ICEARRAY II: A new multidisciplinary strong-motion array in North Iceland

B. Halldorsson[1], S. Jónsson[2], A.S. Papageorgiou[3], R.A. Green[4], I. Kalogeras[5], H. Avery[6], S. Ólafsson[1], S. Remseth[7], C.S. Oliveira[8], O. Polat[9] & R. Sigbjörnsson[1,7]

[1]Earthquake Engineering Research Centre, University of Iceland, Iceland, [2]King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, [3]University of Patras, Patras, Greece, [4]Virginia Tech, Blacksburg, USA, [5]Institute of Geodynamics, National Observatory of Athens), Athens, Greece, [6]Canterbury Seismic Instruments Ltd., University of Canterbury, Christchurch, New Zealand, [7]Department of Structural Engineering, Norwegian University of Science and Technology, Trondheim, Norway, [8]Instituto Superior Técnico, Lisboa, Portugal, [9]Dokuz Eylul University, Izmir, Turkey

15 WCEE
LISBOA 2012

SUMMARY:
The ICEARRAY II is a new small-aperture array of accelerographs and very-high sampling-rate CGPS instruments. It is scheduled for completion in the town of Húsavík in North Iceland (population 2237) in 2012. Húsavík is situated directly atop of the Húsavík-Flatey Fault system (HFF), the largest transform fault in Iceland, having the seismic potential for a magnitude 6.8 earthquake. Moreover, Húsavík partially sits in an extensional basin of relatively soft sediments that are likely to contribute to localised site effects and spatially variable earthquake strong-motions. The array is being deployed for the purpose of (1) monitoring strong-motions from earthquakes on the HFF and in the Northern Volcanic Zone of Iceland, (2) mapping the incoherence of strong-motion across the town, and (3) capturing the intense near-fault motion and the associated permanent displacements.

Keywords: strong-motion, GPS, near-fault motion

1. INTRODUCTION

The South Iceland Seismic Zone (SISZ) in the lowlands of South Iceland and the largely offshore Tjörnes Fracture Zone (TFZ) in North Iceland are the regions in Iceland where earthquake hazard is the highest i.e., where the probability of earthquake ground motions exceeds a certain level. Thus, these regions have the greatest potential for the occurrence of large earthquakes. The potential of the SISZ has been well documented in the historical catalogue, being a region in which damaging earthquakes up to magnitude 7 have taken place in the past; generally as single events or sequences of magnitude 6-7 earthquakes, lasting for several days or years, at an average interval of ~100 years (Stefansson *et al.* 1993; Olafsson, Sigbjornsson, & Einarsson 1998; Sigbjörnsson & Olafsson 2004; Sigbjörnsson *et al.* 2009; Halldorsson & Sigbjörnsson 2009) (see Figure 1.1). The historical earthquake catalogue of the TFZ is less complete, due to the difficulty of estimating the size and location of offshore earthquakes from limited on-land historical accounts.

In combination with the fast growing modern infrastructures in these regions, the seismic risk is also relatively high [risk is defined as the probability of experiencing economic and human losses (building damage, number of people hurt or killed) following a damaging or devastating earthquake]. Recent seismic events worldwide, such as the 2008 M7.9 Sichuan, China; 2009 M6.3 L'Aquila, Italy; 2010 M7.0 Haiti; M8.8 Chile; and M7.1 New Zealand, and 2011 M6.3 New Zealand and M9.0 Tohoku, Japan, have all demonstrated the devastating effect that intense strong ground motions, in particularly those close to the earthquake fault (Mavroeidis & Papageorgiou 2003; Rupakhety *et al.* 2011), can have on critical infrastructure, economy, society developmental progress and the environment. Although the scale of this issue in Iceland may be smaller than in some other regions of the world, the M6.5 earthquake in June 2000 and the M6.3 earthquake in May 2008 in the SISZ have highlighted the impact that significant events can have in Iceland. The importance of the society being able to mitigate such effects becomes clear in this context, as does the responsibility for lowering the

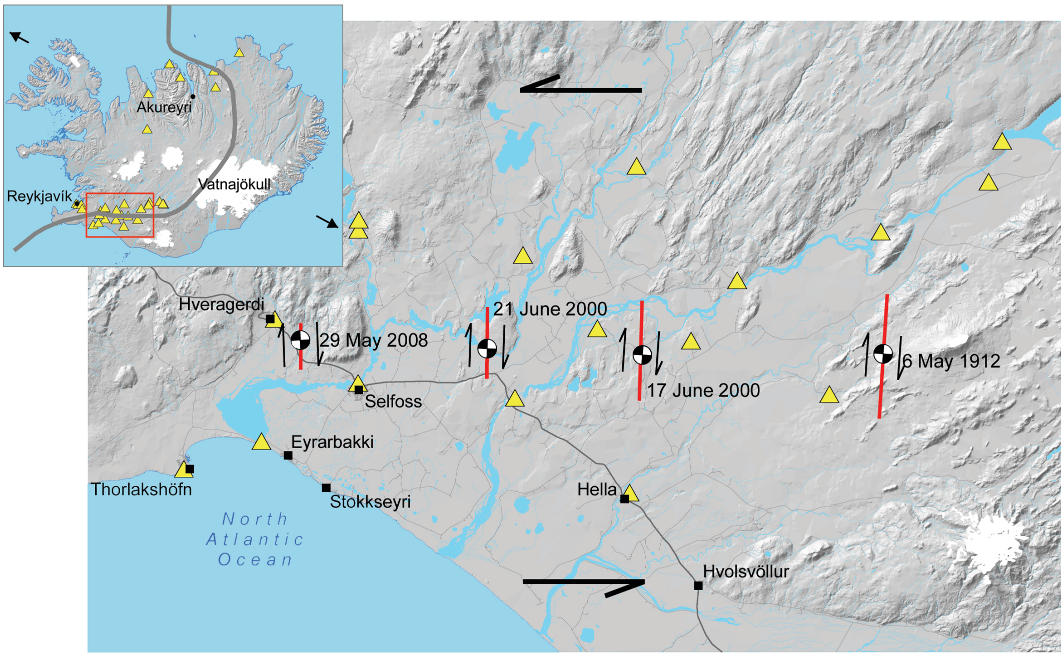

Figure 1.1. The approximate locations and fault alignment of damaging earthquakes larger than M6 over the last 100 years in the South Iceland Seismic Zone. The inset top left right shows Iceland with respect to the present day location of the Mid-Atlantic Ridge and the rectangle indicates the area shown in the main picture. The triangles show the locations of the recording stations of the Icelandic Strong-motion Network.

