

Statistical Modeling and Characterization of Induced Seismicity within the Western Canada Sedimentary Basin

Sidhanth Kothari¹, Robert Shcherbakov¹, and Gail Atkinson¹

¹Western University, London, Ontario, Canada

Contents of this file

Figures S1 to S17

Introduction

This supporting information provides additional context to both the regional (section 4) and the cluster (section 5) analyses in the main paper. In particular, Figures S1-4 show the event maps for each cluster discussed in section 2 and analyzed in section 5. Figure 5 shows the estimated completeness level of the Composite Alberta Seismicity Catalogue between 2010-2018. Figures S6-9 present the additional tests detailed in section 4, namely the nearest-neighbour distance (NND) analyses for randomized catalogues, sensitivity tests for variations in the Gutenberg-Richter b -value and fractal dimension (d_f), and the likelihood-ratio test to assess the validity of a three-component Gaussian mixture model. Figures S10-13 give the regional NND analyses results at higher cutoff magnitudes, which confirm the existence of three earthquake subpopulations and a transformation in earthquake distribution between 1975-2009 and 2010-2018 (analogous to Figures 2 and 5). Finally, Figures S14-17 give the structural representations and statistical parameters of the event families identified in section 5.3 (analogous to Figure 8).

1975 - 2000

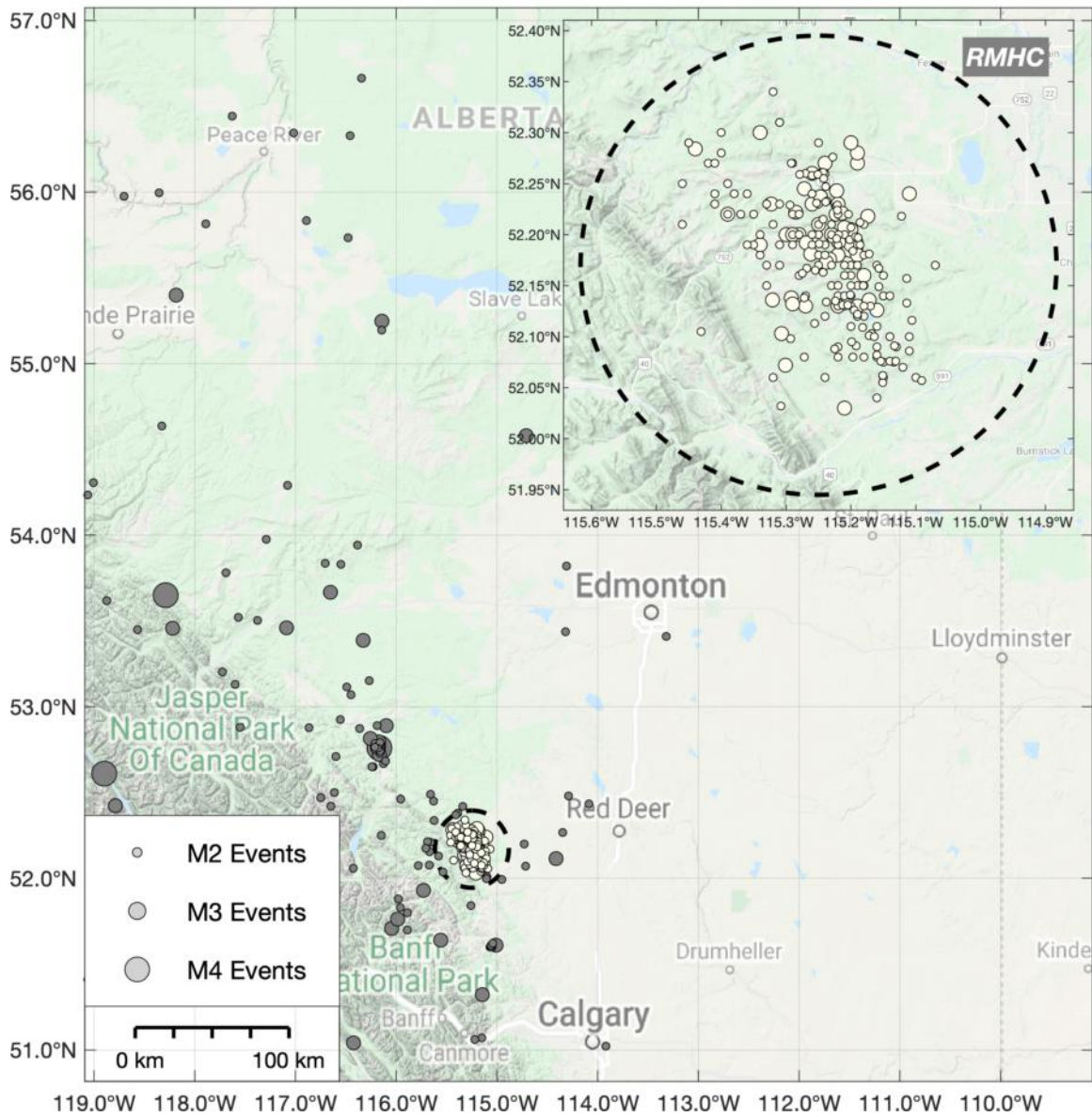


Figure S1. Map of the Rocky Mountain House cluster (RMHC) study area between 1975-2000. Dashed circle represents a 20 km radius from the coordinates [115.24°W, 52.17°N]. Markers are seismic events. White markers are the data points used for analysis.

1984 - 2009

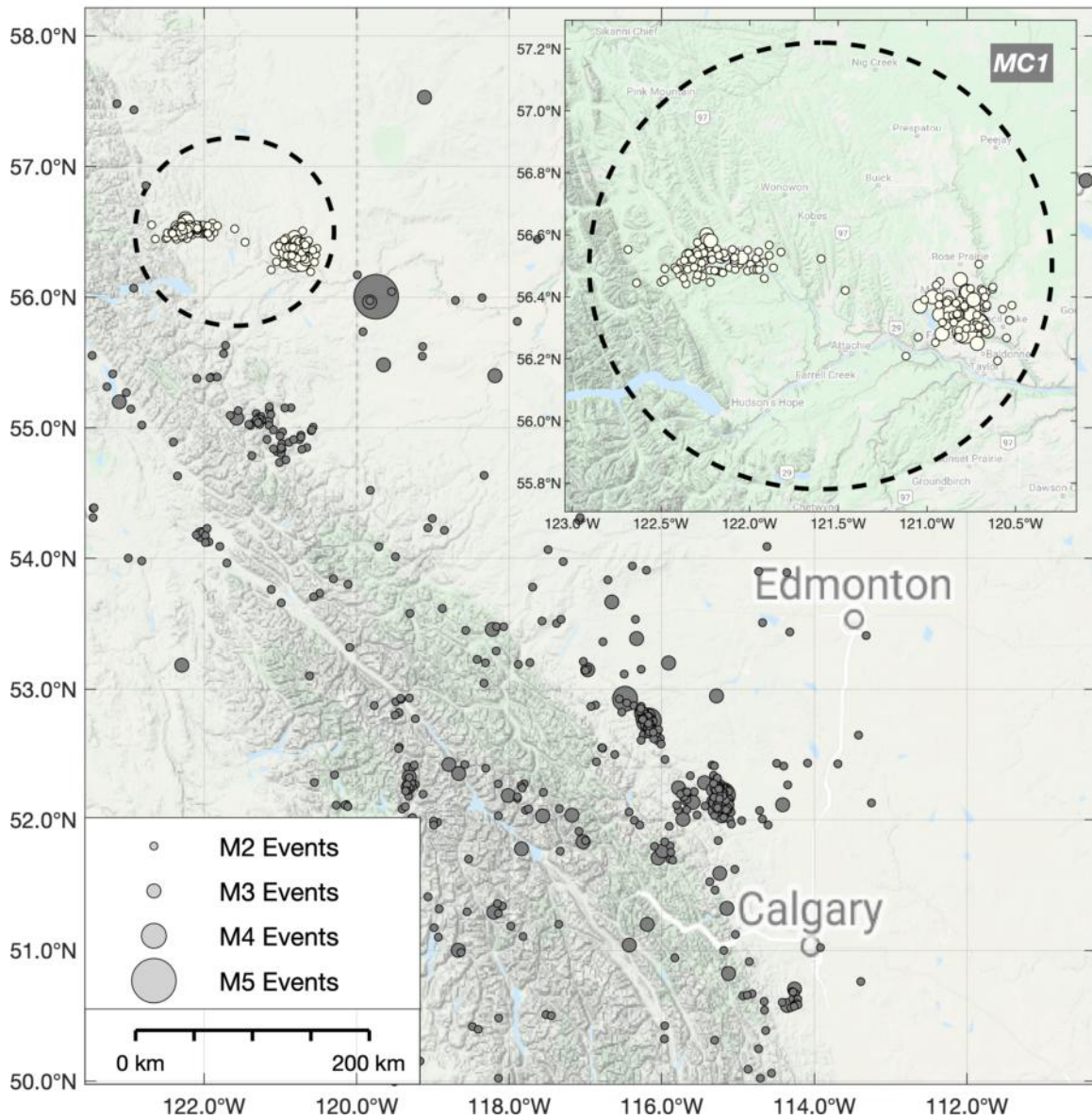


Figure S2. Map of the Montney cluster 1 (MC1) study area between 1984-2009. Dashed circle represents a 75 km radius from the coordinates [121.6°W, 56.5°N]. Markers are seismic events. White markers are the data points used for analysis.

