Lateral migration patterns toward or away from injection wells for earthquake clusters in Oklahoma

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DFG Deutsche Forschungsgemeinschaft German Research Foundation

EGU2020-2649

athenea 3i — EGU General Assembly 2020

1. INTRODUCTION

- Exploring the connections between injection wells and seismic migration patterns is key to understanding processes controlling growth of fluid-injection induced seismicity.
- Numerous seismic clusters in Oklahoma have been associated with wastewater disposal operations, providing a unique opportunity to investigate migration directions of each cluster with respect to the injection-well locations (Figure 1).

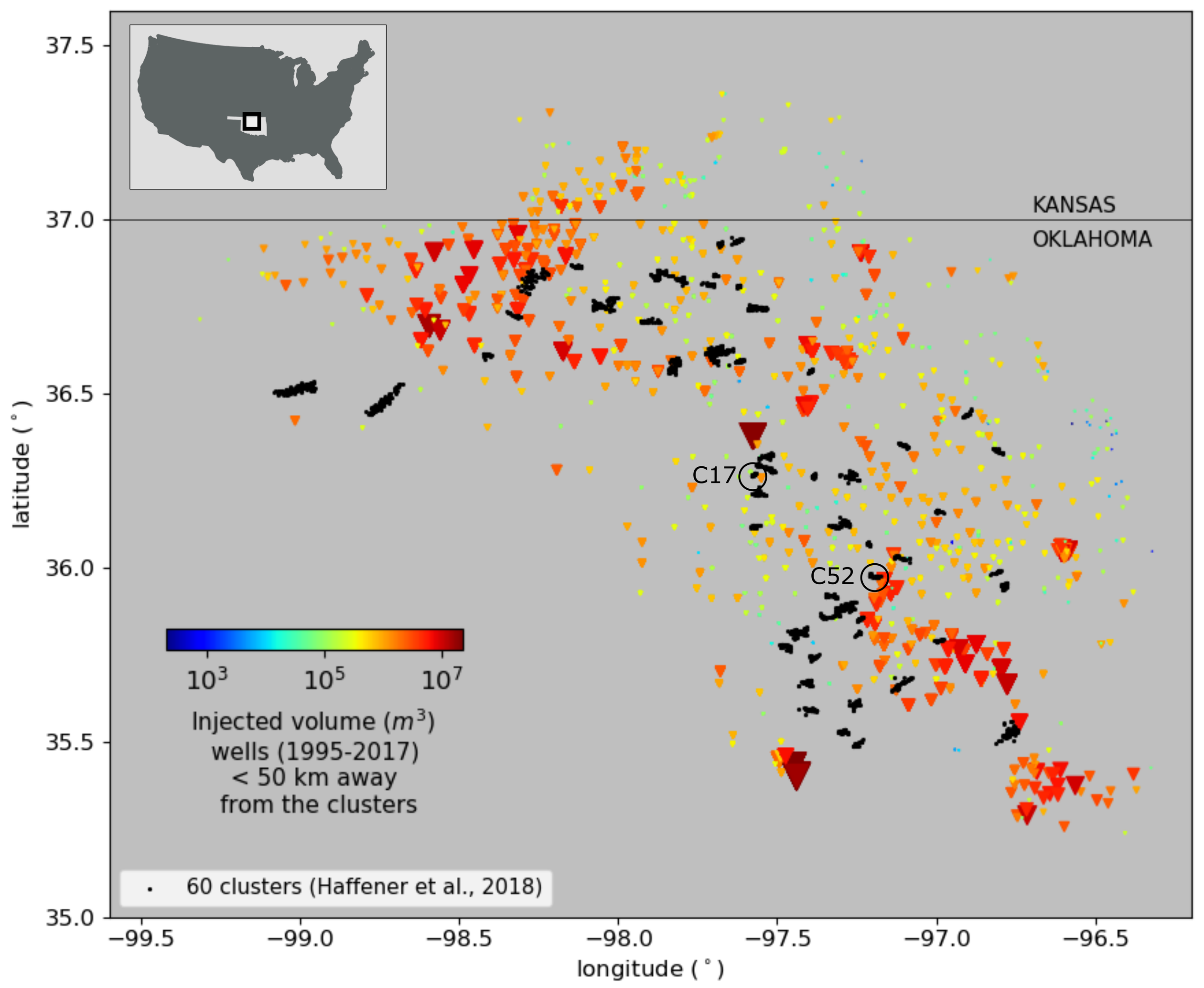

Figure 1. *Map of earthquake clusters in Oklahoma (black dots) and wells (inverted triangles) within a radius of 50 km from the average location in each cluster.*

2. METHODOLOGY

- We introduce a new directivity migration parameter (κ) to identify and quantify lateral migration patterns toward or away from multiple injection wells, comparing the direction of representative migration vectors ($\overrightarrow{v_m}$) and well vectors ($\overrightarrow{v_w}$) (Figure 2).

