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Variations of the earthquake diffusion rates in the Western Gulf of Corinth (Greece)

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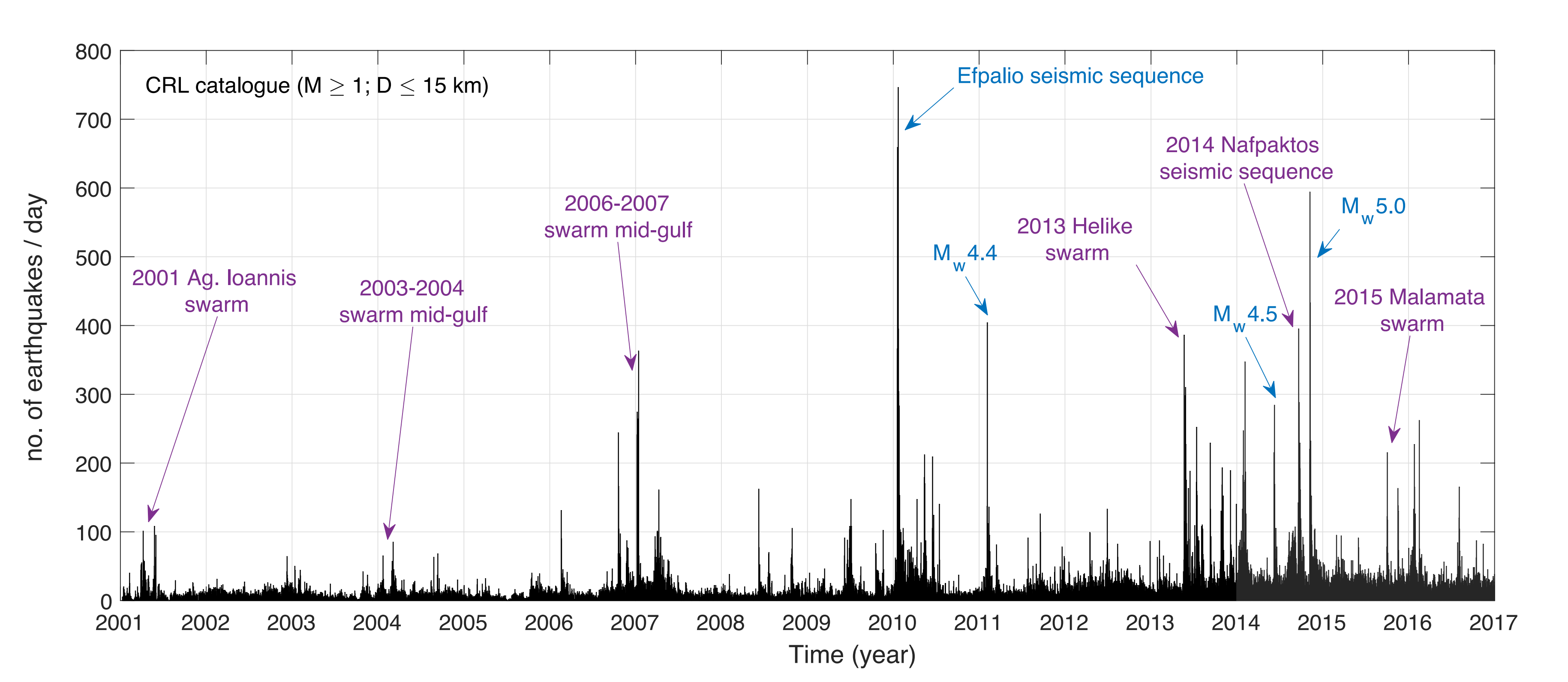
I. Introduction



