

SUPPLEMENTARY MATERIALS for

The Castanhão Reservoir, NE Brazil, Reservoir-Triggered Seismicity in Secondary Transtensional Tectonic Settings within a Major Strike-Slip System.

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The Castanhão Reservoir required a thorough data curation to create an earthquake catalog suitable for the calculation of seismic source parameters. The used dataset consisted of continuous waveforms recorded by the LS network consisting of 6 seismological stations. The data availability for each of them was shown on the Gantt chart (Figure S1). Due to the broadest availability of 250 samples per second waveforms, the authors decided to use them, avoiding undersampling which could result in loss of frequencies related to expected small magnitude of events. The example of seismological data recorded by all six stations was shown on Figure S2.

In order to obtain the best localizations of earthquakes in the Castanhão area, the Hypo71 algorithm was applied. It also helped to determine origin times (Lee and Lahr, 1972). To improve the accuracy of the localizations, various input parameters were tested. The horizontal and vertical localization errors were shown on histograms in Figure S3. The corresponding quality measure for the parameter combination yielding the best results was presented in Figure S4. P-wave velocity was assumed as $V_p = 5.95$ km/s (Nunes et al., 2011), and $V_p/V_s = 1.74$ was calculated based on the Wadati diagram of the TRMLOC localizations (Dębski, 2015). The applied velocity model was visualized in Figure S5. The assumed velocity V_p corresponds to the velocity of P waves characteristic of crystalline basement and were previously used for seismological studies of the region (Ferreira et al., 2008; Nunes et al., 2011). The new V_p/V_s ratio was calculated to match local conditions, but does not vary much from the ratio generally assumed for NE Brazil – 1.73 (Ferreira et al., 1998; Ferreira et al., 2008; Nunes et al., 2011).

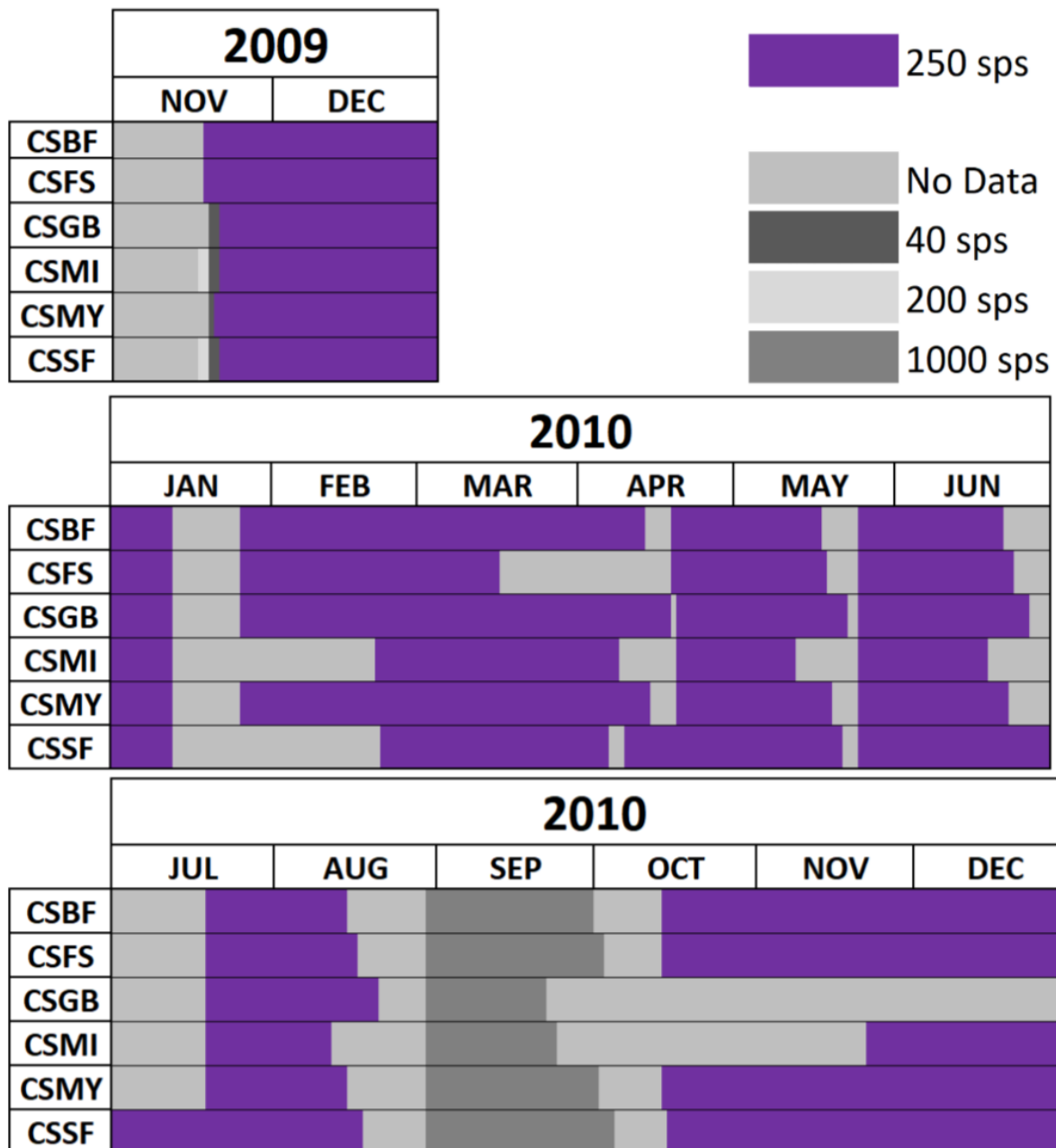


Figure S1: Gantt chart showing the data availability for continuous waveforms recorded by LS network on all its stations. The purple color marks data with sampling 250 sps that was considered for the purpose of this study

