



THE GEOLOGICAL AND URBAN SETTING OF HÚSAVÍK, NORTH ICELAND, IN THE CONTEXT OF EARTHQUAKE HAZARD AND RISK ANALYSIS

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ABSTRACT

The town of Húsavík is situated on the Húsavík-Flatey Fault (HFF), one of the largest active transform faults in Iceland. Recent research concludes that currently the HFF has the potential for an M_w 6,8 earthquake. Differences in the local geology and a diverse building stock may lead to differences in local earthquake hazards and seismic risks. The ongoing ICEARRAY II project aims at quantifying these differences within the town of Húsavík. The purpose of this paper is to investigate site-specific geological situations and the present building stock. Additionally, a georeferenced building data-base containing information on building age, material and usage has been created. In conclusion, the interpretations allow for relative estimations of local variations of primary and secondary earthquake hazard potentials. Areas with an increased potential for primary earthquake hazards can be found especially in the sedimentary units of Húsavík and on tops and along ridges of hills and slopes. Overlaying the areas of high earthquake hazard potential with the building stock allow for outlining areas with relative differences in seismic risks.

INTRODUCTION

The interaction between the Mid-Atlantic Ridge and the Iceland Mantle Plume is responsible for Iceland's existence and the intense earthquake and volcanic activity. Earthquake occurrence in the country follows the tectonic plate margin as it crosses the island and defines its volcanic zones, where earthquakes are frequent but relatively small. On land, a ridge-jump to the eastern part of the country has created two large transform zones where volcanic activity is near nonexistent, but strong earthquakes have historically repeatedly taken place: the South Iceland Seismic Zone (SISZ) in the south and the Tjörnes Fracture Zone (TFZ) in the north. Strong earthquakes of up to magnitude 7 typically occur once every century in these zones (Nadim et al. 2008). Both are – on an Icelandic scale – relatively densely populated and possess a fast growing technical and socio-economical sector, along with heavy industries. In this study we focus on the TFZ and in particular the town of Húsavík which literally sits atop the Húsavík-Flatey Fault (HFF), the main transform fault structure in the TFZ (cf. Figure 1). On the HFF a strong, damaging earthquake has not occurred since 1872, but recent research suggests that the HFF currently has the potential for an M_w 6,8 earthquake (Metzger et al. 2011, 2012).

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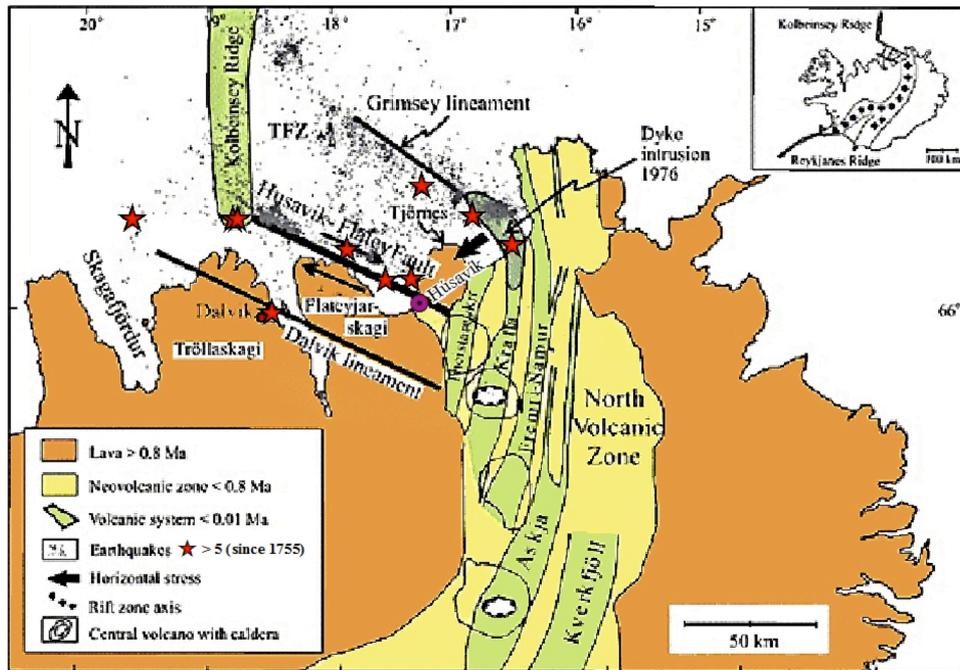