2010 - 2018

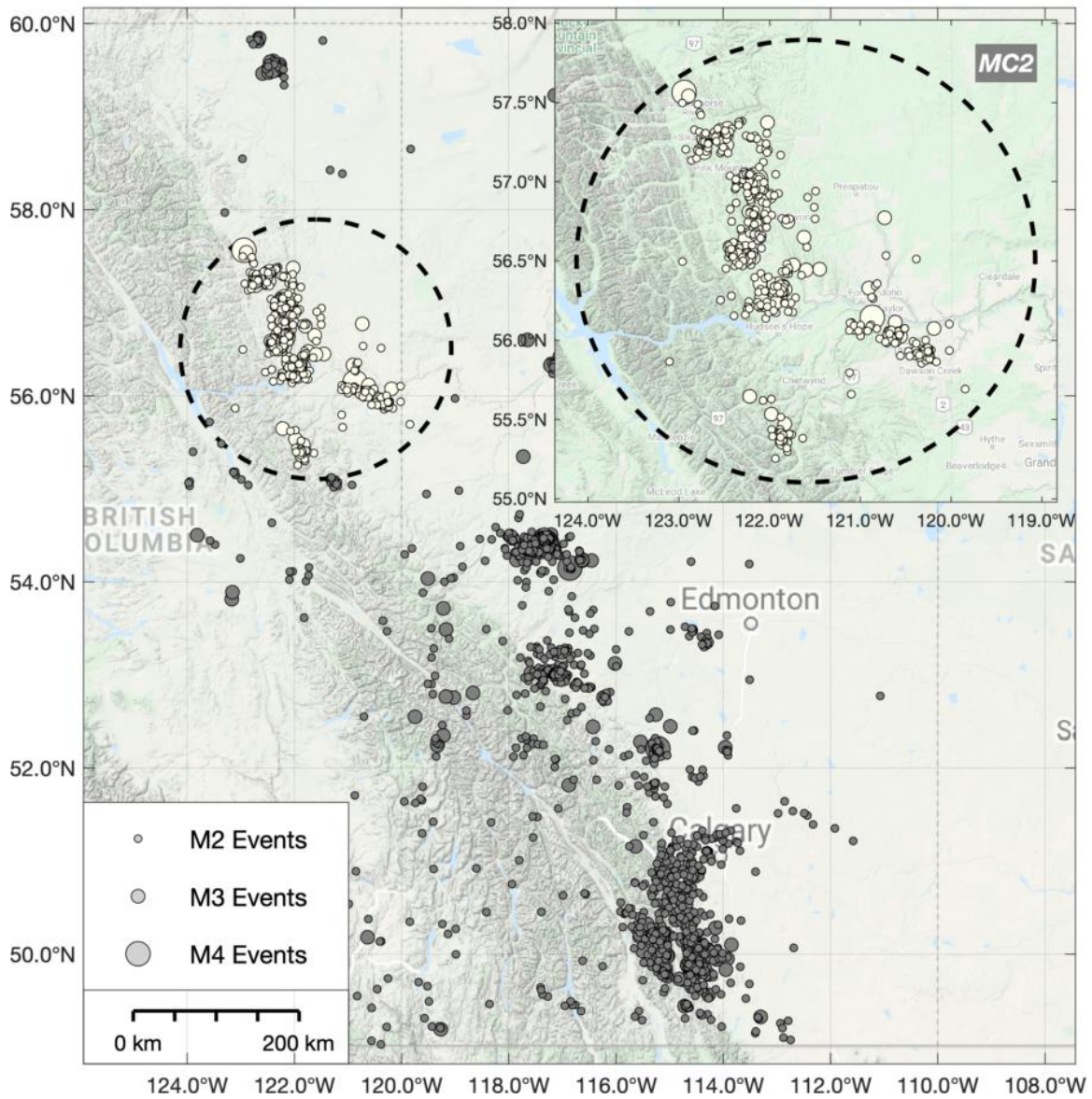


Figure S3. Map of the Montney cluster 2 (MC2) study area between 2010 and 2018. Dashed circle represents a 150 km radius from the coordinates [121.6°W, 56.5°N]. Markers are seismic events. White markers are the data points used for analysis.

2013 - 2020

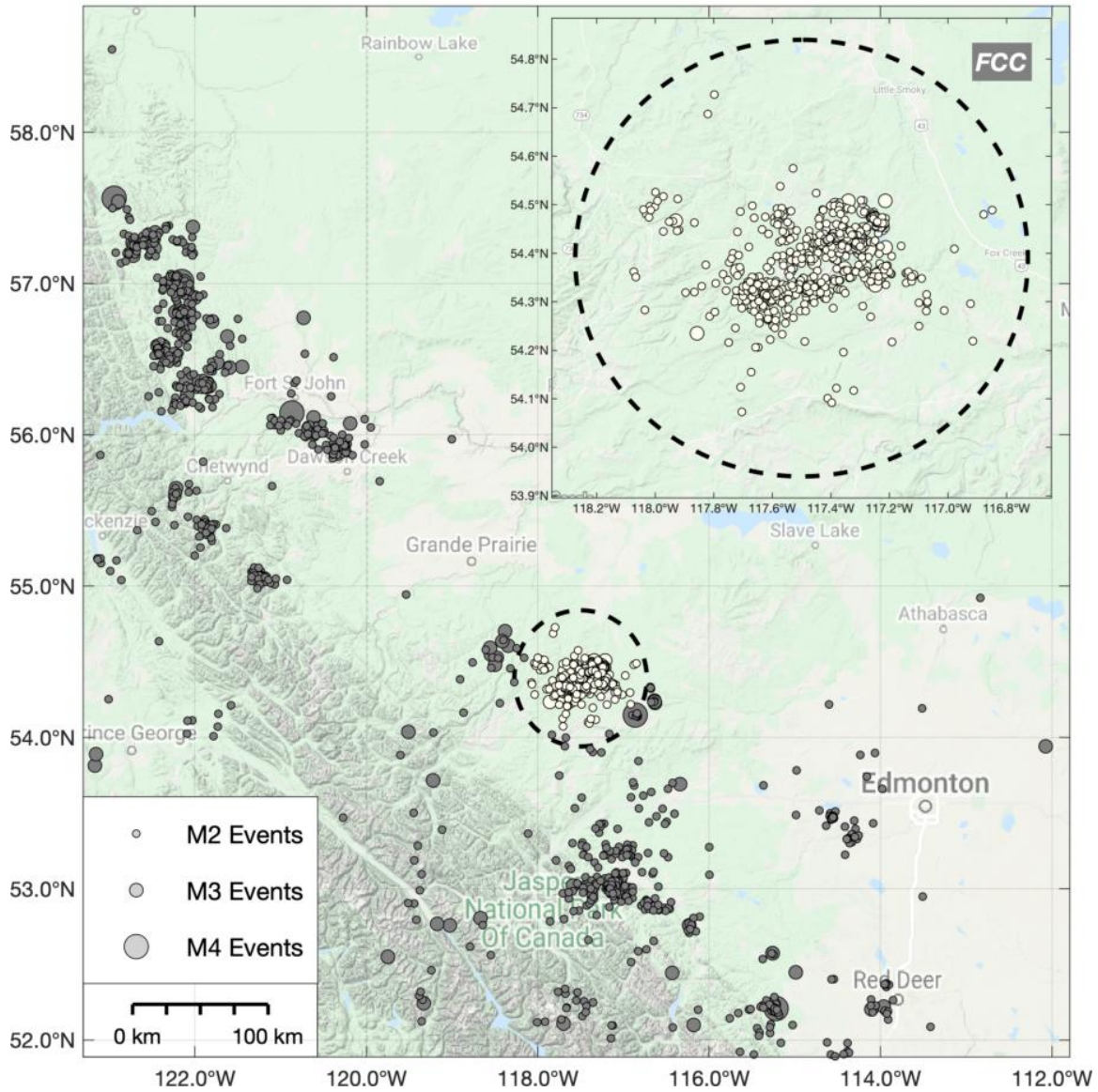


Figure S4. Map of the Fox Creek cluster (FCC) study area between 2013 and January 2020. Dashed circle represents a 45 km radius from the coordinates [117.4°W, 54.4°N]. Markers are seismic events. White markers are the data points used for analysis.