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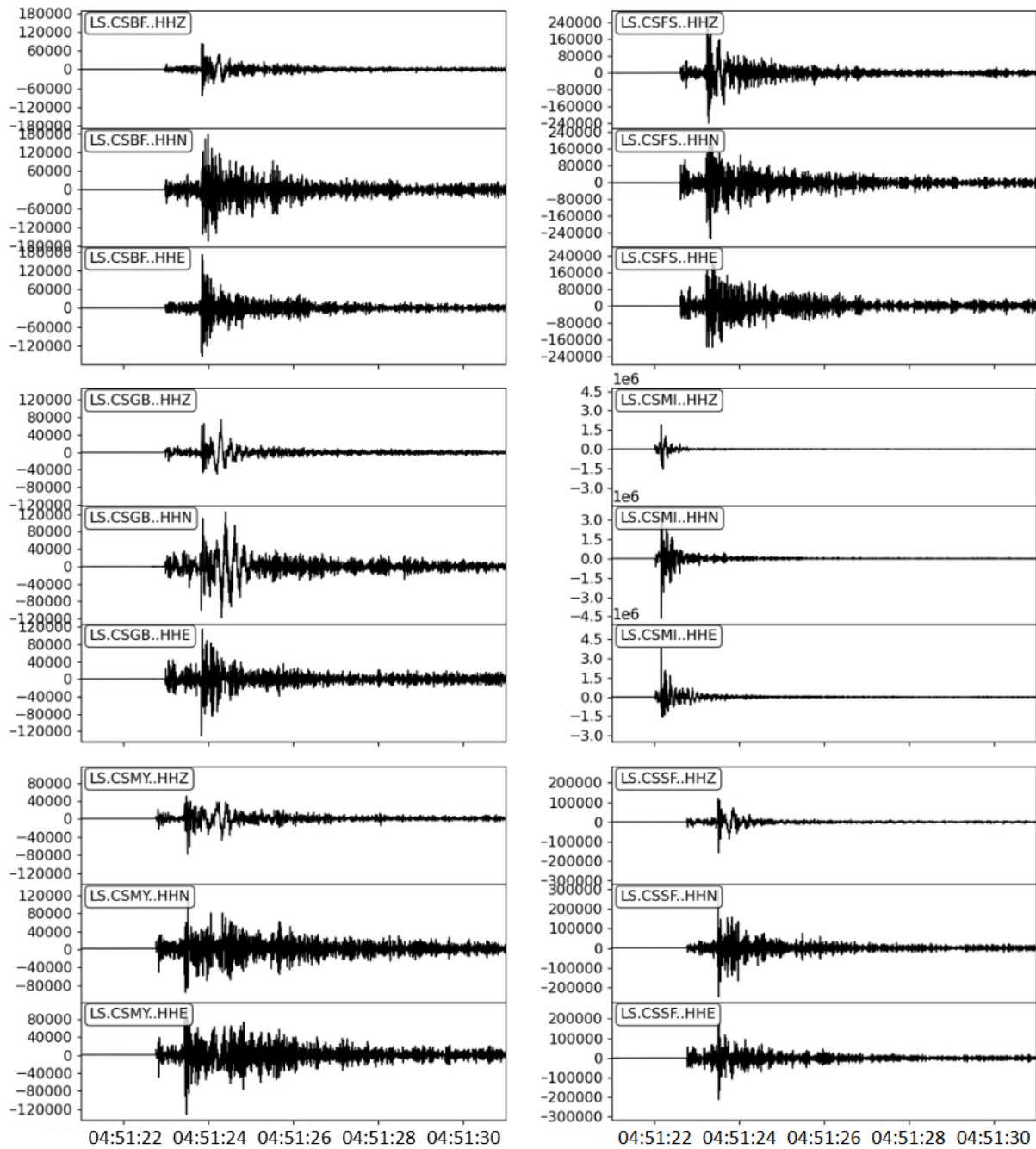


Figure S2: Examples of miniseed waveform data from all the stations (including unused – CSMI). The record of $M_w2.1$ earthquake on August 8th, 2010. Raw seismograms plotted with Obspy.

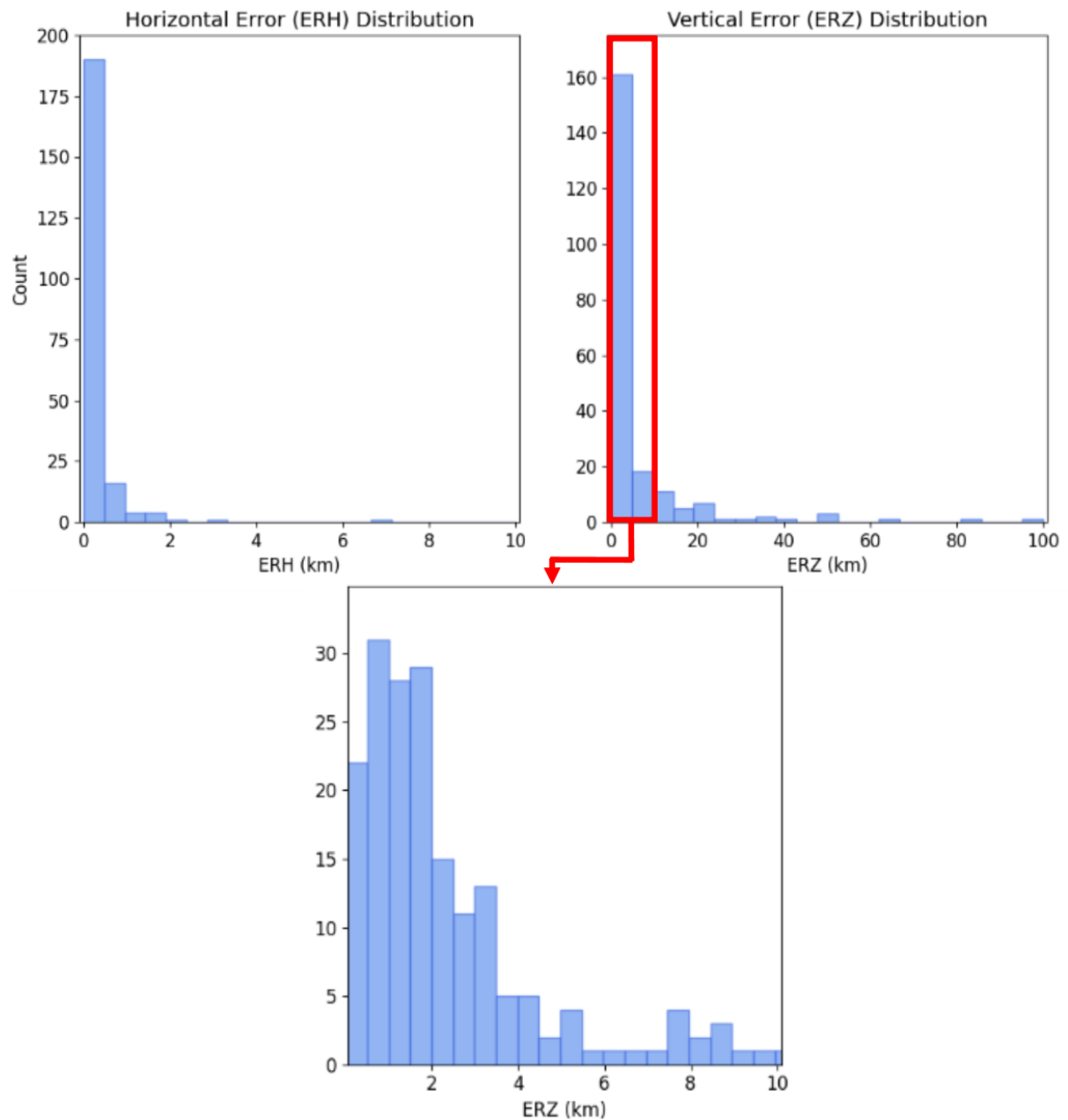


Figure S3: The Hypo71 localization errors. The top left histogram shows the horizontal error (ERH) distribution, while the top right histogram shows the error in the vertical component (ERZ) distribution. The bottom histogram shows a zoom-in on the error distribution in the vertical component.