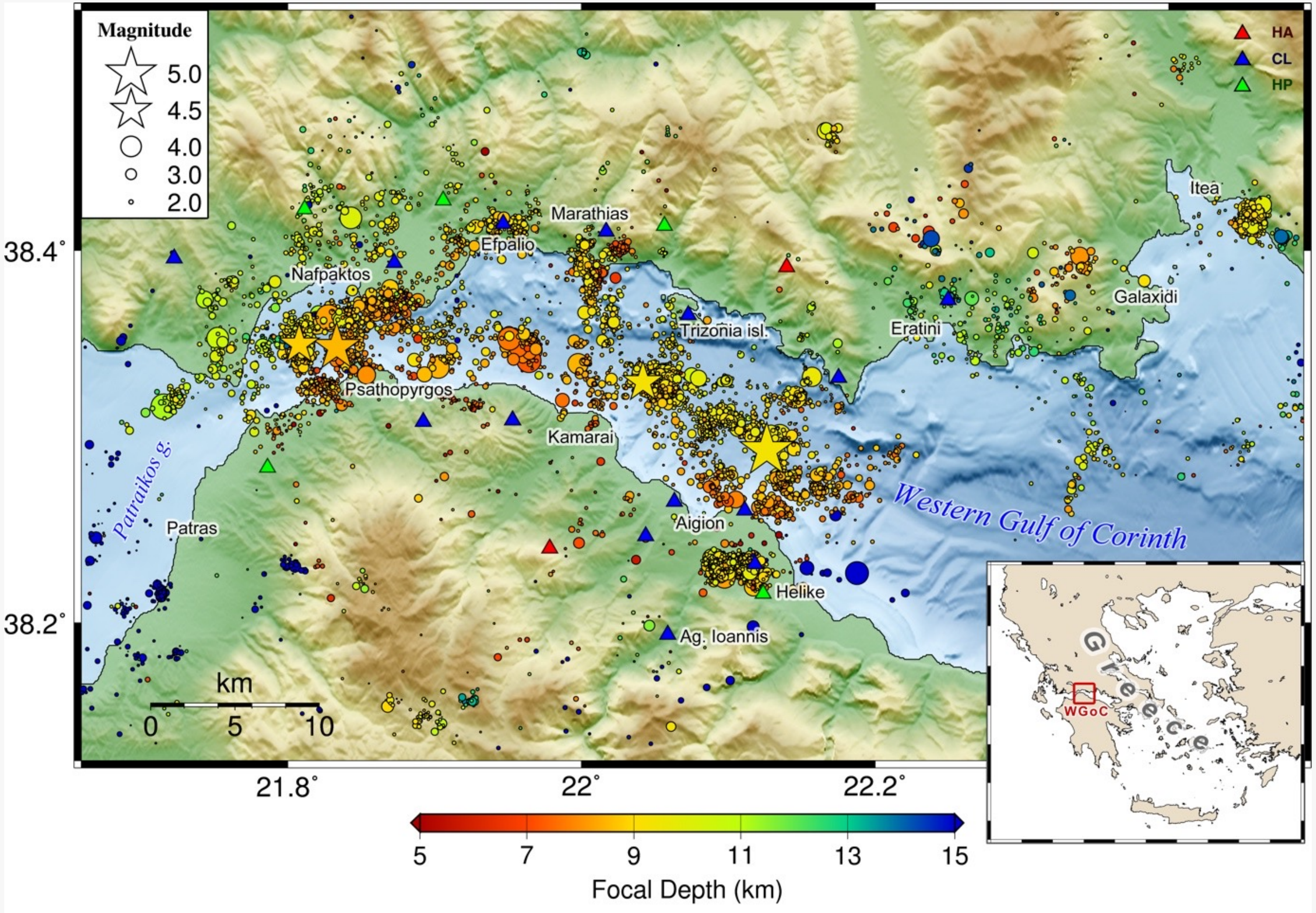
- ❖ The Western Gulf of Corinth (WGoC) is one of the most seismically active areas in Europe, presenting high extension rates, continuous and intense microseismic activity, frequent swarms and moderate to large magnitude earthquakes.
- ❖ In this work we study the migration properties of seismicity in the WGoC by estimating the rates of triggered earthquake diffusion and their possible variations, which may provide novel constraints on the physical mechanisms involved in earthquake triggering (e.g., tectonic loading, stress transfer, fluid diffusion, aseismic slip etc.).