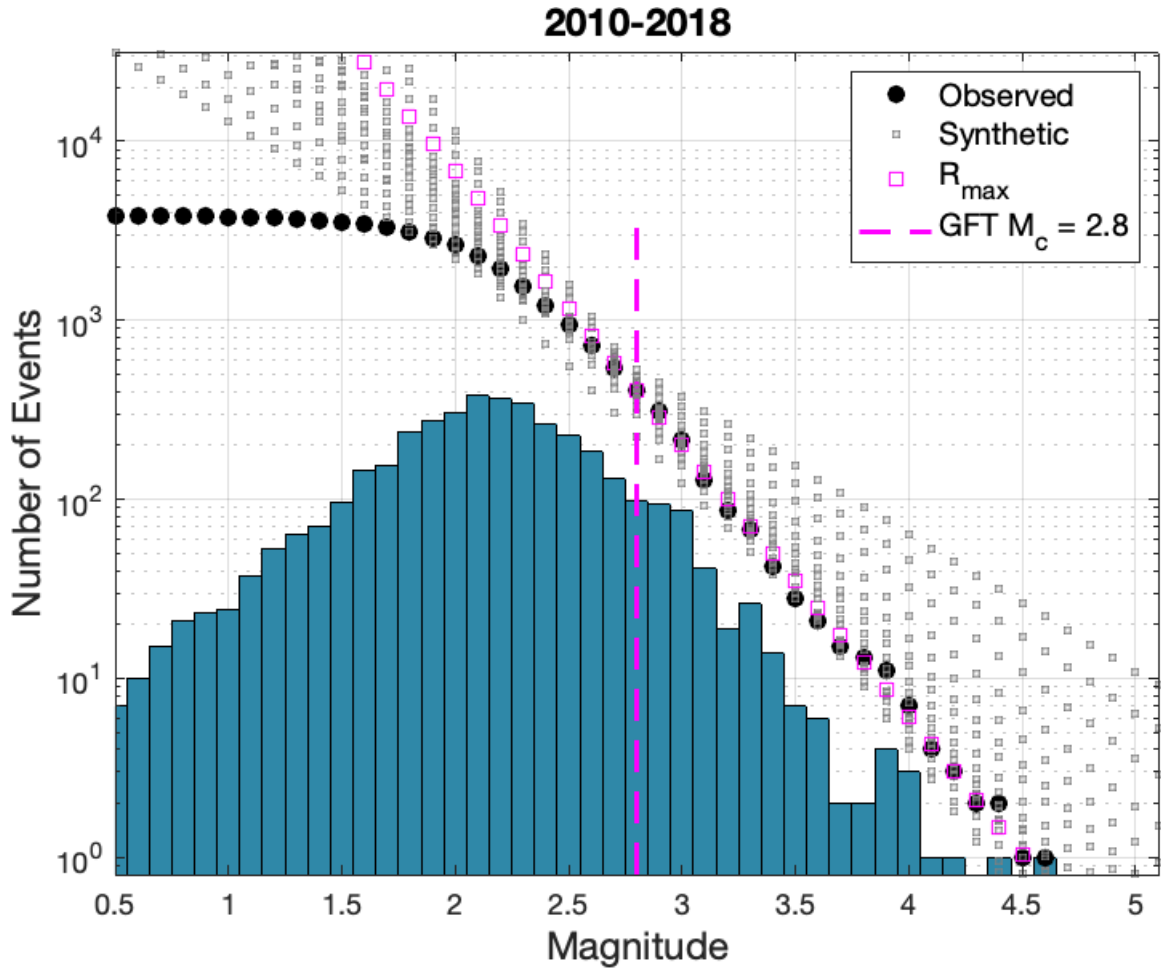


Figure S5. Estimated completeness of the Composite Alberta Seismicity Catalogue, between 2010-2018, using the goodness-of-fit test (GFT) of Wiemer & Wyss (2000). Squares represent synthetic distributions drawn from the (exponential) Gutenberg-Richter relation, for a range of b -values. Pink squares represent the synthetic distribution that maximizes the goodness-of-fit (R), i.e. that minimizes the residual between it and the cumulative frequency-magnitude distribution. Grey squares represent the rejected synthetic distributions. Vertical dashed pink line indicates the corresponding completeness threshold.

$M_0 = 2.0$
1975-2018

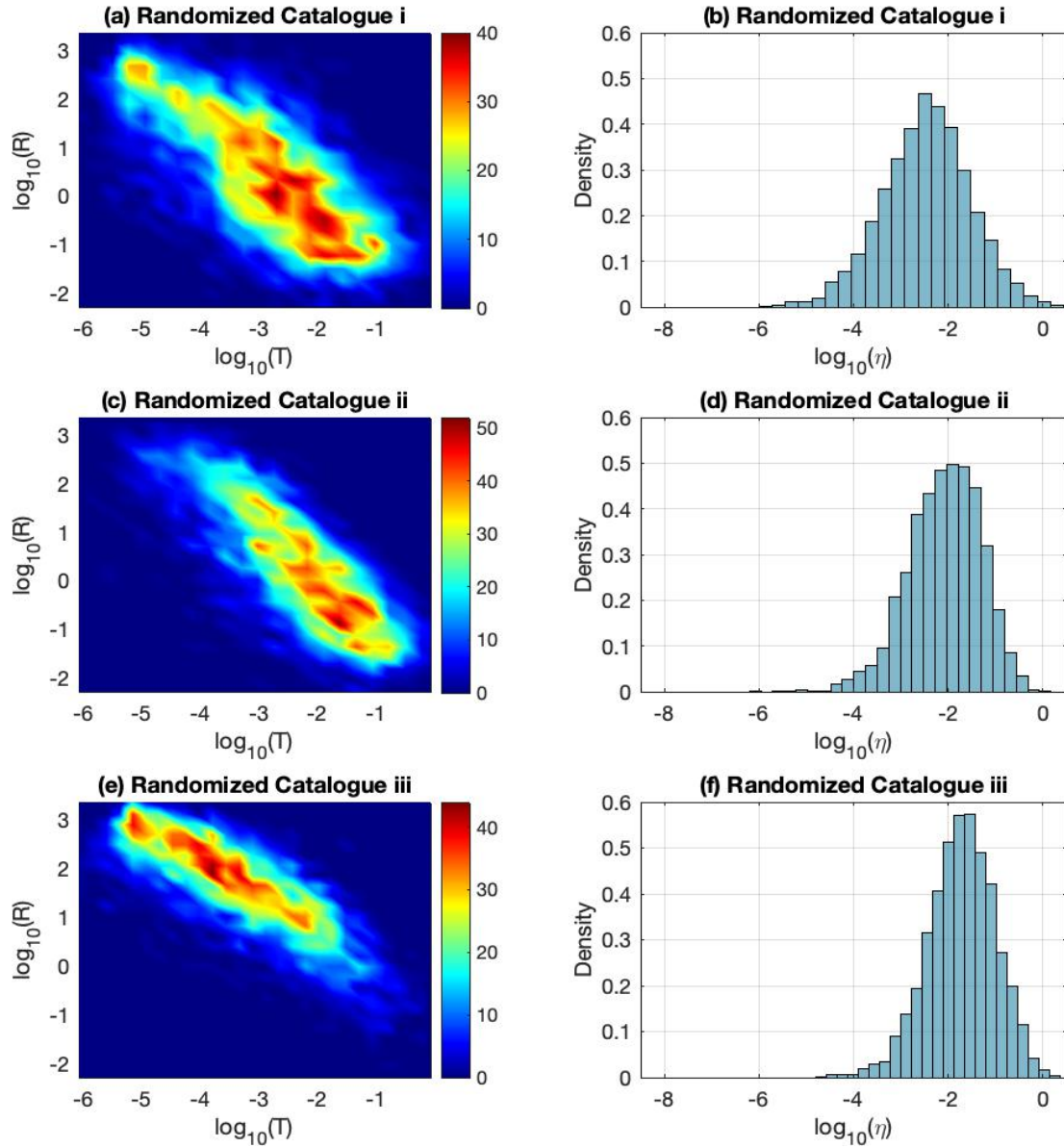


Figure S6. Nearest-neighbour distance distributions of three randomized versions of the Composite Alberta Seismicity Catalogue (CASC). (a, b) Event times and event locations are shuffled. (c, d) Event times are uniformly distributed within the temporal limits of the CASC and event locations are shuffled. (e, f) Original event times are kept and event locations are uniformly distributed within the latitudinal and longitudinal limits of the CASC.

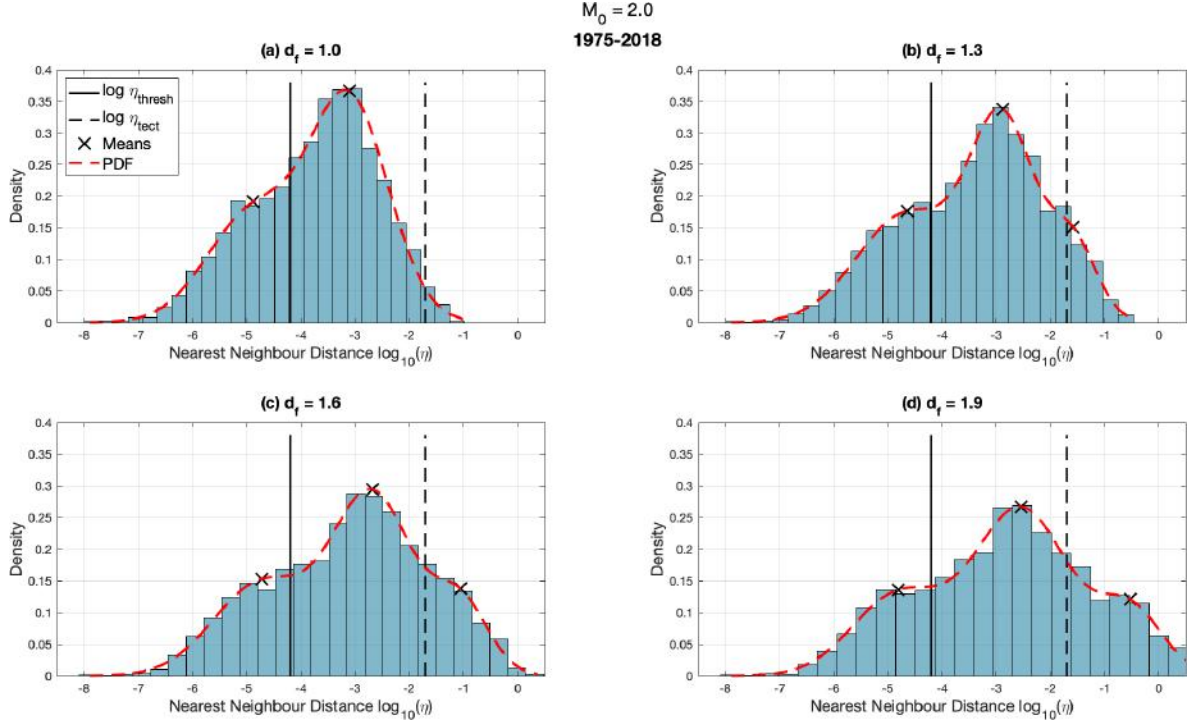


Figure S7. One-dimensional η distributions, analogous to Figure 2b, using a range of fractal dimension (d_f) values. As d_f increases, the distribution spreads and trimodality becomes more apparent.

