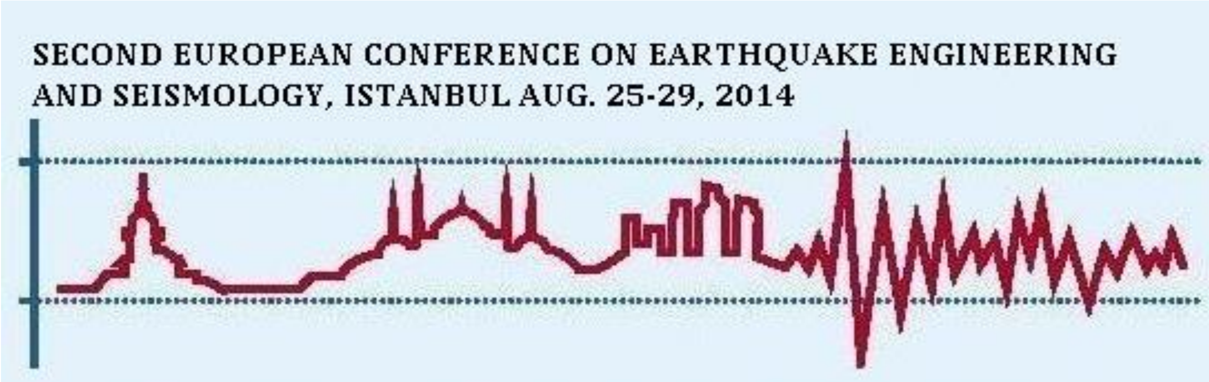

SEISMO-TECTONICS OF SOUTH ICELAND SEISMIC ZONE: THE 'BOOKSHELF' MECHANISM

Rajesh RUPAKHETY[1] and Ragnar SIGBJÖRNSSON[2]

ABSTRACT

This article addresses the question whether or not the so-called bookshelf tectonics can reveal a new understanding and improved modelling of earthquake behaviour in the South-Iceland Seismic Zone. Furthermore, to explore what implications of this new modelling might be for engineering design in the area. The preliminary findings indicate that the bookshelf kinematics, governing shear deformations and counter-clockwise rotating of blocks, is characteristic feature throughout the South-Iceland Seismic Zone. This is resulting in earthquakes that are typically induced by more or less simultaneous fractures on near-to-vertical parallel strike-slip faults. The consequence of this is that quantities used traditionally by engineering in earthquake resistant design need revision. This applies to common basic variables. Especially the following quantities are addressed and discussed: magnitude, location, distance measure, duration, earthquake response spectra, and near-fault effects.

INTRODUCTION

Iceland is a super-structural part of the Mid-Atlantic Ridge, a diverging boundary in the North Atlantic Ocean between the North American and the Eurasian Plates. Across Iceland, from southwest to the north, the rift zone is displaced towards east through two major fracture zones or 'transform faults'. These are the South Iceland Seismic Zone (SISZ), located on-land, and the Tjörnes Fracture Zone (TFZ), which is mainly off-shore. The most destructive earthquakes in Iceland have occurred within the SISZ. It extends about 80 km in the east-west direction through the South Iceland Lowland with earthquake epicentres aligned in a 5-10 km wide band. The area north of the zone belongs to the North-American Plate, which is moving in westerly direction; while the area south of the zone is a part of the eastward moving Eurasian Plate. However, an east-west trending fault is not visible on the surface. On the other hand, the left lateral motion across the zone is accommodated by a series of north-south trending parallel faults, the traces of which are clearly visible on the surface. The characteristic features of a generic fault typically found in the South-Iceland Zone are interchanging right-lateral push-ups and en-echelon fissures. The main right-lateral fault commonly has related left-lateral conjugate faults.

The objective of the article is to discuss the above mentioned phenomenon within the framework of the so-called bookshelf kinematic model. A discussion of some of the consequences of this phenomenon may have on strong ground-motion modelling is presented.