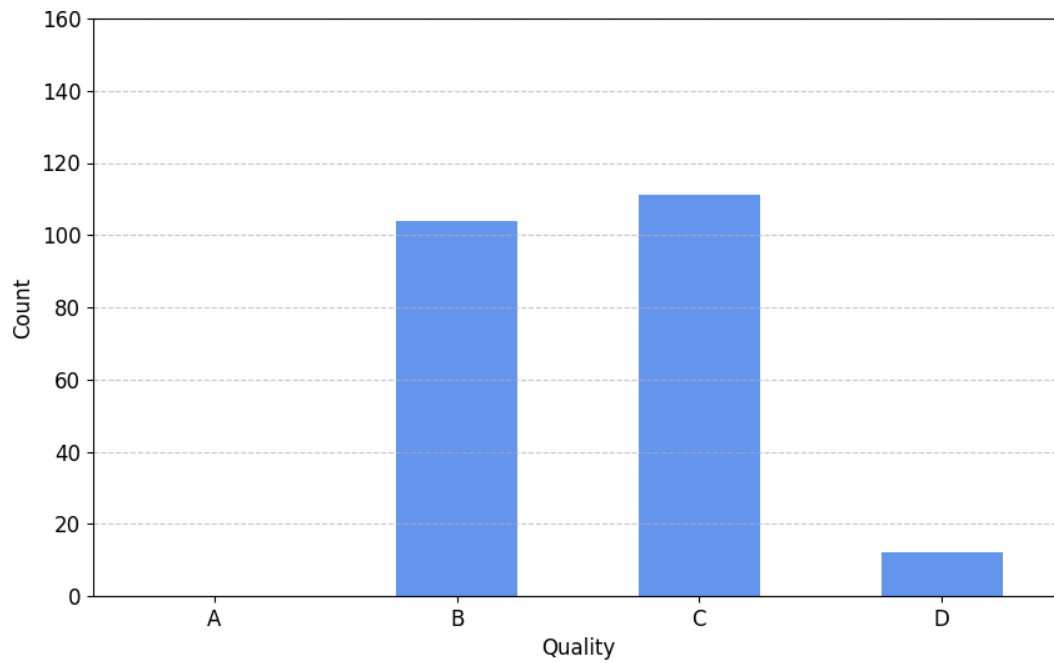


Figure S4: The Quality Measure distribution of the Hypo71 localizations for a full earthquake catalog plotted for the results obtained with the best performing parameters. The letters at axis x mark the quality of epicentral localization data as follows: A - excellent, B - good, C - fair, and D - poor.

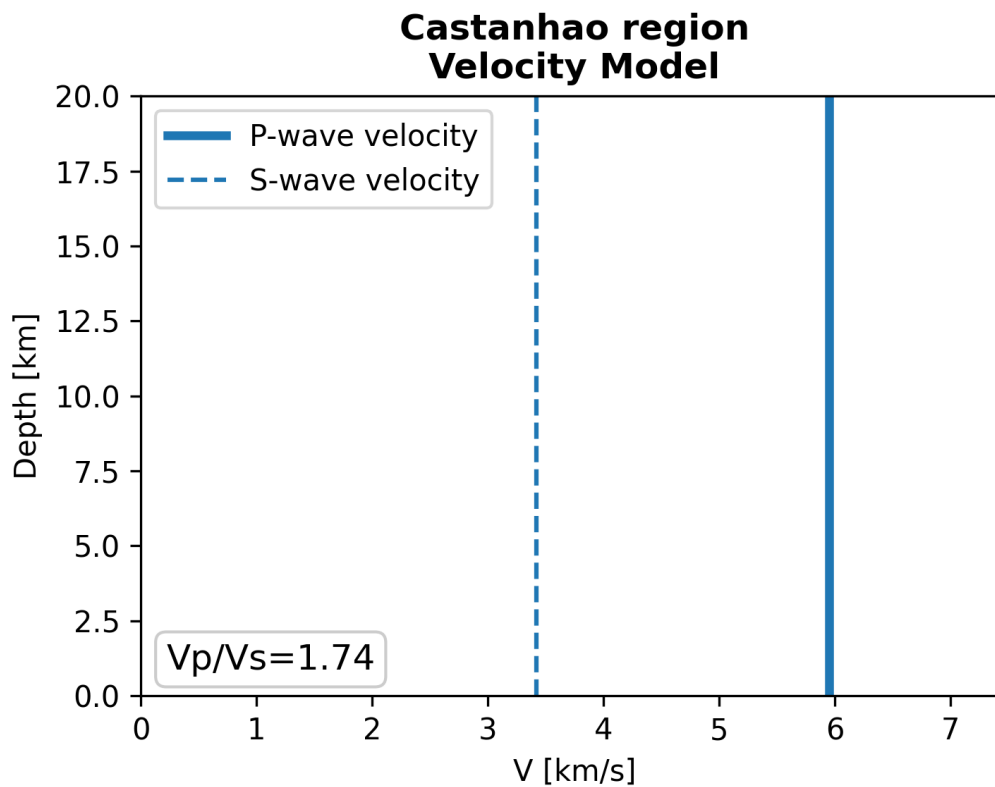


Figure S5: The velocity model based on the Wadati diagram was used for TRMLOC localization. The applied simplified velocity model was used for Hypo71 and HypoDD localizations. It is a 1-layer homogeneous model with a constant velocity assumed for

shallowed earthquakes. Such a selection was made due to the depth of earthquakes in the region.

Due to the poor station coverage, the strength of the seismic events, and the data quality, the authors were not satisfied with the results of Hypo71 localization. There was an attempt to re-localize the events using a double difference method.

HypoDD allows for re-localization of the earthquakes with the use of the initial catalog (Hypo71), as well as re-localization based on cross-correlation of earthquake signals (Waldhauser & Ellsworth, 2000; Waldhauser, 2001). These two methods can be used separately or combined to increase the accuracy of the final results. Given the fact that the Castanhão Reservoir data is planned to be made available within the EPOS EPISODES Platform as an Episode, it seems beneficial to use the combined method of catalog and cross-correlation-based double-difference method re-localization and combine re-localized events with Hypo71 localized catalog for events that were not possible to re-localize with HypoDD. To fully benefit from available methods, the cross-correlation of each earthquake signal was performed for every station used for re-localization (5 stations from the LS network - the CSMI station data had not been used because of their poor quality). The cross-correlation was performed for every 5 samples of the noise preceding the 10 samples of the P-waves arrival taken into consideration. This means that 15 samples of each signal were used to calculate cross-correlation coefficients (Figure S6).

The comparison of the available catalogs is shown in Table S1.

Table S1: The comparison of catalogs. The summary shows how many events were (re)localized with the HypoDD method, as well as how many events have their estimated moment magnitude M_w .

