A provisional seismic source zonation of Iceland for the ESHM20 based on new physics-based bookshelf fault system models and a new revised earthquake catalogue

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Abstract: The earthquake hazard in Iceland is highest in its two transform zones, the South Iceland Seismic Zone in the South and the Tjörnes Fracture Zone in the North and the reliable probabilistic seismic hazard assessment (PSHA) is the prerequisite for the codified aseismic design of structures and mitigation of seismic risk. The three fundamental aspects of a reliable PSHA, the proper specification of the seismic sources, in particular in the transform zones, their activity rates, and the use of acceptable forms of ground motion models that characterize the rapid attenuation of Icelandic strong-motion, need to be based on the latest state-of-the-art information and methods. In this study, we present a new and provisional subdivision of Iceland into seismic area-source zones on the basis of new physics-based fault system models as well as parameter set for each zone based on new revised and harmonised earthquake catalogue for Iceland. The zonation is guided by the systematic spatial distribution of the predominant types of earthquake faulting mechanisms in Iceland, consistent with the volcanic and transform zones in the country. Moreover, the new physics-based estimates of activity rates in the transform zones effectively explain the historical seismicity and allow the specification of subzone activity rates. On the basis of this new zonation finite-fault earthquake catalogues can be simulated for long-time intervals that are consistent with the time-independent estimates of seismicity. The provisional seismic zonation model can therefore both serve as the basis for the revision of the PSHA of Iceland using conventional engineering approaches and lays the foundation for physics-based earthquake rupture simulation approaches to the time-independent PSHA. For the time being however, this provisional model has been provided to the harmonized efforts of PSHA in Europe (ESHM20).

Keywords: Iceland, zonation, SISZ, RPOR, TFZ, PSHA

1. Introduction

Iceland is the most seismically active country in northern Europe as it is located on the Mid-Atlantic Ridge where the extensional tectonic margin interacts with the Icelandic Hot-spot. As a result, an eastward ridge-jump in Iceland has generated two transform zones, the South Iceland Seismic Zone (SISZ) and Reykjanes Peninsula Oblique Rift (RPOR) in the South and the Tjörnes Fracture Zone (TFZ) in the northern part of the country. These transform zones have the greatest capacity for the occurrence of destructive earthquakes in the country (Einarsson 2014; Jónasson et al. 2021) (see Fig. 1). To reduce the risk of earthquakes, probabilistic seismic hazard analysis (PSHA) can be used to incorporate ground motions and occurrence frequencies for all possible earthquake scenarios in a given region over a specified time interval. In order to develop controlling scenarios, the current PSHA generally focuses on the delineation of seismic sources, the definition of seismicity parameters, selection of ground motion models (GMMs), development of the hazard curves and finally disaggregation of the hazard. However, sensitivity and uncertainty analyses of PSHA have shown that GMMs and seismicity parameters are the most influential inputs and thus have the most significant effects on the PSHA results (Cramer 2001; Sabetta et al. 2005; Kowsari et al. 2018).

