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Global EarthquakE ScEnarios (GEESE): An OpenQuake Engine-Based Rupture Matching Algorithm and Scenarios Database for Seismic Source Model Testing and Rapid Post-Event Response Analysis

Christopher Brooks *[1], **Marco Pagani** [1,2], **Manuela Villani** [1,3], **Kendra Johnson** [1], **Richard Styron** [1], **Kirsty Bayliss** [1]

[1]Global Earthquake Model (GEM) Foundation, via Ferrata 1, 27100, Pavia, Italy, [2]Adjunct Professor, Institute of Catastrophe Risk Management, NTU, Singapore, [3]Arup, London, United Kingdom

Author contributions: *Conceptualisation*: M. Pagani. *Data Curation*: C. Brooks, M. Villani, K. Bayliss. *Formal Analysis*: C. Brooks, R. Styron. *Investigation*: C. Brooks. *Methodology*: C. Brooks, M. Pagani, M. Villani, K. Johnson, K. Bayliss. *Software*: C. Brooks, R. Styron. *Supervision*: M. Pagani. *Validation*: C. Brooks, K. Johnson. *Writing – original draft*: C. Brooks. *Writing – review & editing*: C. Brooks, M. Pagani, M. Villani, K. Johnson, K. Bayliss.

Abstract The Global EarthquakE ScEnarios (GEESE) algorithm retrieves from a seismic hazard input model the ruptures matching a set of criteria (e.g., magnitude, location, focal mechanism). We applied the GEESE algorithm to create a publicly available database (version 1.0) of finite rupture models for past earthquakes which can be used for scenario seismic hazard and risk analysis applications. To this end, we selected earthquakes with a moment magnitude larger than 7.0 and hypocentral depth less than 200 km in the ISC-GEM catalogue (version 10.0) and retrieved the best matching ruptures from the seismic hazard models in the GEM Mosaic. The GEESE algorithm also automatically computes a set of ground-motion fields using each matched rupture, which are also provided in the database. The ability of the GEESE algorithm to test whether a Mosaic model can generate a rupture sufficiently representative of a queried event is a useful means of evaluating the Mosaic model's seismic source characterisation (SSC). Sufficiently matching ruptures are retrieved from the Global Mosaic for 90 percent of the tested ISC-GEM events. The GEESE algorithm can also be used in post-event response analysis to rapidly obtain an initial finite rupture when only minimal event information is initially available. A demonstration of these capabilities of the GEESE algorithm is provided using the 2023 Morocco earthquake, the 1994 Northridge earthquake, and the 2023 Kahramanmaras earthquake.

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Non-technical summary When evaluating the seismic hazard within a region or site of interest (e.g., a densely populated city or a nuclear power plant), it is essential to realistically model the characteristics (size, geometry, and surface orientation) of large earthquake ruptures that may occur. The GEESE algorithm checks that seismic hazard models developed within the OpenQuake Engine seismic hazard software can provide ruptures representative of the most significant historically-observed earthquakes. For each earthquake queried, the GEESE algorithm searches for an acceptably matching rupture within the considered seismic hazard models. If a match is returned, it suggests that the seismic hazard model is able to generate realistic ruptures. If a match is not returned, it indicates that the seismic hazard model should be revised to include more representative earthquake sources. A database of the finite ruptures obtained from the GEESE algorithm is presented here for the strongest events included in the global-coverage ISC-GEM earthquake catalogue since 1904. For the set of possible ruptures, a dataset providing the geographical distribution of expected ground-shaking levels is also made available.

1 Introduction

The Global Earthquake Model (GEM) Global Seismic Hazard Mosaic (Johnson et al., 2023; Pagani et al., 2020a) is a collection of regional and national models for probabilistic seismic hazard analysis (PSHA) which collectively result in near-complete onshore global coverage (Figure 1). All models are formatted for the OpenQuake Engine (Pagani et al., 2014). The seismic source characterisation (SSC) for each model can include a set of non-parametric earthquake sources with ruptures, modeled as finite three-dimensional surfaces with an assigned moment magnitude (M_w), style-of-faulting, and occurrence rate, or more traditional parametric sources (broadly divided into either faults or distributed seismicity) producing ruptures using the source location, faulting mechanism (strike, dip and rake), magnitude-frequency distribution (recurrence relationship), magnitude-scaling relationship (e.g. Wells and Coppersmith, 1994), and rupture aspect ratio.

When developing the SSC component of a PSHA

*Corresponding author: christopher.brooks@globalquake-model.org

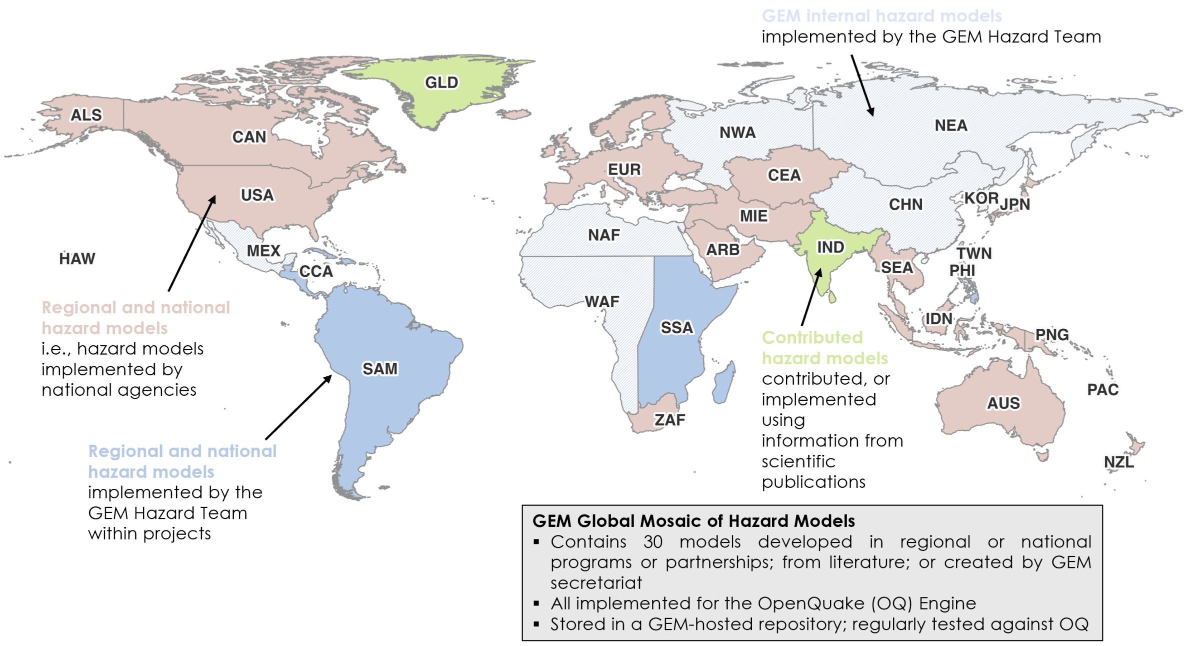

Figure 1 Geographical coverage of the GEM Global Mosaic of Hazard Models. Please refer to https://hazard.openquake.org/gem/ for the complete list of contributors.

model, one aims to include all potential earthquakes that could impact the region of interest. The SSC should contemplate all possible ruptures representing the spatial and temporal distributions of seismicity. The scientific literature presents some approaches for checking the components of an SSC, for example, the consistency of frequency-magnitude distributions (FMDs) with observed catalogues (e.g., Zechar et al., 2010; Rhoades et al., 2011). These approaches usually test the earthquake count, or temporal, spatial, or magnitude distribution of earthquake forecasts compared to some (short) period of observations using a likelihood or information-gain score and can be applied to SSCs. One approach not yet explored within the literature for SSC evaluation is to check if ruptures matching the major geometric and position characteristics of significant historical earthquakes (i.e. appropriate ruptures) can be retrieved from the seismic sources.

For this purpose, we present here the Global EarthquakE ScEnarios (GEESE) rupture matching algorithm and the associated publicly-available database of OpenQuake Engine ruptures obtained from the GEM Mosaic (2023 release - Johnson et al., 2023) for earthquakes $M_w \geq 7.0$ in version 10.0 of the ISC-GEM catalogue (Di Giacomo et al., 2018; Storchak et al., 2013). We only consider ISC-GEM events which occurred onshore or near-onshore and have hypocentral depths of 200 km or less.

In addition to SSC evaluation, the GEESE algorithm can be used to rapidly (near instantaneously) obtain an initial finite rupture for post-event response analysis following a potentially significant event while only minimal information such as magnitude and hypocentral location is available before a more representative rupture model is obtained from (seismic and/or geodetic) data inversion.

The GEESE algorithm differs from other near real-time finite rupture algorithms such as FinDer (Böse et al., 2012, which applies image-recognition techniques to spatial patterns of observed ground-shaking intensities and pre-calculated templates to detect and model ruptures) because it queries the SSCs of the GEM Global Mosaic of PSHA models (the 'Mosaic' herein) rather than using real-time data to obtain the finite rupture model. Therefore, an advantage of GEESE compared to other finite rupture algorithms is that it is capable of generating an initial finite rupture without being dependent on data disseminated post-event. The near-global (onshore) coverage of the Mosaic makes the GEESE algorithm globally applicable, despite regional variability in post-event data response. The GEESE algorithm also computes spatially-correlated and cross-correlated ground-motion fields (GMFs - geographical distributions of the estimated ground-shaking intensities at the sites of interest) for each rupture matched to an event; these GMFs are also provided within the GEESE database. The computed GMF is conditioned (adjusted) using observed ground-shaking intensities if station data is readily available for the event.