	Hypo71 Catalog	HypoDD Catalog	Combined Catalog
No of events	227	103	227
Events with M_w	219	102	219
M_c	0.4	0.4	0.4
Min(M_w)	0.0	0.0	0.0
Max(M_w)	2.7	2.7	2.7

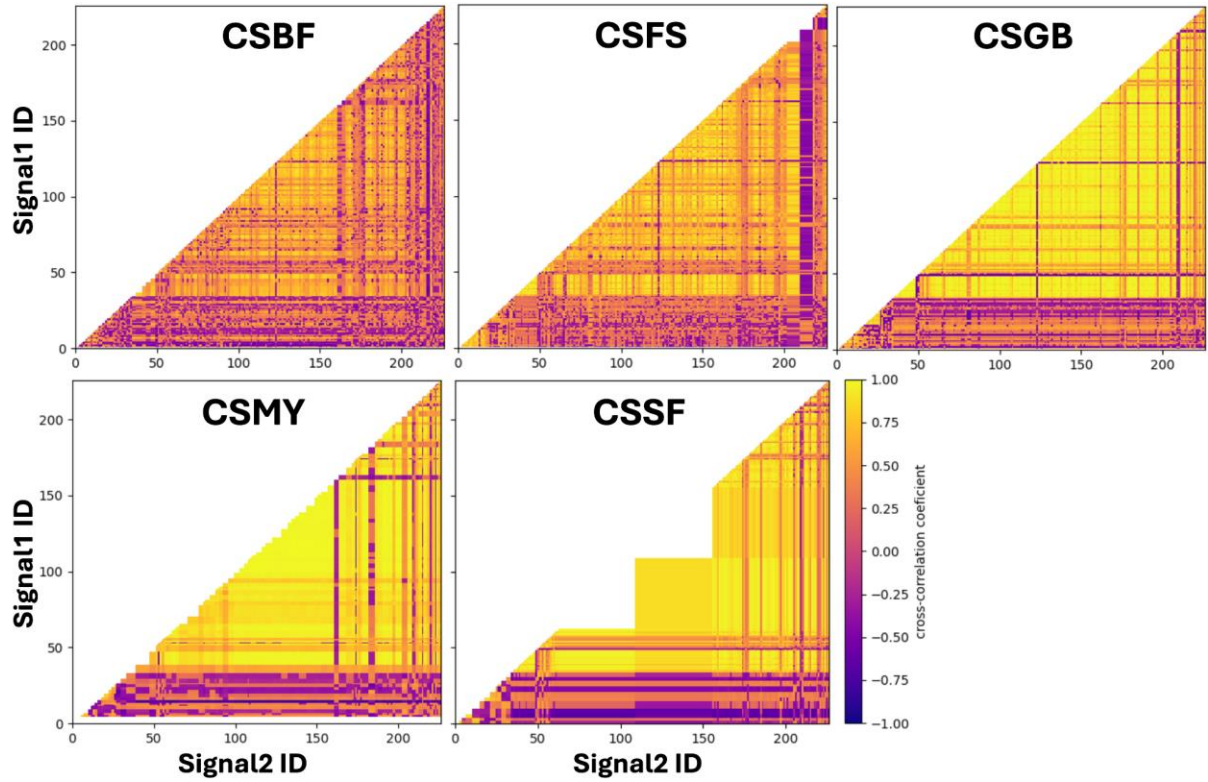


Figure S6: The cross-correlation coefficient computed for each seismological station used in HypoDD re-localization. The signal IDs on both axes correspond with the earthquake indices in the available earthquake catalogs.

For performing re-localization, the LSQR method was selected; however, the results did not present reliable errors, given their value being in rows of meters to tens of meters. Such values called for further investigation and resulted in the re-calculation of the error using the bootstrap method. The error was calculated for 95% confidence interval (Figure S7). In this way, the errors of the initial Hypo71 localizations were improved, where possible. The dataset benefited mostly in terms of vertical error values. Moreover, these values seem more reliable. The average for the error ellipsoid axes was ~ 2.23 km for AX1 and ~ 0.79 km for AX2, while the mean vertical error was ~ 0.85 km.

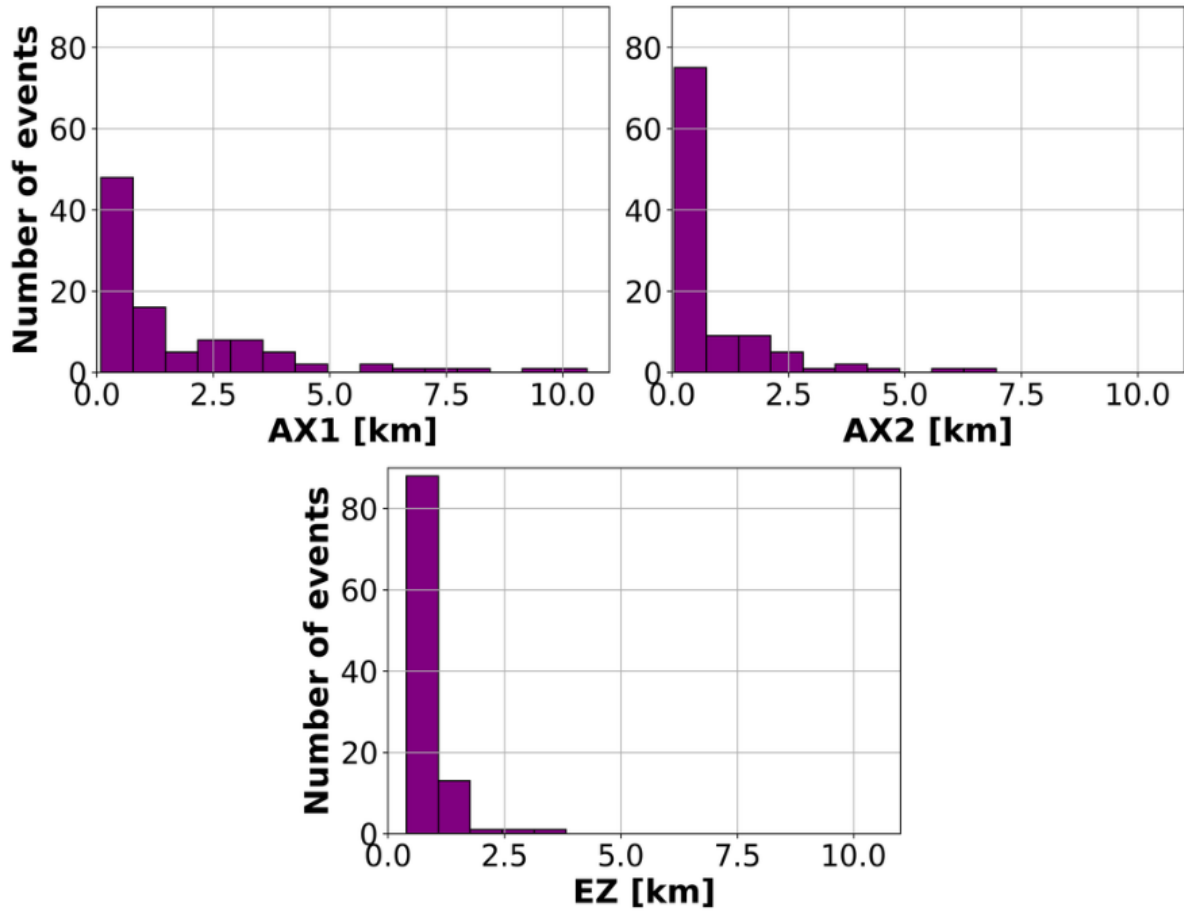


Figure S7: The histograms for the error ellipsoid (left and right top) and depth error (bottom) for 103 HypoDD re-localized events.

As mentioned in the article to which these Supplementary Materials are attached, there are two available catalogs: the Hypo71 catalog and its enhanced version with 103 HypoDD improved localizations (referred to as the combined catalog). KiwiTools was used to compute moment magnitudes for both of these catalogs; however, the main focus of this work is on the combined catalog due to its better accuracy.