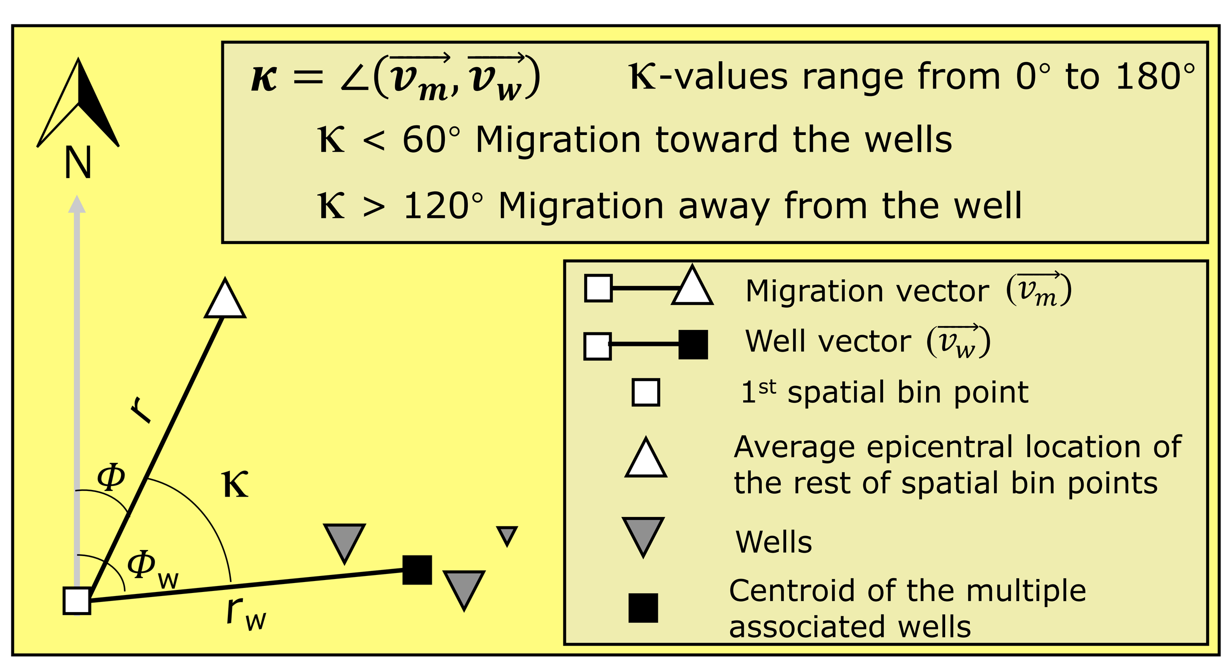

Figure 2. *Sketch showing the new directivity migration parameter (κ) and the migration and well vectors to identify lateral migration patterns toward or away from multiple injection wells.*

2.1. MIGRATION VECTOR FOR EARTHQUAKE CLUSTERS

- Each cluster is characterized by a migration vector ($\overrightarrow{v_m}$) defined as the direction from the midpoint of events in the first bin to the midpoints for subsequent bins (Figure 3).
- Significant changes of the azimuth of the migration vector ($\Delta\Phi > 45°$) between repetitions from a bootstrap analysis indicate that the cluster does not have a prevailing direction of migration. 24 of 60 clusters were then excluded (Figure 3b).
- We also introduced a simple way to quantify the strong/weak migration through a migration coefficient $\chi = r/d_{max}$, computed from the length of the migration vector (r) and the total length of the cluster (d_{max}).

