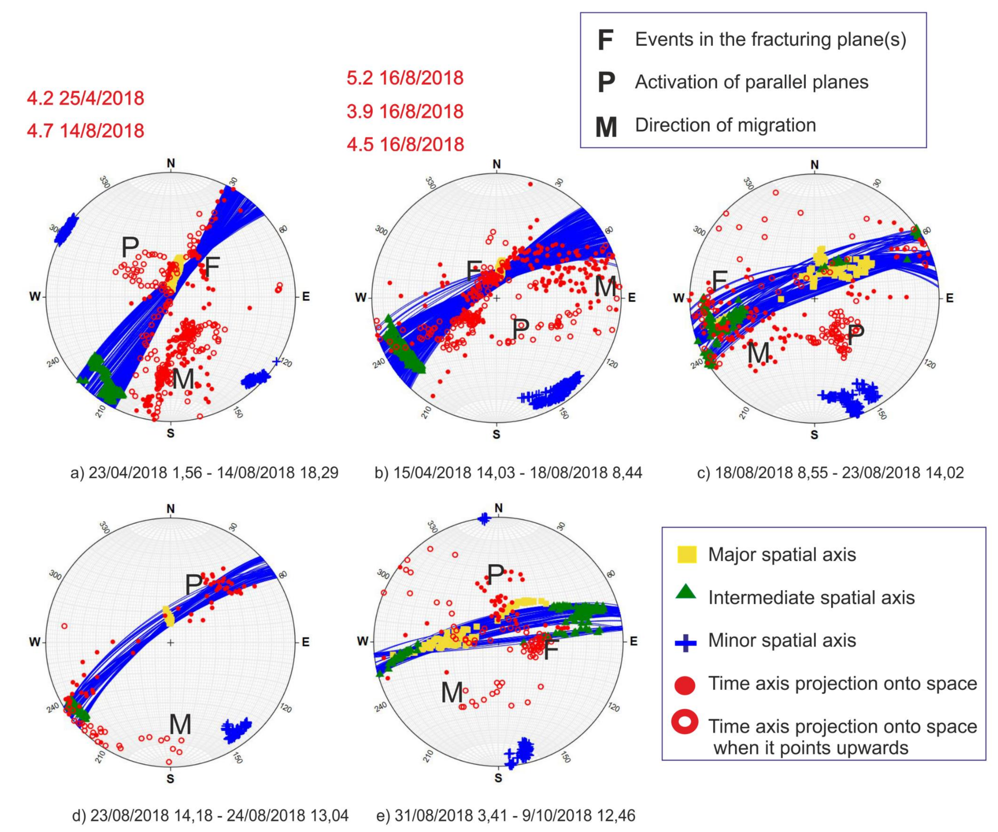


Fig. 5: Comparison with other clusters from NESTORE's features point of view

Brondi et al. 2024: 86% correct classifications in Italy

For further details:
Gentili et al. (2024) Seismic clusters and fluids diffusion: a lesson from the 2018 Molise (Southern Italy) earthquake sequence. Earth Planets Space 76, 157. https://doi.org/10.1186/s40623-024-02096-3 (OPEN ACCESS) and referenced therein

6. PCA ANALYSIS



(a) April represents the start of a phase of activity, that at the beginning extended mainly in the vertical direction with vertical NE-SW trending planes.

(b,c,d,e) Then it activated with the two main shocks of August, a sheaf of subparallel planes, about EW oriented.

The vertical extension could possibly indicate the presence of fluids (Vidale and Shearer, 2006).

Fig. 6: 4D PCA analysis calculated by sliding a window of 100 events along the catalog: the three spatial axes provide the planes that best fit the hypocentres cloud (blue lines), the time axes projection provides the direction of propagation. F: propagation within the fault plane, P: activation of parallel planes; M: migration toward a new cluster.

Hypothesis: the event of April represents the start of a phase of activity.

7. RELATIVE QUIESCENCE (ETAS)

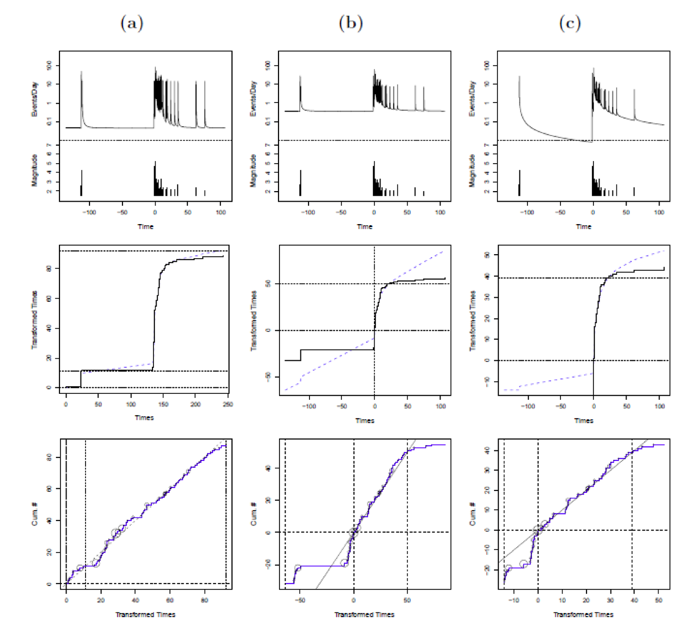


Fig 7: Fitting period: 3-23 April 2018 test period: April 23 2018-4-23 to 2018-12-1 M_{min}=2.0 (b) Fitting period: August 16 September 4 test period: September 4 to 2018-12-1 M_{min}=2.0 (c) Fitting period and test period are the same as (b), M_{min}=2.1