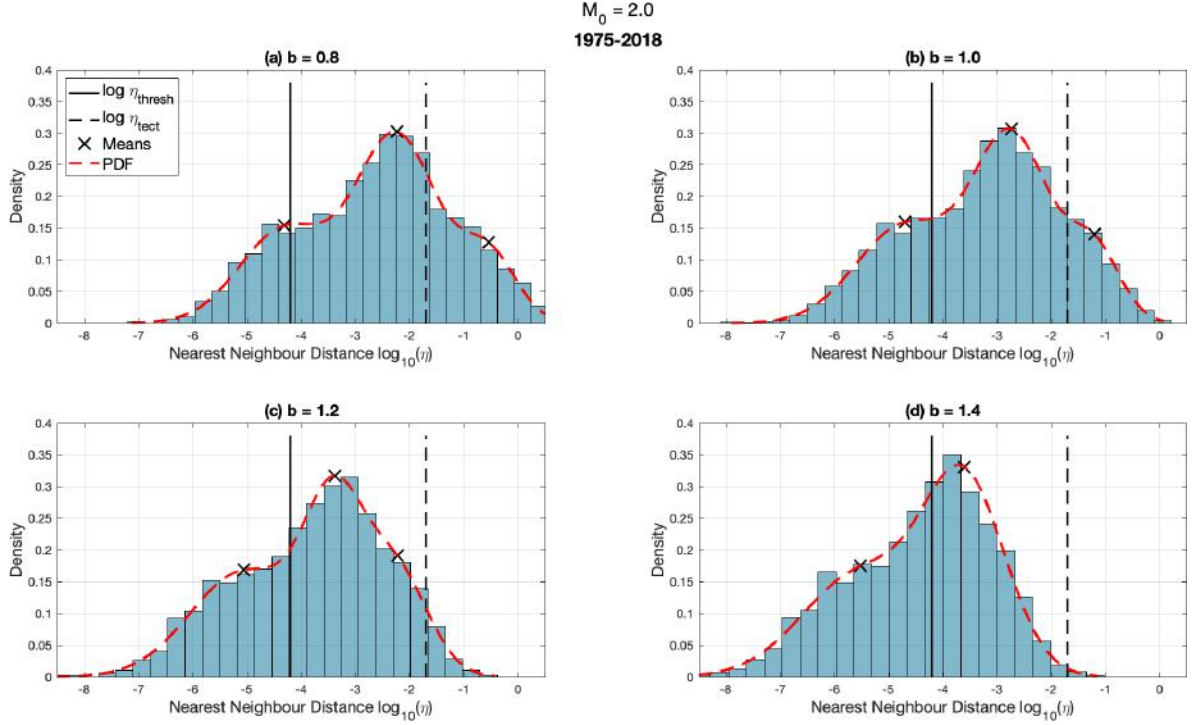


Figure S8. One-dimensional η distributions, analogous to Figure 2b, using a range of Gutenberg-Richter b -values. As b increases, the distribution gets squeezed and shifts leftward, obscuring the distinctive background mode at large η .

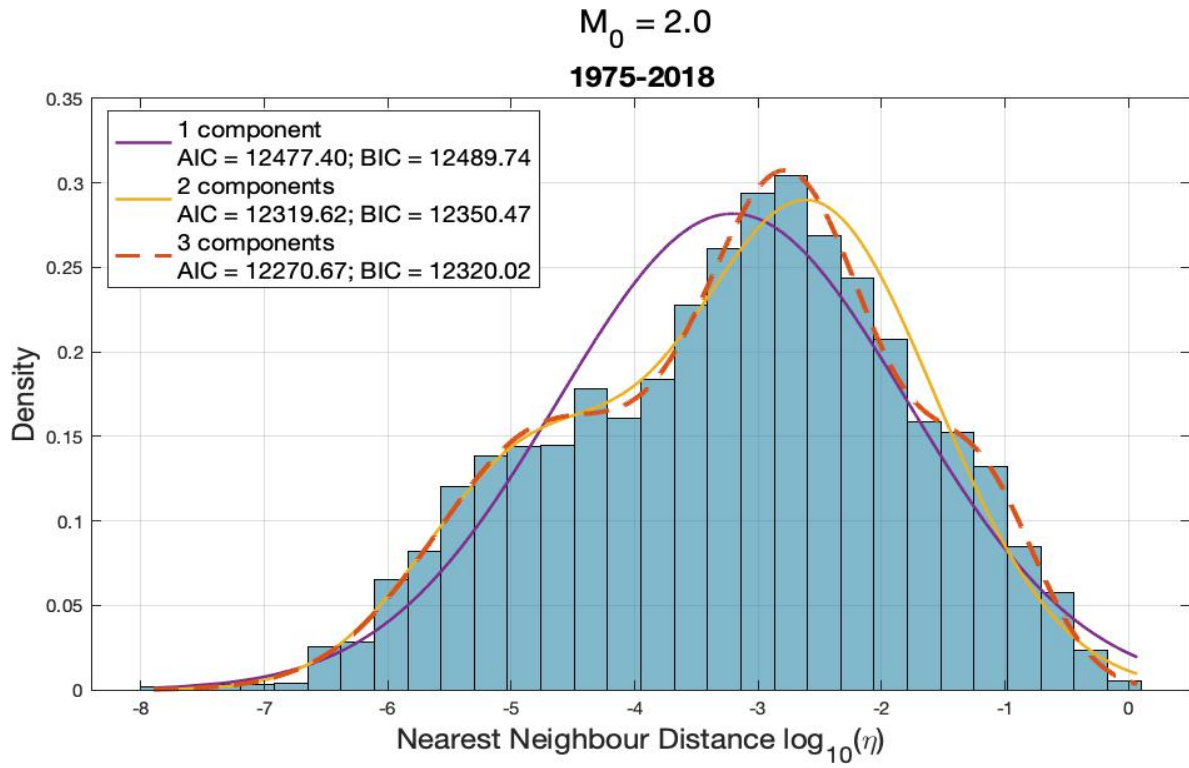


Figure S9. Gaussian mixture models, with 1, 2, and 3 components, for the regional distribution of inter-event distances η . AIC and BIC are their respective Akaike and Bayesian information criteria. The lowest AIC and BIC values correspond to the best fitting model; here they are minimized for a three-component mixture.

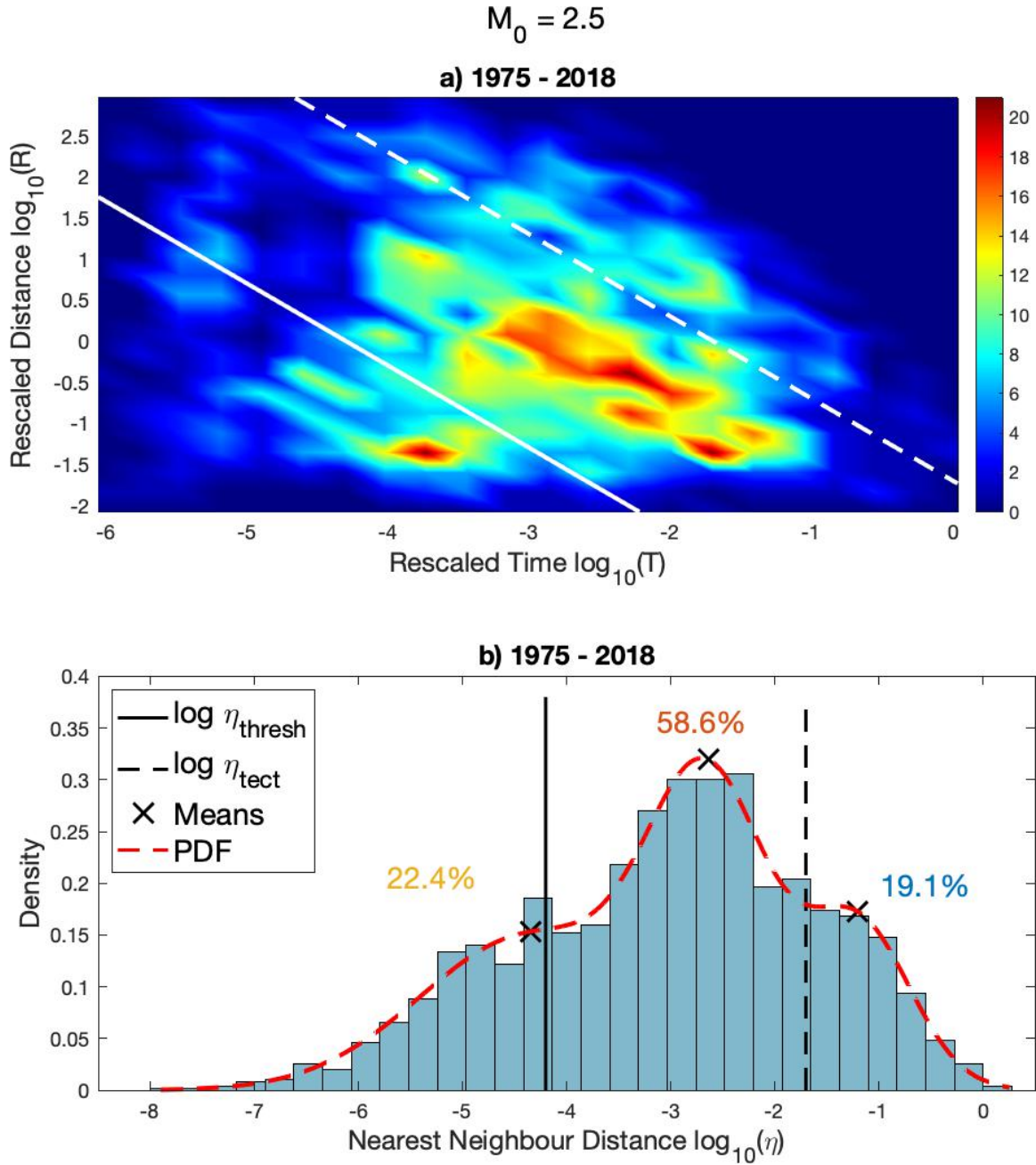


Figure S10. Nearest-neighbor distance distribution of the regional CASC dataset from 1975-2018, using a cutoff magnitude of $M_0 = 2.5$ (analogous to Figure 2). Percentages in subplot (b) reflect the modal mixing proportions. Trimodality remains distinguishable at $M_0 = 2.5$.