Figure 1: North Iceland with the Northern Volcanic Zone (yellow) and its volcanic systems (green) and the TFZ connecting the NVZ and the Kolbeinsey Ridge. The earthquake distribution clearly defines the main seismic structures of the TFZ: The Grimsey lineament and the HFF whereas the Dalvík lineament is defined mainly by the two large earthquakes close to Dalvík and north of Skagafjörður respectively. (alteration of Guðmundsson 2007 and Stefánsson et al. 2008)

Therefore, the generation and implementation of a sustainable natural hazard and risk management that focuses on preventive measures is of great importance in Húsavík and its vicinity. In that context, we find it useful to introduce a working concept based on a “kindynosphere” (gr. kindynos = hazard, sphere = shell, mantle). Ideally, this kindynosphere contains both, natural and anthropogenic hazard and risk factors. Regarding earthquake hazard and seismic risk it could be composed of the plate tectonics, the surface-geology and the geomorphology, and finally the anthroposphere containing human beings and anthropogenic structures. Each of these shells directly contributes to the overall hazard and risk, but also influences the next higher sphere. Local differences in each of these spheres may lead to a heterogenic, locally varying earthquake hazard and seismic risk pattern, even within a small zone such as a densely populated urban area. Recently, a dense network of accelerographs and continuous GPS instruments has been deployed in Húsavík and its vicinity to measure tectonic movements and record earthquake strong-motion: the ICEARRAY II network. It aims at quantifying these locally varying differences within the town of Húsavík (Halldorsson et al 2012). The purpose of the present study is to investigate aspects of the geological and urban setting of Húsavík in the context of sustainable natural hazard and risk management (Waltl 2013). While the geology allows drawing conclusions on direct earthquake effects (e.g. ground acceleration patterns), the geomorphology enables to make statements on secondary earthquake effects or processes that may pose a threat to human being. Additionally, the relevant information on the current building stock in Húsavík is investigated.

TECTONIC SETTING

The TFZ constitutes the WNW-ESE trending transform connection between the axial rift zone in north Iceland (Northern Volcanic Zone) and the Kolbeinsey Ridge offshore Iceland’s north coast (cf. Figure 1). In this fracture zone, the Mid Atlantic Ridge is subjected to an offset of up to 120 km where the overall motion is of a dextral strike-slip type (Garcia et al. 2002, Rögnvaldsson et al. 1998, Saemundsson 1974). According to Metzger et al. (2011) the annual relative motion rate amounts to ~19,6 mm. Microearthquake distributions show that the seismic activity in the TFZ is mainly taken up