seismic risk to ensure the well-being of the population. This can be achieved in several ways, all of which depend on a more accurate and physically realistic assessment of the earthquake hazard, and supported by data. In the past the scarcity of recorded strong-motion data in the SISZ and TFZ had severely hampered the reliable assessment of earthquake hazard, especially in the magnitude range generally considered in such analyses (M>5.0).

2. STRONG-MOTION MONITORING IN THE SISZ

The Icelandic Strong-motion Network (ICESMN) of the Earthquake Engineering Research Centre (EERC) has been operated in Iceland for over 25 years (see Figure 1.1). The largest part of the network is in operation in the SISZ where most of the recording sites are located in single-storey residential buildings, but important buildings and lifeline systems (hospitals, municipal buildings, bridges, hydroelectric power plants, and dams) are also instrumented as a part of the ICESMN. Since its deployment, the ICESMN has produced high-quality acceleration recordings of all significant earthquakes in Iceland (Ambraseys *et al.* 2004). They have all occurred in the SISZ: the 1987 M6.0 Vatnafjoll earthquake (close to Hekla), the two June 2000 M6.5 and M6.4, and the 2008 M6.3 earthquakes in the SISZ (see Figure 1.1). The ICESMN recordings are the only ones of their kind in Iceland. It is emphasized that the ICESMN recorded the June 2000 and May 2008 earthquakes in the near-fault region (distances generally less than one source dimension from the fault). Characteristic of such motions, the ICESMN near-fault data show large amplitude and long-period velocity pulses and intense high-frequency accelerations that attenuate rapidly with distance from the faults (Halldorsson, Ólafsson, & Sigbjörnsson 2007; Sigbjörnsson *et al.* 2009; Halldorsson & Sigbjörnsson 2009). These were the first near-fault recordings of Icelandic earthquakes, and they significantly enhanced the global dataset of such motions, which generally produce the greatest damage during earthquakes (Mavroeidis & Papageorgiou 2003; Rupakhety *et al.* 2011).

3. THE ICEARRAY I AND THE M6.3 ÖLFUS EARTHQUAKE OF 29 MAY 2008

New research opportunities have been created over the last decade in the SISZ that can potentially constrain the above hazard and risk estimates even further. The deployment of the first Icelandic strong-motion array (ICEARRAY I) in 2007 commenced a new era in monitoring earthquake strong-motion and its effects on densely inhabited areas in Iceland (Halldorsson, Sigbjornsson, & Schweitzer 2009). The fundamental difference between the ICESMN and the ICEARRAY I is that the former is a "network" of recording sites where adjacent sites in a seismic zone are at least ~5-15 km apart on average (Figure 1.1, triangles), while the latter is a small-aperture array of recording sites with interstation distances ranging from 50-1900 meters within a densely inhabited area (dots in Figure 3.1). Array data are either analysed using conventional methods or specialized array processing techniques, depending on the level of incoherency of the seismic wave field across the array (Johnson & Dudgeon 1992; Rost & Thomas 2002; Gibbons & Ringdal 2006; Gibbons, Ringdal, & Kværna 2008).

The globally unique and high-quality recordings that ICEARRAY I produced at multiple locations in the town of Hveragerdi during the extreme near-fault earthquake ground shaking due to the magnitude 6.3 Ölfus earthquake on 29 May 2008 (Halldorsson & Sigbjörnsson 2009) (see Figure 3.1), have created the opportunity to investigate nearly all pertinent issues of modern society's vulnerability to earthquakes. Through the "ICEARRAY I" projects (during 2006-2011) the EERC has spearheaded intense earthquake monitoring and research efforts that have received considerable attention in the international scientific literature. In these efforts, the EERC has been supported by a group of international experts that with their multidisciplinary background have contributed to the ongoing analysis of the ICEARRAY I data, modelling efforts and estimation of their practical implications (Halldorsson *et al.* 2007; Halldorsson & Avery 2008; Halldorsson & Sigbjörnsson 2008; Halldorsson *et al.* 2009; Sigbjörnsson *et al.* 2009; Halldorsson & Sigbjörnsson 2009; Halldorsson & Avery 2009; Chanerley, Alexander, & Halldorsson 2009; Chanerley *et al.* 2010; Douglas & Halldorsson 2010; Halldorsson *et al.* 2010a; Rupakhety, Halldorsson, & Sigbjörnsson 2010; Halldorsson *et al.* 2010b; Halldorsson, Mavroeidis, & Papageorgiou 2011; Halldorsson & Papageorgiou 2012a; b).

At present, the ICESMN and ICEARRAY I recordings of the most significant earthquakes in Iceland over the last quarter-century have enabled reliable estimates of earthquake hazard and seismic risk in the SISZ (Sigbjörnsson *et al.* 1998; Solnes, Sigbjörnsson, & Eliasson 2002; Solnes, Sigbjornsson, & Eliasson 2004; Sigbjörnsson *et al.* 2008a; b; c; Rupakhety & Sigbjörnsson 2009a; b), which has led to robust guidelines for earthquake-resistant design of structures (European Committee for Standardization 2003). On the contrary, due to lack of strong-motion data, parallel research for the TFZ in North Iceland, based on regional data, and the corresponding applications for infrastructure has been virtually non-existent (e.g., Björnsson *et al.* 2007).