[1] Associate Professor, Earthquake Engineering Research Center, 800 Selfoss, Iceland, rajesh@hi.is
[2] Professor, Earthquake Engineering Research Center, 800 Selfoss, Iceland, ragnar.sigbjornsson@hi.is

CONCEPTUAL MODELLING AND EMPIRICAL EVIDENCE

Observations of some tectonic environments reveal that shear distortions are accommodated by rotation of an array of parallel faults. Because of its kinematic resemblance to the tilting of books on a bookshelf, the tectonic process has commonly been referred to as “bookshelf” mechanism. The fundamentals of this process have been described by Cloos (1929). Roering (1968), Dennis (1982), and Mandl (1987) give geological evidences and examples of this mechanism along with detailed description and discussions (see, also a comprehensive treatment of mechanics of tectonic faults in Mendel,2000 and references given therein). For the Icelandic case at hand the bookshelf mechanism has been discussed in the geoscience literature (see, for instance, Sigmundsson et al., 1995; Einarsson et al., 1981, Gudmundssson and Brynjolfsson, 1993; Gudmundsson, 2007, Angelier et al., 2004, Bergerat et al.,1998).

Following Mandl (1987) the bookshelf process of rotating parallel faults can be clearly illustrated by a row of books on a shelf with a plank resting on top. With reference to Fig. 1 Mandl (1987) states: “When the lateral support is relaxed, the books tilt to one side and shift the plank; thus the row of books extends in length and decreases in height. Naturally, the process can be reversed by raising up the tilted books. The rotation of the books is accompanied by slip between the individual books, which represents the action of rotating parallel faults in nature. It will be noticed immediately that the direction of the internal slip motion is opposite to the accompanying overall shear displacement (movement of the plank). In other words, lateral shear displacement to the [left] will be accomplished by lateral slip along the rotating faults to the [right] and vice versa. It may also be noted that domino style tilting of the books is associated with some slips between planks and books, whereas steepening of tilted books can proceed without such slippage, but will then produce gaps between the individual books.”

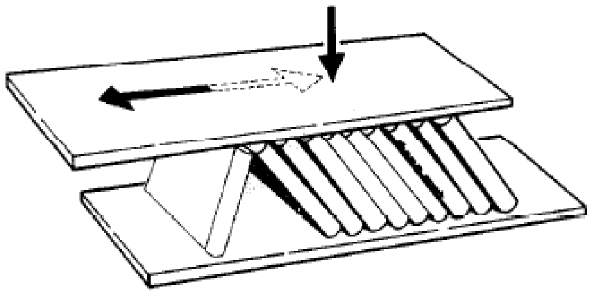

Figure 1. Bookshelf kinematics (from Mandl, 1986)

Empirical evidence of bookshelf faulting is clearly visible in he SISZ. An outline of the seismo-tectonics of SISZ is shown in Fig. 2 along with the main earthquake events in the twentieth and the twentieth first century. The causative faults are north-south oriented; the motion across the faultss is right laterel while the overall motion is left lateral and governed by the differential motion between the Eurasian and North-Americal tectonic plates. Figure 3 visualises the Holocene traces of the surface fracture in the central area of the SISZ. In most cases these surface expressions indicate the alignment of underlying causative faults. Furthermore, in the central area of the SISZ, the surface fault traces are apparently of similar lengths and regularly spaced from east towards west indicating counter-clockwise rotating blocks that accommodate the overall tectonic motion. The tectonic strain thus seems to be relieved by seismic slips, which most often happen on nearby multiple faults, rather than on a single fault. The released seismic moment thus happens to be associated to two or more faults rupturing almost simultaneously. The arrangement of faults of similar lengths could potentially indicate a characteristic earthquake size in the region, as has been observed in recent earthquakes. This arrangement may have implications in scaling of released seismic moment to the length of faults.