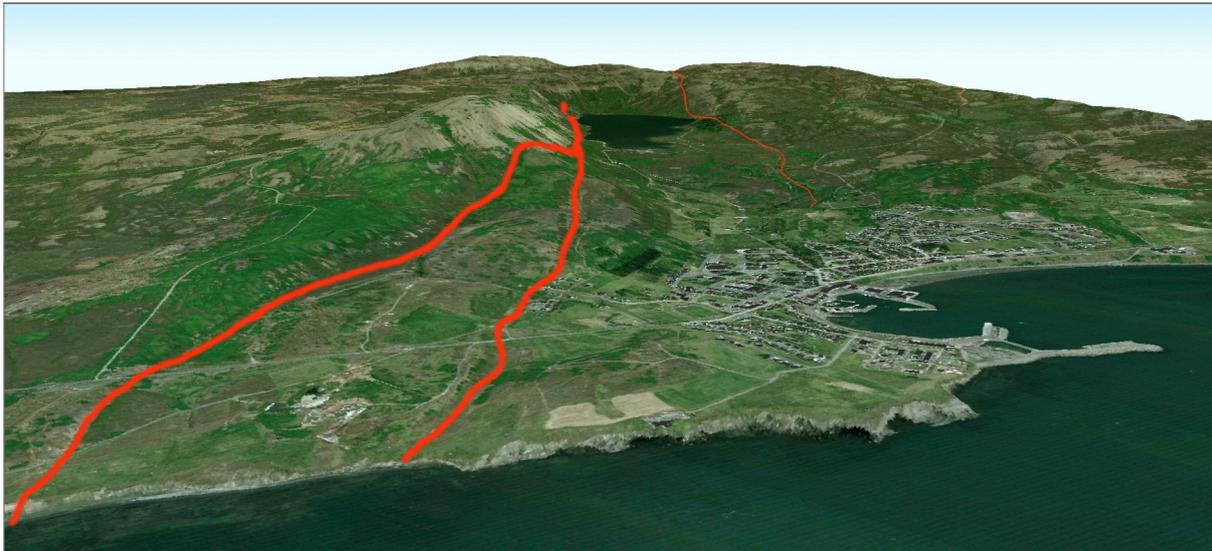


Figure 2: The surface trace of the HFF (red lines) plotted on a DEM overlaid with aerial photographs: North of Húsavík the surface trace of the HFF branches into the Skjálbrekka (left) and Laugardalur (right) faults. A third, less important fault east of Húsavík may be seen behind the settlements. In the background, Lake Botnsvatn is a manifestation of the pull-apart basin which Húsavík sits in (Waltl 2013, data from Loftmyndir.is 2012 and Magnúsdóttir and Brandsdóttir 2011)

by three tectonic features: the Grímsey Lineament (a.k.a. Grímsey Oblique Rift, GOR) in the north, the Húsavík-Flatey Fault (HFF) 40 km further south and the (much less active) Dalvík Lineament (DL) 30 km south of the HFF (cf. Figure 1, e.g. Guðmundsson et al. 1993, Rögnvaldsson et al. 1998). Although the majority of the current partial motion within the TFZ seems to occur on the GOR (~60%), the HFF delineates a real oceanic transform fault (which is partly exposed on land) and is thus the main transform structure of the TFZ, taking up around 40% of the transform motion (Geirsson et al. 2006, Guðmundsson 2007, Metzger et al. 2011). The approximately 90 km long fault has its eastern origin in the N-S trending Þeistareykir fissure swarm on the Tjörnes peninsula, enters Skjálfandi bay just north of Húsavík, traverses between Flatey island and the Flateyjarskagi peninsula, continues north of Eyjafjörður and finally merges with the Eyjafjarðaráll Rift, the southern extension of the Kolbeinsey Ridge (cf. Figure 1, e.g. Guðmundsson et al. 1993, Metzger et al. 2011, Rögnvaldsson et al. 1998, Saemundsson 1974). The overall transform motion occurs as right lateral strike-slip. Saemundsson (1974) found a horizontal displacement of at least 5 to 10 but possibly up to 60 km. Though defined as a typical oceanic transform fault, it is clearly exposed on land on the Tjörnes and Flateyjarskagi peninsulas (Guðmundsson et al. 1993).

Both extensional and compressional stress fields have several effects on local tectonic processes and the topography in Húsavík. As a consequence of extensional forces, two pull-apart basins (sag ponds) developed in the hinterland of Húsavík (cf. Figure 2). On the other hand, compressional processes lead to vertical uplift and dip-slip behavior on the fault. Up to 200 m high fault scarps (e.g. the Skjálbrekka slope just north of Húsavík) on the Tjörnes peninsula indicate a significant dip-slip component, which may indeed have caused a vertical displacement of up to 1.400 m on land and 1.100 m under water. (Guðmundsson et al. 1993, Rögnvaldsson et al. 1998)

Looking at the town of Húsavík, the HFF can be traced mainly along two massive faults running directly north of town: the Laugardalur and the Skjálbrekka Faults (cf. Figure 2). These two faults constitute the main tectonic structure of the massive transform fault system with the largest seismic potential. As is frequently described by other authors, further, smaller faults may traverse through the Húsavík area, too (e.g. Saemundsson and Karson 2006). Compressional stress fields lead to the oblique movement of the plates south of the fault escarpment where Húsavík is situated, which can be clearly seen at the Skjálbrekka Fault. Hence, Húsavík is located on the “hanging wall” of the fault.

GEOLOGY

The local near surface geology plays a crucial role for earthquake hazard and seismic risk for two reasons. Firstly, it strongly influences the propagating earthquake waves just before they reach the surface of the ground amplifying (or reducing) the seismic motion (e.g. Anderson et al. 1996). Secondly, it strongly correlates with the local landforms and the processes occurring therein; the geomorphology (Waltl 2013).