The ICEARRAY I deployment and the strong-motion recordings discussed above motivated a new *International Symposium on Strong-motion Earthquake Effects* (ISSEE) which is held biannually in Iceland by the EERC. The first symposium was held in May 2009, the first anniversary of the Ölfus earthquake, and the second in April 2011. The ISSEE focuses on earthquake source mechanics and strong-motions, in particular near-fault effects, strong-motion attenuation, earthquake response of structures and lifelines, in addition to seismic risk and economic effects of earthquakes. The symposia have received considerable contributions from the international scientific community, in addition to domestic contributions (see e.g., Guðmundsdóttir 2009; Thorvaldsdóttir 2009; Ansal, Kurtulus, & Tonuk 2011; Carr 2011; Green 2011; Ivanov 2011). All presentations at the ISSEE are readily available on the EERC website (www.eerc.hi.is). The next ISSEE will be held in the spring of 2013.

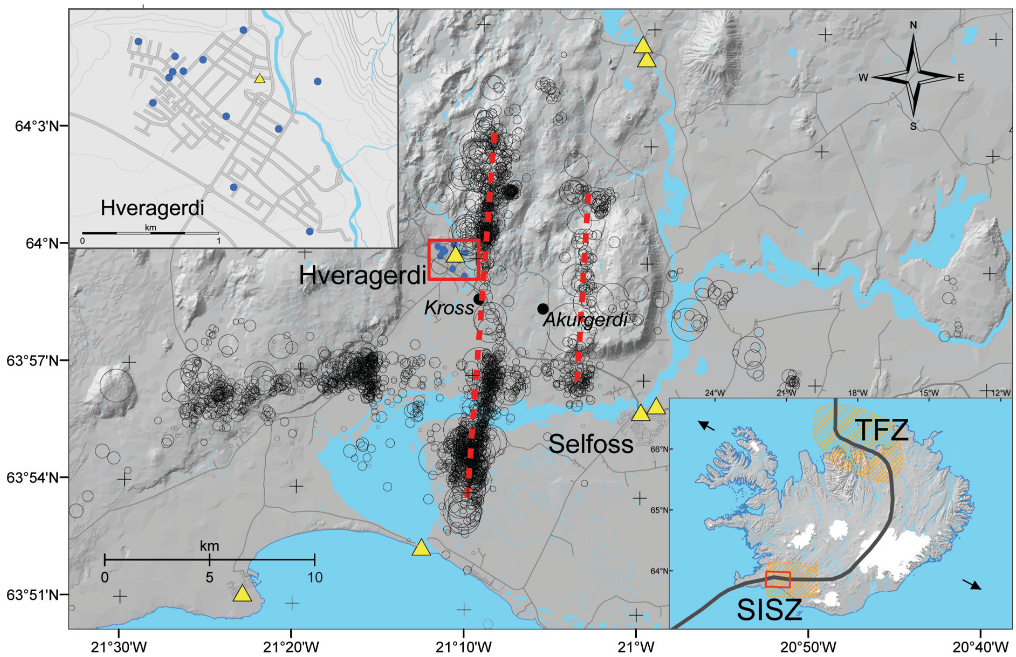

Figure 3.1. The north-south trending alignment of the seismicity (circles, IMO) distribution for the duration of May 29 - June 29, 2008, in South-west Iceland indicates the location of the causative faults (dashed lines) of the 15:45 UTC May 29 2008 earthquake. The inset picture bottom right shows Iceland with respect to the Mid-Atlantic Ridge, the Tjörnes Fracture Zone (TFZ) in the north and South Iceland Seismic Zone (SISZ) in the south by the dashed outlined areas. The thick solid rectangle indicates the area shown in the main picture. The inset picture at top left shows the locations of the recording stations of the ICEARRAY in the village of Hveragerdi. Note the proximity of the fault to the ICEARRAY. [from Halldorsson & Sigbjornsson, 2009].

4. THE TJÖRNES FRACTURE ZONE

The TFZ is a ~120 km offset in the Mid-Atlantic Ridge that is spreading at a rate of about 2 cm/yr (DeMets *et al.* 1994; Sigbjörnsson *et al.* 2006; Árnadóttir *et al.* 2009; Metzger, Jónsson, & Geirsson 2011). Earthquakes occur mainly along two main seismic lineaments in the TFZ, the Húsavík-Flatey Fault (HFF) and the Grímsey Oblique Rift (GOR). The HFF is the largest transform fault in Iceland (Brandsdóttir *et al.* 2005), extending over 100 km from Theistareykir fissure swarm in the east, through the town of Húsavík, and west to the Eyjafjarðaráll Rift (Figure 4.1).

The epicentres of the most important earthquakes of the last 300 years within the TFZ are graphically summarized in Figure 4.1 (Stefánsson, Guðmundsson, & Halldórsson 2008; Metzger *et al.* 2011). During the past 140 years no major earthquake has released the stress that has probably accumulated on the HFF. Four major earthquakes occurred on the HFF during the past 300 years. In 1755, an earthquake estimated at M7 took place in Skjálfandi Bay and an M6.5 occurred near its western end in 1838. The last major earthquake sequence on the eastern part of the HFF occurred in 1872 with the two biggest events likely reaching M6.5 and located close to Flatey and Húsavík. Most of the present-day seismicity of HFF is located on the northwestern part of the fault (Figure 4.1).