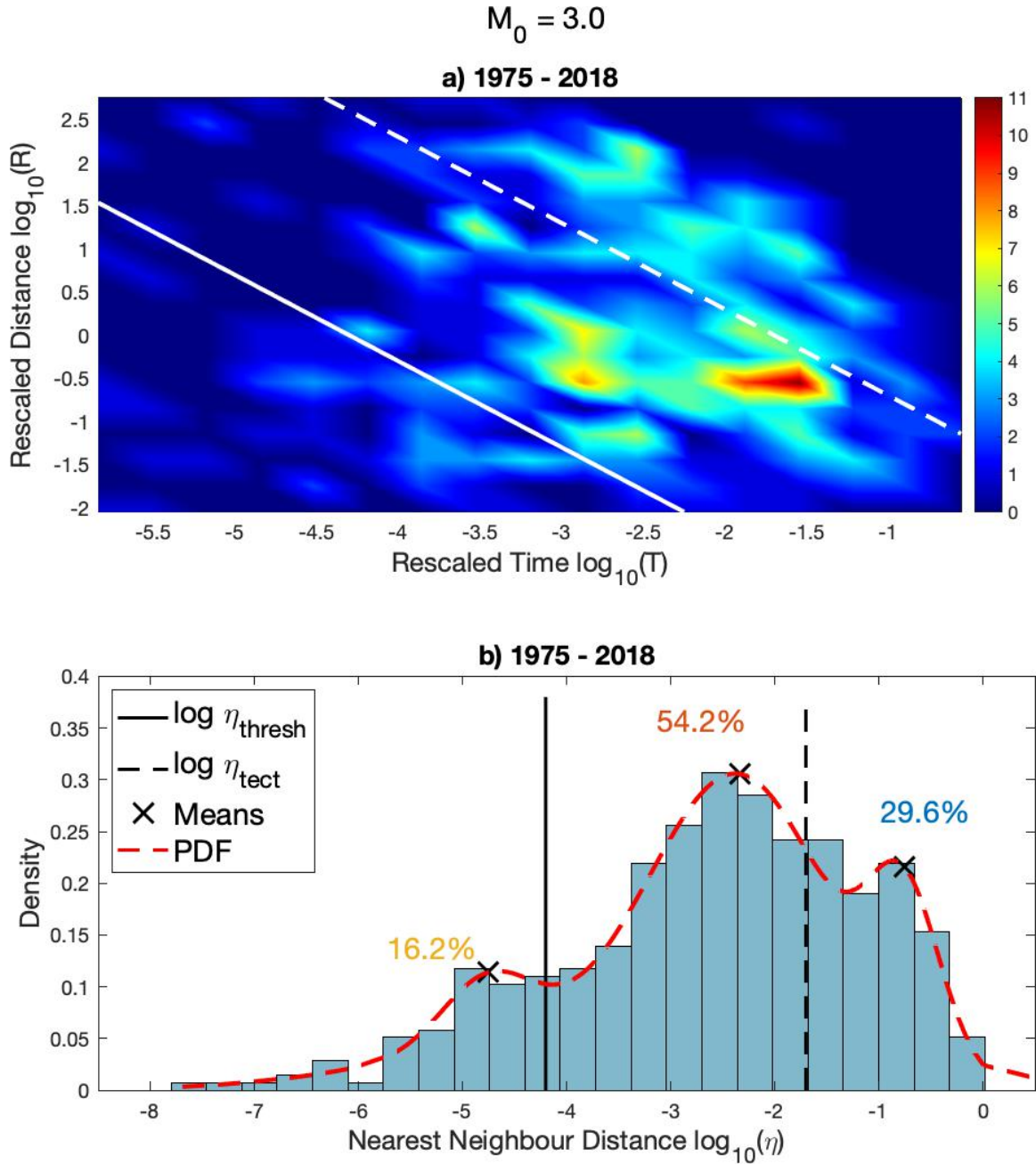


Figure S11. Nearest-neighbor distance distribution of the regional WCSB catalogue from 1975-2018, using a cutoff magnitude of $M_0 = 3.0$ (analogous to Figure 2). Percentages in subplot (b) reflect the modal mixing proportions. Trimodality remains distinguishable at $M_0 = 3.0$.

$$M_0 = 2.5$$

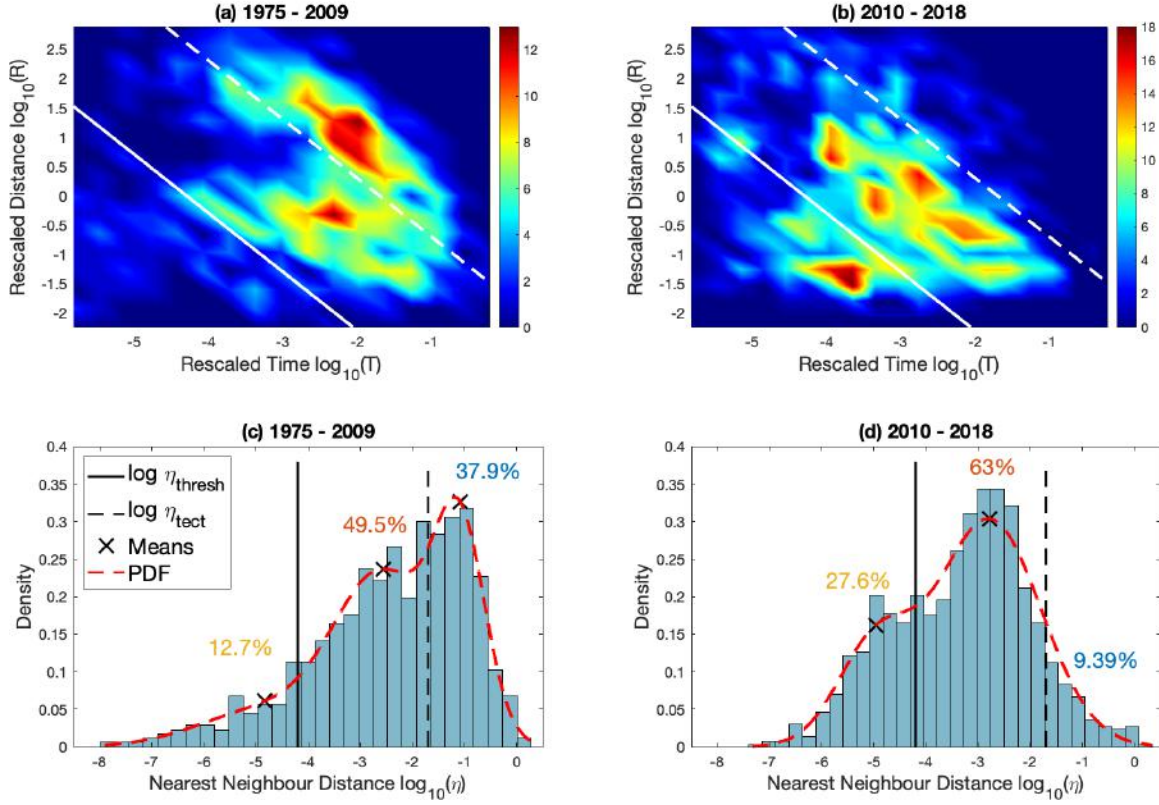


Figure S12. Comparison of nearest-neighbor distance distributions of the regional WCSB catalogue across time using a cutoff magnitude of $M_0 = 2.5$ (analogous to Figure 5). (a, c) 1975-2009. (b, d) 2010-2018. Percentages in subplots (c, d) reflect the modal mixing proportions.

$M_0 = 3.0$

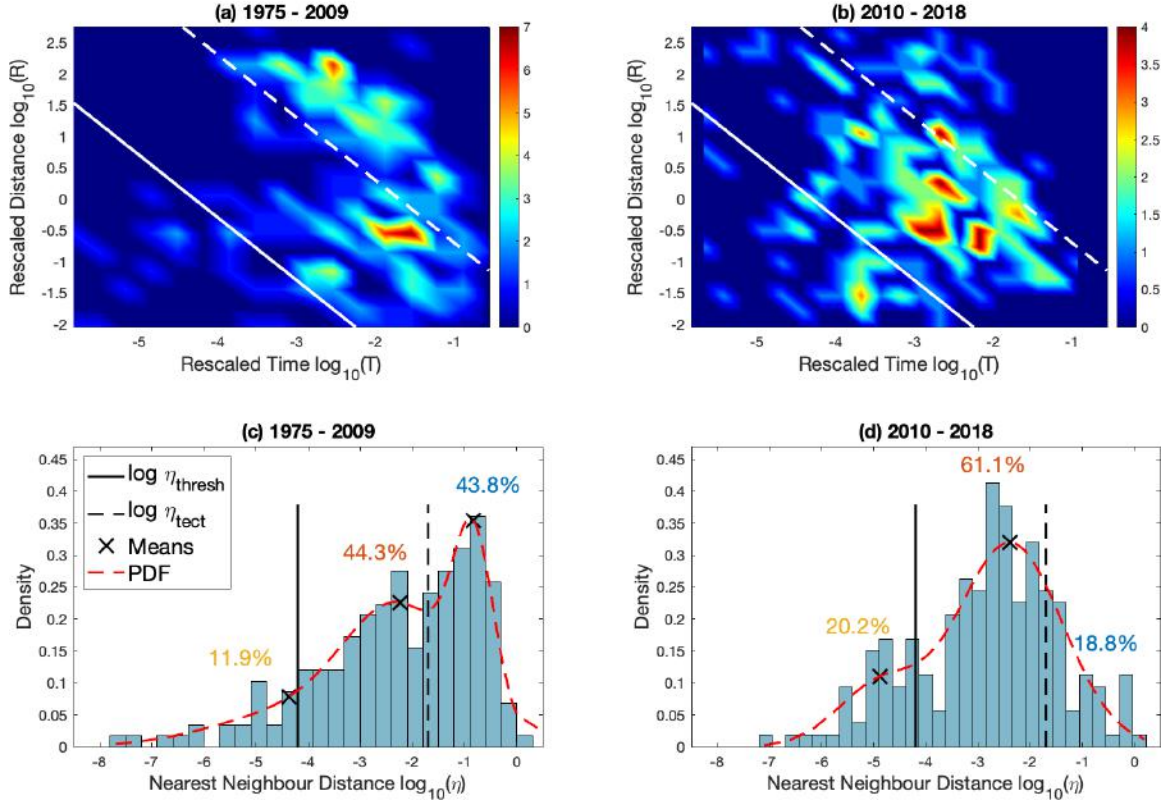


Figure S13. Comparison of nearest-neighbor distance distributions of the regional WCSB catalogue across time using a cutoff magnitude of $M_0 = 3.0$ (analogous to Figure 5) (a, c) 1975-2009. (b, d) 2010-2018. Percentages in subplots (c, d) reflect the modal mixing proportions.