KiwiTools allows the computation of moment magnitude and focal mechanisms. The majority of events could benefit from obtaining the M_w values (219 out of 227 could have their magnitude calculated with that software). Because earthquake magnitudes are small, it was not possible to obtain a stable solution with well-fitting synthetics for any of the events. The small number of stations in the network, as well as the data quality, was insufficient to compute focal mechanisms with the full waveforms method. The fit between synthetic seismograms and recorded signals was poor and cannot be considered.

To further investigate the focal mechanisms of the earthquakes, the composite solution was considered. We used P-wave polarities from stations in the combined catalog and calculated composite focal mechanisms for the two identified clusters using FocMec (Snoke et al., 2003). A total of 235 and 297 polarities constituted the western and eastern cluster datasets, from which 16 and 19 acceptable solutions were obtained, respectively, allowing 61 and 52 polarity

errors. The number of allowed polarity errors represented the minimum required for FocMec to return viable solutions.

The resulting solutions (Figure S8) show similar strike-slip mechanisms with limited nodal-plane dispersion and good agreement between the NW–SE-trending nodal planes and the cluster's epicentral distributions. However, P-wave polarity misfits are distributed broadly around the focal sphere for both clusters. Furthermore, the number of allowed polarity errors was high, corresponding to 26% and 18% of the western and eastern datasets, respectively.

The high misfit rates and spatial spread of polarity inconsistencies may compromise the accuracy of the composite mechanisms and suggest that they may not fully represent the clusters' faulting style. This behavior may reflect more complex fault architectures, such as subclusters with distinct faulting styles and/or orientations within the spatially defined clusters, and warrants further investigation.

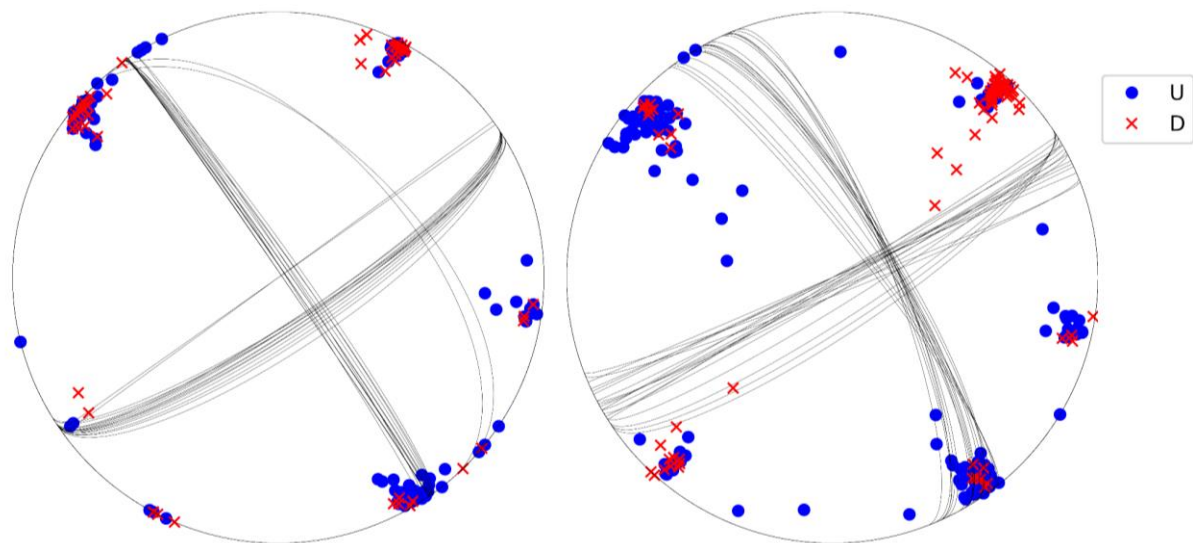


Figure S8: Composite focal mechanism solutions for the two identified clusters (left: western cluster; right: eastern cluster). Up (U) and Down (D) polarities are shown as blue circles and red crosses.

In the estimation of pore-pressure change in the reservoir, we considered various scenarios. Using Orlecka-Sikora et al. (2023) approach, we computed the diffusivity c for different assumptions shown in Figures S9–S10 and further detailed along with computational results in Table S2 (results of diffusivity computations were shown in Figure S11).

Various approaches were tested to finally select the one that would most accurately describe the situation based on the available seismological and hydrological data. This one was presented in the main text of the manuscript. The tested scenarios were shown in Table S2. Diffusivity used for pore-pressure modelling was a mean diffusivity c calculated from formula (1). Firstly, we computed distance L used in formula (1) for different cases: (I) as distance between each earthquake and reservoir center obtained with QGIS centroid function, (II) as shortest distance between seismic events and reservoir border (an effective diffusivity under a minimum-path assumption), and (III) interevent distances. After that, we considered different

starting times $t=0$ (04.12.2009 – which is the first event in our seismic catalog, and 01.01.2002 which is the time when the reservoir became operative). Finally, three different starting points were checked in order to find how much they would differ from one another. Events with ID from 1 to 5, shown in Table S2, were established at the location of the first earthquake in our catalog, events 6–8 were marked in the middle of cluster A described by Ferreira et al. (2008) that was the first activated cluster during their monitoring campaign. Due to lack of access to their catalog we selected the event to be at depth 1.0 km – which corresponds to the seismic activity recorded by Ferreira et al. (2008), Nunes et al., (2011), and our work. Events 9–11 are located at the reservoir center.