Matsu'ura (1986, 1991) showed that **before the onset of a large aftershock**, the time series of the transformed time sequence obtained based on the Omori-Utsu formula show lower occurrence rate than the expected standard Poisson process (**relative quiescence**).

This concept has been generalized using this **ETAS model** (e.g., Ogata, 1988, 1992). We analyzed the sequence fitting it around event #1 and around event #3.

In both cases a clear relative quiescence between event #1 and #2 is detected.

This could be caused by seismic deviations from ETAS clustering such as fluid up-flow in the fault (Kumazawa and Ogata, 2014).

8. FLUIDS

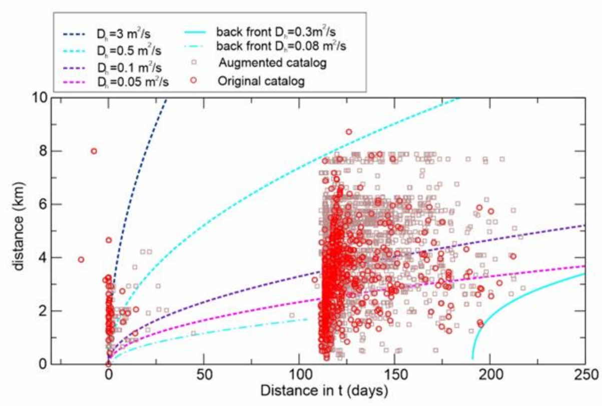


Fig 8: Distances from April 25, 2018, ML= 4.2 event versus time for the events of the original catalog (red circles) and the Catalog_TM (brown squares). Dashed lines: triggering front for different values of the hydraulic diffusivity D.

Shapiro et al., 2002 approach: *distance* $r = \sqrt{4\pi Dt}$

The analysis supports the fluid diffusion hypothesis, showing seismicity migration with varying diffusivity between April and August, suggesting increased permeability during stronger August activity.

The methodology of Danré et al. (2022) confirmed fluid migration as a significant factor in the seismicity following the August events.

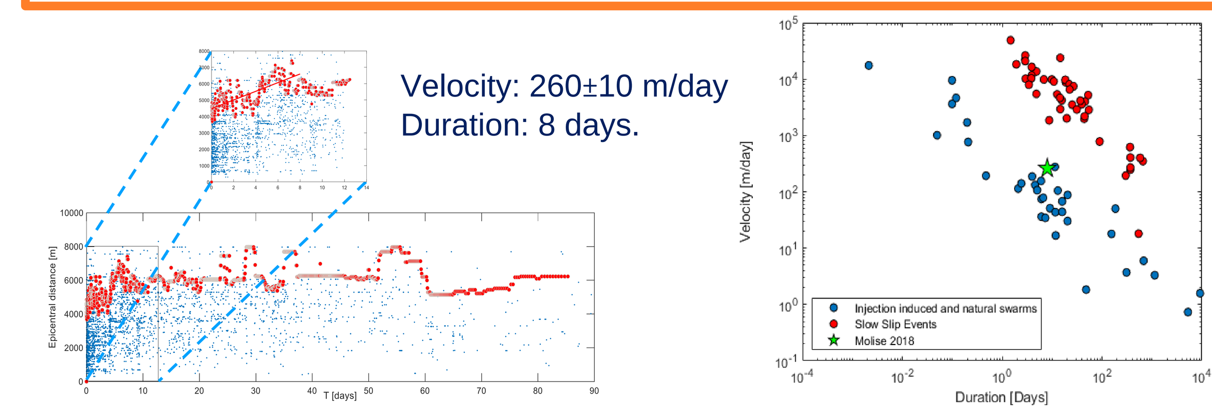


Fig. 9: The seismicity front is determined by evaluating the 90th percentile of the distances of the events from the center of the swarm (after event #3) within a moving window of 50 events.

We hypothesize that **fluid pressure variation caused the relative quiescence** of seismicity **detected by ETAS** between events #1, #2, and that due to events #2 and #3, **fluids are released**, resulting in **migration of seismicity** after event #3.

Molise 2018 seismicity is an interesting **case-study** which **highlights the possible outcomes of model limitation in cluster identification** and stresses the necessity for ongoing research into characterizing complex seismic sequences.