2 The GEESE Algorithm

The GEESE algorithm can be subdivided into a small number of phases which are summarised within this article: firstly, the generation of ruptures from appropriate sources; secondly, the identification of the generated ruptures which best match the admitted event information; and lastly, the computation of GMFs using the retrieved ruptures and the exporting of the GEESE results as OpenQuake-calculation-formatted input and output files. This article primarily focuses on demonstrating the rupture matching components of the GEESE algorithm (Sections 3 - 8), which leverages the capabilities of the OpenQuake Engine and the Mosaic, and the results when applied to the ISC-GEM catalogue. The post-rupture matching components of the algorithm are also briefly described here to complete the workflow summary (Sections 9 and 10).

To provide a step-by-step demonstration of the rupture matching component of the GEESE algorithm, we consider here three earthquakes of engineering significance. The first is the M_w 6.8 Morocco event which occurred on 8th September 2023, the second is the M_w 6.7 Northridge event which occurred on 17th January 1994 in California, and the third is the M_w 7.8 Kahramanmaras event which occurred on 6th February 2023 in Türkiye. The first two of these events are slightly smaller than the GEESE version 1.0 threshold of M_w 7.0 (chosen to reduce the size of the initial database version, allowing for easier validation and quality assessment). However, they are ideal events for demonstrating the GEESE algorithm, given that one is a very recent event and therefore was not directly considered in the development of the pertinent Mosaic model, and one is a well-studied historical event, with consensus on the rupture characteristics and directly considered in developing the corresponding Mosaic model. Additionally, the use of events less than M_w 7.0 demonstrates that the GEESE algorithm can be used to obtain finite ruptures for moderate size events. The 2023 Kahramanmaras event is also not included in version 1.0 of the GEESE database since it post-dates the ISC-GEM catalogue version 10.0, which ends in February 2019, but we believe it is important to demonstrate the ability of GEESE to provide a finite rupture for this event given its considerable engineering significance. Some basic information for these events is provided in Table 1 as obtained from the USGS ShakeMap service (https://earthquake.usgs.gov/data/shakemap/ - last accessed in June 2025).

3 Preprocessing of the Admitted Events

The GEESE algorithm preprocesses the inputted earthquake catalogue to obtain necessary information for the subsequent stages of the workflow. In our application, we opted for a subset of the earthquakes in the ISC-GEM (version 10.0) earthquake catalogue, but the algorithm works with any catalogue, provided it contains essential information like hypocentral coordinates, magnitude, and (if available) focal mechanism.

This preprocessing first assigns a simplified tectonic region type (TRT), i.e., crustal, subduction intraslab, subduction interface, or deep (greater than 400 km hypocentral depth), for each event using the earthquake classification tools in the Subduction module of the OpenQuake Model Building Toolkit (see also Pagani et al., 2025, 2020b). The TRT is not used to filter the possible sources that may generate the earthquake in order to avoid erroneously removing potential rupture candidates, but is instead used in the GMF computation stage (please see Section 9 for more details).

Following the assignment of a TRT, each event is matched to a Mosaic model based on its epicentre. A buffer of 15 km is applied to SSC boundaries, accounting for potential epicentral uncertainty. The version of GEESE used here cannot find ruptures for offshore events located outside such buffers, but will be possible in the near future as Mosaic coverage expands to include the oceans.

For the test cases, GEESE assigned the 2023 Morocco event a crustal TRT and the Northern Africa (NAF) model; the 1994 Northridge event a crustal TRT and the USA model; and the 2023 Kahramanmaras event a crustal TRT and the European (EUR) model. The epicentre of the 2023 Kahramanmaras event is located within the SSC boundaries of both the EUR model and the MIE (Middle East) model (the geographical coverage of the SSCs of these models overlap). GEESE permits manual selection of the Mosaic model in instances in which the event is located within the boundaries of more than one SSC. Here, for the 2023 Kahramanmaras event we selected the EUR model, which is more recent than MIE. The NAF model was developed by GEM for the Global Mosaic (Poggi et al., 2020). The USA model is an OpenQuake Engine implementation of the 2018 Conterminous United States National Seismic Hazard Model (Petersen et al., 2019). The EUR model is the 2020 European seismic hazard model (ESHM20 - Danciu et al., 2021) which was developed in the OpenQuake Engine format (i.e. it's a native model).

4 Identifying the Seismic Sources

Next, the algorithm identifies the sources which are potentially capable of generating ruptures consistent with the event data. The source-filtering component of the GEESE algorithm is schematically summarised in Figure 2. When the SSC of a Mosaic model contains multiple seismic source models (SSMs) (e.g., for EUR, which contains both a distributed seismicity and fault-based SSM and an area source SSM), all are parsed to ensure that every possible source is considered.

The first filtering stage compares the magnitudes and depths of the sources to the given event. For both the event and the sources, magnitude and depth uncertainty are considered to ensure sources which could potentially generate good rupture candidates are not removed. The uncertainty in the event magnitude and event focal depth is taken from the ISC-GEM catalogue. Approximately 40 percent of the tested events have a very small magnitude uncertainty (0.1 or less) and approximately 5 percent have a large magnitude uncertainty (greater than 0.5). Approximately 15% of the tested events have a focal depth uncertainty of 25 km or greater. To account for the uncertainty in source parameterisation when developing an SSC, we apply the following uncertainties to each source: -0.5 to the minimum magnitude, +0.5 to the maximum magnitude, and 25 km to the lower seismogenic depth. In the OpenQuake Engine, the lower seismogenic depth of a source is a firm boundary that constrains the maximum depth to which a rupture can extend.

After filtering the sources by magnitude and lower

Event ID	Date	Time	Hypo. Lon. (°)	Hypo. Lat. (°)	Hypo. Depth (km)	M_w	Strike (°)	Dip (°)	Rake (°)
Morocco	2023-09-08	22:11:01	-8.385	31.058	19	6.8	255	69	69
Northridge	1994-01-17	12:30:55	-118.537	34.213	18	6.7	130	53	111
Kahraman-maras	2023-02-06	01:17:04	37.014	37.26	10	7.8	227	89	-1

Table 1 Basic information for each of the events considered in this study for demonstrating the rupture matching component of the GEESE algorithm. Only the nodal plane solution most favourably fitting to the rupture matched in the GEESE algorithm is provided here for each event. Information for these events is from https://earthquake.usgs.gov/data/shakemap/ (last accessed June 2025).

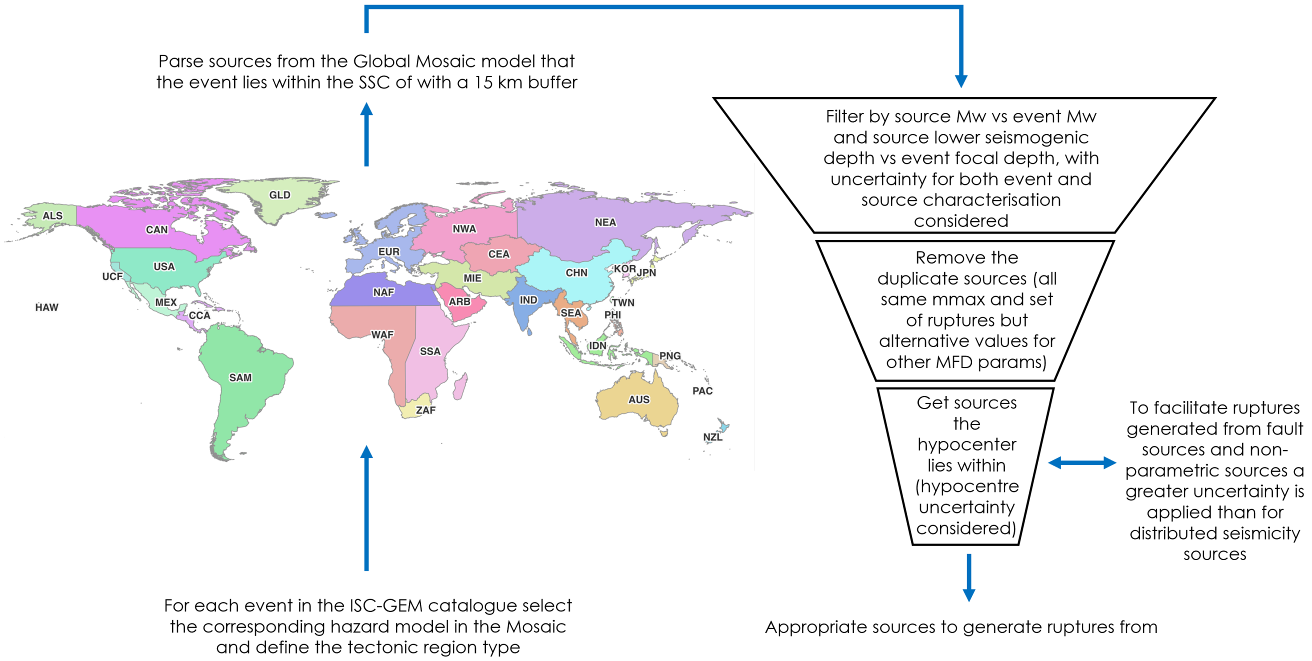

Figure 2 Schematic diagram summarising the process for the identification of appropriate sources to generate ruptures from within the GEESE algorithm.

seismogenic depth, "duplicate" sources that consider epistemic uncertainty of only the earthquake recurrence parameters are removed – but keeping the full magnitude range among sources – to reduce the number of sources used to generate ruptures in subsequent steps. Epistemic uncertainty refers to the lack of knowledge regarding the underlying physical processes contributing to the potential seismic hazard, and is accounted for within a PSHA model by considering all realistically conceivable "realisations" of such physical processes. Within the SSCs of the Mosaic models the epistemic uncertainty is captured by considering multiple parameterisations of each seismic source. Some models in the Mosaic contain sources that generate exactly the same set of ruptures – in terms of geometry and magnitude – but with different rates of occurrence. In the context of GEESE, where we do not consider the rates of occurrence, these sources are effectively duplicates. Therefore, if the magnitude range and set of ruptures are the same among duplicate sources, it is only necessary to retain one 'version' of these duplicate sources (i.e. we can arbitrarily retain any single version of these duplicate sources and not unintentionally reduce the number of potential candidate ruptures). An exception is made, however, in the case of non-parametric seismic sources, which contain a set of predefined ruptures paired with probability of occurrence in a given time window, rather than an annual occurrence rate obtained from a FMD – as for conventional parametric seismic sources. Therefore, given each 'version' of a non-parametric seismic source contains a different set of ruptures, we retain all realisations to ensure potential rupture candidates are not discarded in such cases.