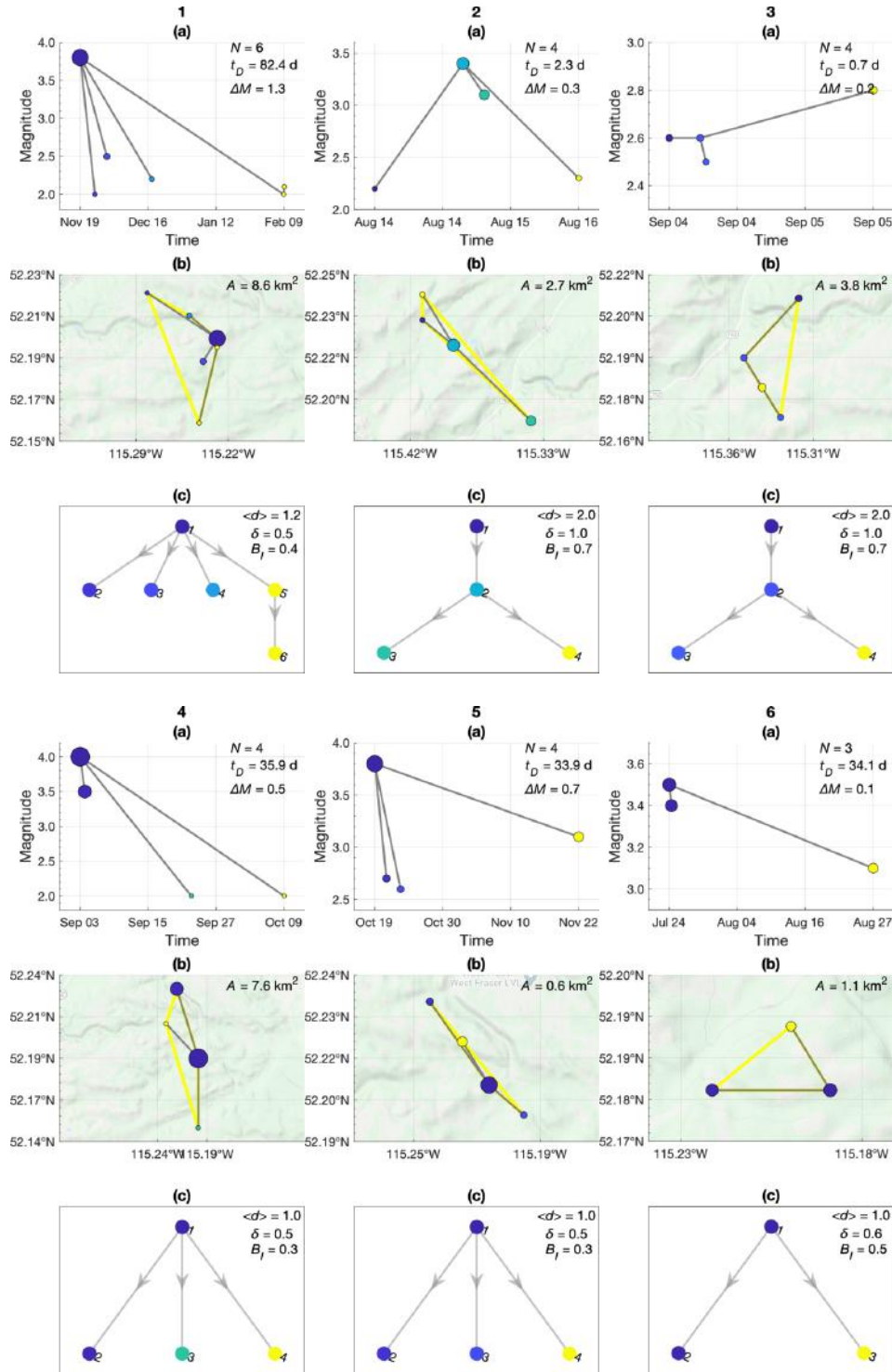


Figure S14. Event family structures in the Rocky Mountain House cluster (RMHC). a) Moment magnitude vs. time in days. b) Spatial map; yellow border outlines the hull area occupied by the sequence. c) Directed tree graph in dimensionless space. Data points are coloured chronologically from darkest to lightest.

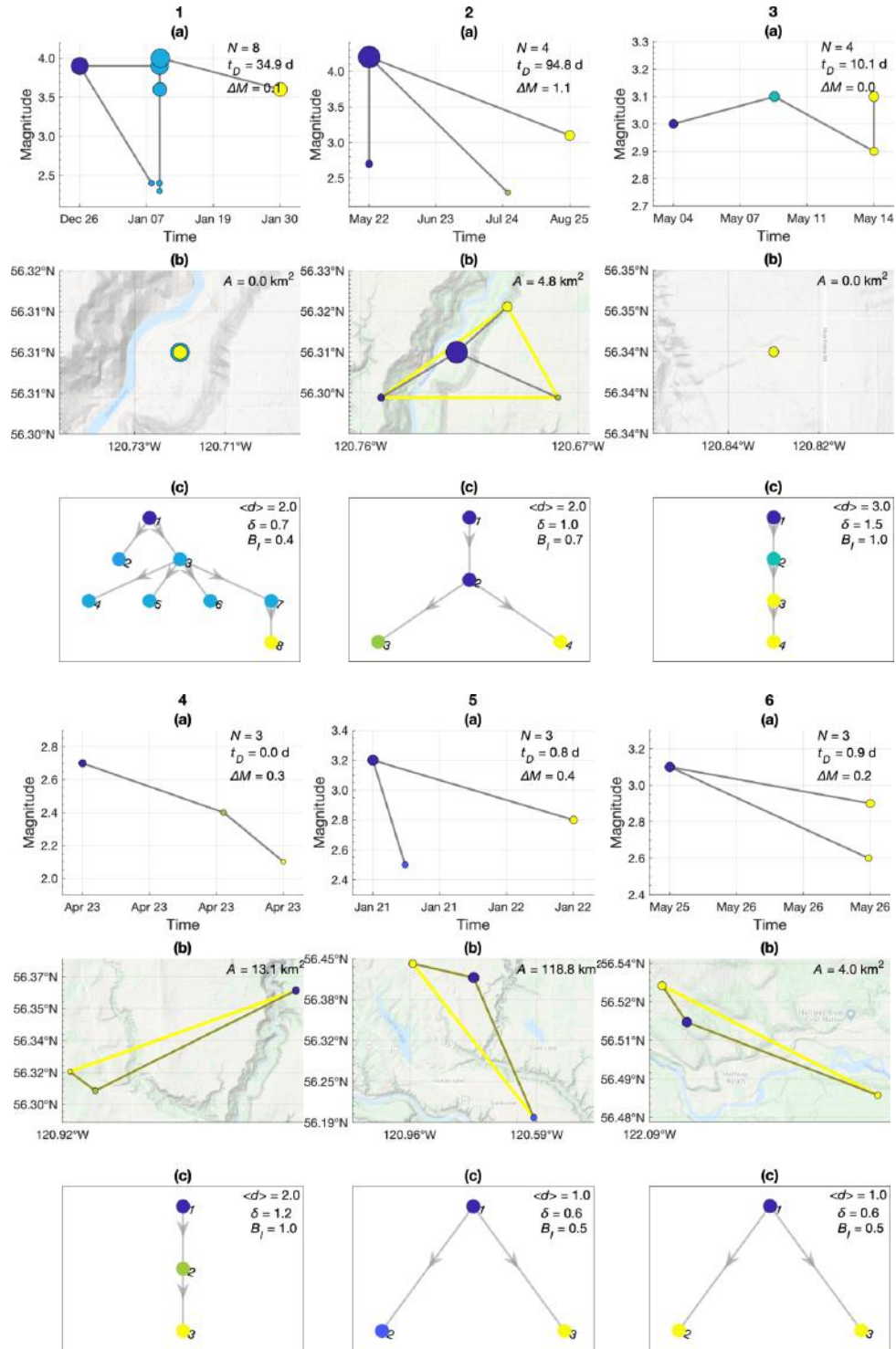
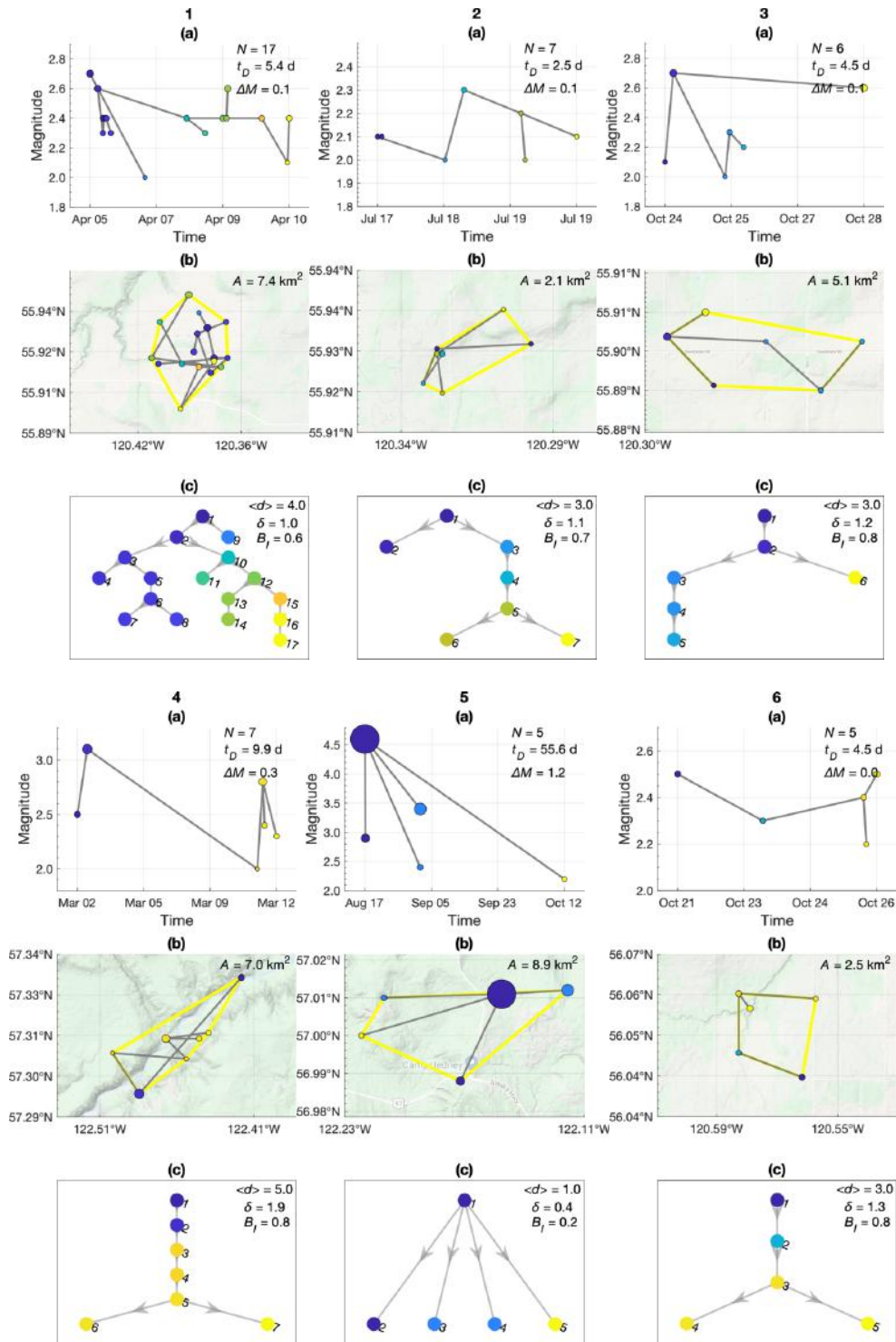