The geology in the wider Húsavík area is characterized by rocks of different types, origins and ages (cf. Figure 3). Basic and intermediate igneous rocks alternate with maritime, fluvial and glacial sedimentary units, the oldest reaching back into the Miocene and the youngest forming during the Holocene. The units can be summed up to Tertiary basalts (Miocene), Quaternary effusive rocks (the youngest ones from the Pleistocene), Tillite (Pleistocene), and late Pleistocene and Holocene sediments. (Saemundsson and Karson 2006)

The oldest present rock is a 8,5 to 10 Ma old basalt (cf. Figure 3). The 1.500 m thick formation can be found north of the Húsavík Flatey Fault (specifically the Skjólbrekka fault). These Tertiary basalts are regularly intercalated with lithified sediments. Both are cut by numerous dikes and the individual blocks of lava or sedimentary rock are heavily jointed and faulted, which is attributed to the tectonic processes on the HFF. The unit abruptly ceases at the tectonic transform fault and is not known to reoccur south of it. (Saemundsson and Karson 2006)

Younger Quaternary effusive rocks constitute the lowest strata at the city of Húsavík (cf. Figure 3). The youngest of these rocks originates from a series of effusive eruptions by the nearby Grjótháls shield volcano about 200.000 years BP. At higher elevations, the Grjótháls lava is present as lava rock, whereas at lower elevations, Hyaloclastite, a volcanic breccia, supersedes the lava rock, indicating that the lava flowed into the sea. (Saemundsson 1974)

Húsavík itself is characterized by several Pleistocene and Holocene sedimentary rocks and sediment layers, which generally overlay the Grjótháls lava and breccia (cf. Figure 3). These units testify to a complex interaction between glaciers, glacial rivers, lakes and lagoons, and a fluctuating sea level. The oldest of these units consists of glacial deposits from the early Weichsel glaciation. These layers have altered to solid Tillite rock. It is well exposed in up to 50 meter high cliffs in the northern part of town where it is overlaid by glaciolacustrine and –marine sediments and moraine material, and further up to the Skjólbrekka fault, but probably underlays most parts of Húsavík. (Eiriksson 1985, Pétursson 1988, Saemundsson and Karson 2006)

In the north-eastern, central and southern part of town (here named Húsavík basin and Haukamýri) younger, late Pleistocene and early Holocene horizontally layered sediments constitute the upper most layers (cf. Figure 3). At the coast, they are at least 25 meters thick. It can only be assumed, that this also applies to the adjoining area further inland to the east. The layers themselves are alternating fluvial, fluvio-glacial and purely glacial deposits from either a glacial river or the glacier itself at times of glacial advances and retreats. Marine sediments can also be found in some layers indicating a fluctuating sea level. All sediment layers show very different degrees of hardness: from loose and easily breakable to almost solid rock and all gradations in between. (Halldórsson 2006, Pétursson 1988)

In the southeastern part of town (known as Hóll), several kames characterize the topography (Waltl 2013). Their structure is fairly complex. Fluvio-glacial deposits alternate with glacial deposits, often in a chaotic, unstructured and rearranged way. It results from the material's movements when it was deposited but also from the glacier advancing and retreating several times (Saemundsson and Karson 2006).

BUILDING STOCK

The last and uppermost hazard sphere contains all anthropogenic structures with the building stock leading the way. With regard to seismic risk, the three primary building-specific factors are the building age, the building material, and the building usage.

Building age can indicate how earthquake resistant a building is constructed with regard to (earthquake) building codes that were implemented at times when a building was constructed. Four