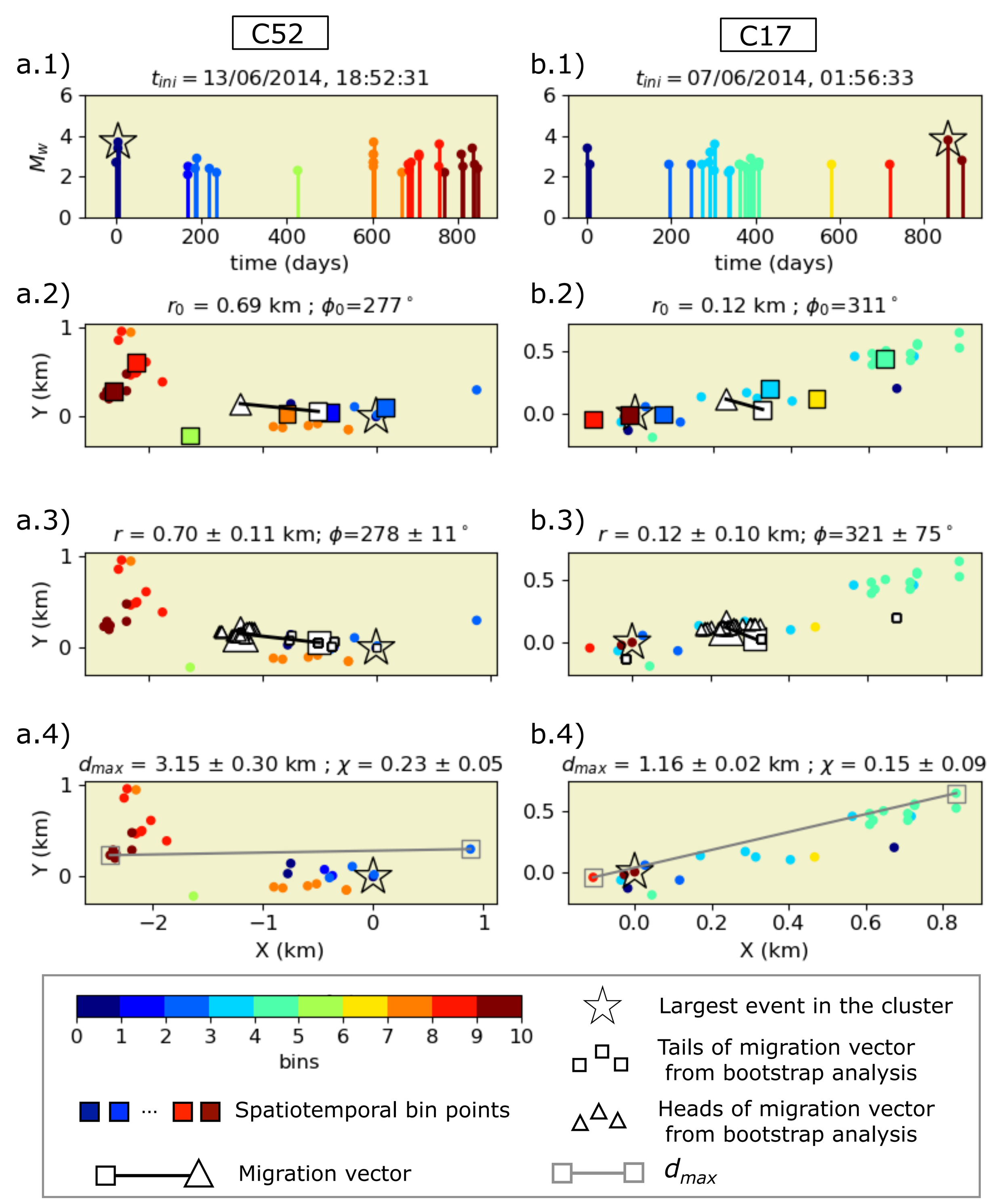

Figure 3. *Migration analysis for cluster 52 showing results for a stable migration vector (a) and cluster 17 for an unstable migration vector (b). (a.1, b.1) Temporal evolution; earthquakes are divided into 10 temporal bins of equal duration spanning the period of the entire sequence. (a.2, b.2) Length (r_0) and azimuth (Φ_0) of the migration vector calculated using all events in the cluster. (a.3, b.3) Final length (r) and azimuth (Φ) of the migration vector and their uncertainties. Small white triangles and small white squares depict the heads and tails of 100 migration vectors for the bootstrap analysis, randomly removing 10% of events in each repetition. The final migration vector is depicted by a black line from the tail (large white square) to the head (large white triangle). (a.4, b.4) Maximum cluster length (d_{max}) and migration coefficient (χ) with their uncertainties.*

2.2. WELL VECTOR FOR MULTIPLE INJECTION-WELL LOCATIONS

- The well vector ($\overrightarrow{v_w}$) represents the direction where fluids were originated, which is defined as the vector from the 1st spatial bin point of the cluster (used previously to define the migration vector) to an injection midpoint (Figure 4).
- The injection midpoint is determined as the weighted centroid of locations of wells, taking into account the spatial distribution of wells, the temporal evolution of the injected volumes in all individual j wells, and the expansion of the diffusion front.
- We take into account cumulative volume (Figure 4 and 5a) and injection rate (Figure 5b) from multiple injection wells, which leads to the weights in the forms of $V_j(t-t_D)/d_j$ and $\Delta V_j(t-t_D)/d_j$, being $t_D=d^2/4\pi D$; distance between each well and cluster (d) and diffusion coefficient (D).