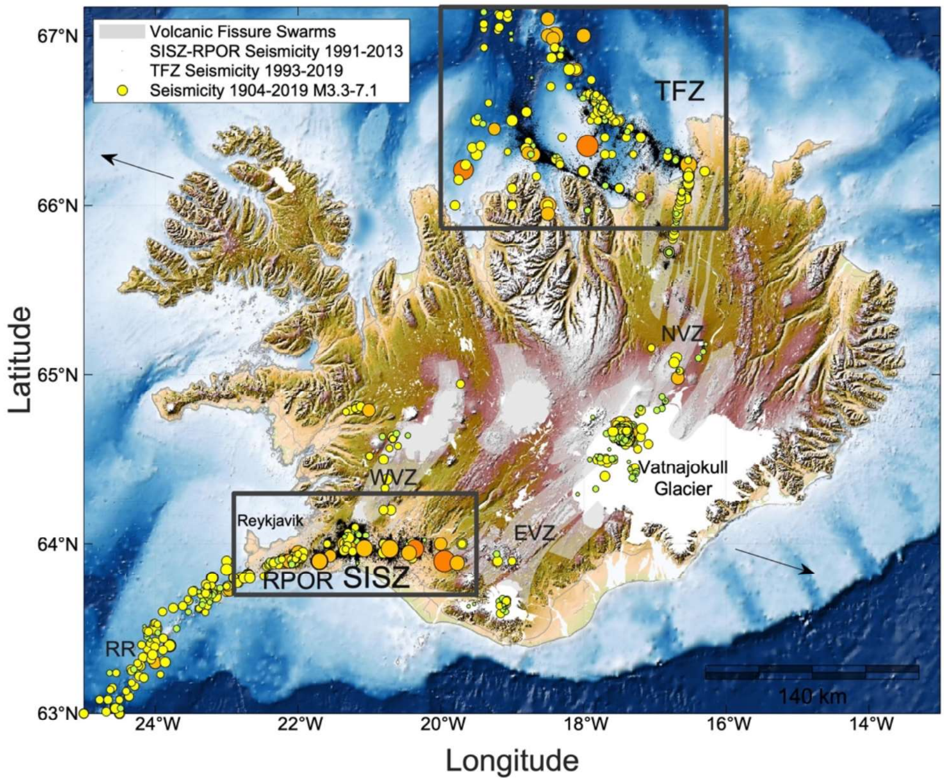

Fig. 1- Topography and bathymetry map of Iceland along with the two principal transform zones (rectangles): the South Iceland Seismic Zone (SISZ), and the Reykjanes Peninsula Oblique Rift (RPOR) in Southwest Iceland and the Tjörnes Fracture Zone (TFZ) in Northern Iceland. The complete instrumented catalogues over different periods are shown as black dots, while the circles denote the revised earthquake catalogue of Iceland, the ICEL-NMAR (Jónasson et al. 2021). The gray shaded polygons indicate distinct volcanic systems and acronyms denote specific volcanic zones (see text). The arrows indicate the approximate vectors of active tectonic extension of the Mid-Atlantic Ridge (MAR).

In Iceland, while the duration of the entire catalogue of reported destructive earthquakes is fairly long, about 1000 years, it is inescapably riddled with uncertainties particularly in the size, location and time and to varying degrees, all of which has not been formally accounted for in conventional hazard assessment (e.g., Solnes et al. 2002, 2004). The adverse effects of such uncertainties on the seismic hazard results are expected to be greater for North Iceland where most strong earthquakes occur off-shore and thus many may not have been reported in the historical annals (Thorgeirsson 2012). Partially addressing the uncertainty issue, previous PSHA studies in Iceland have employed a Monte Carlo simulation to generate and extend the earthquake catalogue on the basis of simplifying assumptions (Sigbjörnsson et al. 1995; Solnes et al. 2002, 2004; Sigbjörnsson and Snæbjörnsson 2007; Snaebjornsson and Sigbjornsson 2007, 2008). However, these approaches were based on a statistical analysis of the available earthquake catalogue that admittedly are sparse and incomplete, in particular at larger magnitudes. The seismicity parameters including the Gutenberg–Richter (G–R) relationship parameters, and the minimum and maximum earthquake magnitudes, can be established by studying the spatial and temporal distribution of the seismicity, as well as the frequency of occurrence of the earthquake magnitudes through an earthquake catalogue. Accordingly, the size, time and location of earthquakes which are collected to form an earthquake catalogue, generally are associated with different sources and levels of uncertainties. In addition to these uncertainties, the spatial and temporal heterogeneity of the seismicity add more complexity to the earthquake catalogue (Kagan 2003).