The EERC has been operating seven free-field 3-component accelerographs in North Iceland for 23 years (see inset Figure 1.1). In stark contrast to the SISZ, during the operation of the ICESMN no significant earthquakes producing damaging strong-motions (i.e., seismic ground motions large enough to cause damage; generally peak ground acceleration (PGA) ≥0.2 g; where g is the acceleration of gravity) have taken place in the TFZ. The network has recorded several light-to-

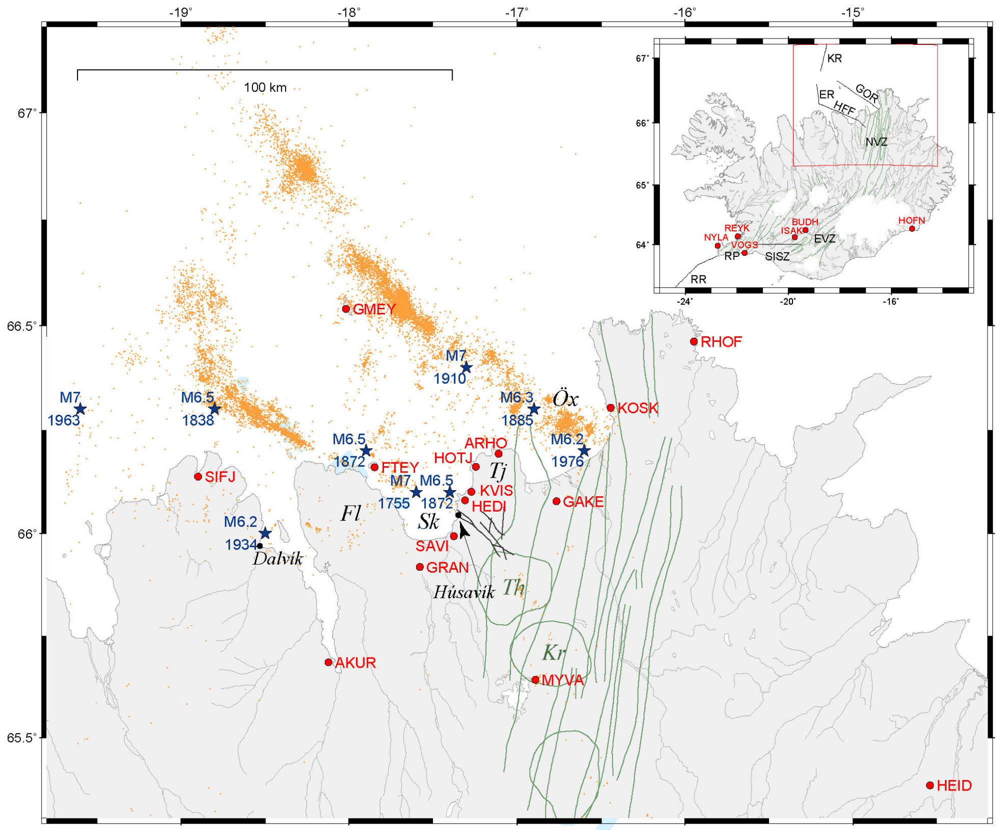

Figure 4.1. Tectonic setting, seismicity and continuously operating GPS stations in (North) Iceland. The Mid-Atlantic Ridge is offset by the South Icelandic Seismic Zone in the South (SISZ) and by the Húsavík Flatey Fault (HFF) and the Grímsey Lineament (GOR) in the North (inset). Large historical earthquakes with given magnitude and year are marked with blue stars (after Stefánsson et al. 2008). Orange dots show the M>2 earthquake locations 1992-2008 (after SIL 2008). The surface fault traces of the HFF in the Húsavík area are plotted as dark grey lines (after Rögnvaldsson et al. 1998). Fissure swarms are indicated with green lines. Central volcanoes: Th – Theistareykir, Kr – Krafla. Other plate boundary segments: RR – Reykjanes Ridge, RP – Reykjanes Peninsula, EVZ – Eastern Volcanic Zone, NVZ – Northern Volcanic Zone, ER – Eyjarfjarðaráll Rift, KR – Kolbeinsey Ridge. Other features: Fl – Flateyjarskagi peninsula, Sk – Skjálfandi bay, Tj – Tjörnes peninsula,Öx – Öxarfjörður bay. [from Metzger et al., 2011].

moderate (i.e., M4.0-5.8) earthquakes at distances of ~12-90 km in the TFZ that have produced strong motion (i.e., ground shaking at levels felt by humans, generally with peak ground acceleration ≥0.01-0.05 g) (Sigbjornsson, Olafsson, & Thórarinsson 2004). The instruments act in triggered-recording mode and record 100-200 samples of ground acceleration per second, which is required to sufficiently sample fast ground motions. The wide dynamic range of the ICESMN accelerographs allows for the recording of strong-motions up to or exceeding the acceleration of gravity (±1 g) along three orthogonal components.

Continuous GPS (CGPS) observations in the TFZ began in 1999 and by 2002 three CGPS stations were operating in the region. The network of CGPS instruments was significantly improved in 2006-7 and it now contains 14 stations, including stations positioned on a profile across the on-land portion of the Húsavík-Flatey Fault (Figure 4.1). The main purpose of the CGPS network is to monitor crustal movements and to provide detailed insight into the kinematics of the transform zone (Geirsson *et al.* 2006, 2007). The mostly offshore location of the TFZ and its complex tectonics make it challenging to resolve the transform kinematics and evaluate the seismic potential of the two main transform structures, the Grímsey Oblique Rift, and the Húsavík Flatey Fault. However, the network results show that currently the transform motion in the TFZ is currently accommodated ~34% by the HFF and ~66% by the GOR. The resulting slip velocity of ~6.9 mm/yr on the HFF and the time since the