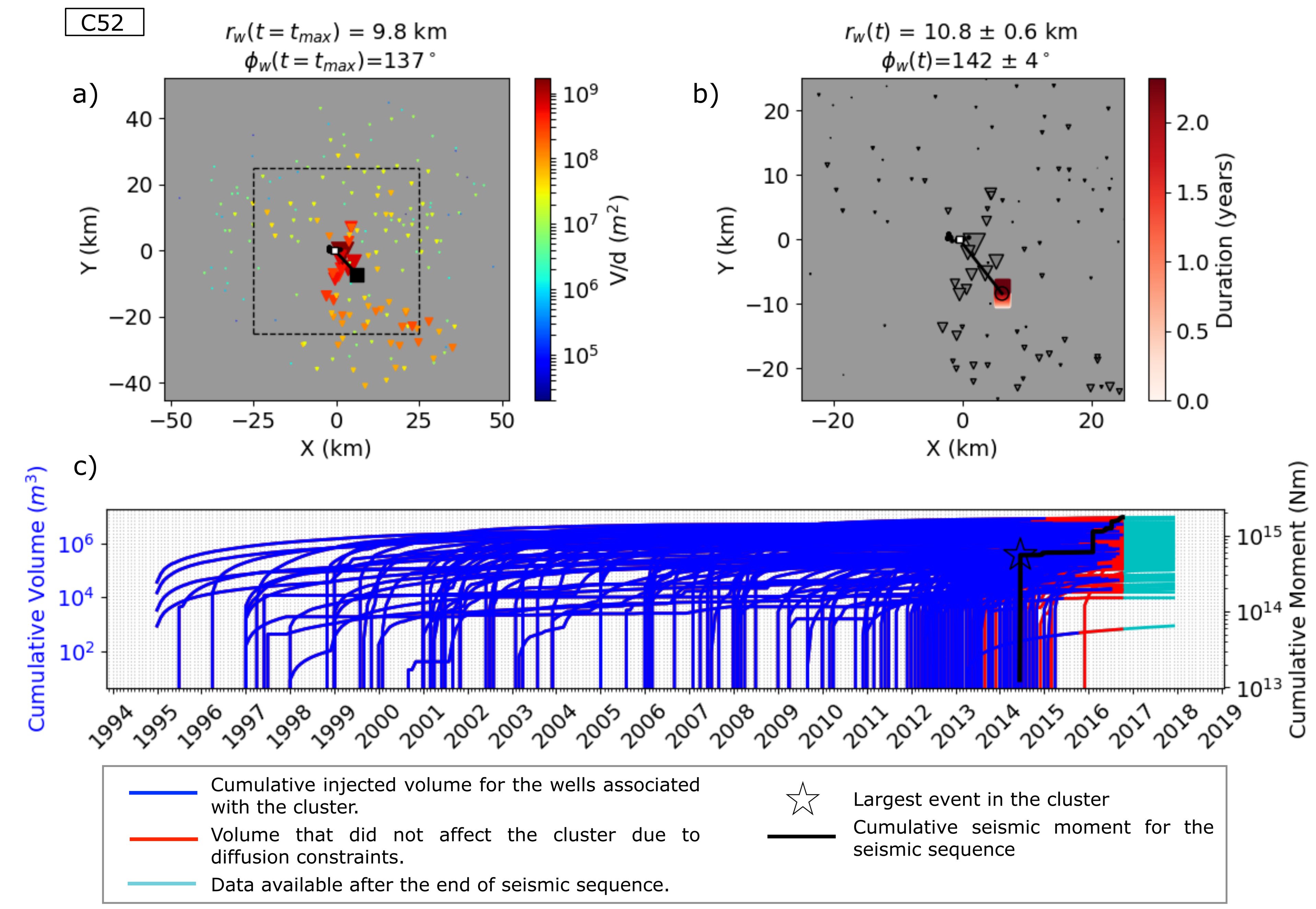

Figure 4. *Calculating the well vector for cluster 52 considering the cumulative-injected volume weighting and D = 1.5 m²/s. (a) Well vector at the final time of the seismic sequence t_{max}. (b) Final length (r_w) and azimuth (Φ_w) of the well vector and their uncertainties considering the injection midpoints during the whole seismic sequence (t increases in steps of 30 days); cases with significant changes of the azimuth of the well vector are excluded ($\Delta\Phi_w > 45°$) (c) Cumulative injected volumes for the wells associated with the cluster.*