II. Earthquake Datasets

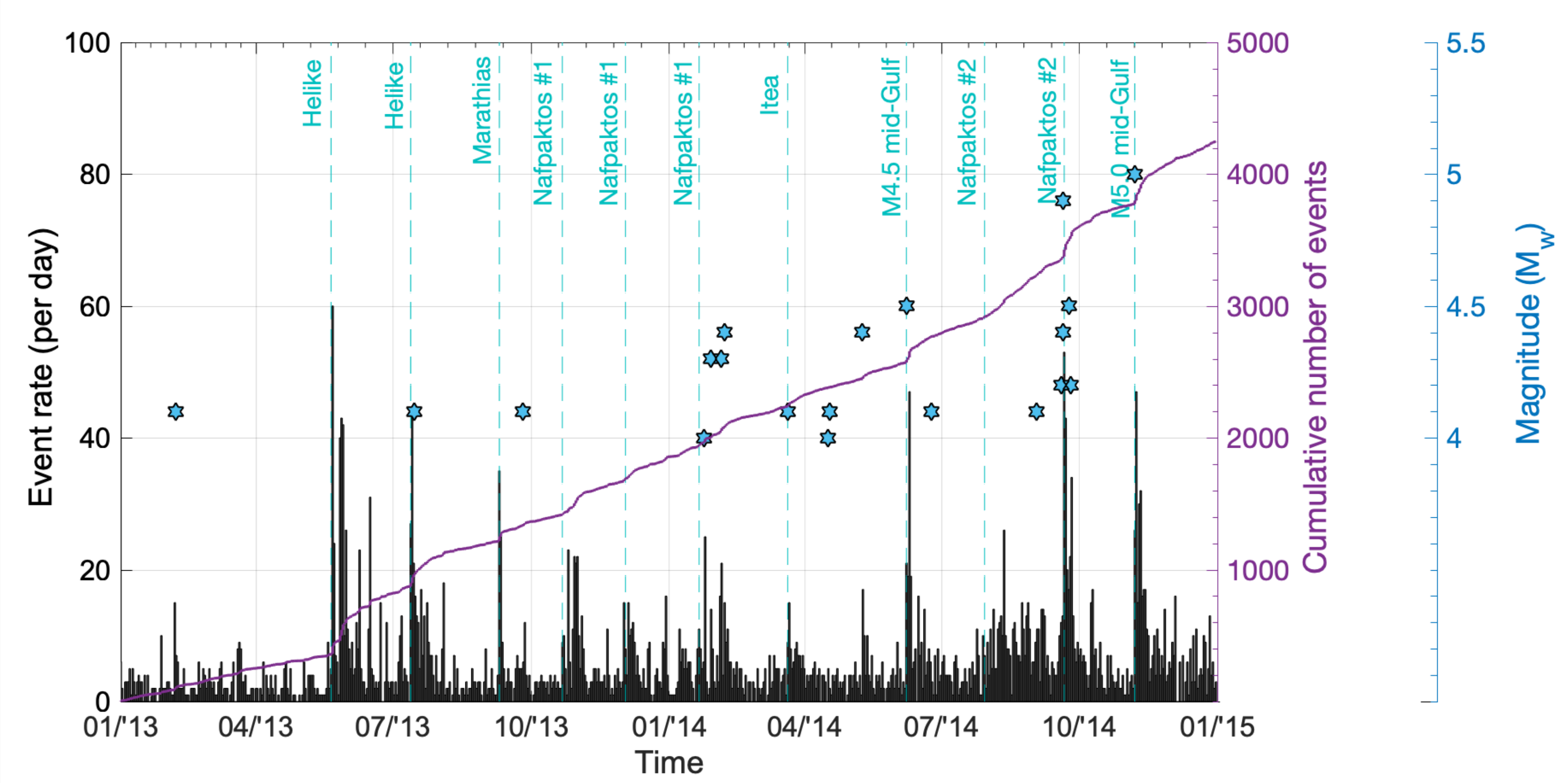
- We focus on the 2013–2014 seismic activity, a period with abundant and continuous local seismicity.

- A high-resolution catalogue of ~9000 manually analysed earthquakes is used. Seismicity was initially located using the HypoInverse code (Klein, 2002), employing the local velocity model of Rigo et al. (1996), except for the 2013 Helike swarm, for which a more specific local velocity model was used (Kapetanidis et al., 2015).

- The seismicity was relocated with the double-difference algorithm HypoDD (Waldhauser & Ellsworth, 2000), using both catalogue and cross-correlation data (Figure), with relative location errors of the order of ~100-200 m .



II. Earthquake Datasets



- During 2013–2014 the seismic activity was characterized by continuous background seismicity, as well as by sudden seismic bursts. The most significant ones include the 2013 Helike swarm (Kapetanidis et al., 2015; Kaviris et al., 2017; Mesimeri et al., 2016), the seismic sequences offshore Nafpaktos in 2013 and 2014 (Nafpaktos #1, Nafpaktos #2) (Kapetanidis, 2017; Kaviris et al., 2018) and the mainshock-aftershock sequences of the M_w4.5 and M_w5.0 events that occurred in June and November 2014, respectively, offshore Aigion.