The above activity rates have been calculated for seismic area source zones that cover the spatial distribution of the historical and instrumented earthquake catalogues in question. However, the spatial discrepancies in the sparsity of earthquake occurrences in these area source zones make difficult the subdivision of e.g., the Southwest Iceland seismic zone to capture the apparent variation in maximum earthquake magnitudes in the region. The new fault system model of the bookshelf strike-slip fault system of the SISZ and the RPOR proposed by Bayat et al. (2022) has the potential of addressing both of the abovementioned shortcomings. Namely, they have calibrated a three-dimensional earthquake fault system model for the main seismogenic zone in Southwest Iceland, the transform fault systems of the SISZ-RPOR. The model has been developed for the purpose of enabling a consistent time-independent physics-based approach to PSHA that is free from the shortcomings of an incomplete earthquake catalogue. Approaching the problem from a physical standpoint, the models are constrained by the steady-state velocity of the tectonic extension associated with plate spreading in the region and are consistent with the fault tectonics and seismicity distribution of the region (Hreinsdóttir et al. 2001; Stefansson et al. 2008; Einarsson 2014; Panzera et al. 2016; Steigerwald et al. 2018). The fault models are thus fully specified in terms of fault locations, dimensions, strike and dip along with estimates of annual fault slip and moment rates on each finite-fault. They show that the estimated cumulative moment rate release of the fault system matches that estimated from the earthquake catalogue for the last 300 years. In this study, therefore, we take advantage of the new 3D fault system model and propose a new approximate seismic area-source zonation, guided by the systematic spatial distribution of the predominant types of earthquake faulting mechanisms in Iceland. We also take advantage of the new revised catalogue of instrumentally recorded earthquakes, the ICEL-NMAR, that covers the time period from 1901 to 2019 (Jónasson et al. 2021), from which we derive seismicity parameters for large sub-zones of the volcanic zones of Iceland. Combining the extent and activity rates of the physics-based fault system models for the SISZ-RPOR and TFZ, respectively, with the rough zonation of the volcano tectonic earthquakes in the volcanic zones of Iceland, we present a provisional and hybrid area source zonation model for Iceland that can be used in future PSHA studies in Iceland, and has been applied in the recent ESHM20 efforts (Danciu et al. 2021).

2. The transform zones zones of Iceland

The eastward ridge-jump of the Mid-Atlantic plate boundary over to the location of the Icelandic Hot spot in East-Central Iceland while the rest of the ridge has migrated gradually towards Westnorthwest, has led to the formation of two major transform zones in the country, the SISZ-RPOR zone in Southwest Iceland, and the Tjörnes Fracture Zone in North Iceland (Einarsson 2014). The Western Volcanic Zone (WVZ) is the continuation of the Reykjanes Ridge that comes onshore and connects to the RPOR while the Easter Volcanic Zone (EVZ) is the shifted eastward rift zone that extends to the north as the Northern

Volcanic Zone. Between these two volcanic zones, a small block fragment is formed with no volcanic or seismic activity. Instead, the seismicity seems to concentrate on the south edge of this block in the SISZ transform zone (Sigmundsson et al. 1995; Einarsson 2014; Einarsson et al. 2020). The SISZ is an E-W left-lateral transform zone with an approximately 80 km long, that is located at an intersection of three main rift zones of the EVZ, the WVZ, and the RPOR (Stefánsson et al. 2006; Decriem and Árnadóttir 2012; Einarsson 2014). The SISZ is migrating southwards due to a southwestward propagation of the EVZ with an average rate of about 3-5 cm/year (Decriem and Árnadóttir 2012; Einarsson 2014) that has been also confirmed by the modelling of the GPS measurements (e.g., Sigmundsson et al. 1995; Lafemina et al. 2005). This leads to the continuous counter clockwise rotation of blocks between numerous N-S "bookshelf faults" and creates a large number of right-lateral strike-slip structures (Sigmundsson et al. 1995; Einarsson 2010, 2014) rotating with an average slip rate of about 0.05-0.5 cm/yr (Sigmundsson et al. 1995, 2020). On the other hand, Normal faults which have been in most cases created by the volcanic processes, e.g., inflation and deflation of magma bodies, thermal cracking, rifting and heat mining (Pálmason 1981), take up the divergent component in the SISZ (Sigmundsson 2006; Einarsson 2014, 2015). They all are concentrated on the volcanic zones and fissure swarms and are mostly aseismic except during rifting and magmatism. It is noteworthy here that the normal faulting earthquakes occur quite frequently but rarely exceed M5.5, and thus are insignificant relative to the more dominant strike-slip faulting that host tectonic earthquake as large as M7 (Einarsson 2014). Fig. 2 shows the main characteristics of the SISZ-RPOR transform zone, indicating six subzones of different seismogenic potentials (Bayat et al. 2022).