3. RESULTS AND CONCLUSIONS

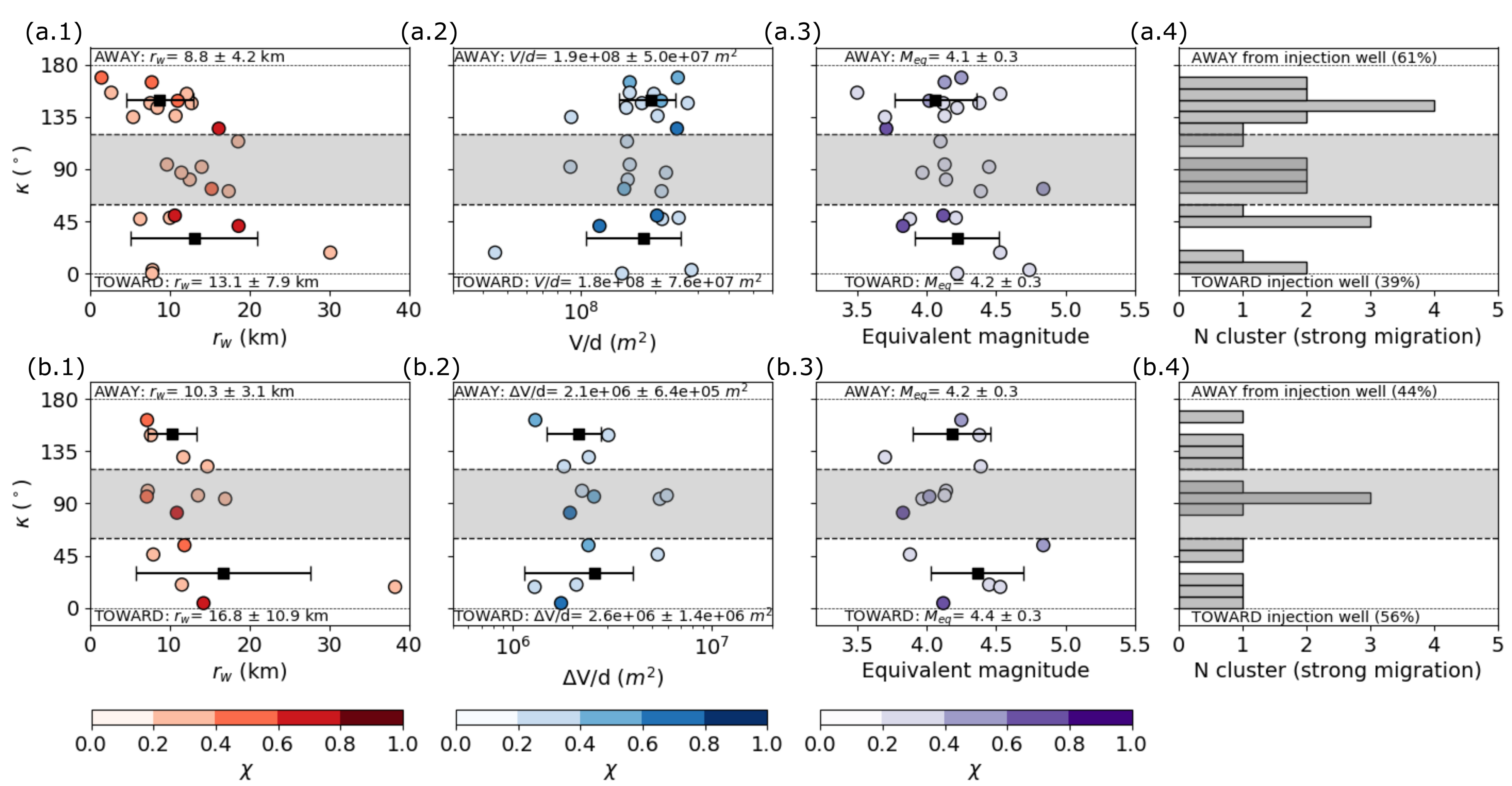

Figure 5. *Lateral migration patterns toward or away from injection wells characterized by κ-values. Clusters with strong migration are only considered (χ > 0.2) taking into account cumulative volume weighting (a) and injection rate volume weighting (b). Results are shown for each cluster according to the length of the well vector (a1, b1), the total weights assigned to the multiple associated wells based on cumulative injected volumes and injection rate volumes (a2, b2), and the equivalent magnitude (a3, b3). Average values and error bars (black squares and lines) are indicated for propagation toward (κ < 60°) and away (κ > 120°) from the injection point. Histograms are also shown including percentages values (a4, b4). Intermediate cases (60° < κ < 120°) are not considered (gray background separated by black dashed lines).*

- A comprehensive migration analysis is applied to decipher the potential relationship between direction of lateral earthquake migration of induced seismic events and the location of multiple injection wells. Different variables are considered to assess their influence in these lateral migration behaviours toward or away from multiple injection wells (Figure 5).
- Migration away from injection wells is found for distances shorter than 5-13 km, while an opposite migration towards the wells is observed for larger distances (Figure 5a.1 and 5b.1), suggesting an increasing influence of poroelastic stress changes.
- This finding is more stable when considering cumulative injected volume instead of injection rate.
- We do not observe any relationship between migration direction and injected volume or equivalent magnitudes.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement Nº 754446 and UGR Research and Knowledge Transfer Found – Athenea3i.