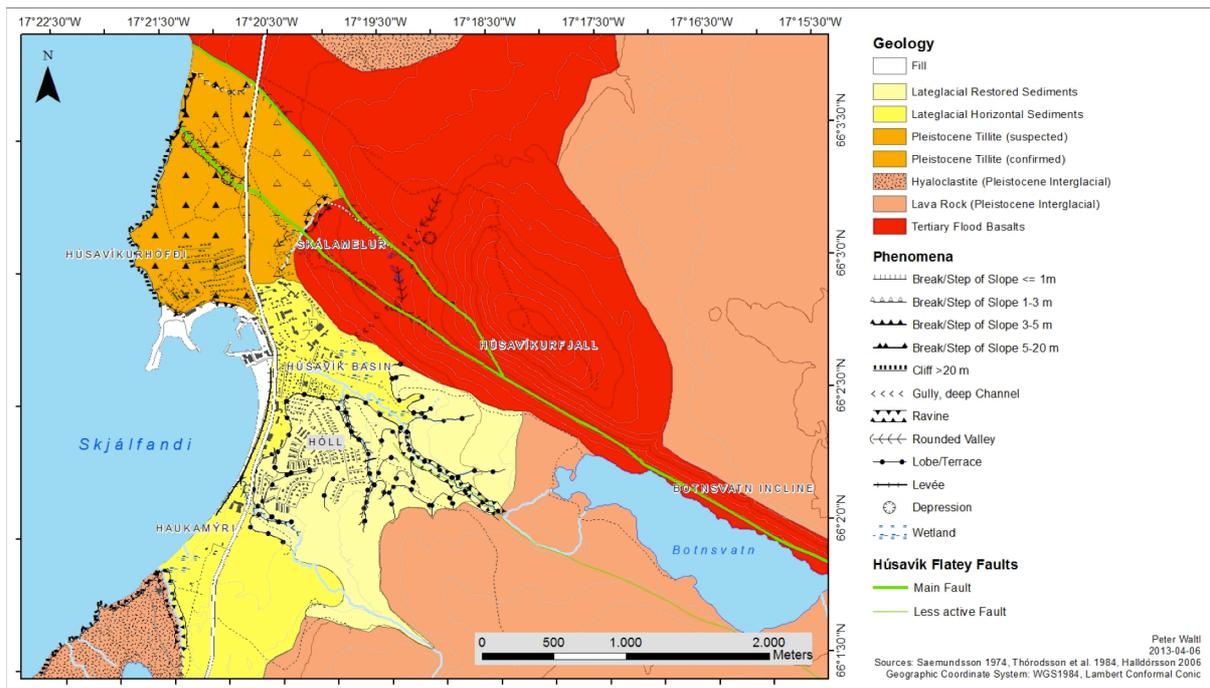


Figure 3: Geological main units in the greater Húsavík area. (Waltl 2013)

classes can be differentiated: Buildings from the first half of the 20th century and older were built at a time when quality standards were practically non-existent in Iceland. It was not until the end of World War II, that building standards were introduced and the effects of earthquakes were taken into account as a static horizontal force equal to 1/15th of a building's weight. The first earthquake-specific building code known as IST-13 norm was implemented in 1976. Building projects in zones of highest earthquake hazard (like Húsavík) had to be adjusted to a PGA of 0,2 g. In 2002 these building codes were further tightened when the Eurocode 8 norm was implemented in Iceland. Now, the design PGA for buildings in the zones of highest earthquake hazard is 0,4 g (Sigbjörnsson et al. 2008). The building material in combination with the subsurface material (geology), and the height, geometry, and statics of the building all influence seismic risk. The usage of a building influences seismic risk emanating from earthquakes in a way that it can indicate whether and how many people or other valuables may be present in a building at different times of day.

With the oldest house being 140 years old, Húsavík's building stock is relatively young. However, with regard to earthquake resistance, the majority (60%) of the 977 defined building structures were erected prior to the introduction of earthquake specific building codes (cf. Figure 4). Various building materials are in use, concrete being used most often, followed by timber and cinderblocks or bricks. Since the IST-13 norm was introduced in Iceland, concrete buildings have had to be reinforced with steel.

The present buildings have various functions (cf. Figure 5). The vast majority serves residential purposes. These buildings range from single family houses to row houses, and apartment blocks. They also typically have a garage. Thus, garages and other storage facilities represent the second most common type of building. Since Húsavík is the political and functional center of the Norðurljóning municipality, the town also hosts many public, retail, office, infrastructural, and industrial buildings. Many of these buildings are crucial for the functioning of the town and the wellbeing of its inhabitants and thus, delineate structures of important daily usages. The damaging or collapsing of these functional buildings due to earthquakes will also lead to a disturbance of the general wellbeing of the whole town of Húsavík.