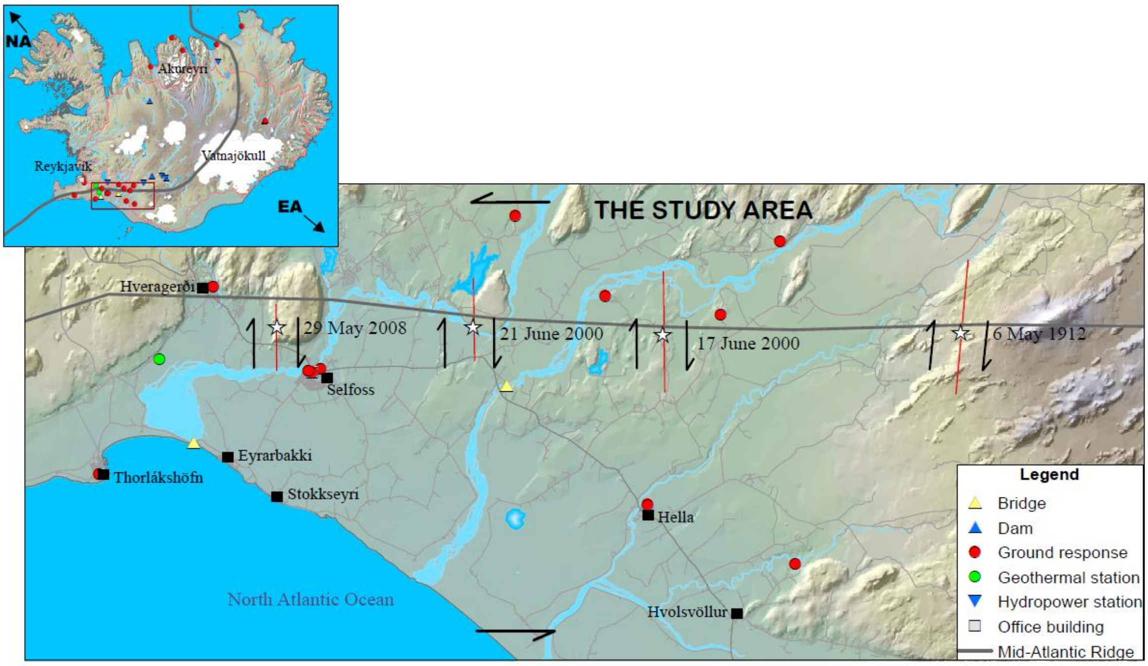

Figure 2. Seismo-tectonics of Iceland and the SISZ. The inset map of Iceland shows the relative motion across the boundary of the North American (NA) and the Eurasian (EA) tectonic plates. Four major earthquakes in SISZ are indicated by red lines indicating the approximate locations of causative faults. The small black arrows show the relative displacements across the faults identifying right-lateral strike-slip motion. Left-lateral transform motion of the SISZ is indicated by the large black arrows at the top and bottom of the main image. The indicated earthquakes are the following: 6 May 1912 - *Ms* 7; 17 June 2000 - *Mw* 6.5; 21 June 2000 - *M*w 6.4; and 29 May 2008 - *Mw* 6.3. The locations of the stations of Icelandic Strong-Motion Network are indicated by the symbols described in the legend.