For the retained (magnitude filtered and deduplicated) sources a simple spatial filtering is performed based on the hypocentre location and its reported uncertainty. If an uncertainty is not provided by the catalogue a default value of 5 km is assigned. A 25 km buffer is applied to the polygon representing the surface of each fault source and a 10 km buffer is applied for all other source types, in order to favour the assignment of fault sources from which potentially better matching ruptures can be generated. Further pref-

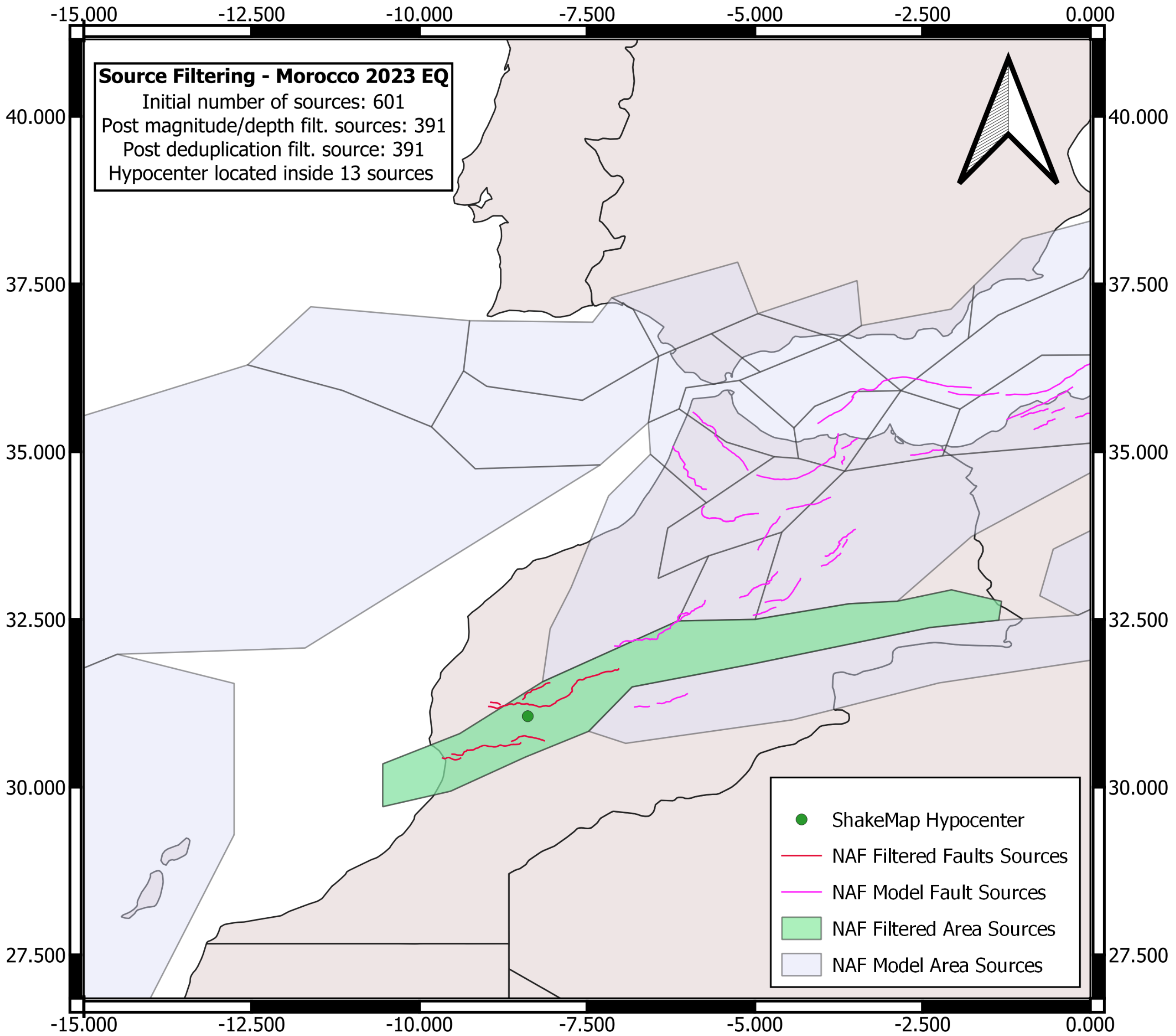

Figure 3 Example of the seismic source filtering process for the 2023 Morocco event, with the identified multi-point sources (an OpenQuake source typology used to model distributed seismicity) not plotted.

erence to faults is enforced in the rupture matching algorithm by giving priority to ruptures generated from faults over those from distributed seismicity sources. We also apply the same preferential conditions to non-parametric sources because similar to faults they may generate better matching ruptures than the distributed sources (given they contain sets of predefined ruptures). If no source is associated to the event, a simple fallback is employed in which any sources within 25 km of the event hypocentre are considered.

For each event, following all filtering steps (i.e., magnitude, depth, deduplication, and spatial), the algorithm either proceeds to the rupture generation stage or terminates if no sources are retained. Figure 3 provides an example of the source filtering for the 2023 Morocco event, where we obtain thirteen sources, with four of these sources being fault sources.

5 Generating Ruptures from the Sources

After the GEESE algorithm has identified the sources capable of potentially generating appropriate ruptures for a given event, for each of them the full set of ruptures is generated using the OpenQuake Engine. For each rupture, information about the surface geometry, M_w, rake, centroid location and the associated source is readily available. It is important to note that because the GEESE algorithm is leveraging the OpenQuake Engine's capabilities and the Mosaic models, we must consider the specificities of the various typologies (classes) of sources which can be used to model seismicity within

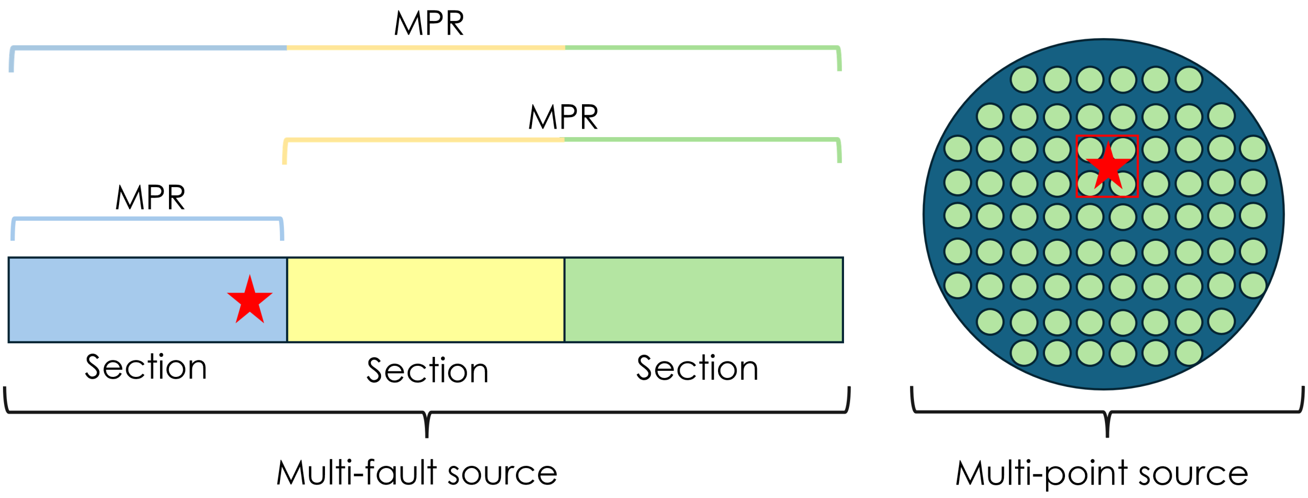

Figure 4 Visualisation of methodology for parsing down the number of ruptures to be generated from multi-fault (left panel) or multi-point sources (right panel). The red stars represent the event hypocentres. The red box in the right panel shows the hypocentre location uncertainty. Green circles represent the nodes within the multi-point source. MPR = multi-planar rupture, each of which consists of different combinations of the sections within the multi-fault source.

a hazard model. Some of these source typologies, such as multi-fault sources (probabilistic rupture forecasts considering many potentially connecting fault sections) or large area sources or multi-point sources (a typology for modeling distributed seismicity) contain potentially millions of ruptures. Consequently, to minimise computational demand and execution time of the GEESE algorithm we must reduce the number of ruptures generated from each source where possible.