Figure S15. Event family structures in the Montney cluster 1 (MC1). a) Moment magnitude vs. time in days. b) Spatial map; yellow border outlines the hull area occupied by the sequence. c) Directed tree graph in dimensionless space. Data points are coloured chronologically from darkest to lightest.



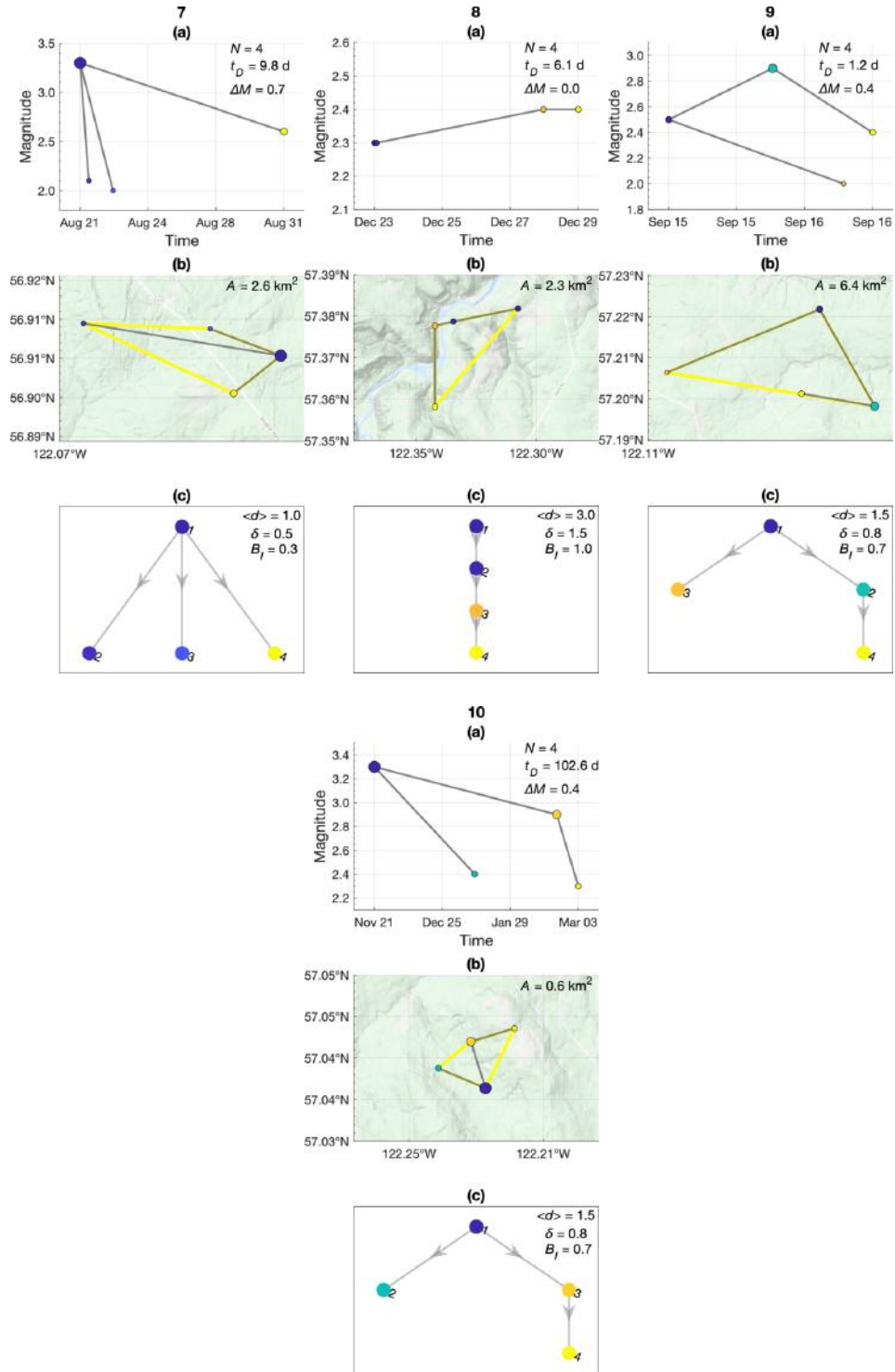
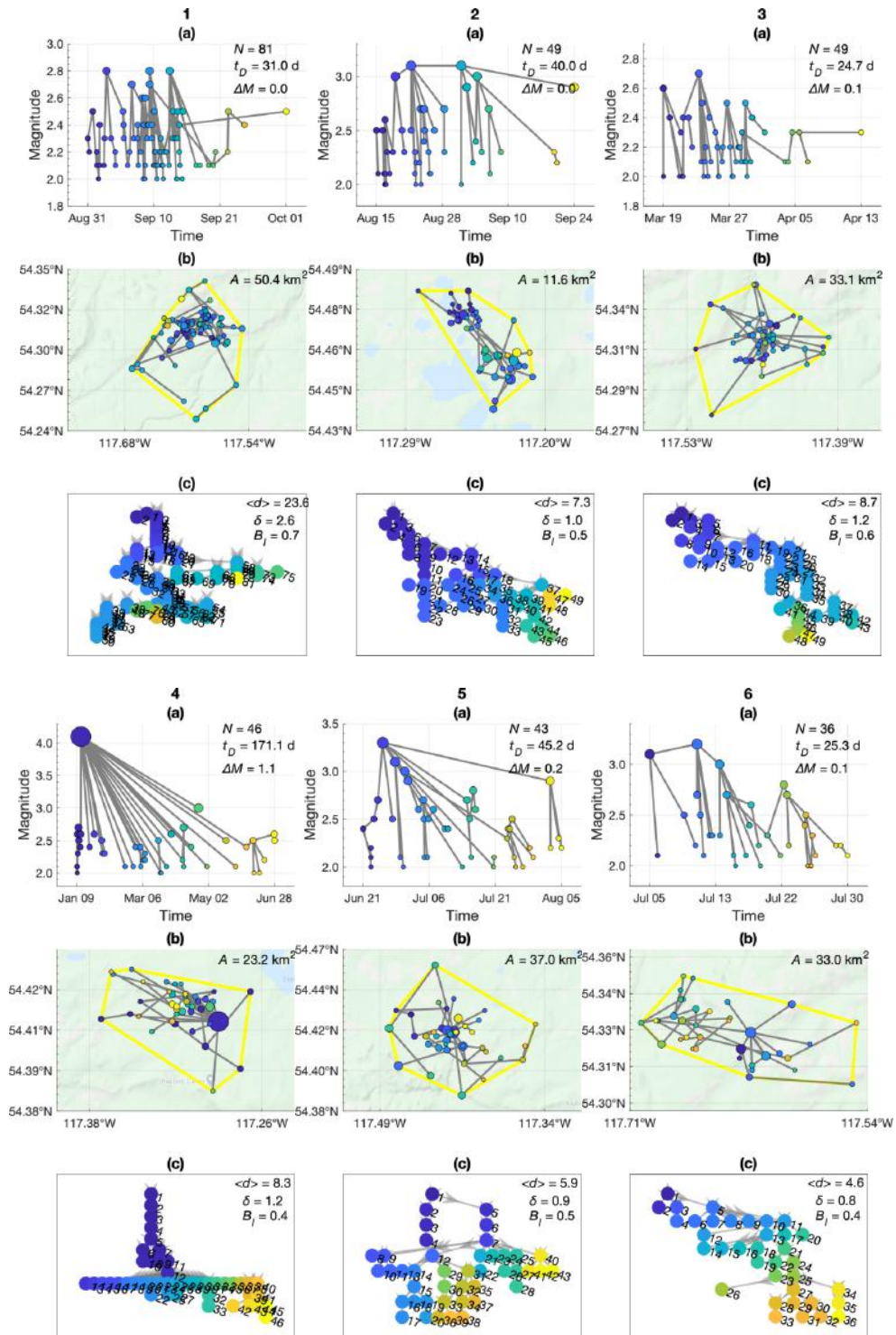
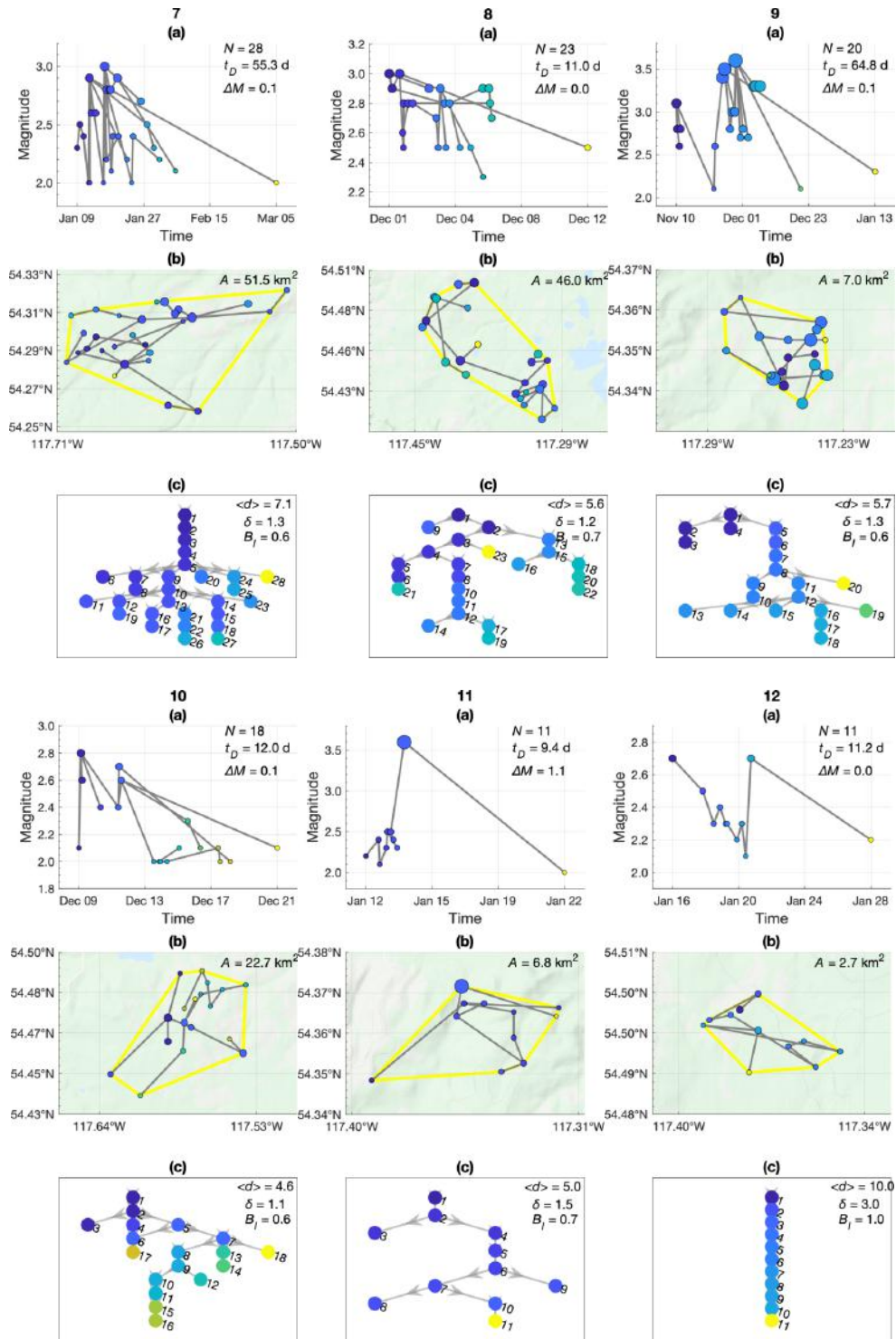