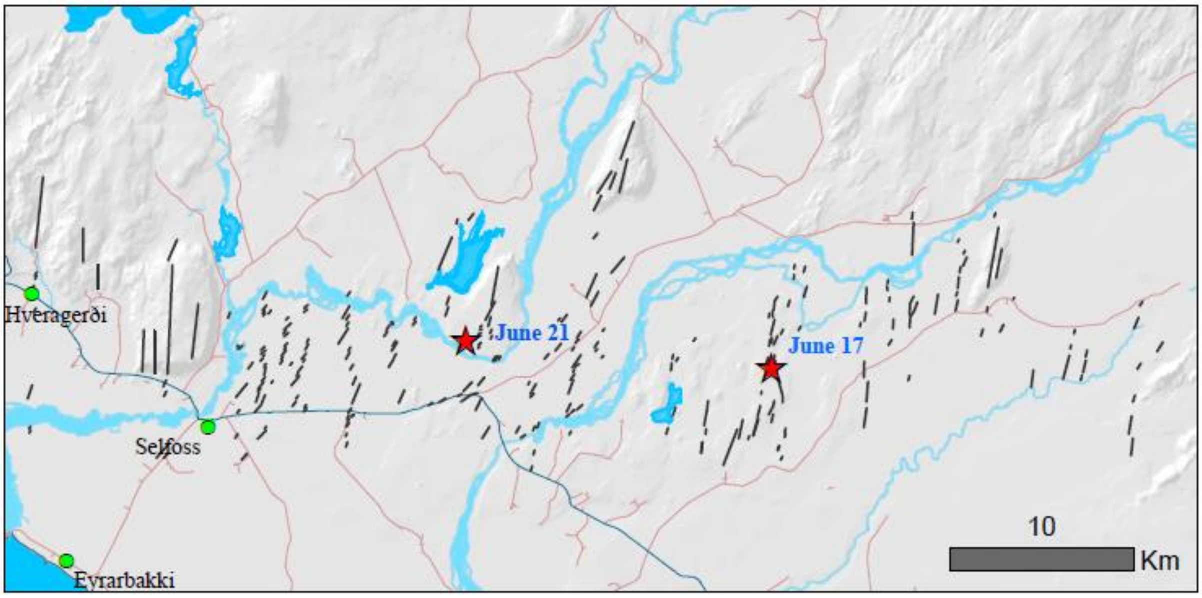

Figure 3. A map of Holcene surface fractures identified in the central area the South Iceland Seismic Zone. Bulk of the data on surface fractures have been collected by Einarsson (see, for instance, Einarsson, 2010). The map clearly reveals the en-echelon pattern of the surface fault traces.

CASE HISTORIES

A noteworthy feature of the 'bookshelf' mechanism, as it surfaces in the SIZS, is that more than one north-south trending faults rupture almost simultaneously. This could be observed clearly in the 2008 Ölfus Earthquake when two neighbouring faults ruptured at the same or nearly the same time. Similar mechanisms were also observed during the June 2000 Earthquake Sequence as well as in the 1896 South Iceland Earthquake Sequence. Some characteristics of these earthquakes in relation to the observed strong ground motion and damage to the built environment are discussed in the following.

The 1896 South-Iceland Earthquake Sequence

The 1896 South Iceland Earthquake Sequence is described in details by Thoroddsen (1899). Figure 4 displays, along with the main events of the sequence, the spatial distribution of damage ratios for the total collapse damage state (see, for further detailes, Sigbjörnsson and Rupakhety, 2014).

The damage distribution shown in Figure 4 indicates that the 26 August event might have occurred on two nearby faults. This earthquake was felt in Reykjavik as two shocks, with shaking intensity increasing at first, then decreasing, and increasing again towards the end. Similar observations were reported in Ísafjördur in the West Fjords. These observations being more pronounced farther away from the source, but not reported in the immediate vicinity, indicates two events separated by a small time interval. Being farther away from the source extends the difference in arrivals of the two shocks, which results in more conceivable feeling of two separate events. The 'bookshelf' tectonic environment explained above along with the relatively small length of the north-south trending faults might be the reason behind major earthquakes in this region occurring on separate faults almost simultaneously.