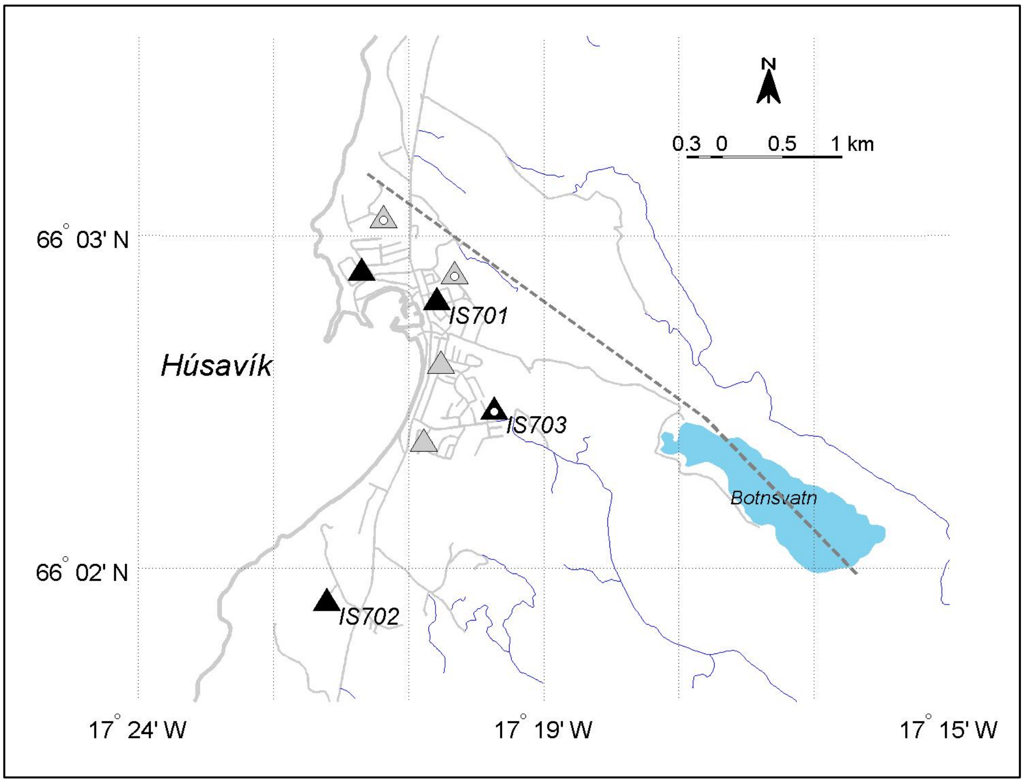

Figure 5.1. Locations of ICEARRAY II strong-motion stations in Husavik, north Iceland, that have been installed (black triangles) and are planned (grey triangles). Three stations within the town will be collocated with high-rate sampling GPS units (white dots in triangles), scheduled for deployment in 2012. The thick grey line denotes the coastline, with Skjalfandi-bay to the west of Husavik, and the thin grey lines denote the road-system of Husavik and its vicinity. The lake Botnsvatn sits directly on the HFF, where its approximate location on land is denoted by the thick dashed grey line.

last two strong M6.5 earthquakes in 1872 indicate a slip deficit on the fault of ~0.83-1.05 meters, assuming a steady slip rate since 1872. This slip deficit corresponds to the seismic potential of the HFF being equal to ~M6.8 earthquake (Metzger *et al.* 2011) (the maximum considered earthquake potential of the western HFF is ~M7.3 (Björnsson *et al.* 2007)).

5. HÚSAVÍK AND THE ICEARRAY II

With Húsavík being the second largest town in North Iceland (2,300 people, Figure 5.1) and located directly on top of the HFF (Sæmundsson 1974; Sæmundsson & Karson 2006), it is exposed to relatively high seismic risk. Moreover, the local soil conditions in Húsavík are in part characterized by soft sediments of varying depths depending on the location inside the town. Buildings and critical infrastructure on and across such soft site conditions are much more susceptible to earthquake damage than infrastructure built on firm ground. This is supported by theoretical and empirical evidence in all damaging earthquakes since the dawn of earthquake and geotechnical engineering and seismological monitoring (see e.g., Kawase 2003; Youd 2003, and references therein). In addition, discussions of significant industrial development for the Húsavík area have arisen during the past decade, which would possibly include the construction of an aluminium smelter (Hönnun engineering consultants 2005; Sæmundsson & Karson 2006; Björnsson *et al.* 2007; Sigbjörnsson & Snæbjörnsson 2007).

Figure 5.1 shows the locations of the proposed ICEARRAY II stations with respect to Húsavík, the coastline and the HFF. In addition to one existing ICESMN station, three new ICEARRAY II stations were deployed in 2011. The additional strong-motion and CGPS stations shown in Figure 5.1 will be

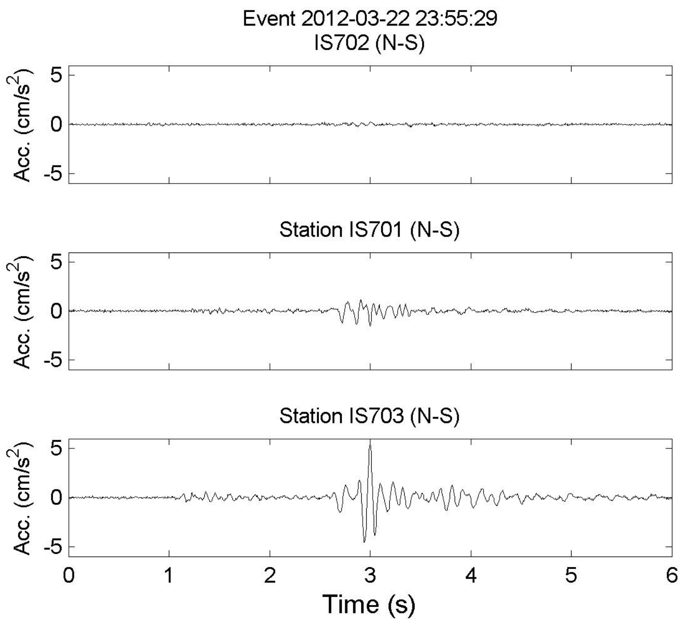

Figure 5.2. Recorded acceleration along the north-south component at three different ICEARRAY II stations for the earthquake event of 22 March 2012 at 23:55 (M_L2.2, epicentral distance 14 km). The difference in the recorded ground motion is dramatic.

deployed during the summer of 2012. Eventually, therefore, the ICEARRAY II will consist of eight strong-motion stations, three of which will be collocated with high-rate-sampling GPS units. The GPS units of ICEARRAY II will be an addition to the six profile CGPS stations lying to the north and south of Húsavík (Metzger *et al.* 2011). The closest CGPS stations in this network are currently ~3 km from the ICEARRAY II stations shown in Figure 5.1.