Figure S16. Event family structures in the Montney cluster 2 (MC2). a) Moment magnitude vs. time in days. b) Spatial map; yellow border outlines the hull area occupied by the sequence. c) Directed tree graph in dimensionless space. Data points are coloured chronologically from darkest to lightest.





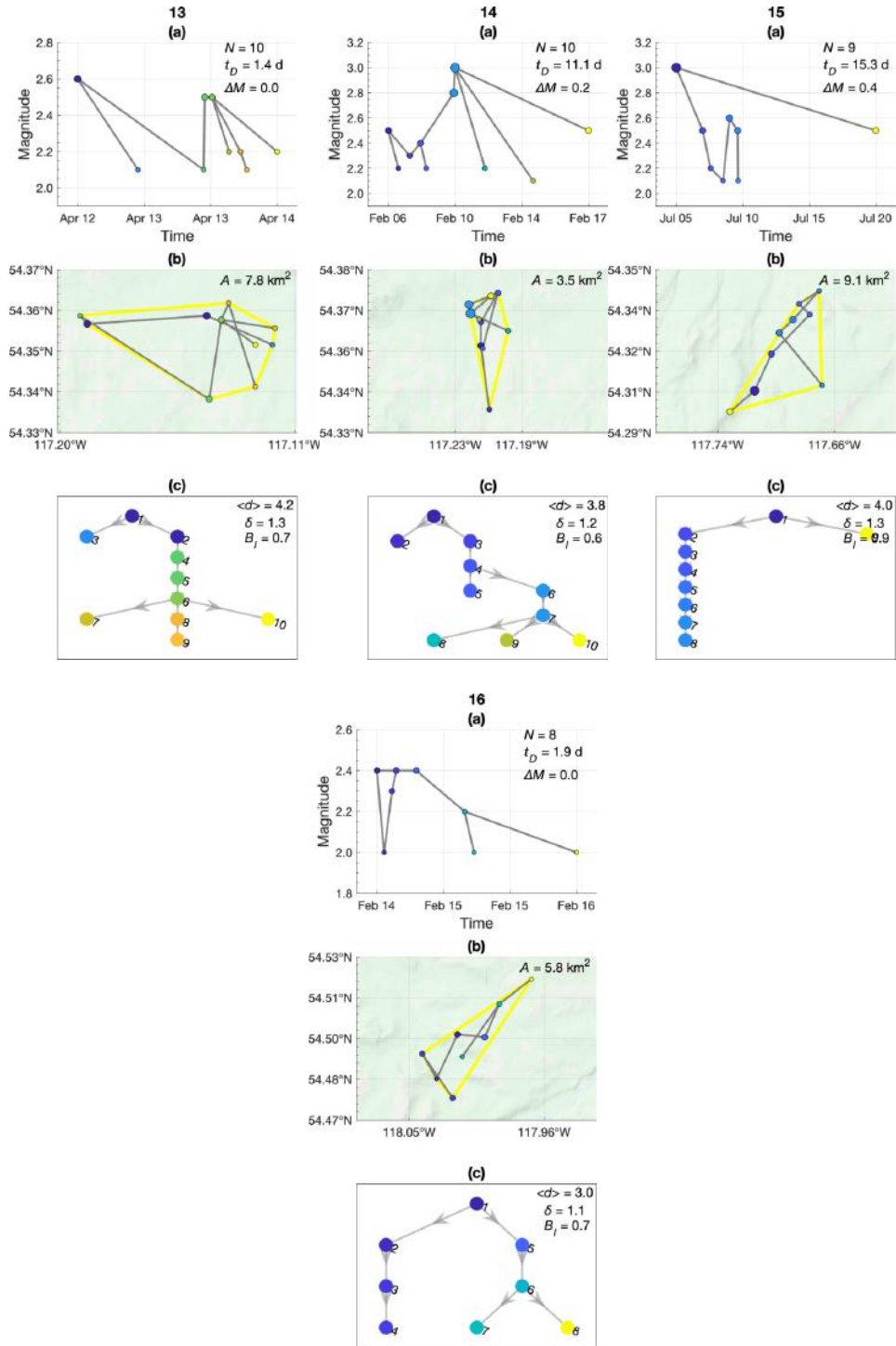


Figure S17. Event family structures in the Fox Creek cluster (FCC). a) Moment magnitude vs. time in days. b) Spatial map; yellow border outlines the hull area occupied by the sequence. c) Directed tree graph in dimensionless space. Data points are coloured chronologically from darkest to lightest.