For sources of the multi-fault typology we only consider multi-planar ruptures (ruptures resulting from the conjoining of individual fault rupture sections) that are associated with the fault sections within 25 km of the event hypocentre, rather than generating ruptures from the entire multi-fault source (i.e. avoiding generating all possible combinations of sections predefined in the multi-fault source). If no sections are within 25 km of the event hypocentre, the multi-fault source is discarded. An initial filtering of the multi-planar ruptures by magnitude is applied prior to the distance calculations required to obtain the closest multi-fault source sections to the event hypocentre, which helps further reduce the computational demands of generating ruptures from this source typology.

Similar steps to reduce the number of ruptures generated are also undertaken for area or multi-point sources, in which we only consider the rupture generating nodes within the hypocentre location uncertainty of the event. The process for parsing down the number of ruptures generated from a multi-fault source and a multi-point source is summarised in Figure 4.

6 Matching Ruptures to Events

The generated ruptures must now be evaluated in terms of how well they match the information available for the considered events. This evaluation is performed using a rupture matching algorithm initially developed for the OpenQuake-leveraging HAMLET (tools for hazard model evaluation and testing) software package (Styron et al., 2023). Figure 5 provides a schematic diagram summarising the rupture matching component of the workflow.

The algorithm computes likelihood scores to describe the match between particular characteristics of the ruptures (magnitude, hypocentre location and nodal planes) and the information describing the considered event. Table 2 provides some basic information for each considered likelihood score, including how each is computed from the OpenQuake ruptures and the admitted event information. The total likelihood score for each admitted rupture is taken as the geometric mean of the individual likelihood scores, and is considered representative of how well the rupture matches the event overall. If both nodal plane solutions are available then both sets of strike, dip and rake are by default compared against the candidate ruptures. The total likelihood score associated with the best matching event nodal plane solution is taken for each rupture. If no nodal plane solutions are available for the event, then evaluation of the degree of similarity between the strike, dip and rake of the admitted ruptures and of those constrained for the event is not possible. In such cases an arbitrary default value of 0.5 is assigned to the nodal plane likelihood score, and the rake likelihood score.

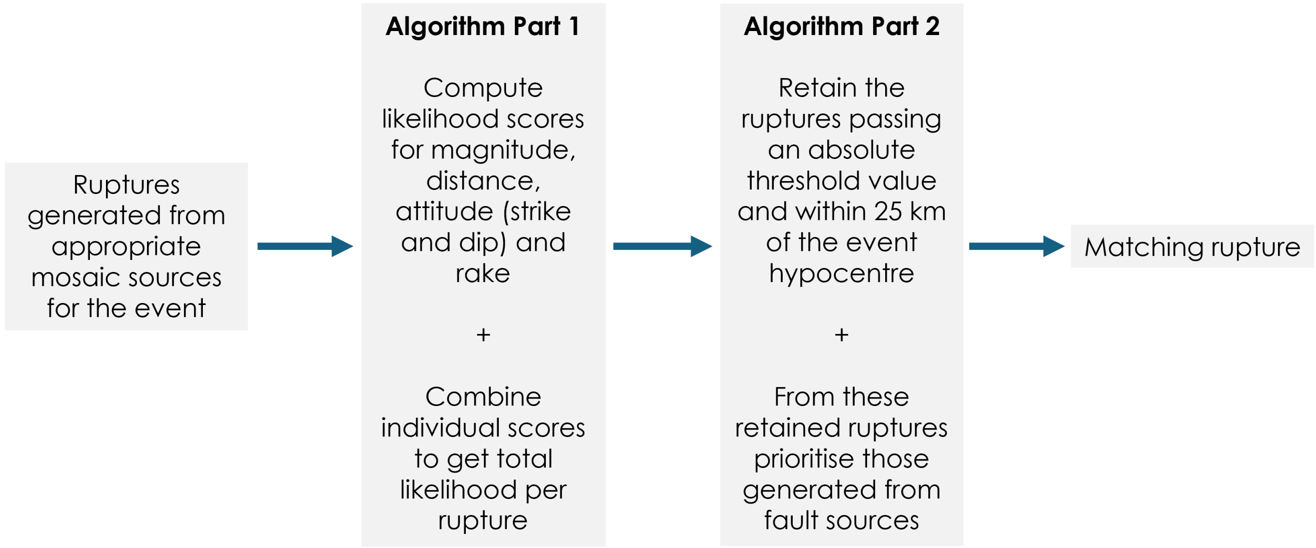

Figure 5 Schematic representation of the rupture matching component of the GEESE algorithm.

Using a default value for the nodal plane and rake likelihood scores in such cases turns off the impact of the nodal plane and style of faulting on the chosen solutions because we are assigning uniform values to all of the ruptures which could be matched to the given event, and therefore such scores will have no impact on the total likelihood score for each rupture. If the dip of the admitted event is steep (greater than 80 degrees), each nodal plane's strike plus/minus 180 degrees is also considered. This choice is made because for near-vertically dipping events, a rupture with a similar overall orientation to one of the event's nodal plane solutions can potentially be obtained if plus/minus 180 degrees is applied to the matched rupture's strike (this is emphasised here because otherwise a matched rupture's strike for a steeply dipping event may appear unfavourable without applying this logic).

By default, ruptures with total likelihood scores exceeding a threshold of 0.1 are considered as matching sufficiently to the event. A threshold of 0.1 was found to differentiate well between ruptures which sufficiently and insufficiently match the information provided for the admitted events, based on careful manual comparison of the locations, geometries, and magnitudes of the matched ruptures and the ISC-GEM catalogue events. There is subjectivity associated with the default threshold of 0.1 given it is informed by these manual comparisons, and the threshold is configurable within the GEESE algorithm inputs.

Ruptures generated from fault sources are prioritised by the algorithm – i.e. a rupture with a lower likelihood score from a fault source will be retained over a rupture with a higher likelihood score from a distributed seismicity source, assuming the total likelihood score of the rupture from the fault source exceeds the 0.1 score threshold. By default, if the distance between the rupture centroid and the event hypocentre is greater than 50 km the rupture is discarded, even if the rupture's total likelihood score exceeds the threshold of 0.1. Beyond a distance of 50 km we assume that the rupture centroid and the event hypocentre are too far apart to be considered an acceptable match. We found that a 50 km distance threshold returned a well-matching rupture for most of the tested ISC-GEM events. This distance threshold parameter is also configurable within the algorithm inputs. OpenQuake ruptures always model the rupture hypocentre as equivalent to the rupture centroid (whereas in reality the hypocentre location can vary along the fault plane) and therefore this constraint may need to be relaxed in certain instances to obtain a matching rupture when querying some events. Future versions of GEESE could use a model for distributing the hypocentral locations along the rupture planes to help alleviate the dependency of the rupture matching process on this simplified treatment of the rupture centroids as being equivalent to the event hypocentres.

It should lastly be noted that in instances where no ruptures are matched to an event but likely appropriate sources were identified (i.e. no ruptures generated obtain a total likelihood score greater than 0.1), the sources from which ruptures were generated are logged as "failed", and thus can be examined manually to better understand why no matching ruptures could be obtained from the given Mosaic model's SSC. This is a useful application of the GEESE algorithm from an SSC development and testing perspective – that is, it permits us to quickly identify sources which are not capable of generating an event known to be possible.

7 Matches Obtained for the Example Events

Figures 6, 7, and 8 show the positions of the best matching ruptures obtained relative to the hypocentres of the 2023 Morocco, 1994 Northridge, and 2023 Kahramanmaras events, respectively. Some basic information is also provided regarding the characteristics of each matched rupture and the corresponding characteristics for the queried events obtained from

Likelihood Score	Definition	Formula
Magnitude	Evaluate degree of similarity between rupture M_w and event M_w.	$likes_{mag} = 1 - M_{eq} - M_{rup} \vee$
Nodal plane	Evaluate degree of similarity in rupture plane orientation and the nodal plane solutions provided for the event in terms of strike and dip.	$likes_{nodal} = \cos(\Delta_{nodal})$ where Δ_{nodal} is the overall angle in radians between the rupture's nodal plane and an event nodal plane.
Rake	Evaluate degree of similarity between rupture rake and event rakes (i.e. style of faulting).	$likes_{rake} = \cos(\Delta_{rake})$ where Δ_{rake} is the angle in radians between the rupture's rake and an event rake value.
Distance	Evaluate degree of similarity in rupture centroid location and event hypocentre location. Hypocentral depth is considered.	$likes_{dist} = e^{\frac{-R_{geodetic}}{\lambda_{dist}}}$, where $R_{geodetic}$ is the geodetic distance between the rupture centroid and the event hypocentre, and λ_{dist} is a constant of 20 km.

Table 2 Overview of the individual likelihood scores used to evaluate the degree of similarity between the OpenQuake ruptures and the admitted event information.

the USGS ShakeMap service. The corresponding finite rupture models downloadable from ShakeMap are also plotted, although it should be noted that the properties of these rupture models usually diverge slightly from the ShakeMap event information provided in Table 1 due to the potential use of additional data such as aftershock patterns, geodetic measurements, teleseismic waveforms and station recordings to further refine them (i.e. the compilation of the ShakeMap event information and the source inversions used to obtain the ruptures available from ShakeMap are performed independently). It is also important to clarify that the downloaded "ShakeMap ruptures" are obtained from detailed source inversions, rather than being generated within the ShakeMap service itself.