The TFZ in North Iceland is a broad and complex region with a history of damaging earthquakes such as Ms 7 on 11 September 1755, Ms 6.5 on 12 June 1838, Ms 6.5 on 18 April 1872 and Ms 6.3 on 25 January 1885 (Stefansson et al. 2008) (Fig. 2). The TFZ connects two divergent segments of the Mid-Atlantic plate boundary, i.e., the southern end of the Kolbeinsey Ridge and the Northern Volcanic Zone (NVZ). Thus, the TFZ accommodates ~2 cm/yr of transform motion between the NVZ and the Kolbeinsey Ridge. At present, the deformation measurements show that the Grímsey Lineament (GL) and Grímsey Oblique Rift (GOR) is responsible for about 2/3 of the tectonic deformation across the zone while the Húsavík-Flatey Fault Zone (HFFZ) accounts for the remaining (Metzger and Jónsson 2014). The GOR is composed of several active volcanic systems with N-S trending fissure swarms (Hjartardóttir et al. 2012). The large earthquakes on the GOR often occurs on transverse faults mostly caused by strike slip faulting (Rögnvaldsson et al. 1998). Moreover, the temporal behaviour of the seismicity indicates that the GOR has high levels of background seismicity resulting in seismic swarms every few years. The HFFZ that is located about 40 km south of the GOR is the largest strike slip fault system in Iceland. The HFF is a ∼100-km-long right-lateral transform fault that has been active since 7–9 Myr. From ~20 years of GPS data, present-day deformation shows that 6-9 mm/yr of right-lateral strike-slip motion is focused on the HFFZ (Metzger and Jónsson 2014). The instrumental seismicity along the HFFZ indicates an uneven spatial distribution with the western third of the fault much more active than the eastern part (Passarelli et al. 2018). The low seismicity rate of the eastern part of the HFFZ is due to stress-shadowing caused by the Krafla rifting episode in 1975-1984 (Maccaferri et al. 2013). Fig. 2 shows the subdivision of the Tjörnes Fracture Zone (TFZ), as modified from Abril (2018) (Halldorsson et al. 2022).

Finally, the seismicity that falls outside these transform zones is primarily characterized by volcano tectonic earthquakes in the volcanic zones where active tectonic extension drives the seismicity and, admittedly rare but episodic, volcanic activity (Sæmundsson 1974; Gudmundsson et al. 2008; Einarsson 2014; Sæmundsson et al. 2020).