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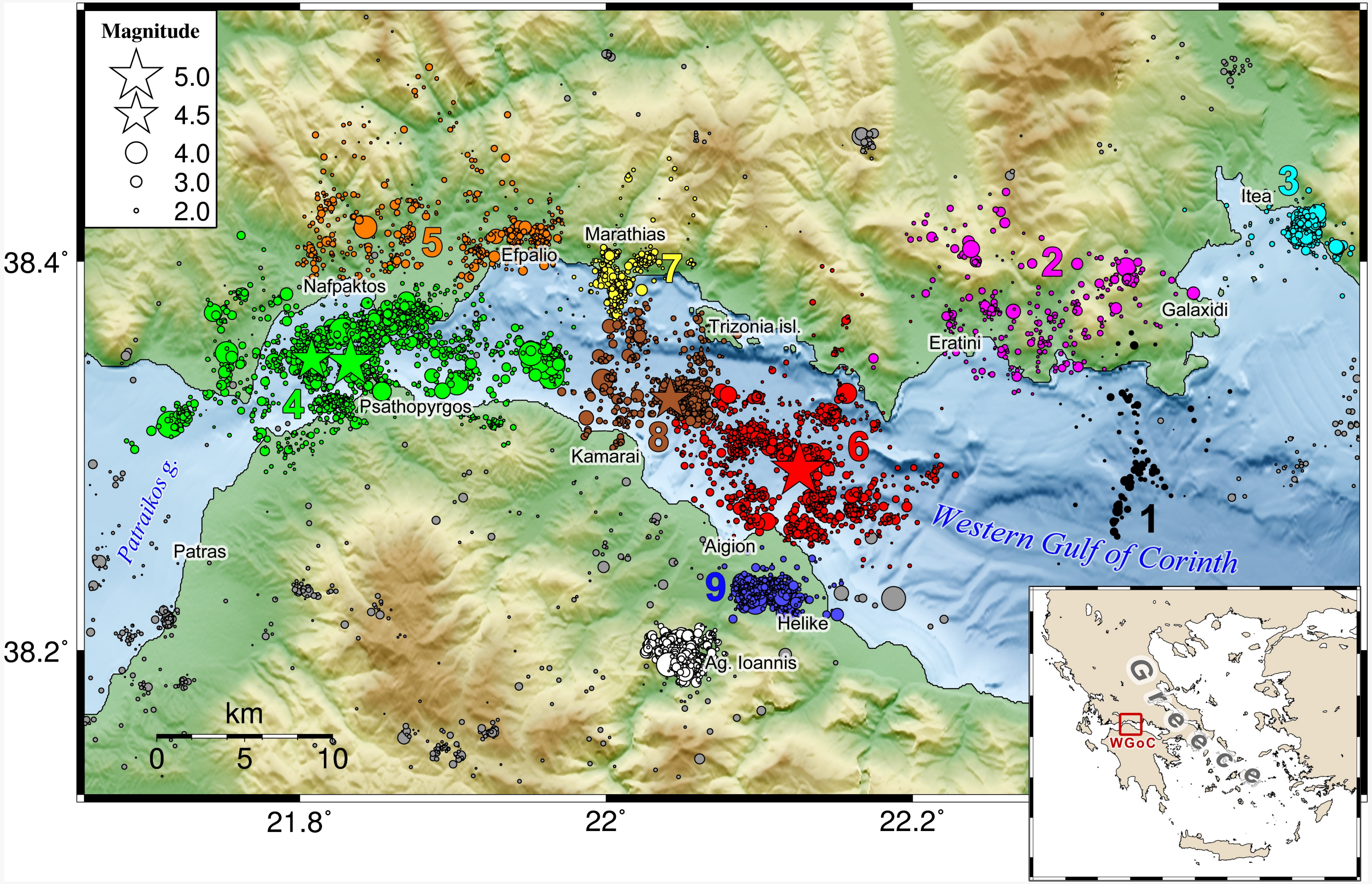
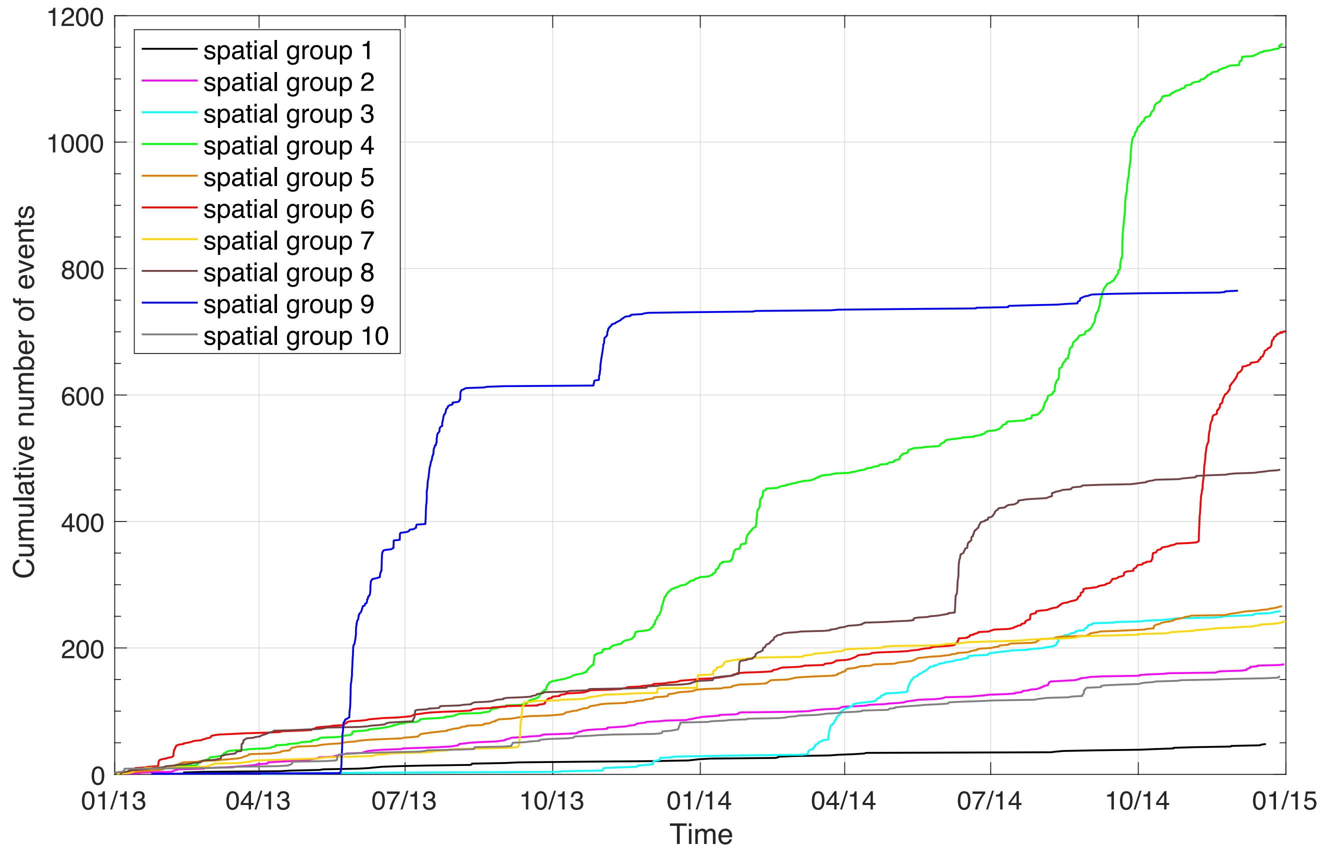
II. Earthquake Datasets