For the 2023 Morocco event, a rupture with a total likelihood score of approximately 0.72 was obtained from a nearby fault source. A total likelihood score of 0.72 is far above the match threshold of 0.1, suggesting that the properties of the retrieved rupture should well represent the ShakeMap information admitted into GEESE for the 2023 Morocco event. The rupture surface is approximately 13 km (in terms of rupture distance) from the estimated hypocentre provided for this event. The matched rupture is also positioned close to the ShakeMap rupture, and the rupture surfaces are similar in orientation (i.e. strike). The surface of the matched rupture is more complex than the surface of the ShakeMap rupture because the GEESE rupture captures the geometric details (i.e. a fault trace that follows a mapped surface trace) of the respective fault source in the NAF model's SSC, while ShakeMap uses a planar rupture. The matched rupture does not reach the surface, which is consistent with the ShakeMap rupture. The 2023 Morocco event is classified as an oblique-reverse faulting-style event (rake of 69 degrees), and this is fairly well represented by the matched rupture's rake value of approximately 90 degrees (reverse faulting). The matched rupture and the ShakeMap rupture have reasonably comparable dip angles (37 degrees and 69 degrees respectively). The difference in these dip angles could be attributed to potential differences in the modelling of fault geometries within the NAF Mosaic model's SSC and the source inversion used to obtain ShakeMap rupture; Poggi et al. (2020) based the NAF fault dip on values from literature, and use commonly assumed shallow-to-moderate dips for reverse faults, but note that other inherited structures in the Atlas mountains dip at steeper angles. The M_w of the matched rupture (M_w 6.75) is in effect identical to the M_w provided by ISC-GEM (M_w 6.8), and the overall area of the rupture surfaces is reasonably similar too.

For the 1994 Northridge event, a rupture with a total likelihood score of approximately 0.83 was obtained from the nearby multi-fault source, which suggests the rupture retrieved for this event should also well represent the ShakeMap information admitted into GEESE. The rupture surface is approximately 3 km (in terms of rupture distance) from the estimated hypocentre provided for this event. The ShakeMap rupture provided for this event is based on the Wald et al. (1996) finite rupture model. Comparisons herein are made to the Wald et al. (1996) rupture's nodal plane solution rather than the ShakeMap nodal plane solution reported for this event (although as mentioned above they only marginally differ). The matched rupture is M_w 6.7, which is the same as the M_w provided for this event. The overall size of the matched rupture's surface and the Wald et al. (1996) rupture model are similar. The matched rupture's surface geometry is more complex than that of the Wald et al. (1996) rupture. The increased complexity of the surface geometry of the rupture retrieved by GEESE can potentially be attributed to the rupture having been generated from a multi-fault source. The rake of the matched rupture is 107 degrees and the rake of the Wald et al. (1996) rupture is 102 degrees. These rake values are similar and can both be classified as reverse style faulting. The dip values are also similar for the matched rupture (35 degrees) and the Wald et al. (1996) rupture (40 degrees). The matched rupture's overall strike (i.e. the average strike given the rupture is multi-planar) is 114 degrees, which is similar to the strike of the Wald et al. (1996) rupture (122 degrees). The good match observed here demonstrates GEESE's ability to manage and retrieve the most appropriate combinations of the multi-

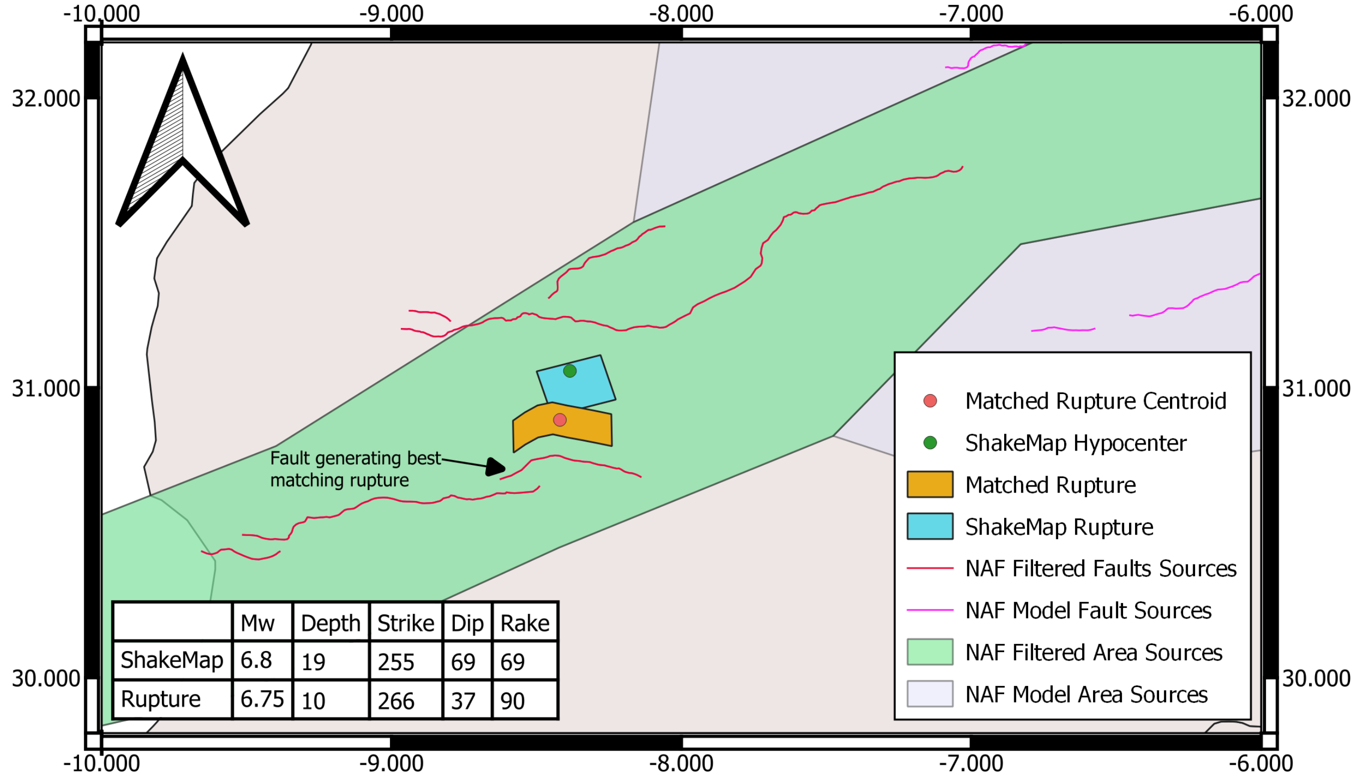

Figure 6 Rupture matched to the 2023 Morocco event by the GEESE algorithm and the rupture obtained from ShakeMap.

planar ruptures from the large and schematically complex multi-fault sources, which are a major component of the USA model's SSC.

A characteristic of the 1994 Northridge event often noted in the literature (Jones et al., 1994; Hough et al., 2024) is that this rupture was blind (i.e. the rupture did not reach the surface). The rupture obtained from the Mosaic for this event is also blind (none of the points in the three-dimensional surface used to construct this rupture's surface reach a depth of zero), thus suggesting that the blind nature of this event is well represented by the ruptures available within the USA model's SSC. This demonstrates another application of the GEESE algorithm for evaluating the SSC of an OpenQuake Engine format hazard model – that is, we can obtain the best matching rupture from a statistical (total likelihood) perspective for an important event and then further interrogate to check if any additional information provided in detailed studies (e.g. whether the rupture is blind as considered here for the 1994 Northridge event) is represented by the retrieved rupture.

While the positive performance for the Northridge event is validating for the GEESE algorithm, it is important to note that for this event in particular we expect high performance, as the USA model and ShakeMap are both USGS products with a significant overlap in the information used for each. The SSC for the faults in California in the USA model (i.e. UCERF3; Field et al., 2017) is one of the most detailed in terms of both modelling complexities and data availability, and the Northridge rupture would have been directly considered in the inversion. Thus, this event remains an important test case for the minimum performance expected.

For the 2023 Kahramanmaras event, a rupture with a total likelihood score of 0.82 was obtained from an adjacent fault source, which is reflective of the good overall match between the retrieved rupture and the admitted ShakeMap information. The 2023 Kahramanmaras event is classified as a strike-slip faulting-style event (rake of -1 degree), which closely matches the rake of the retrieved rupture (-5 degrees). The matched rupture is M_W 7.6, which is slightly smaller than the M_W 7.8 provided by ShakeMap for this event. Both ruptures are near-vertically dipping (84 degrees for the GEESE rupture and 89 degrees for the ShakeMap rupture), and the average strikes are identical, confirming that the matched rupture and the ShakeMap rupture are similarly oriented. Both ruptures have complex surface traces that reflect how both the EUR model and ShakeMap considered the fault trace, which was mapped prior to the event. The position of the event hypocentre relative to the smaller rupture segment (which is only present in the ShakeMap rupture) indicates that the rupture likely originated on a smaller fault plane before extending onto the larger fault plane. The GEESE rupture does not include the smaller segment because it is not included in the EUR model's SSC (see the fault traces in Figure 8). However, this smaller rupture segment is only about 45 km in length, which is fairly small compared to the total length of both the