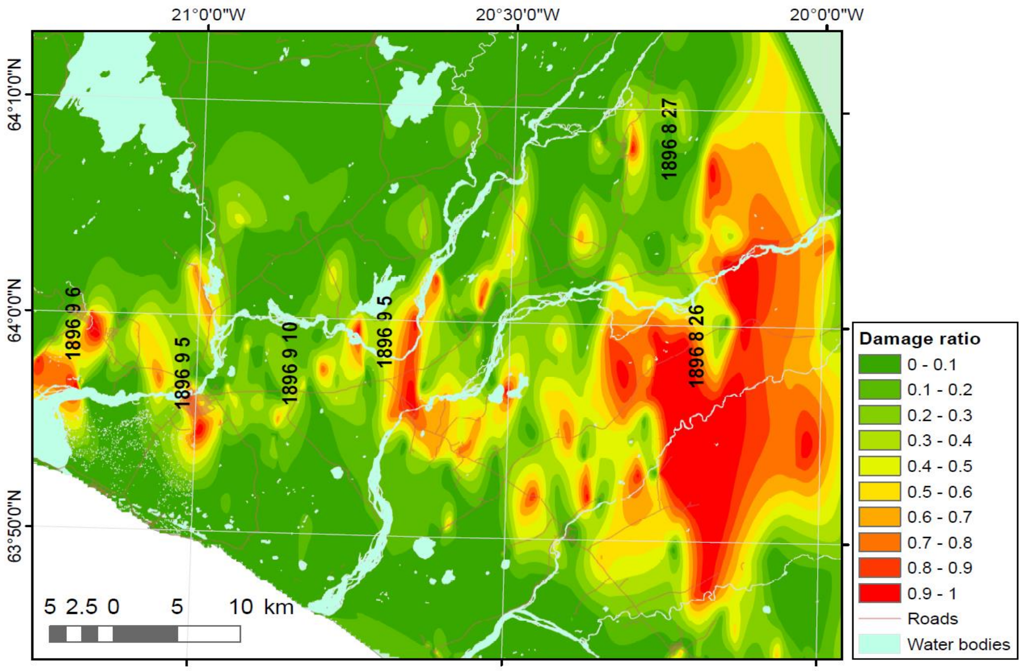

Figure 4. Spatial distribution of damage ratios for damage state total collapse (adapted from Sigbjörnsson and Rupakhety, 2014) of residential and farm houses during the 1896 earthquake sequence in South Iceland. Approximate locations of the major earthquakes of the sequence are indicated by the texts corresponding to their dates.

Occurrence of earthquakes on two faults seems to have enlarged the damage area. This might have consequences in estimating earthquake size based on the size of damaged area. For example, the SHARE (Stuchhi et al., 2012) catalogue lists, citing the Icelandic Meteorological Office, a moment magnitude of 6.9 for the 26 August event. This estimate is apparently based on the size of the damaged area (Hallorsson, 2005), and has likely been over-estimated. Damaged area due to an earthquake on a single large fault is likely to be different from that due to almost simultaneous earthquakes on two smaller faults, and therefore the relationship between the damaged area and earthquake size in these two cases can be different. The surface wave magnitude of the 26 August event reported by Ambraseys and Sigbjörnsson (2000) is significantly smaller than that reported in the SHARE catalogue. Further evidence in support of the smaller magnitude estimate of Ambraseys and Sigbjörnsson (2000) lies in the observation that the earthquakes in 1986 had similar characteristics, in terms of the felt area and the extent of damage, as the earthquake sequence of June 2000 (Sigbjörnsson and Olafsson, 2004) during which the largest event has been estimated to have a moment magnitude of 6.5, which is comparable to the estimate of 26 August 1986 Earthquake magnitude reported in Ambraseys and Sigbjörnsson (2000). As many earthquakes in the SISZ are known to consist of almost simultaneous ruptures on two nearby faults, what are considered as one event are actually two events separated by a small time interval. This phenomenon was clearly observed 5 September 1896 when a simultaineous rupture occurred at a fault near Selfoss and a second fault near the Thjorsa River Bridge (Thoroddsen, 1899; see also Fig. 4).

The June 2000 South-Iceland Earthquake Sequence

The 17 June 2000 South-Iceland sequence consisted of two events closely spaced in time originating on two separate faults. The separation time was no more than two minutes, and the second smaller event has commonly been described as an aftershock (Stefansson et al., 2003). When earthquakes occur so close to each other in time, the distinction between a mainshock and an aftershock, at least from an engineering perspective, is not obvious as when the they occur well separated in time. The effects of this double-event is clearly visualised by the macroseismic intensities mapped in Fig. 5a. The two-pronged red area of high damage near the epicenter indicates multiple events.