There are recognizable patterns regarding the age and the usage of the buildings, but not their material. By tendency, all houses built during the oldest building period are located within the Húsavík basin. With some exceptions, younger buildings become more and more frequent with increasing distances from this oldest core zone (cf. Figure 6). Usage-specific patterns accord with the spatial

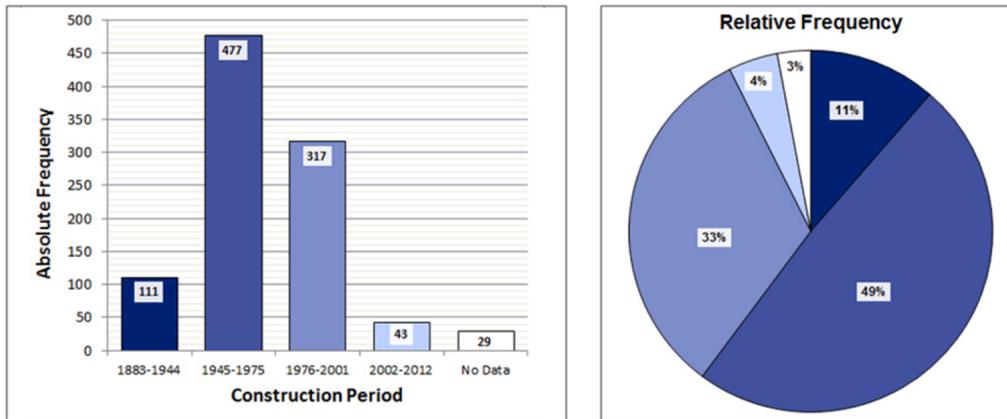


Figure 4: Absolute (a) and relative (b) frequency distributions by the building periods present. (Waltl 2013)

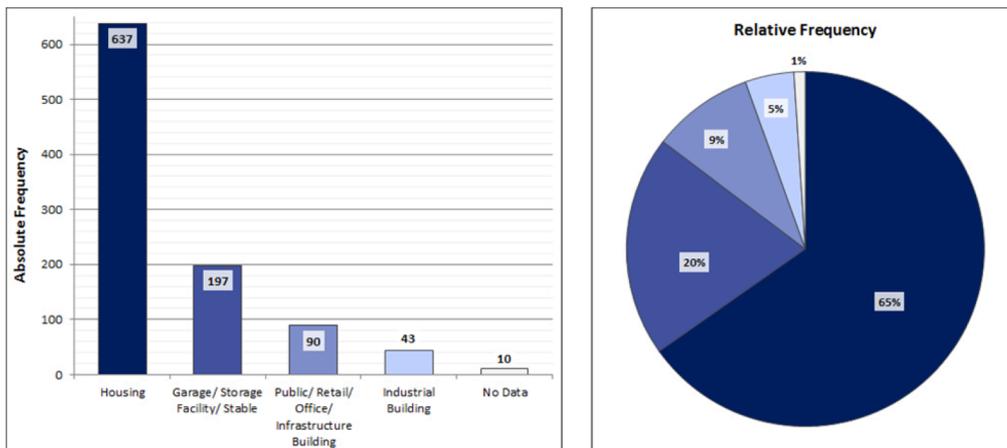


Figure 5: Absolute (a) and relative (b) frequency distributions by classified usage categories. (Waltl 2013)

planning zones of Húsavík. With some variation in the respective sections, basically all building materials were used in all building periods and all functions. (Waltl 2013)

DISCUSSION

In the following, features and characteristics of each of the earthquake hazard spheres are linked up spatially. Based on a geological interpretation, areas with high primary effect or hazard potential can be outlined. Next, we examine whether building structures are involved. If so, potential zones of seismic risk can be identified. Furthermore, elements of uncertainty shall be listed and the need for further research is outlined.

While the earthquake intensity strongly depends on the location of the epicenter and the earthquake fault rupture propagation relative to the town of Húsavík, insignificant spatial variations of earthquake strength are to be expected due to tectonic influencing factors (source- and path effects). This is because of the town's small spatial scale relative to the HFF fault dimensions. However, areas directly on either of the two local main faults, the Laugardalur- and the Skjólbrekka Faults, face the highest hazard potential due to the possible occurrence of tectonic fissures (e.g. Halldórsson 2006). This is well-known in Húsavík and therefore, no buildings apart from stables/barns and storage facilities are permitted in the Skálamelur unit.