❖ Shallow seismicity in the region of interest has been separated into nine spatial groups (Figure) using a hierarchical clustering algorithm (Ward's linkage; Ward, 1963), applied to the matrix of hypocentral inter-event distances. Seismicity at the margins or deeper than 15 km was placed in a 10th, "miscellaneous" group.

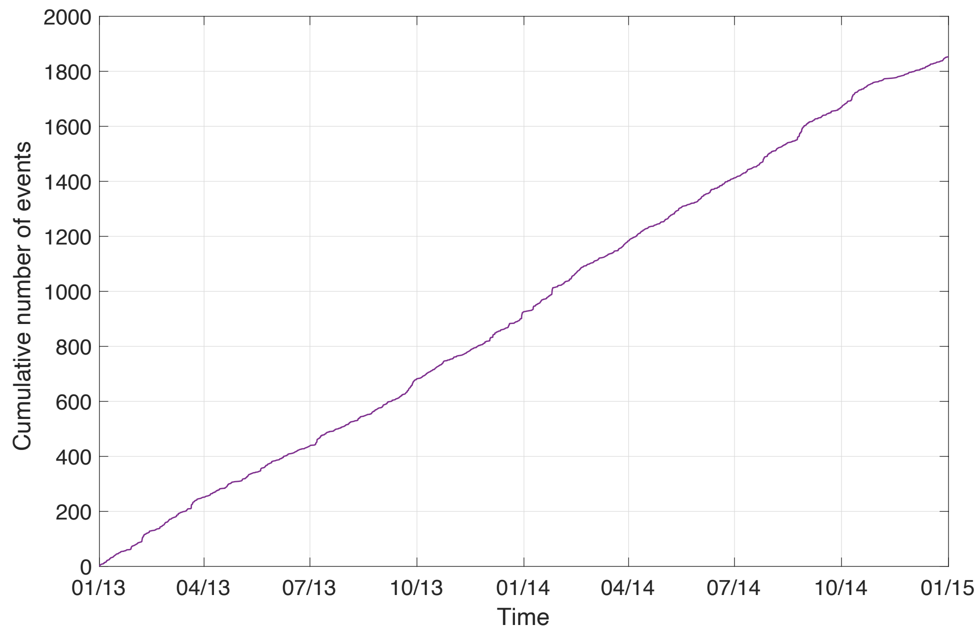
❖ In the Figure, the 2001 Agios Ioannis seismic swarm (Pacchiani & Lyon-Caen, 2010; Michas & Vallianatos, 2018) is also shown for comparison of the results.