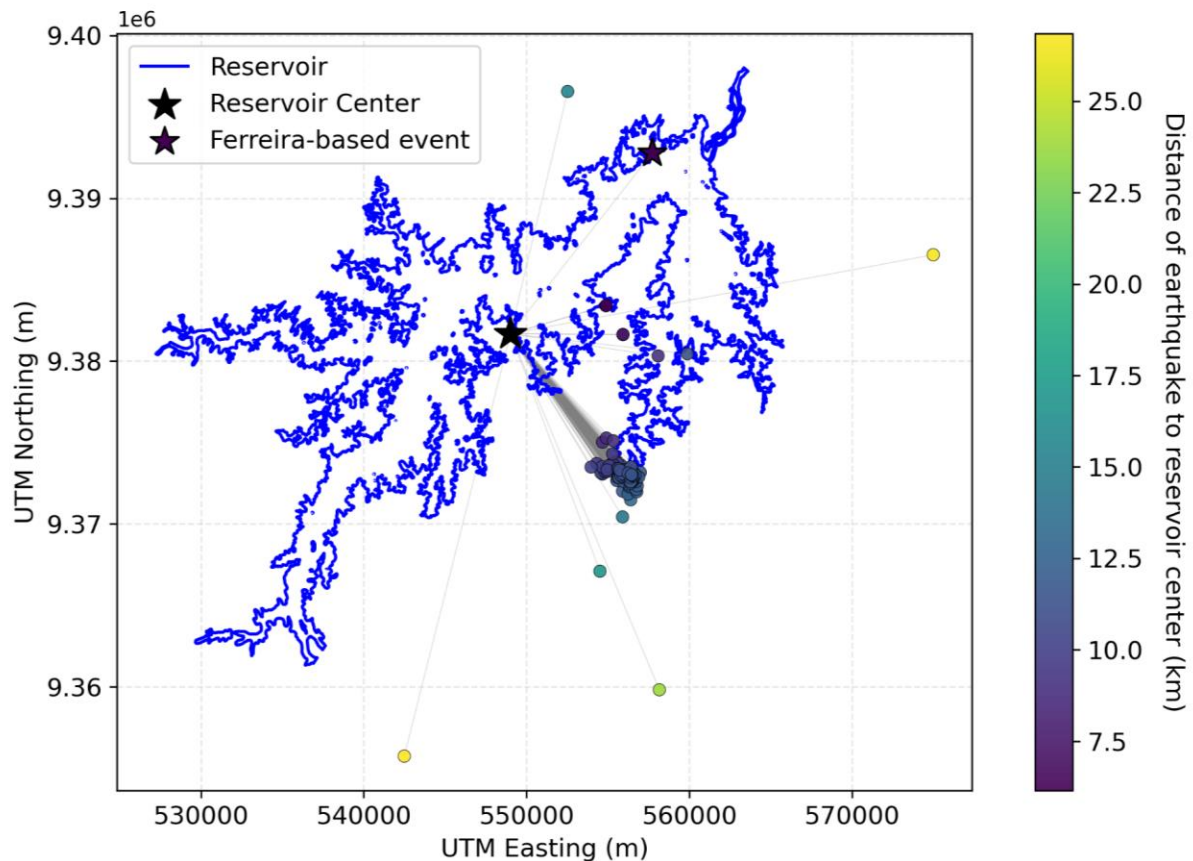


Figure S9: The visualization of calculations of the distance between seismic events and the reservoir center. The circles mark earthquakes from the catalog; the color is based on the computed distance in kilometers. The black star marks the reservoir center and the purple star marks the additional “Ferreira” event.

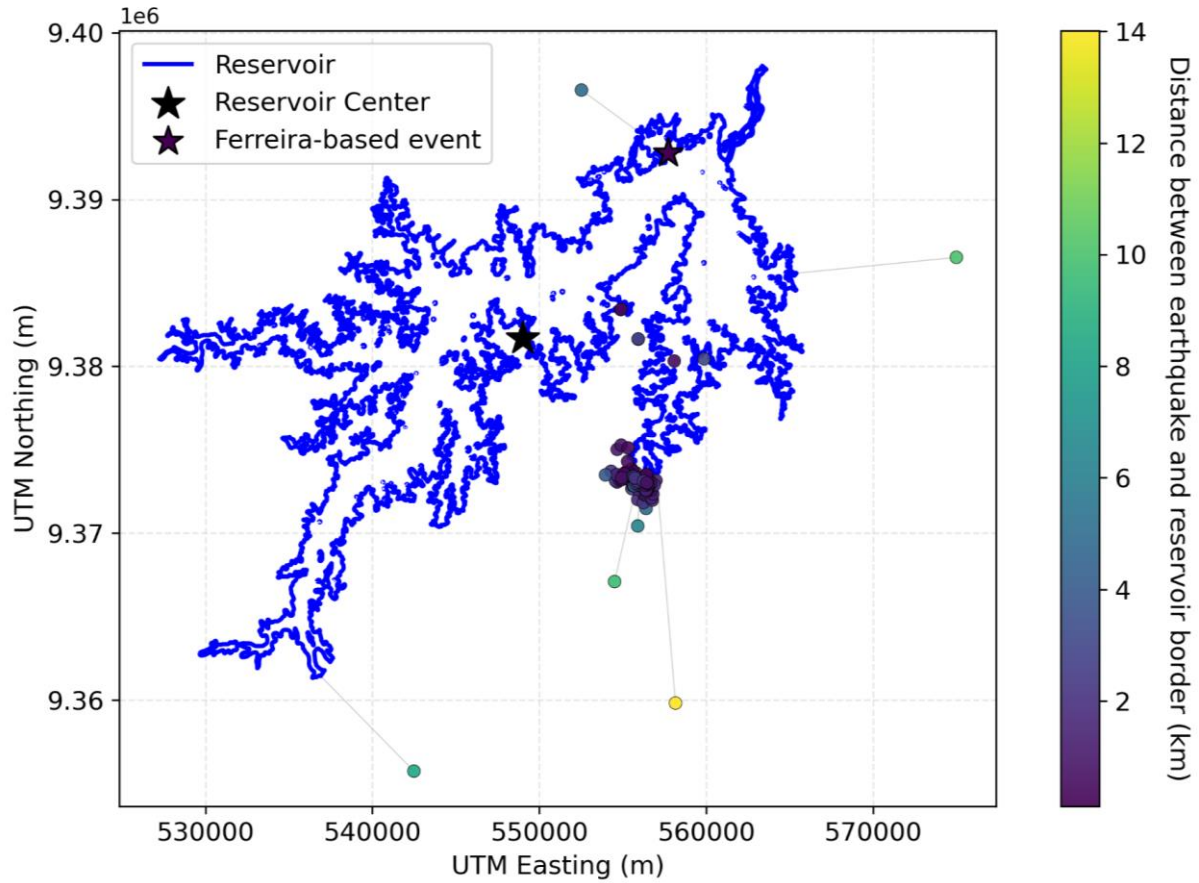


Figure S10: The visualization of calculations of the distance between seismic events and the reservoir border. The circles mark earthquakes from the catalog; the color is based on the computed distance in kilometers. The black star marks the reservoir center and the purple star marks the additional “Ferreira” event.

Table S2: Details of 11 tested approaches for computation of diffusivity c for further use in pore-pressure modelling. The pale blue row marks the approach and diffusivity c value used in the manuscript; the pale purple row marks the approach selected for further computation of pore-pressure change within supplementary materials.

ID	Time of 1st event	Epicentral location of 1st event	Mean diffusivity c (m ² / s)	Distance calculated
1	04.12.2009	(-5.67631, -38.4907)	0.07993 (CI: 0.06085–0.09901)	EQ to reservoir border
2	04.12.2009	(-5.67631, -38.4907)	0.05907 (CI: 0.04312–0.07502)	intervent distance
3	04.12.2009	(-5.67631, -38.4907)	0.12476 (CI: 0.11598–0.13353)	EQ to reservoir center
4	01.01.2002	(-5.67631, -38.4907)	0.00400 (CI: 0.00187–0.00612)	EQ to reservoir border
5	01.01.2002	(-5.67631, -38.4907)	0.05907 (CI: 0.04312–0.07502)	intervent distance

6	01.01.2002	(-5.49337, -38.4790)	0.12476 (CI: 0.11598–0.13353)	EQ to reservoir center
7	01.01.2002	(-5.49337, -38.4790)	0.00400 (CI: 0.00187–0.00612)	EQ to reservoir border
8	01.01.2002	(-5.49337, -38.4790)	0.01874 (CI: 0.00805–0.02943)	intervent distance
9	01.01.2002	(-5.5939, -38.5574)	0.12476 (CI: 0.11598–0.13353)	EQ to reservoir center
10	01.01.2002	(-5.5939, -38.5574)	0.00400 (CI: 0.00187–0.00612)	EQ to reservoir border
11	01.01.2002	(-5.5939, -38.5574)	0.01874 (CI: 0.00805–0.02943)	intervent distance

The diffusivity computational results presented in the Table S2 were obtained by calculating mean values of diffusivity calculated for each seismic event that were later filtered to narrow values for those representative of the local crystalline basement (diffusivities ≤ 10 m²/s).