Since the deployment of the first ICEARRAY II stations, we have recorded three small earthquakes on the HFF. One of them was an M_L2.2 earthquake at a distance of 14 km from Húsavík. Figure 5.2 shows a comparison of the recorded acceleration (vs. time) along the north-south component on the three numbered stations in Figure 5.1. The difference in the strong-motion is dramatic and is most likely due to the difference in local site conditions at the stations. We note in particular the difference between stations IS701 and IS703. The former is located on soil in the basement of a 2-storey office building near the harbour while the latter is located in a residential house on the edge of a large hill (which is composed of gravel). Both instruments are located at the base of a low-rise reinforced concrete structure but between them there is a considerable difference in elevation (~20-30 meters). Finally, station IS702 is located ~1-2 km away from Húsavík on a completely different type of bedrock. We were aware of the qualitative differences in site conditions inside Húsavík (which controlled the station locations). Nevertheless, we did not expect the extent of this relative difference in ground motion amplitudes as shown in Figure 5.2. More data will eventually enable us to draw a clearer picture of the relative differences in earthquake ground motions inside Húsavík.

6. CONCLUSIONS

This study is intended to give a brief overview of the tectonics of Iceland with respect to earthquake potential and thus focuses on the two transform zones in the south and north of the country and presents the motivation behind the deployment of the ICEARRAY II strong-motion and GPS array in Húsavík, North Iceland. It builds on the current state of strong-motion monitoring in Iceland and, in particular, its latest developments, namely the deployment of the ICEARRAY I in South Iceland, and the research results and opportunities created from the data it recorded during the M_w6.3 Ölfus earthquake of 29 May 2008. The data shows considerable variability in recorded earthquake strong-motion, even over distances of less than 2 km in the town of Hveragerdi, for which local site conditions are believed to be fairly uniform (though with notable exceptions). The situation in the town of Húsavík was therefore expected to be more extreme, as the town sits in a pull-apart basin on the Húsavík-Flatey Fault, and the local site conditions were known to vary considerably across the town. The deployment of ICEARRAY II will be finished in 2012, and the recorded data so far, albeit limited, indicate that our reasons for deploying a permanent strong-motion (and GPS) monitoring system in Húsavík are warranted.

ACKNOWLEDGMENT
This study was supported by the Earthquake Engineering Research Centre (EERC) of the University of Iceland, in Selfoss, Iceland (www.eerc.hi.is) and the Research Fund of the University of Iceland. The ICEARRAY II is partially funded by Iceland Catastrophe Insurance and the Icelandic Centre for Research (RANNIS) Equipment Fund (No. 61038). The authors are grateful for this support, and to the municipality of Norðurþing, Húsavík, for providing logistical support.

REFERENCES

Ambraseys, N.N., Douglas, J., Sigbjörnsson, R., Berge-Thierry, C., Suhadolc, P., Costa, G. & Smit, P.M. (2004) Dissemination of european strong-motion data, volume 2. *Proceedings of the13th World Conference on Earthquake Engineering* p. 13.

Ansal, A., Kurtulus, A. & Tonuk, G. (2011) Site Response from Istanbul Vertical Arrays and Strong Motion Network. *2nd International Symposium on Strong-motion Earthquake Effects (2ISSEE)* Reykjavik, Iceland.

Árnadóttir, T., Lund, B., Jiang, W., Geirsson, H., Bj\örnsson, H., Einarsson, P. & Sigurdsson, T. (2009) Glacial rebound and plate spreading: results from the first countrywide GPS observations in Iceland. *Geophysical Journal International*, **177**, 691–716.

Björnsson, A., Sæmundsson, K., Sigmundsson, F., Halldórsson, P., Sigbjörnsson, R. & Snæbjörnsson, J.T. (2007) *Geothermal Projects in Iceland at Krafla, Bjarnarflag, Gjástykki and Theistareykir. Assessment of Geohazards Affecting Energy Production and Transmission Systems Emphasizing Structural Design Criteria and Mitigation of Risk*. Report done for Þeystareykir ehf., Landsnet hf. and Landsvirkjun.

Brandsdóttir, B., Riedel, C., Richter, B., Helgadóttir, G., Kjartansson, E., Dahm, T., Detrick, R., Mayer, L., Calder, B. & Driscoll, N. (2005) Multibeam bathymetric maps of the Kolbeinsey Ridge and Tjörnes Fracture Zone, N-Iceland. *Geophysical Research Abstracts* p. A–07219.

Carr, A. (2011) The M7.0 and M6.3 New Zealand Earthquakes. *2nd International Symposium on Strong-motion Earthquake Effects (2ISSEE)* Reykjavik, Iceland.

Chanerley, A.A., Alexander, N.A. & Halldorsson, B. (2009) On fling and baseline correction using quadrature mirror filters. *12th International Conference on Civil, Structural and Environmental Engineering Computing (CC2009)* p. Paper no. 177. Funchal, Madeira, Portugal.

Chanerley, A.A., Alexander, N.A., Halldorsson, B., Sigbjörnsson, R. & Perryman, R. (2010) Baseline correction made easier using an automated method base on the wavelet transform. *9th US National and 10th Canadian Conference on Earthquake Engineering (9USN/10CCEE)* p. Paper no. 358. Toronto, Canada.

DeMets, C., Gordon, R.G., Angus, D.F. & Stein, S. (1994) Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters*, **21**, 2191–2194.

Douglas, J. & Halldorsson, B. (2010) On the use of aftershocks when deriving ground-motion prediction equations. *9th US National and 10th Canadian Conference on Earthquake Engineering (9USN/10CCEE)* p. Paper no. 220. Toronto, Canada.

European Committee for Standardization. (2003) *Eurocode 8: Design of Structures for Earthquake Resistance - Part1: General Rules, Seismic Actions and Rules for Buildings*. European Standard.