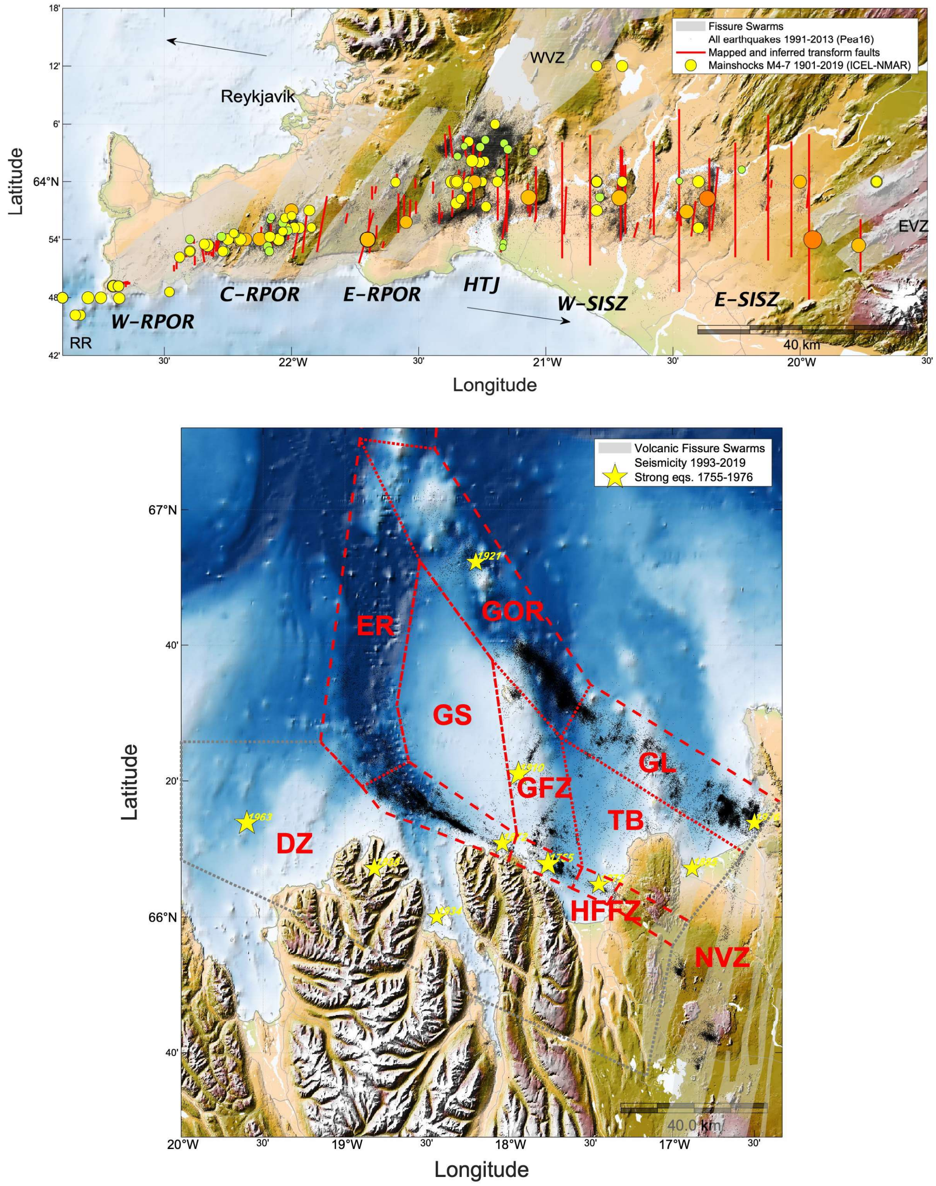

Fig. 2- The subzones of the South Iceland Seismic Zone and the Reykjanes Peninsula Oblique Rift (top) and Tjörnes Fracture Zone (bottom). The circles on top denote the significant earthquakes from 1901-2019 (ICEL-NMAR) (Jónasson et al. 2021) and the black dots denote the revised instrumented microearthquake catalogue of 1991-2013 (Panzera et al. 2016) in the SISZ and RPOR. At bottom, the relocated microearthquakes from 1991-2013 in the TFZ (Abril and Gudmundsson 2018) are shown as black dots, with significant earthquake locations marked as stars (Einarsson 2014).

3. Results and discussion

The first step in PSHA is the identification of seismic sources and source regions. The seismic source models are defined to account for distinct differences in the earthquake recurrence rate, define completeness magnitude (Mc), maximum earthquake magnitude and expected future earthquake characteristics (e.g., depth distribution, style of faulting and rupture orientation). Therefore, for the purpose of a reliable PSHA, seismic source models that are consistent with the geology and seismicity of the target region and appropriately describe the seismicity parameters are needed.

We present a new, but provisional, and more detailed subdivision of Iceland into seismic area-source zones for the purpose of PSHA in Iceland. The model is based on 1) a new approximate seismic area-source zonation, guided by the systematic spatial distribution of the predominant types of earthquake faulting mechanisms in Iceland, consistent with the volcanic and transform zones in the country; 2) information found in the literature (e.g., surface fault mappings) and complete earthquake catalogues for the two transform zones (Panzera et al. 2016; Abril et al. 2021b) and the most recent and complete ICEL-NMAR earthquake catalogue (Jónasson et al. 2021); 3) activity rates for subzones of the two major transform zones in the country based on new 3D finite-fault models of the zones. Therefore, the earthquake source regions in Iceland (i.e., TFZ and SISZ-RPOR) that are associated with the highest earthquake hazard in the country have been subdivided to quantify their spatially varying seismic potential. In other words, they are divided into multiple subzones on the basis of types and spatial distribution of predominant earthquake faulting mechanisms, location of the present-day center axis of plate divergence across the country, and locations of volcanic systems.

It is worth noting that only geophysical information was considered in their development and their moment rate is controlled by the rate of tectonic plate spreading across the transform zones, the orientations and extents of known existing faults (accounting also for potential unknown faults) thus taking into account the internal differences between subregions of the zones themselves. For the TFZ, fault zone geometries are constrained by relocated seismicity, revealing and confirming suspected fault patterns. For the SISZ-RPOR, the seismic zones are constrained by historical fault locations, deformation studies and earthquake catalogues and bookshelf tectonics. These models have been calibrated against the steady state relative velocity of plate extension in Iceland. They are found to produce total moment rates that are fully consistent with the historical catalogues in each zone, respectively. Moreover, they allow for the specification of seismic activity for subzones of the SISZ-RPOR on one hand, and the TFZ on the other, which is not captured by the historical or instrumental catalogues but is fully consistent with the physical constraints of the tectonic system, such as fault locations, fault lengths, maximum seismogenic depths, etc. found in the literature.