II. Earthquake Datasets



❖ Within the ten spatial groups we search for temporally clustered activity, counting at least 200 events (Figure to the left). Such activity was observed during 2013 in Helike (#9), offshore Nafpaktos in the end of 2013 and in 2014 (#4), in Itea during 2014 (#3) and also after the M_w4.5 (#8) and M_w5.0 (#6) events that occurred on 8 June 2014 and 7 November 2014, respectively.



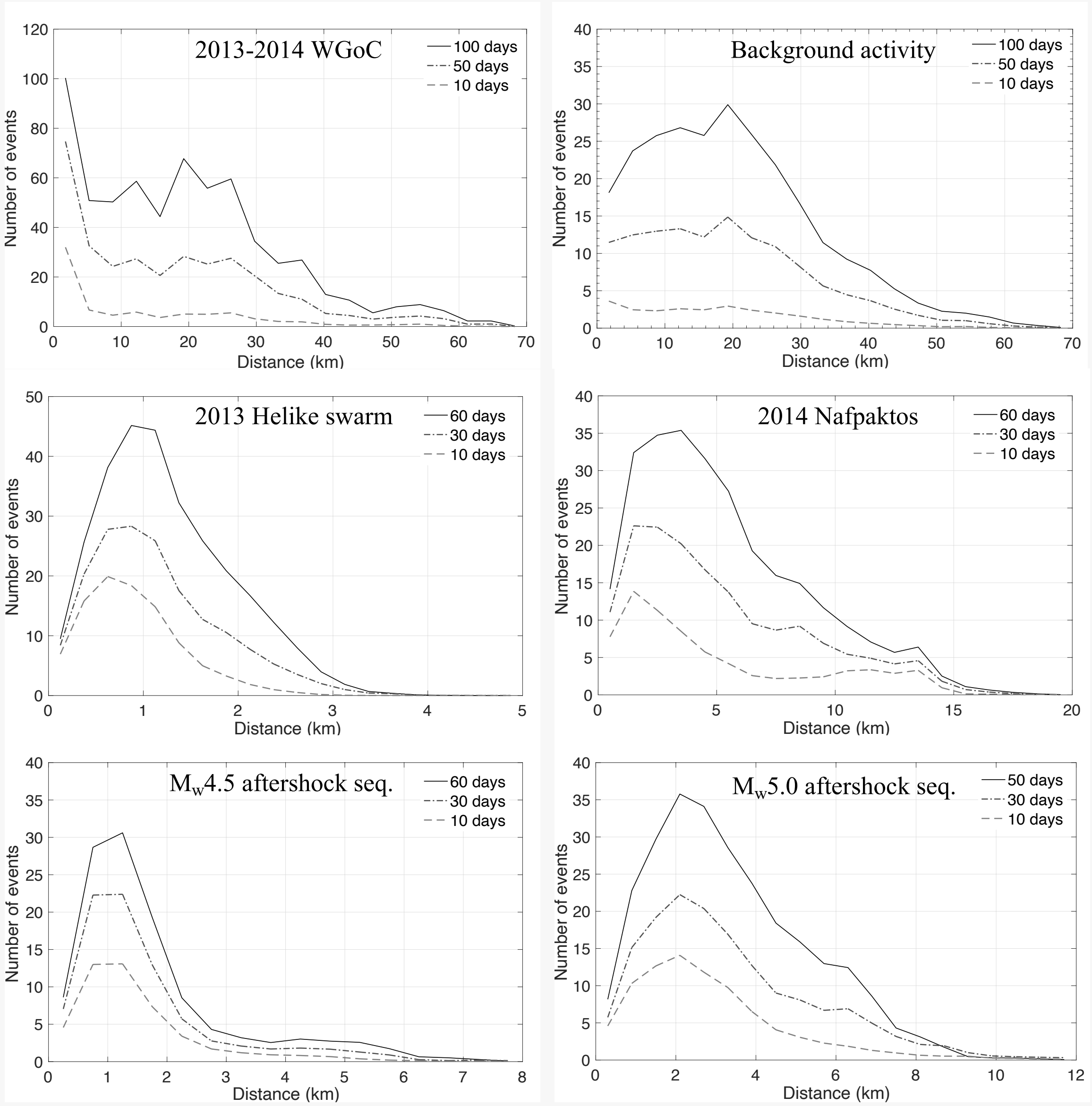
❖ The remaining seismicity presents an almost constant event rate (Figure to the right) and was considered as the background seismic activity.