The near-surface geology (which can be several tens of meters, depending on wave frequency), however, has a strong influence on propagating earthquake waves just before they reach the surface of the ground, amplifying (or reducing) the seismic motion (e.g. Anderson et al. 1996). Therefore, variations in primary earthquake hazards need to be estimated qualitatively by correlating local surface geology with measurements of earthquake ground motions on different geological formations in Húsavík (Halldórsson et al 2012).

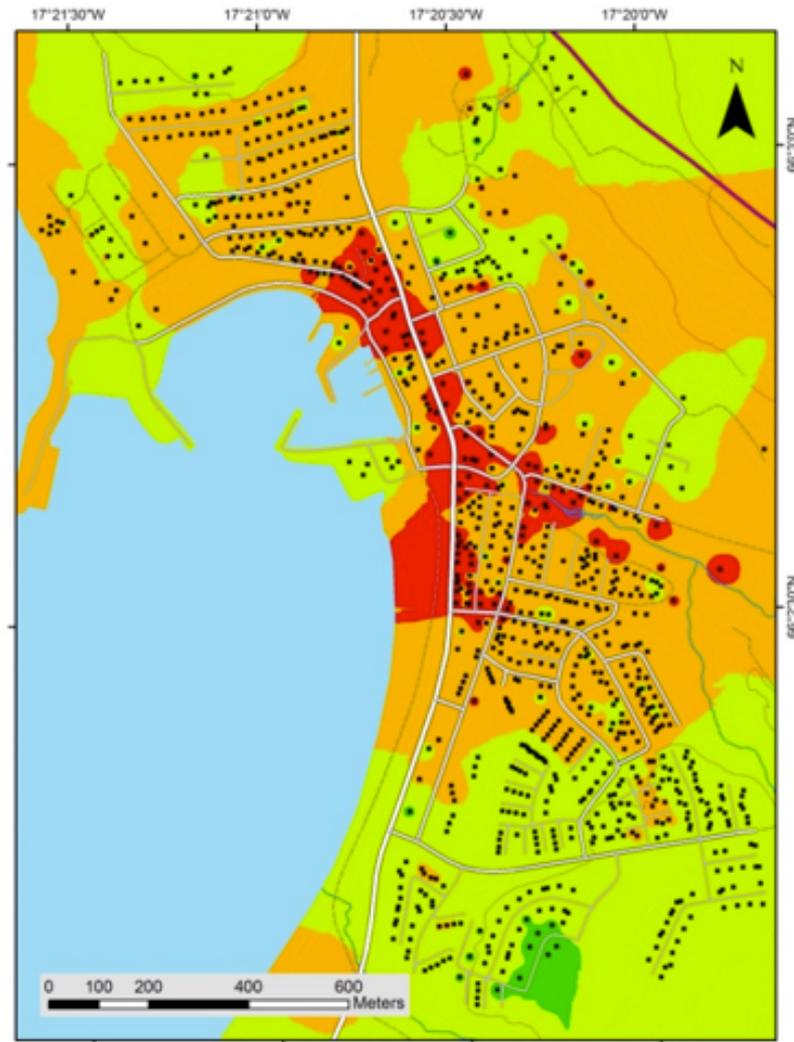


Figure 6: Areal view of the building stock's age distribution characteristics in Húsavík. Red: <1945, orange: 1945-1975, bright green: 1976-2001, dark green: 2002-2012 (right). (Waltl 2013). The red line in the top-right corner denotes the surface fault trace of the Laugardalur fault branch of the HFF.

In earthquake building codes that include the EN 1998/Eurocode 8 norm, geological formations classified as hard bedrock are considered relatively safe formations (Bisch et al. 2011). In the larger Húsavík area these are Tertiary basalts and Quaternary lavas like the Grjótháls formation. However, practically no buildings among the analyzed building stock are constructed on these formations.

Tillite is the bedrock formation that makes up the entire Húsavíkurhöfði hill in the northern part of town (cf. Figure 3). It is overlain by altered, fine glaciolacustrine and –marine sediments (Eiríksson 1985, Pétursson 1988). Through the alteration process they also became very hard, almost as hard as bedrock.