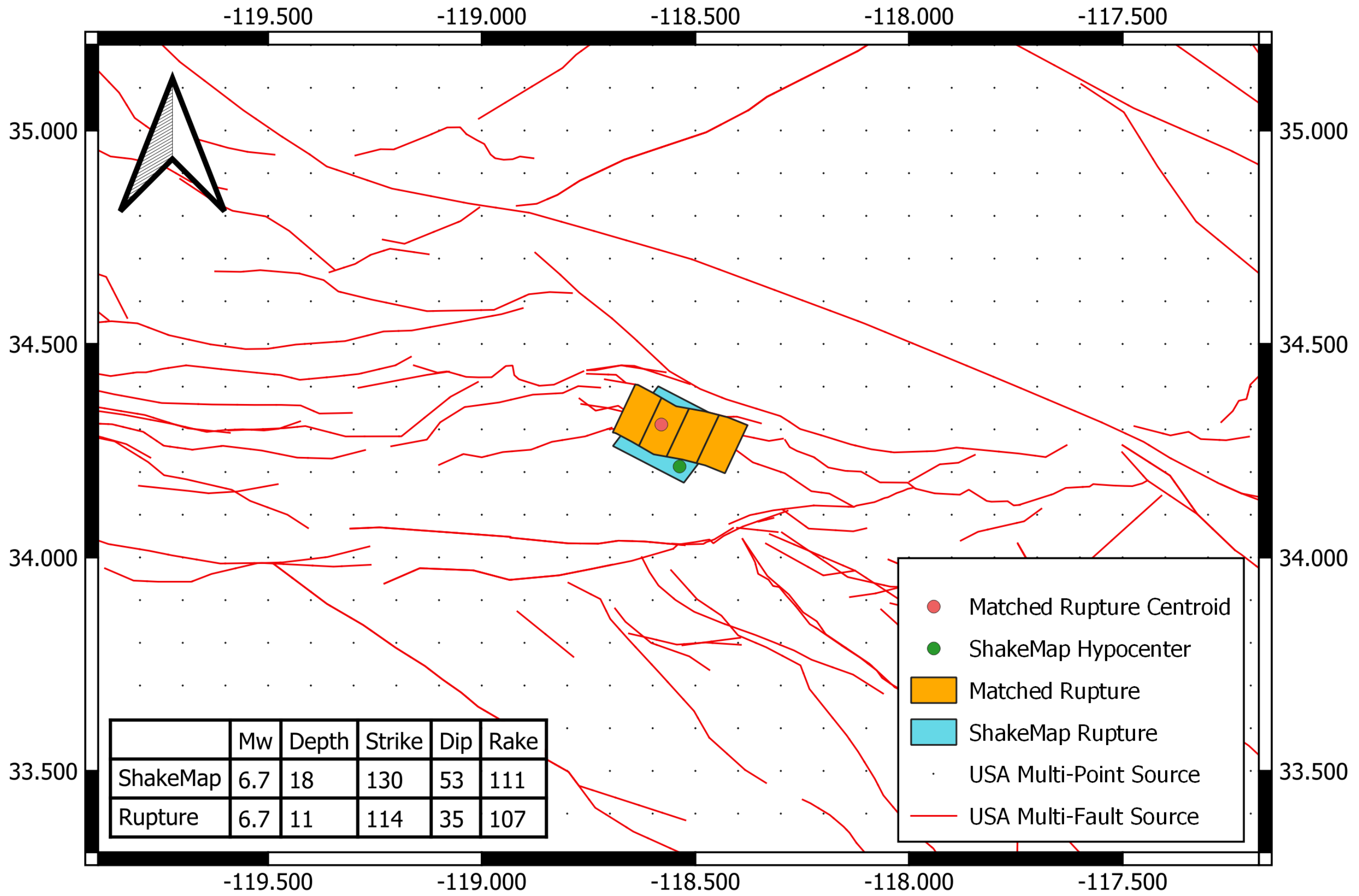

Figure 7 Rupture matched to the 1994 Northridge event by the GEESE algorithm and the rupture obtained from ShakeMap. The event information here corresponds to Table 1 (ShakeMap info) rather than the nodal plane solution of the Wald et al. (1996) rupture model (the rupture plotted here and downloaded from ShakeMap).

ShakeMap rupture and the rupture retrieved by GEESE (lengths of approximately 270 km and 310 km respectively). In addition to the absence of the smaller rupture segment, the matched rupture is approximately 40 km longer than the ShakeMap rupture in the northeast. This results from the geometric assumptions used to delimit ruptures from OpenQuake fault sources in the EUR model, e.g. the rupture aspect ratio and magnitude scaling relationship, whereas the source inversion used to obtain the ShakeMap rupture considers seismic and geodetic data to determine the rupture boundaries; such a discrepancy is reasonable given the range of rupture dimensions and shapes for earthquakes of this magnitude. Despite the reduced geometrical complexity and moderately greater length of the matched rupture, the (non-conditioned) GMFs computed using either this rupture or the ShakeMap rupture (with the same GMM logic tree and local site conditions) are comparable (Figure 9 – the maximum absolute difference for SA(0.3) is observed close to the event hypocentre and is approximately 37%), which is reassuring given the GEESE rupture is near-instantly obtained without additional data, and further validates the utility of GEESE for obtaining a usable initial finite rupture in post-event response analysis prior to more information becoming available.

8 Matches Obtained for the ISC-GEM Catalogue Events

Of the 1204 ISC-GEM events of M_w 7.0 or greater with hypocentral depths of 200 km or less, 1116 could be assigned to a Mosaic model, and 1006 of them (90 percent) successfully had a rupture matched to them from the corresponding SSC. Of these matched ruptures, 752 (75 percent) were generated from fault sources or nonparametric sources (i.e. sources which likely generate better matching ruptures because they more explicitly model the large events admitted here into GEESE). Of the 110 events assigned to a Mosaic model but to which no rupture could be matched, the majority of these events were assigned to the PAC model (23 events), the IDN model (23 events), the PNG model (16 events) and the JPN model (12 events) (see Figure 1 for model locations). Ruptures should theoretically be retrievable for these events given they can be successfully assigned to

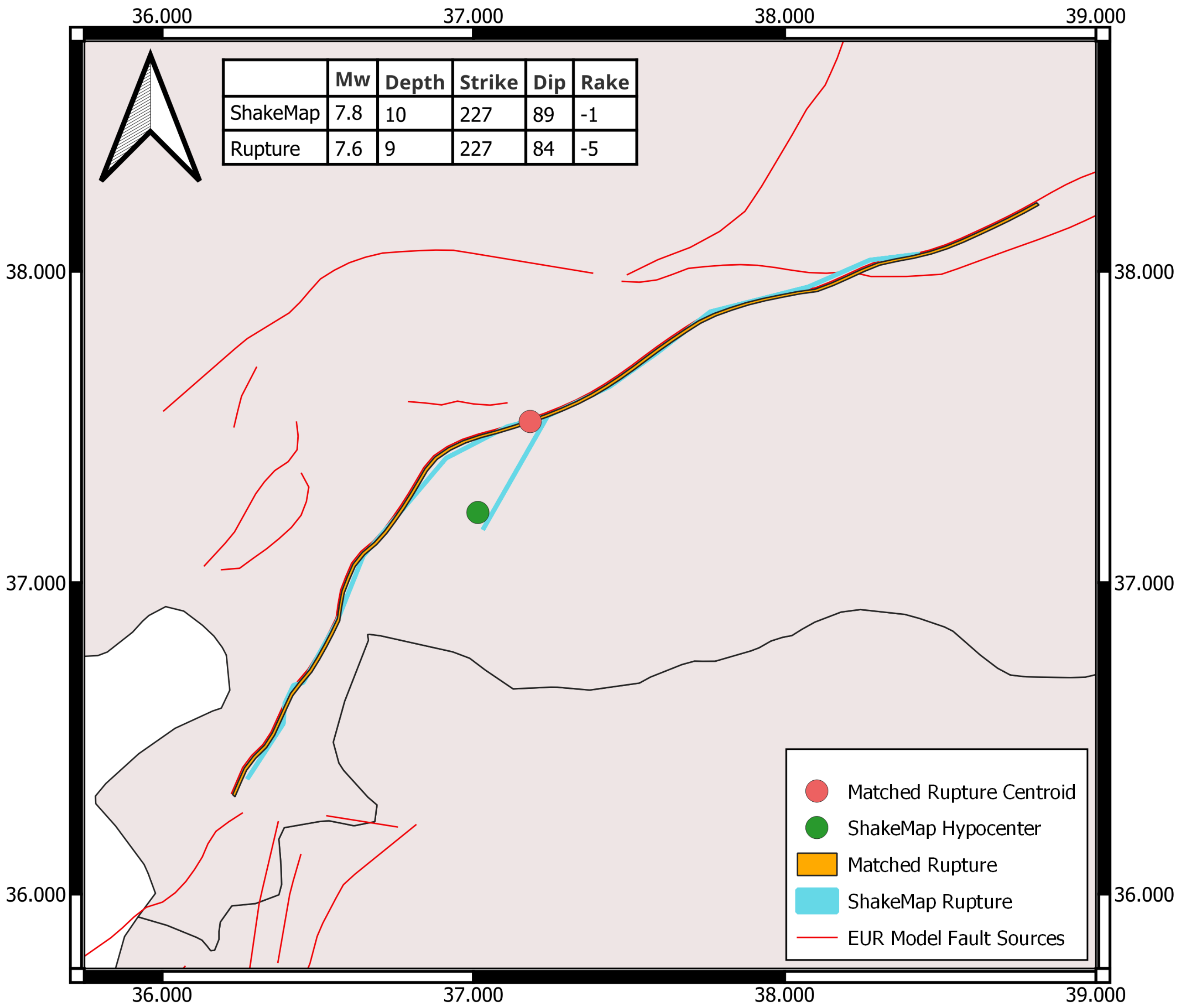

Figure 8 Rupture matched to the 2023 Kahramanmaras event by the GEESE algorithm and the rupture obtained from ShakeMap. The distributed seismicity sources of the EUR model SSC are not plotted here for brevity.

a Mosaic model during the preprocessing stages of the GEESE algorithm. Therefore, the inability to acquire matches for such events can be used to assess where improvements must be made in the SSC of each Mosaic model. This demonstrates another key utility of the GEESE algorithm from an SSC development and testing perspective – that is, we can evaluate from a (simple) statistical point of view the performance of each Mosaic model against a catalogue of the largest events observed in the region covered by the corresponding SSC. Furthermore, through then combining these model-by-model results with the information retrieved regarding “failed” seismic sources, it is possible to build a comprehensive overview of which Mosaic model SSCs are potentially in need of adjustment on a source-by-source basis to provide ruptures more representative of the tested events.