Geirsson, H., Árnadóttir, T., Bennett, R., Hreinsdóttir, S., Jónsson, S., LaFemina, P.C., Sturkell, E., Villemin, T. & Miyazaki, S. (2007) A new high-rate continuous GPS network in Iceland for crustal deformation research. *Geophys. Res. Abs*, **9**, EGU2007–A– 06993.

Geirsson, H., Árnadóttir, T., Völksen, C., Jiang, W., Sturkell, E., Villemin, T., Einarsson, P., Sigmundsson, F. & Stefánsson, R. (2006) Current plate movements across the Mid-Atlantic Ridge determined from 5 years of continuous GPS measurements in Iceland. *Journal of Geophysical Research*, **111**, B09407.

Gibbons, S.J. & Ringdal, F. (2006) The detection of low magnitude seismic events using array-based waveform correlation. *Geophysical Journal International*, **165**, 149–166.

Gibbons, S.J., Ringdal, F. & Kværna, T. (2008) Detection and characterization of seismic phases using continuous spectral estimation on incoherent and partially coherent arrays. *Geophysical Journal International*, **172**, 405–421.

Green, R.A. (2011) The M7.0 Haiti Earthquake of 12 January 2010. *2nd International Symposium on Strong-motion Earthquake Effects (2ISSEE)* Reykjavik, Iceland.

Guðmundsdóttir, B. (2009) Psychological effects of the 29 May 2008 Ölfus Earthquake in Iceland: Preliminary findings. *1st International Symposium on Strong-motion Earthquake Effects (1ISSEE)* Reykjavik, Iceland.

Halldorsson, B. & Avery, H. (2009) Converting Strong-motion Networks to Arrays via Common Triggering. *Seismological Research Letters*, **80**, 572–578.

Halldorsson, B., Mavroeidis, G.P. & Papageorgiou, A.S. (2011) Near-Fault and Far-Field Strong Ground Motion Simulation for Earthquake Engineering Applications Using the Specific Barrier Model. *Journal of Structural Engineering*, **137**, 433–444.

Halldorsson, B., Ólafsson, S. & Sigbjörnsson, R. (2007) A Fast and Efficient Simulation of the Far-Fault and Near-Fault Earthquake Ground Motions Associated with the June 17 and 21, 2000, Earthquakes in South Iceland. *Journal of Earthquake Engineering*, **11**, 343.

Halldorsson, B., Ólafsson, S., Snæbjörnsson, J.T., Sigurðsson, S.U., Rupakhety, R. & Sigbjörnsson, R. (2012) On the Effects of Induced Earthquakes due to Fluid Injection at Hellisheidi Geothermal Power Plant, Iceland. *15th World Conference on Earthquake Engineering (15WCEE)* p. Paper no. 4069. Lisbon, Portugal.

Halldorsson, B. & Papageorgiou, A.S. (2012a) Variations of the specific barrier model - Part I: Effect of subevent size distributions. *Bulletin of Earthquake Engineering*, Doi: 10.1007/s10518–012–9344–0.

Halldorsson, B. & Papageorgiou, A.S. (2012b) Variations of the specific barrier model - Part II: Effect of isochron distributions. *Bulletin of Earthquake Engineering*, Doi: 10.1007/s10518–012–9345–z.

Halldorsson, B. & Sigbjörnsson, R. (2008) Design and installation of ICEARRAY, a new small-aperture strong-motion array in South Iceland. *14th World Conference on Earthquake Engineering (14WCEE)* pp. Paper no. 02–0097. Beijing, China.

Halldorsson, B. & Sigbjörnsson, R. (2009) The M_w6.3 Ölfus earthquake at 15:45 UTC on 29 May 2008 in South Iceland: ICEARRAY strong-motion recordings. *Soil Dynamics and Earthquake Engineering*, **29**, 1073–1083.

Halldorsson, B., Sigbjörnsson, R., Chanerley, A.A. & Alexander, N.A. (2010a) Near-fault strong-motion array recordings of the Mw6.3 Ölfus earthquake on 29 May 2008 in Iceland. *9th US National and 10th Canadian Conference on Earthquake Engineering (9USN/10CCEE)* p. Paper no. 1157. Toronto, Canada.

Halldorsson, B., Sigbjörnsson, R., Rupakhety, R. & Chanerley, A.A. (2010b) Extreme near-fault strong-motion of the M6.3 Ölfus earthquake of 29 May 2008 in South Iceland. *14th European Conference on Earthquake Engineering (14ECEE)* p. Paper no. 1640. Ohrid, Macedonia.

Halldorsson, B., Sigbjörnsson, R. & Schweitzer, J. (2009) ICEARRAY: the first small-aperture, strong-motion array in Iceland. *Journal of Seismology*, **13**, 173–178.

Hönnun engineering consultants. (2005) *Primary Aluminium Plant Located Near Húsavík. Site Study*.

Ivanov, R. (2011) The M9.0 Japan Earthquake of 11 March 2011. *2nd International Symposium on Strong-motion Earthquake Effects (2ISSEE)* Reykjavik, Iceland.

Johnson, D.H. & Dudgeon, D.E. (1992) *Array Signal Processing: Concepts and Techniques*. Simon & Schuster.

Kawase, H. (2003) Site effects on strong ground motions. *International Handbook of Earthquake and Engineering Seismology* International Geophysics Series. pp. 1013–1030. Academic Press for IASPEI.

Mavroeidis, G.P. & Papageorgiou, A.S. (2003) A Mathematical Representation of Near-Fault Ground Motions. *Bulletin of the Seismological Society of America*, **93**, 1099–1131.

Metzger, S., Jónsson, S. & Geirsson, H. (2011) Locking depth and slip-rate of the Húsavík Flatey fault, North Iceland, derived from continuous GPS data 2006-2010. *Geophysical Journal International*, **187**, 564–576.