Furthermore, we expand the zonation not only for the TFZ and SISZ-RPOR but also for whole country that is shown in Fig. 3. In the proposed seismic area-source model, individual faults are not modelled, but instead the seismogenic sources as equivalent seismic area-sources are modelled and presented. This is due to the different types of seismogenic structures in Iceland, their varying levels of complexity and spatial extents, relative differences in the completeness of available fault-plane and slip-rate information, and the aleatory nature of faulting in a complex volcano tectonic environment. This way we are able to provide an efficient and optimal model by capturing the salient characteristics of, and differences between, the zones in sufficient detail for the purposes of a nationwide PSHA.

Due to the details in the physical modeling of the fault systems, we can develop simple and equivalent Gutenberg-Richter models for the subregions of the transform zones, something that the limited earthquake catalogues cannot produce, and in turn allows a more accurate approach to standard-practice PSHA. Moreover, the magnitude-frequency relationships (MFR) for most of the proposed seismic area-source zones can be derived from the ICEL-NMAR catalogue. Table 1 presents the parameters of the MFRs for the seismic area-source zones proposed for Icelandic for the purpose of PSHA. From this Table, we conclude that the Hreppar microplate is confined by zones 4, 5, 10, 13 and 11 and is assumed close to being aseismic, similar to zones 12 and 13 (zones 12 and 13 are remnants of past volcanic zones). The background zone 17 is assumed to cover most of the Icelandic oceanic shelf. Its activity is based on intraplate earthquakes of the ICEL-NMAR. Zone 14, the Central Eastern Volcanic Zone, is approximately the location of the center of the Icelandic Hot Spot, and is the most seismically active region in Iceland, characterized by seismicity associated with volcanic and rifting episodes. Due to symmetry of the eastward jump of the Mid-Atlantic Ridge as it traverses Iceland, forming the two transform zones, the total activity of the two transform zones is approximately equivalent. Zones 9 and 16, the parts of the Mid-Atlantic Ridge not affected by the Icelandic Hot Spot, are shown as finite-size areas confined by their respective polygons. Their activity was estimated based on the ICEL-NMAR seismicity the epicenters of which were inside, or close proximity to, the area of the polygons. Thus, the zone activity per unit area (not shown in the table) should be indicative of the activity of the Mid-Atlantic Ridge south and north of Iceland.

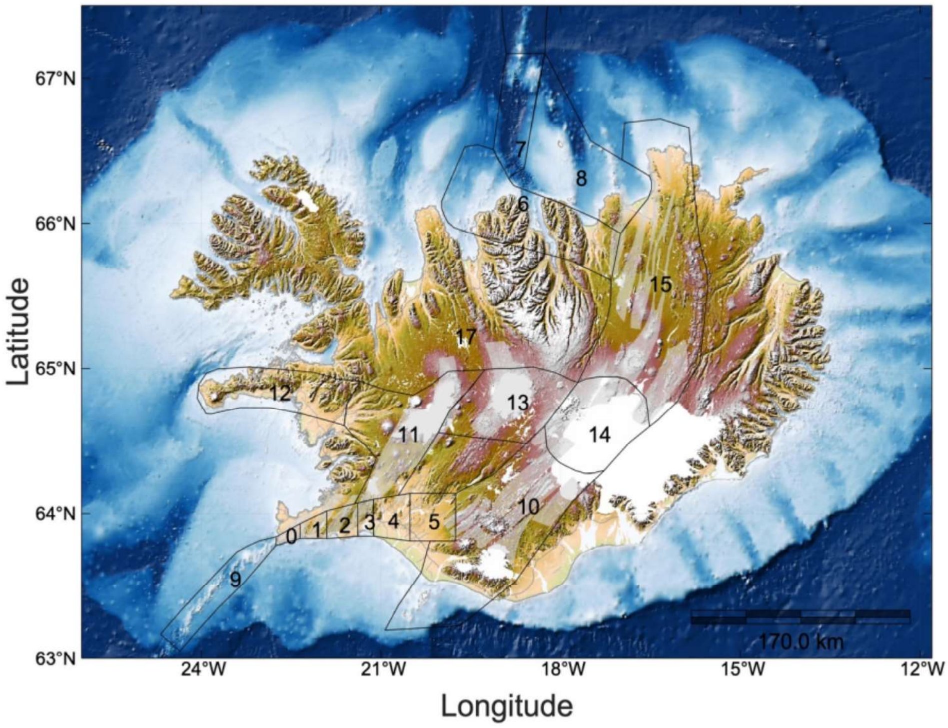

Fig. 3- Iceland and the proposed area earthquake source zones for use in PSHA, drawn on the basis of geological, seismotectonic and volcanic information available in the literature, and finite-fault modelling of the two transform zones in Iceland (0-5 i.e., the SISZ-RPOR, and 6,8, the TFZ and Dalvík Zone).