9 Computation of Ground-Motion Fields for the Example Events

For each rupture matched to an event, the GEESE algorithm automatically computes a set of ground-motion fields (GMFs) using the appropriate ground motion characterisation (GMC) logic tree of the Mosaic model from which the rupture was generated. For example, for the 1994 Northridge event, given the rupture was produced from the USA model, and the TRT of the matched rupture is Active Shallow Crust, the corresponding GMC logic tree from the USA model is used to compute a set of GMFs for the requested intensity measures. GMFs are computed for peak ground acceleration (PGA) and spectral acceleration (SA) at various periods (0.1 s, 0.2 s, 0.3 s, 0.6 s, 1.0 s and 2.0 s) with spatially varying Vs30 (time-averaged depth in the uppermost 30m of the subsurface). The Vs30 values for

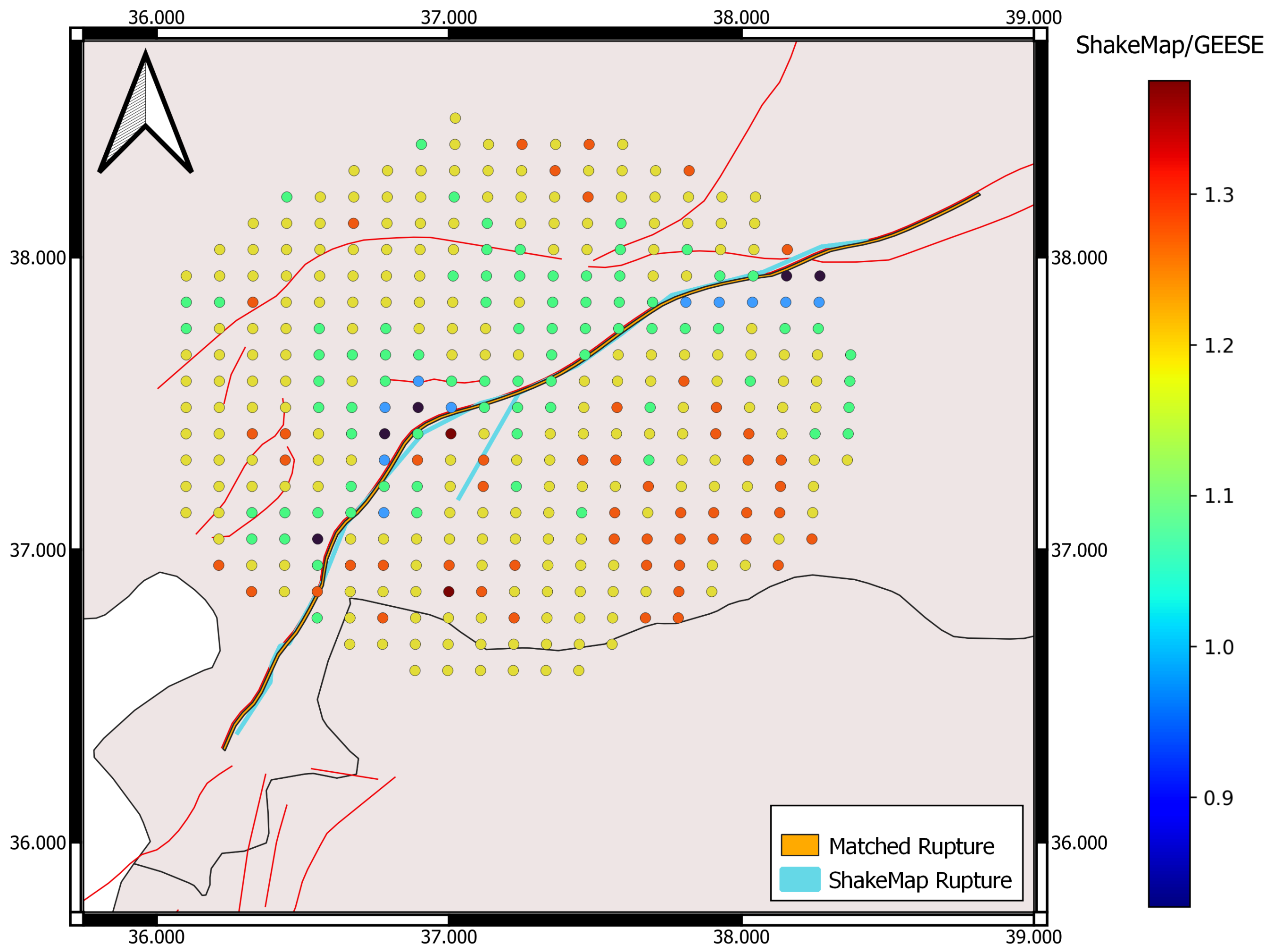

Figure 9 Ratio of the average (non-conditioned) ground-motion fields for SA(0.3) obtained using the ShakeMap rupture and the GEESE rupture. The average ground-motion field is computed by aggregating the computed ground-shaking intensity levels over all individual realization of the ground-shaking at each site considered. Each realization computes the ground-shaking at each site using a single GMM from the GMM logic tree and a random sampling of the GMM's sigma.

the Mosaic sites are taken from the USGS Global Vs30 Mosaic (https://earthquake.usgs.gov/data/vs30/ - last accessed June 2025). Each GMF is computed across onshore sites of ~6 km spacing within 300 km of the rupture surface. In instances in which the ground-motion intensities are very low (in effect zero) at all sites within 300 km of the rupture surface, a set of GMFs will not be computed (this occurs when the rupture is offshore far from the onshore Mosaic model sites).

The computed GMFs are spatially correlated, that is, we enforce correlation of the random sampling of the intra-event component of the sigma of each ground-motion model (GMM) at neighbouring sites to obtain more physically realistic patterns of ground-shaking. The OpenQuake Engine applies the Jayaram and Baker (2009) spatial correlation model during the GMF calculations, which permits clustering based on site Vs30 values.

The GMFs we calculate are also cross-correlated, which means a correlation is enforced for the random sampling of the GMM sigma at each site across different intensity measure types. Like the spatial correlation, this helps to obtain more physically realistic patterns of ground-shaking, but with respect to variation in intensity measure type at a single site (i.e. the spectrum), rather than with respect to site location for a single intensity measure type. The OpenQuake Engine applies the cross-correlation during the GMF calculations using the model by Goda and Atkinson (2009) which considers correlation in the inter-event component of a GMM's sigma.

If a GMM's sigma model only considers the total aleatory variability, we can provide the between-event and within-event variability using the OpenQuake Engine's ModifiableGMPE capability to split the total aleatory variability into between-event and within-event using a specified ratio. ModifiableGMPE is a capability within the OpenQuake Engine that allows any GMM within the OpenQuake GMM library to be altered in various ways including splitting the total aleatory variability (as required here), adjusting the median ground-motion by a scalar value or a vector of intensity

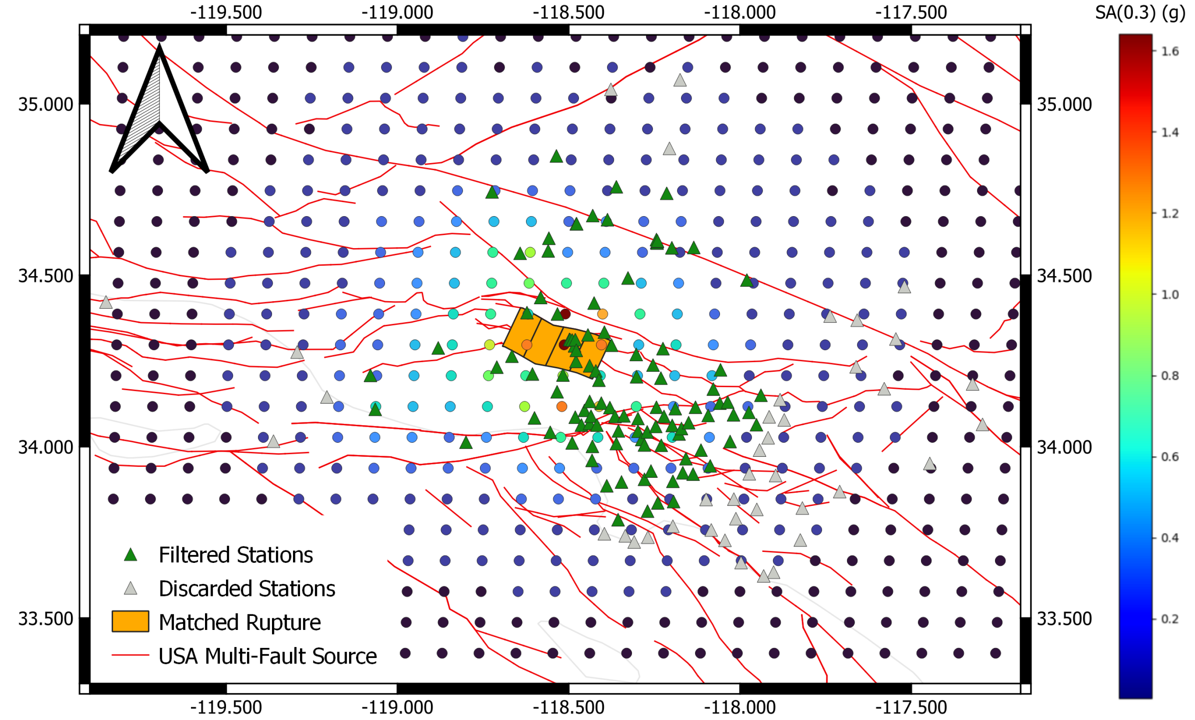

Figure 10 Plot of a conditioned ground-motion field for the 1994 Northridge event computed automatically by the GEESE algorithm using the best-matching rupture retrieved from the USA Mosaic model.