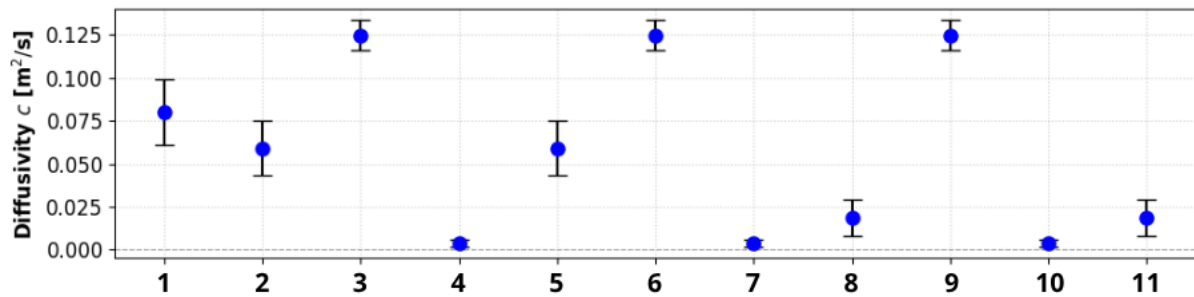


Figure S11: Mean diffusivity c and their confidence intervals for Table S2.

We plotted the pore-pressure diffusion fit for Castanhão Reservoir seismicity for scenario 1 and scenario 4 (Figure S12).

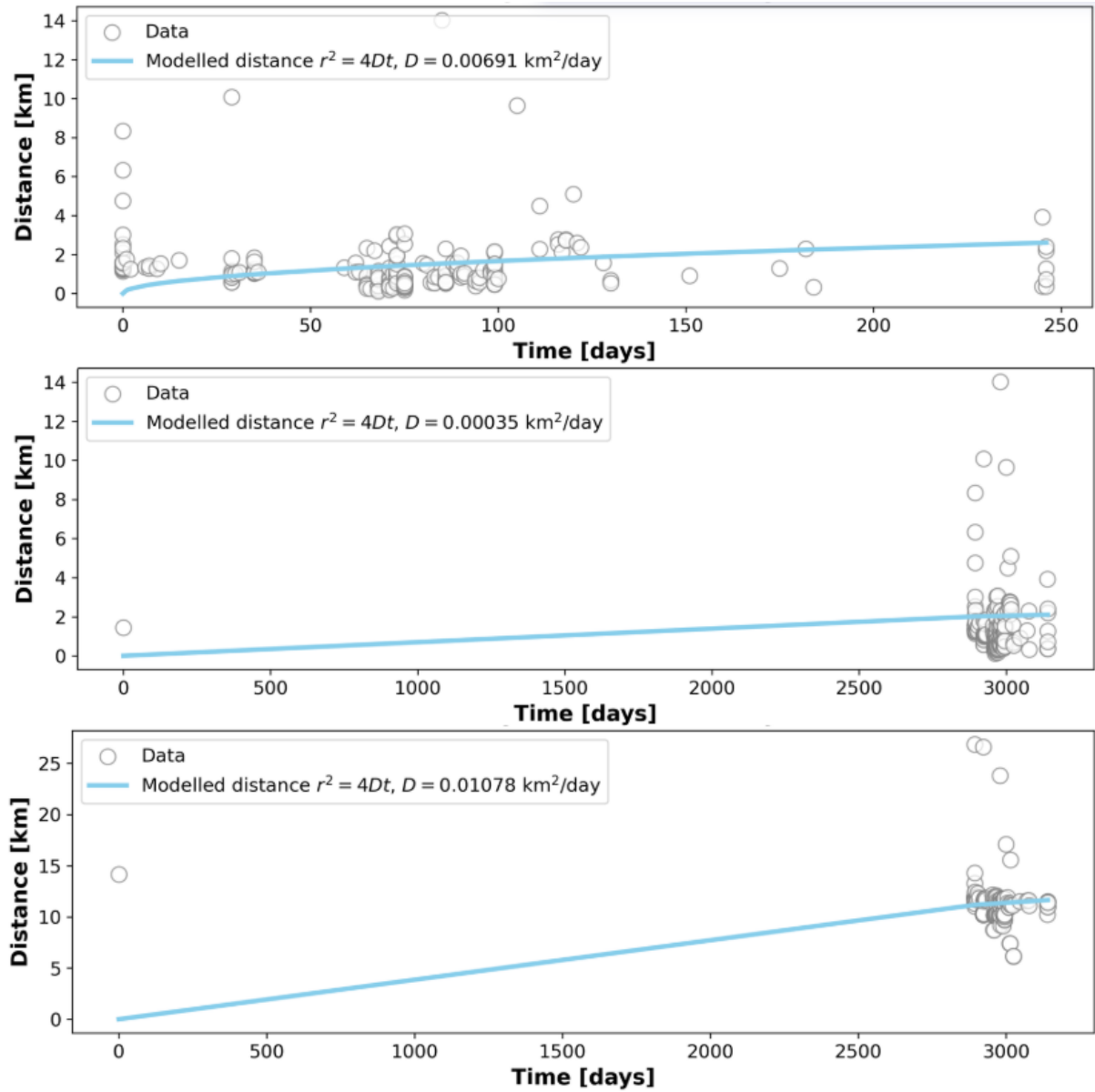


Figure S12: Pore Pressure Diffusion Fit to Castanhão Reservoir Seismicity: (Top) plotted for scenario 1 (Table S2); (Middle) plotted for scenario 4 (Table S2); (Bottom) plotted for scenario 6 (Table S2).

The pore-pressure change was modelled. Here, we present the pore-pressure change for scenario 4 (Figure S13)