4. Conclusions

The largest earthquakes in Iceland occur in two transform zones, the SISZ-RPOR in the south and the TFZ in the North. The input parameters required to conduct probabilistic seismic hazard analysis can be estimated by studying the spatial and temporal distribution of the seismicity, as well as the frequency of occurrence of the earthquake magnitudes. Notable spatial and temporal variations of seismicity parameters have been observed in most earthquake catalogues which have made the modelling of the spatiotemporal distribution of earthquakes a paramount issue in any seismic hazard study. In spite of that however, the uncertainties in size and location of the earthquakes still hamper such analyses for Iceland. This study uses a new 3D fault system model of the SISZ-RPOR that is calibrated to the steady-state relative velocity of plate extension in Southwest Iceland and constrained by fault maximum extents and their random locations in the region. Then, a new, detailed subdivision of Iceland into seismic area-source zones is proposed guided by the systematic spatial distribution of the predominant types of earthquake faulting mechanisms in Iceland, consistent with the volcanic and transform zones in the country and complete earthquake catalogues for the two transform zones. The results of this study can be expanded to allow simulating a catalogue of earthquake magnitudes for a long-time interval with random locations in the region that is completely consistent with the average activity predicted by the 3D fault system (Kowsari et al. 2022). Such synthetic earthquake catalogue of finite-size earthquake fault planes in 3D facilitates a) the conventional engineering approach to PSHA using empirical ground motion models, such as the new suite of hybrid Bayesian models for "rock" sites in Iceland (Kowsari et al. 2020) and in particular the new hybrid Bayesian empirical ground motion model that quantitatively accounts for site effects on four key geological units in Iceland (Rahpeyma et al. 2022a, b). Then, b) a physics-based seismic hazard assessment using either dynamic or kinematic earthquake rupture models and the corresponding ground motion simulation approaches, in particular for low-frequency and near-fault ground motion simulations. Combining the two will produce a hybrid physics-based PSHA over the entire frequency range of engineering interest. For the time being however, this provisional model has been provided to the harmonized efforts of PSHA in Europe (ESHM20) to improve upon past European estimates of PSHA in Iceland.

Table 1. Parameters of the magnitude-frequency relationships for the proposed seismic area-source zones.

Zone	ID	a-value	a-annual	b-value	Mc	Mmax
RPOR-West	0	4.54	2.54	0.73	4.0	5.5
RPOR-Central	1	4.39	2.39	0.73	4.0	6.0
RPOR-East	2	4.43	2.43	0.75	4.0	6.5
HTJ	3	4.40	2.40	0.73	4.0	6.5
SISZ-West	4	3.66	1.66	0.59	4.0	6.7
SISZ-East	5	3.50	1.50	0.54	4.0	7.0
Dalvík Zone	6	4.87	2.81	0.73	4.7	6.9
Eyjafjarðaráll	7	7.03	4.97	1.29	4.5	5.4
Tjörnes Fracture Zone	8	5.46	3.41	0.78	4.3	7.1
Reykjanes Ridge	9	9.09	7.03	1.50	4.9	5.8
Southern EVZ	10	6.62	4.78	1.20	4.3	5.3
Western Volcanic Zone	11	7.01	4.95	1.25	4.5	5.7
Snaefellsnes	12		4.10	1.20	4.5	5.5
Hofsjokull	13		4.30	1.20	4.5	5.5
Central EVZ	14	8.35	6.29	1.32	4.3	5.8
Northern EVZ	15	10.59	8.54	1.85	4.9	5.7
Kolbeinsey Ridge	16	8.48	6.42	1.48	4.4	5.8
Background Plateau	17		2.87	1.00	4.5	5.5
Hreppar microplate			4.10	1.20	4.5	5.5

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