measure-type dependent values, or providing a sigma model or a site amplification model. The use of ModifiableGMPE (as applied here within GEESE) thus allows the calculation of spatially- and cross-correlated GMFs within the OpenQuake Engine when using GMMs which otherwise would not permit the use of correlation models.

If observed ground-motions (i.e. station data) are readily available for an event, this station data is automatically retrieved by the GEESE algorithm and used to condition the GMFs using the ShakeMap conditioning approach of Engler et al. (2022), which is implemented within the OpenQuake Engine. All station data is queried from a homogenised set of publicly available ground-motion datasets which the GEESE algorithm can automatically convert into the station data input format required by the OpenQuake Engine to condition an event's GMFs. Sufficient station data was only available within this homogenised ground-motion dataset for 46 of the events for which a rupture could be matched, inherently meaning that only a small number of GMFs could be conditioned within version 1.0 of GEESE (relative to the large number of events for which matching ruptures were obtained). We plan to continue expanding this homogenised ground-motion dataset to improve the number of events with conditioned GMFs within future releases of GEESE. This homogenised ground-motion dataset will potentially also be made publicly-available by GEM in the near future.

A TRT-dependent rupture distance (shortest distance from the rupture surface to the site) is used to filter out stations which could potentially be too far away from the matched rupture and therefore introduce significant bias into the adjusted GMFs. For events classified within the GEESE preprocessing as crustal we use a default rupture distance of 120 km, whereas for subduction events we use a larger distance of 200 km. The generally larger rupture aspect ratios of (commonly offshore) subduction events means the rupture distance is more sensitive to the relative orientations of the rupture and the stations (i.e. rupture strike relative to station position) and therefore a larger rupture distance is required to retain a sufficient number of stations for the conditioning for subduction events. Furthermore, if 10 or more records are within 50 km rupture distance of the matched rupture, we only use these near-source recordings to condition the GMFs. This latter case is observed for the 1994 Northridge event (50 km maximum station distance) because of the abundance of recordings in the near-source region based on the surface of the rupture retrieved by GEESE, resulting in 106 recordings being retained for the GMF conditioning process.

A conditioned GMF computed automatically by GEESE for the 1994 Northridge event's matched rupture for SA(0.3) (spectral acceleration of 0.3 seconds) is plotted in Figure 10. A maximum SA(0.3) of 1.64 g is obtained using the OpenQuake rupture, the GMC logic tree associated with the rupture's TRT, and the retrieved station data, which is comparable to the maximum ShakeMap SA(0.3) intensity contour (200 %g) obtained using the ShakeMap rupture and a different GMC logic tree and also conditioned to station data. The general spatial pattern is also noticeably similar. It should be noted that given both GMFs are conditioned using overlapping sets of station data that comparable values and spatial patterns are expected to some extent.

10 The GEESE Database

The rupture models and GMFs for the 1006 ISC-GEM events for which appropriate ruptures were retrieved are available within the GEESE database (Brooks et al., 2025). The database also provides the input files required for the user to compute GMFs for each of the selected ISC-GEM events, as computed automatically by the GEESE algorithm using the OpenQuake Scenario Calculator. These input files include the calculation parameter file (the job file), the GMC logic tree file, the site model (consisting of sites within 300 km of the given rupture with spatially varying Vs30), and the finite rupture model file, and can be readily modified to the user's requirements (e.g., changing the sites model or the GMC logic tree). A plot of the rupture's surface and position relative to the surrounding fault sources is also provided. If the GMF for the given ISC-GEM event has been conditioned, the retrieved station data is also provided within the OpenQuake Engine input format required for GMF conditioning. For instances in which the GMF calculation fails due to very low (effectively zero) ground-shaking intensities being computed at all sites, the rupture model, site model, GMC logic tree, and job file are still exported.

The GEESE results for the ISC-GEM events are stored by the Mosaic model their matching ruptures are obtained from. For the events assigned to each Mosaic model a lookup table of the rupture matching results is provided, which can be searched by event ID and other earthquake parameters provided within the ISC-GEM catalogue to permit the querying of individual events in the GEESE database. These lookup tables contain the properties of the ruptures matched to each event (if any) including the likelihood scores and the ID of the source which generated the rupture, alongside more conventional information such as rupture centroid location, magnitude, strike, dip, and rake in self-explanatory columns. Some brief information regarding the GMF calculations for each matched rupture is also provided within the lookup tables. A geoJSON file providing the locations and basic information of each event to which a rupture could be matched is also provided. The OpenQuake scenario calculation input files provided in version 1.0 of GEESE were generated using version 3.23 of the OpenQuake Engine (the current long-term support version of this software). Therefore, the user is advised to also use this version to ensure full compatibility between the input files provided here and their own installation of the OpenQuake Engine.

11 Conclusions

Within this article we demonstrated the rupture matching component of the GEESE algorithm using three example events. We then used the GEESE algorithm to query the GEM Mosaic with an ISC-GEM catalogue of onshore and near-offshore M_w 7.0 and larger events with hypocentral depths of 200 km or less. An acceptably matching rupture was obtained for 90 percent of these tested events, suggesting that the SSCs of the Mosaic models contain ruptures representative of most of the largest 20th and 21st century events globally. The results of this application of the algorithm were presented as the open-access GEESE (version 1.0) database (Brooks et al., 2025), which contains the finite rupture model and associated GMFs for each event to which a sufficiently matching rupture could be obtained when querying the GEM Mosaic with the available information in the ISC-GEM catalogue.

While seismic hazard applications are a primary incentive for developing the GEESE database, it is additionally valuable as a test of the Mosaic's collective effectiveness in accounting for large earthquakes known to be possible. The identification of Mosaic models that encompass the hypocentres of test events but do not produce rupture matches is a useful exercise for illuminating regions where the respective SSC could be improved in this regard. The ability to also identify (failed) sources which should theoretically be capable of generating matching ruptures (based on hypocentral location, magnitude and nodal plane solution of the given event) for the queried event (but do not do so) permits additional interrogation of these Mosaic model SSCs (i.e. we can rapidly identify seismic sources that in theory should generate well matching ruptures for a given event but do not, and then assess these sources to understand the limitations of their current parameterisations). Such applications of the GEESE algorithm demonstrate its general utility from a seismic hazard model testing and development perspective. Furthermore, the GEESE algorithm provides a means of SSC evaluation which examines the appropriateness of the ruptures for significant historical events, rather than evaluating how well the spatial-temporal-magnitude distributions of the seismicity generated by the SSC reflect the observed seismicity in a given region, which is the only approach currently explored within the available literature. We argue that the GEESE algorithm can be used to test the extent to which a hazard model is able to reproduce the ruptures caused by large events that occurred in the recent past (say, the last 100 years).

The well-matching ruptures obtained for the three example events demonstrate the applicability of the GEESE algorithm for obtaining initial finite ruptures within post-event response analysis. A substantial advantage of GEESE against other finite rupture algorithms used for post-event response is that GEESE is not reliant upon the dissemination of post-event data, instead leveraging the SSCs of the PSHA models within the GEM Mosaic, which has near-complete onshore global coverage, and therefore is also less dependent on the region-to-region variability of how reliably post-event information is disseminated. The use of GEESE within post-event response also provides an additional means of PSHA model SSC verification because we can check if significant events inherently not considered in the development of a model's SSC are represented by the ruptures generated from it.

Future improvements will be made to the GEESE algorithm and database. These improvements include lowering the magnitude threshold of the ISC-GEM catalogue to M_w 6.0 to incorporate potentially damaging (shallow crustal) events in more densely populated and infrastructure-concentrated regions, and automatically obtaining finite rupture model and event information for each event (if available) from ShakeMap and other databases (e.g. SRCMOD - Mai and Thingbaijam, 2014). Available lnSAR information and the spatial distribution of aftershocks will be used to refine the rupture modeling itself. The integration of the GEM hazard models for the oceans into the GEM Mosaic will permit the matching of ruptures to more events located far offshore. These planned improvements will increase the global coverage of the GEESE database and the number of events of engineering significance with readily-available finite rupture models.

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Data and code availability

The GEESE version 1.0 database as described within this article is available for download for free from a Zenodo repository (Brooks et al., 2025). The GEESE version 1.0 database has a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International copyright license.

Competing interests

The authors confirm that they have no competing interests.

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