Ólafsson, S., Sigbjörnsson, R. & Einarsson, P. (1998) Estimation of source parameters and Q from acceleration recorded in the Vatnafjoll earthquake in south Iceland. *Bulletin of the Seismological Society of America*, **88**, 556–563.

Rost, S. & Thomas, C. (2002) Array seismology: methods and applications. *Reviews of Geophysics*, **40**, 1008.

Rupakhety, R., Halldorsson, B. & Sigbjörnsson, R. (2010) Estimating coseismic deformations from near source strong motion records: methods and case studies. *Bulletin of Earthquake Engineering*, **8**, 787–811.

Rupakhety, R. & Sigbjörnsson, R. (2009a) Ground-motion prediction equations (GMPEs) for inelastic response and structural behaviour factors. *Bulletin of Earthquake Engineering*, **7**, 637–659.

Rupakhety, R. & Sigbjörnsson, R. (2009b) Ground-Motion Prediction Equations (GMPEs) for inelastic displacement and ductility demands of constant-strength SDOF systems. *Bulletin of Earthquake Engineering*, **7**, 661–679.

Rupakhety, R., Sigurdsson, S.U., Papageorgiou, A.S. & Sigbjörnsson, R. (2011) Quantification of ground-motion parameters and response spectra in the near-fault region. *Bulletin of Earthquake Engineering*, **9**, 893–930.

Sæmundsson, K. (1974) Evolution of the axial rifting zone in northern Iceland and the Tjornes fracture zone. *Bulletin of the Geological Society of America*, **85**, 495.

Sæmundsson, K. & Karson, J.A. (2006) *Stratigraphy and Tectonics of the Húsavík–Western Tjörnes Area*. ÍSOR, Reykjavík.

Sigbjörnsson, R., Bessason, B., Sigfússon, T.I., Sigfússon, T. & Thorvaldsdóttir, S. (1998) Earthquake risk mitigation in South Iceland. *11th European Conference on Earthquake Engineering (11ECEE)* Balkema.

Sigbjörnsson, R., Higgins, S.M., Olafsson, S., Halldorsson, B. & Snæbjörnsson, J.T. (2008a) Comparative study of uniform hazard spectra derived using different ground motion estimation model: A case study. *14th World Conference on Earthquake Engineering (14WCEE)* pp. Paper No. 07–0099. Beijing, China.

Sigbjörnsson, R. & Olafsson, S. (2004) On the South Iceland earthquakes in June 2000: strong-motion effects and damage. *Bollettino di Geofisica Teorica ed Applicata*, **45**, 131–152.

Sigbjörnsson, R., Ólafsson, S. & Thórarinsson, Ó. (2004) Strong-motion recordings in Iceland. *Proceedings of the 13th World Conference on Earthquake Engineering* Mira, Vancouver, BC, Canada.

Sigbjörnsson, R., Sigurdsson, T., Snæbjörnsson, J.T. & Valsson, G. (2006) Mapping of crustal strain rate tensor for Iceland with applications to seismic hazard assessment. *First European Conference on Earthquake Engineering and Seismology (1ECEES)* p. Paper no. 1211. Geneva, Switzerland.

Sigbjörnsson, R. & Snæbjörnsson, J.T. (2007) *Earthquake Hazard - Preliminary Assessment for an Industrial Lot at Bakki Near Húsavík*. Earthquake Engineering Research Centre. University of Iceland, Selfoss.

Sigbjörnsson, R., Snæbjörnsson, J.T., Higgins, S.M., Halldorsson, B. & Ólafsson, S. (2009) A note on the Mw 6.3 earthquake in Iceland on 29 May 2008 at 15:45 UTC. *Bulletin of Earthquake Engineering*, **7**, 113–126.

Sigbjörnsson, R., Snæbjörnsson, J.T., Higgins, S.M., Olafsson, S. & Halldorsson, B. (2008b) Mapping of inelastic effects and structural behaviour factors for EUROCODE 8: A case study for Iceland. *14th World Conference on Earthquake Engineering (14WCEE)* pp. Paper No. 01–0042. Beijing, China.

Sigbjörnsson, R., Snæbjörnsson, J.T., Higgins, S.M., Olafsson, S. & Halldorsson, B. (2008c) Probabilistic hazard assessment of fault displacements. *14th World Conference on Earthquake Engineering (14WCEE)* pp. Paper No. 07–0096. Beijing, China.

Solnes, J., Sigbjörnsson, R. & Eliasson, J. (2002) Mapping of earthquake induced risk in Iceland. *12th European Conference on Earthquake Engineering (12ECEE)* p. Paper no. 215. Oxford. Elsevier Science, London, UK.

Sólnes, J., Sigbjörnsson, R. & Elíasson, J. (2004) Probabilistic seismic hazard mapping of Iceland: Proposed seismic zoning and de-aggregation mapping for EUROCODE 8. *Proceedings of the 13th World Conference on Earthquake Engineering* Vancouver, BC.

Stefansson, R., Bodvarsson, R., Slunga, R., Einarsson, P., Jakobsdottir, S., Bungum, H., Gregersen, S., Havskov, J., Hjelme, J. & Korhonen, H. (1993) Earthquake prediction research in the South Iceland seismic zone and the SIL project. *Bulletin of the Seismological Society of America*, **83**, 696–716.

Stefánsson, R., Guðmundsson, G.B. & Halldórsson, P. (2008) Tjörnes fracture zone. New and old seismic evidences for the link between the North Iceland rift zone and the Mid-Atlantic ridge. *Tectonophysics*, **447**, 117–126.

Thorvaldsdóttir, S. (2009) Recovery guidelines for local government and community staff. *1st International Symposium on Strong-motion Earthquake Effects (1ISSEE)* Reykjavik, Iceland.

Youd, T.L. (2003) Liquefaction Mechanisms and Induced Ground Failure. *International Handbook of Earthquake and Engineering Seismology* International Geophysics Series. pp. 1159–1174. Academic Press for IASPEI.