III. Analysis & Results

- To determine the rates of earthquake diffusion, spatial correlation histograms and their evolution with time are examined. In this analysis, each earthquake is considered as a possible triggering source and spatial histograms of hypocentral distances between each source and the subsequent events are constructed.

- These calculations allow the estimation of the number of earthquakes that have occurred within a distance range from *x* to *x*+*dx* and then the construction of the spatial correlation histograms for various bin sizes *dx* (minimum *dx*=0.5 km).

- These histograms, calculated for all source events in selected spatial groups and for various time windows, are stacked into a single one for each time window and normalized with the total number of source events. The normalized spatial correlation histograms $N(x,t)$ represent the average expansion of seismicity that follows an earthquake within a certain time window, in terms of the average number of events that occur at a distance $x \pm dx/2$ up to time t (Figure).



III. Analysis & Results

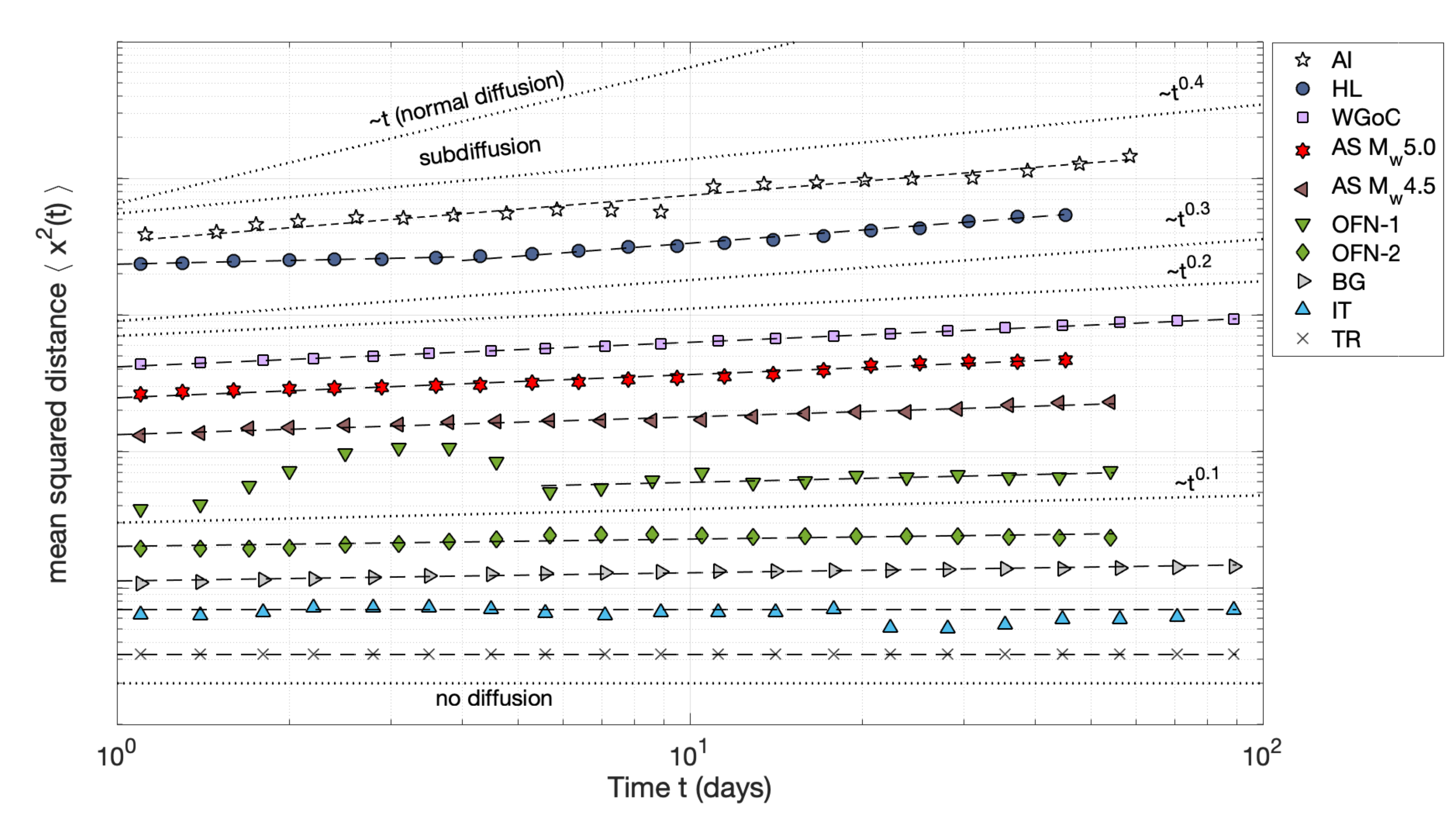
- From the average spatial correlation histograms $N(x,t)$, the mean squared distance $\langle x^2(t)\rangle$ for each sequence is estimated as:

$$\langle x^2(t)\rangle = \frac{\sum_x x^2 N(x,t)}{\sum_x N(x,t)}$$

- The evolution of $\langle x^2(t)\rangle$ with time t is examined (Figure) by fitting to the power-law function:

$$\langle x^2(t)\rangle = D_0 t^a$$

The non-linear growth of $\langle x^2(t)\rangle$ with time is the hallmark of anomalous diffusion. For α>1 the process is super-diffusive, for 0<α<1, sub-diffusive and for α=1 normal (Gaussian) diffusion is recovered.



AI: Agios Ioannis swarm, HL: Helike swarm, WGoC: Western Gulf of Corinth, AS: mainshock-aftershock sequence, followed by the mainshock's M_w magnitude, OFN-1: offshore Nafpaktos seismic sequence 1, OFN-2: offshore Nafpaktos seismic sequence 2, BG: background seismic activity, IT: Itea seismic sequence, TR: temporally random catalogues.

III. Analysis & Results

- D_0 presents higher values for larger activated areas.
- In all cases, the estimated diffusion exponents α are quite small and much smaller than unity, indicating *anomalous diffusion* and *sub-diffusion* of seismicity.
- For the full catalogue (WGoC) α=0.18, while for temporally random catalogues (TR) α=0, indicating that the local earthquake diffusion is due to event-event correlations in the temporal evolution of seismicity.
- For the two mainshock-aftershock sequences (AS), α=0.13 and α=0.17, similar to the diffusion exponents of various aftershock sequences in California (Helmstetter et al., 2003).
- The largest diffusion exponents are observed for the 2001 Ag. Ioannis (AI; α=0.34) and the 2013 Helike (HL; α=0.32 for 4-45 days) swarms, which have been associated with pore-fluid pressure diffusion (Kapetanidis et al., 2015; Michas & Vallianatos, 2018).

Seismic sequence*	Time period	N	M_{max}	D_0	δD_0	α	$\delta\alpha$	CLID
AI	28 March to 31 May 2001	863	4.3	0.46	0.05	0.34	0.04	n/a
HL	21 May to 6 November 2013	711	4.1					
1–4 days				1.17	0.02	0.09	0.02	9
4–45 days				0.80	0.07	0.32	0.03	9
WGoC	2013–2014	4248	5.0	276.8	3.8	0.18	0.01	n/a
AS M_w 5.0	7 November to 31 December 2014	333	5.0	9.86	0.40	0.17	0.02	6
AS M_w 4.5	8 June to 27 August 2014	202	4.5	3.3	0.1	0.13	0.02	8
OFN-1 5–55 days	22 October 2013 to 9 February 2014	288	4.4	47.6	9.4	0.10	0.06	4
OFN-2	30 July to 29 December 2014	588	4.9	40.3	2.2	0.05	0.02	4
BG	2013–2014	1853	4.1	488.0	9.5	0.06	0.01	n/a
IT	9 March to 30 August 2014	204	4.4	2.77	0.23	-0.03	0.03	3
TR	2013–2014	4248	5.0	649.5	0.5	0.00	0.00	n/a

N - number of selected events, M_{max} - maximum magnitude, D_0 and α estimated parameters, δD_0 and $\delta\alpha$ their corresponding 95% confidence intervals, CLID - spatial group.

IV. Discussion & Conclusions

- The results lay further support to previous conclusions on slow earthquake diffusion of regional seismicity, akin to anomalous (non-Gaussian) diffusion (sub-diffusion).

- The variations of the earthquake diffusion rates between the various seismic sequences may provide further implications on earthquake triggering mechanisms in the WGoC.

- Larger exponents and higher diffusion rates are observed for seismic swarms that have been associated with a pore-fluid pressure triggering mechanism (Kapetanidis et al., 2015; Michas & Vallianatos, 2018; Michas & Vallianatos, 2020).

- Smaller exponents and lower diffusion rates are observed for mainshock-aftershock sequences, which are attributed to stress transfer effects and/or a cascade of triggering/triggered events (Huc & Main, 2003; Helmstetter et al., 2003; Michas, 2016).

- However, more complex mechanical processes that incorporate the long-term tectonic loading rate, static and dynamic stress transfer, cascading effects, fluid overpressures and aseismic creep transients may be at play in earthquake triggering in the WGoC.

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