The softer/looser the surface material, the more severe are the site specific earthquake hazards (e.g. Bisch et al. 2011). Therefore, the geological formation in central Húsavík and Haukamýri with its alternating horizontal sediment layers and their varying degrees of hardness (from loose to very hard) has – like in Hóll with its rearranged sediments – the highest potential for a local amplification of the earthquake strength. The horizontal sediments are thought to be around 25 m thick and located either on top of Tillite or Grjótháls lava/Hyaloclastite (Pétursson 1988). The thickness is derived from the situation along the coast and may alternate the further inland one goes (Halldórsson 2006). Additionally, the topographic and geological situation in these areas lead to the formation of wetlands as can be found in Haukamýri and the eastern part of the Húsavík basin, where they have partly been drained and used as a building area (cf. Figure 3).



Figure 7: Topography of Húsavík. (Wältl 2013). The colors show clearly the varying elevations within the urban area of the town, and the proximity to the Húsavík mountain (top-right) and the Skjálbrekka and Laugardalur surface fault traces of the HFF.

Regarding the rearranged sediments in the Hóll area, no research has been conducted concerning the thickness or the underlying geological formations. However, geomorphological interpretations of this area lead to the conclusion that the thickness of the sedimentary layers on the individual kames varies between ~10 and ~30 meters. Moreover, they most likely overlay the Grjótháls formations or Tillite. (Wältl 2013)

With respect to the building stock, it is conspicuous that most of Húsavík's oldest buildings and such being important for a proper functioning of the town are situated in the area with the horizontal sediments and in several cases on former wetlands, too. This will undoubtedly lead to a relatively

higher seismic risk for individual houses but also for the whole town and its well-being if important functional buildings (such as schools, etc.) are damaged or even destroyed. (Waltl 2013)

The primary earthquake hazard may also be influenced by topographic amplification effects that lead to an increase in the amplitude of ground motion. Generally, these topographic amplifications are the largest on top of or along the ridges of slopes (Murphy 2006). Since Húsavík is embedded in a hilly to montane environment, topographic effects are expected to play a role. However, to what extent has not been investigated yet. Affected locations within the settled areas of Húsavík might be Húsavíkurhöfði and the kames of Hóll as well as the coastal line where peaks and ridges can be found (cf. Figure 7).

Summing up, it can be said that there are spatial variations within Húsavík that affect both primary earthquake hazard and seismic vulnerability of structures. They are caused by different geological formations near the surface and the topography, as well as the characteristics of the building stock. On the other hand, the tectonic environment is not expected to have significant influence on relative differences in earthquake hazard, apart from the areas directly positioned on the fault trace of the main faults where earthquake ruptures are expected to occur at the surface. It has to be pointed out that these conclusions are based on field observations and geological-geomorphological interpretations. Currently, neither quantitative or far-reaching statements on the spatial extent nor the exact degree of the variations can be made due to the lack of quantitative geological knowledge of the greater Húsavík area.

CONCLUSIONS

It was this survey's goal to determine, examine, interpret, and combine tectonic, geological-geomorphological, and building stock-specific phenomena and processes with respect to locally varying earthquake hazards and seismic risks in the greater Húsavík area.

Due to a lack of detailed knowledge on the near-surface geology, it is currently not possible to make any well-founded and reliable quantitative or absolute statements about earthquake hazard patterns within the urban area of Húsavík. However, interpreting and combining the obtained information on the local hazard spheres has allowed for a robust qualitative and relative identification of local earthquake hazard- and seismic risk patterns. Simultaneously, this relative hazard- and risk gradation without absolute numbers and statements calls for an immediate research on the local near-surface geology in order to draw reliable quantitative and absolute conclusions on the local hazard- and risk patterns. Besides the dense accelerograph network within the town, test drilling and further geophysical applications could provide important additional information on the site-specific influencing factors that lead to locally varying earthquake hazards.

Summa summarum it can be concluded that quantifying the relative risk pattern in Húsavík with respect to earthquakes is a work in progress. Importantly however, efficient measures have been taken by the local municipality and civil defense committee to raise awareness and lower the vulnerability and increase the resistance of the community to seismic risk. In view of the high primary earthquake hazard potential, however, it is important to continue the work on mapping the relative differences in both earthquake ground motion and seismic risk across Húsavík.

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