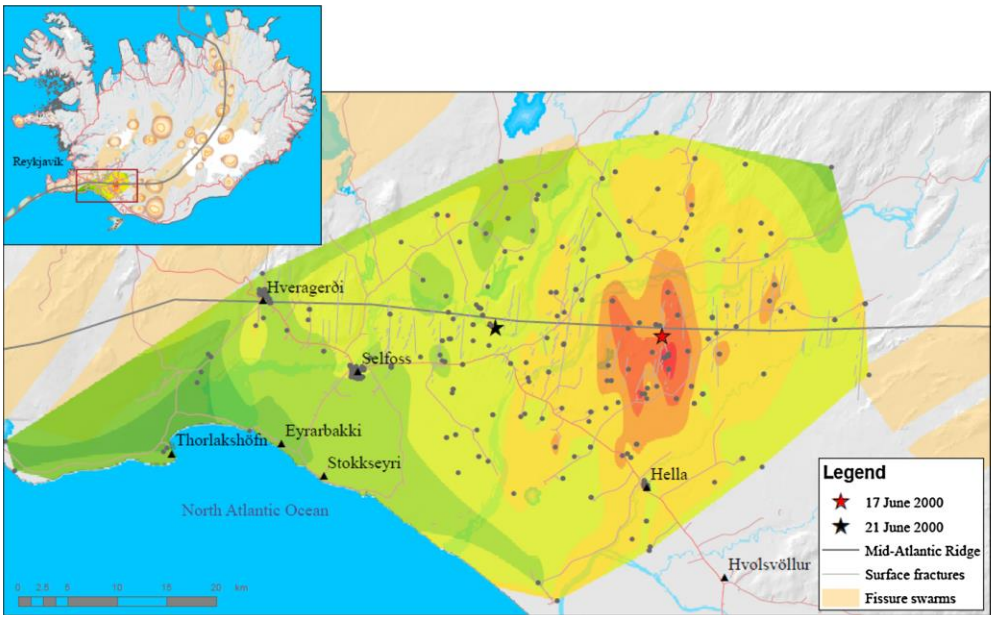

Figure 5a. Spatial distribution of macroseismic intensities. The inset on the top-left shows a map of Iceland with the Mid-Atlantic Ridge passing through it. The red rectangle in this map indicates the epicentral area of the June 2000 earthquakes—the main figure is an enlarged view of this area. The red and the black stars are the locations of the epicentres of the 17 June and 21 June earthquakes, respectively. The colour scale in the main map, ranging from green to red represents modified Mercalli intensity in the range of 4–10 due to the 17 June Earthquake. The two-pronged red area of high intensity near the epicentre is due to the complex source mechanism of this earthquake, which involved fracture along two nearby faults, first on a fault to the east, followed by a second fracture minutes later on a fault to the west of the first rupture. The distribution of intensities shows that the region with most damages is within a radius of 20 km from the epicentre (from Rupakhety and Sigbjörnsson, 2014).