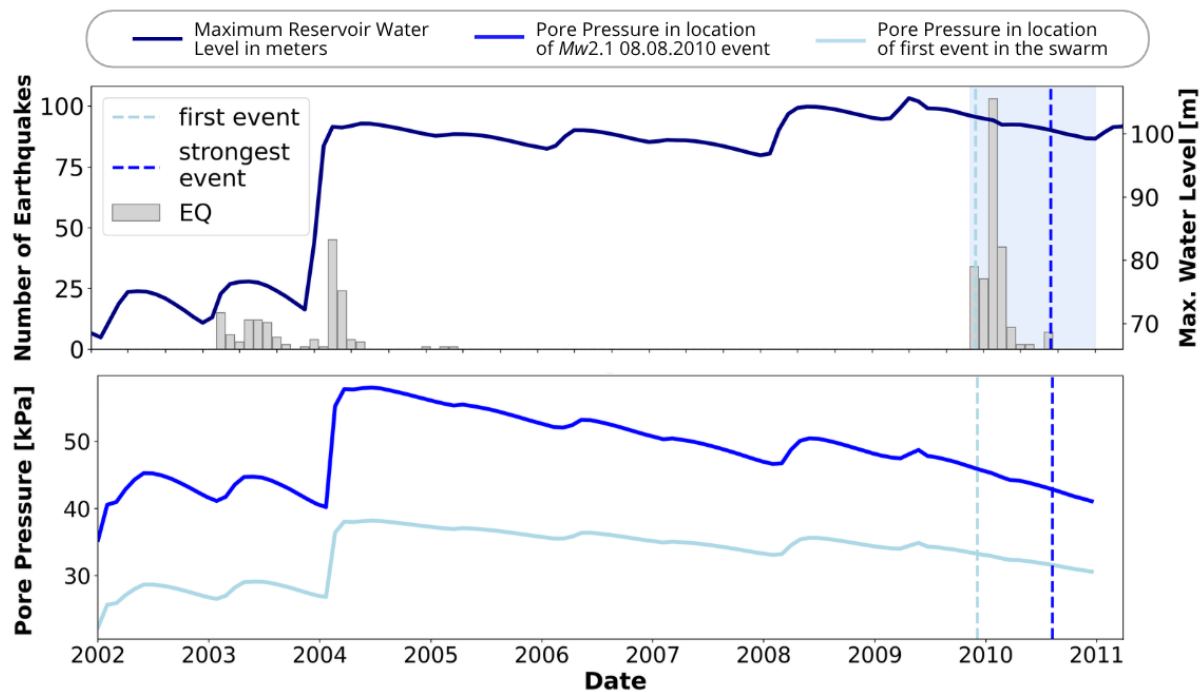


Figure S13: Seismic activity alongside maximal reservoir water levels (given in meters), and pore-pressure change at the hypocentral location of the largest event in the main cluster computed for the scenario 4 (Table S2). The dashed blue line marks the time of Mw2.1 main event, while the light blue dashed line marks the moment of first event within the investigated swarm. **(Top)** Monthly seismic activity compared with the maximum water level of the Castanhão Reservoir. The seismicity in 2003 – 2005 was adapted from the plots in Ferreira et al. (2008). The blue-shaded region indicates the time period during which LS network data were available. The solid navy-blue line shows the monthly maximum reservoir water level (in meters). Light-gray bars represent the number of seismic events per month from the Hypo71-located earthquake catalog. **(Bottom)** Pore-pressure evolution between 2002 and 2011. The light-blue curve denotes pore-pressure changes at the hypocenter of the first earthquake in the Castanhão swarm (4 December 2009). The dark-blue curve shows pore-pressure changes at the hypocenter of the Mw 2.1 event—the largest earthquake in the cluster, which occurred on 8 August 2010.

Additionally, we plotted the pore-pressure at earthquake hypocenters on the day of the Mw 2.1 event (8 August 2010) for scenario 4. This result was shown on Figure S14 and the values do not vary significantly from results computed for scenario 1. From the following analysis, it can be derived that the diffusivity values computed for different scenarios presented in Table S2 do not significantly vary from one another. Our choice was based on the data availability and consideration of the worst-case scenario from the perspective of seismic hazard assessment, thus scenario 1 was selected as such based only on the recorded data, with no additional assumptions of hypothetical onset of RTS within Castanhao Reservoir area.

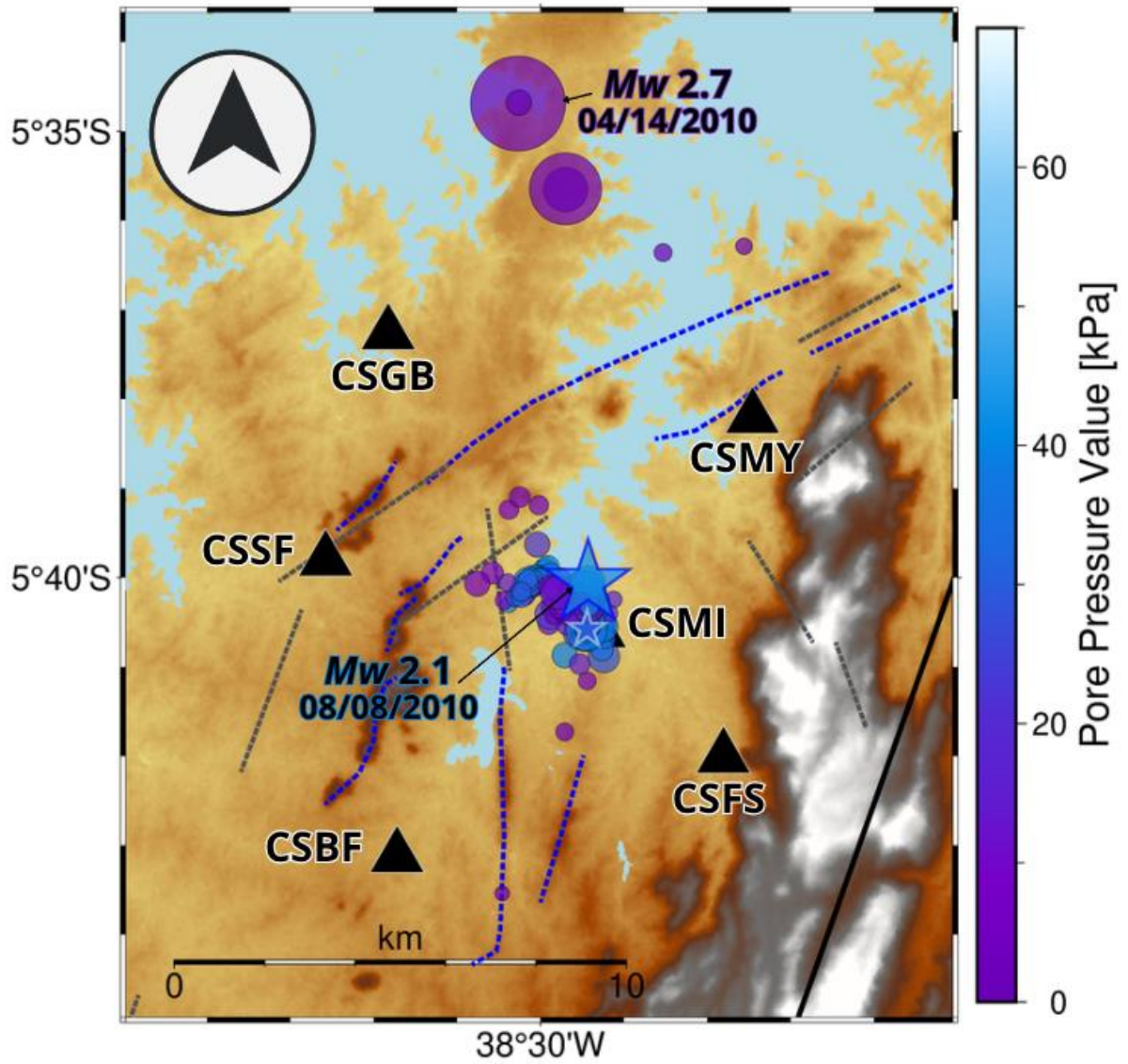


Figure S14: The pore-pressure values computed for the day of the *Mw*2.1 seismic event for scenario 4 (Table S2). Circles colors indicate the total pore-pressure values (in kPa), while point sizes scale with event magnitude, stars mark the first (light blue outline) and main event (blue outline) in the cluster. Black triangles denote the locations of the LS network seismological stations.

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