The map of the macroseismic intensities displayed in Fig 5b reveal similar features for the 21 June 2000 South-Iceland event. The accelerometric recordings of the June 2000 sequence indicate arrivals of shear waves from multiple sources. This is exemplified herein by recordings obtained in Hveragerdi and plotted in Fig. 6. The time series of ground acceleration shown in Fig. 6 clearly shows arrival of seismic waves from multiple events. Although it is not straight-forward to identify the contributions of different events, especially when they are tightly super-imposed in time, the time series clearly shows that there were multiple arrivals of strong shear waves, for example the relatively strong motion around 22s after an earlier arrival has decayed. These time series therefore reveal a 'conglomerate'of effects induced by multiple events. In a special situation like the one presented here, it is not practical, from an engineering perspective, to classify the strong motion around 22s as being that due to an aftershock. In these situations, the distinction between a main-shock and an after-shock is blurred. It is noteworthy that the motion around 22s and that at during the main shaking are of comparable amplitudes. Such effects are not commonly reported in other tectonic regimes, where the strong-motion time series generally consists of a single strong shear-wave motion. Such multiple events have been observed to some extent during the Tohuku-Kanto Earthquake in Japan, which ruptured a much longer fault than the June 2000 Earthquakes, and had much larger magnitude. A direct implication of such multiple windows of strong shaking lies in structural response. Our preliminary analysis shows that while elastic response spectra are not affected significantly by the latter arrivals, more so when they are not of larger amplitude than the earlier ones, response of inelastic structures is significantly affected by them. For example, if a structure is deformed beyond its yield limit during the first part of the shaking, the secondary arrivals can induce larger ductility demands and therefore damage to the structures. When the multiple events are super-imposed in time, the overall effect on the structures is expected to be higher than that when the events occur well separated in time. This is due to possible constructive interference of waves from the multiple events thereby amplifying the total shaking of ground. On the other hand, if the multiple events are not simultaneous but occur within small difference, like in the case shown in Figure 6, the duration of strong ground motion tends to be larger, which has direct consequence in structural response, and in particular in liquefaction potential of soils.

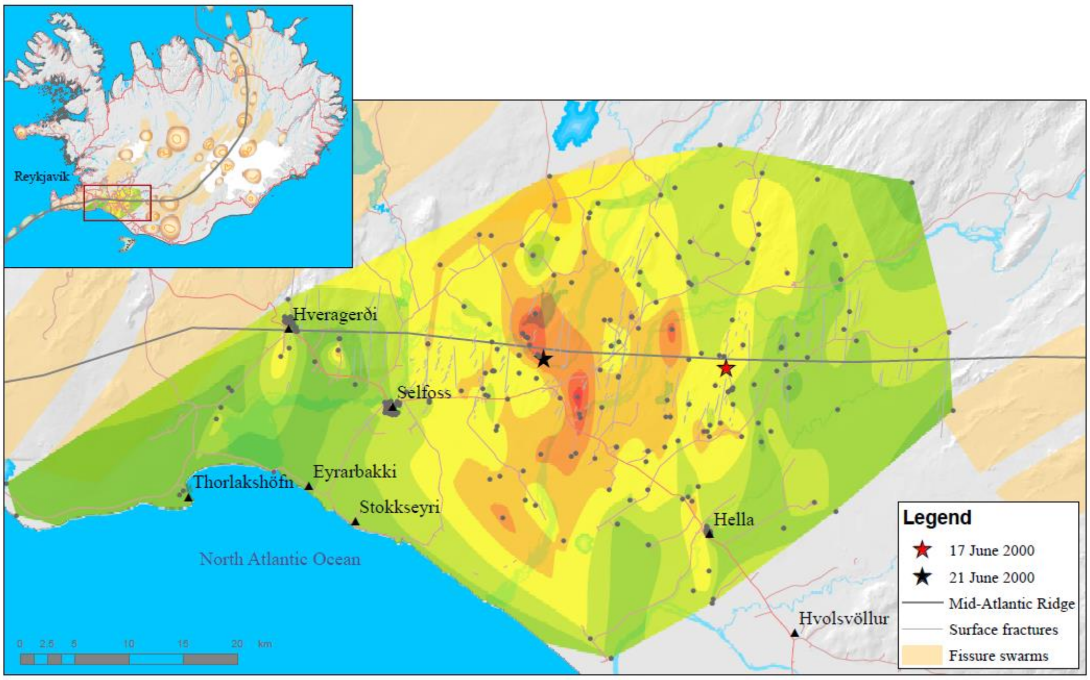

Figure 5b. Same as Fig. 5a but for the 21 June 2000 Earthquake. The source mechanism has been identified as complex, involving simultaneous fracture along faults near the epicentre (from Sigbjörnsson and Rupakhety, 2014).

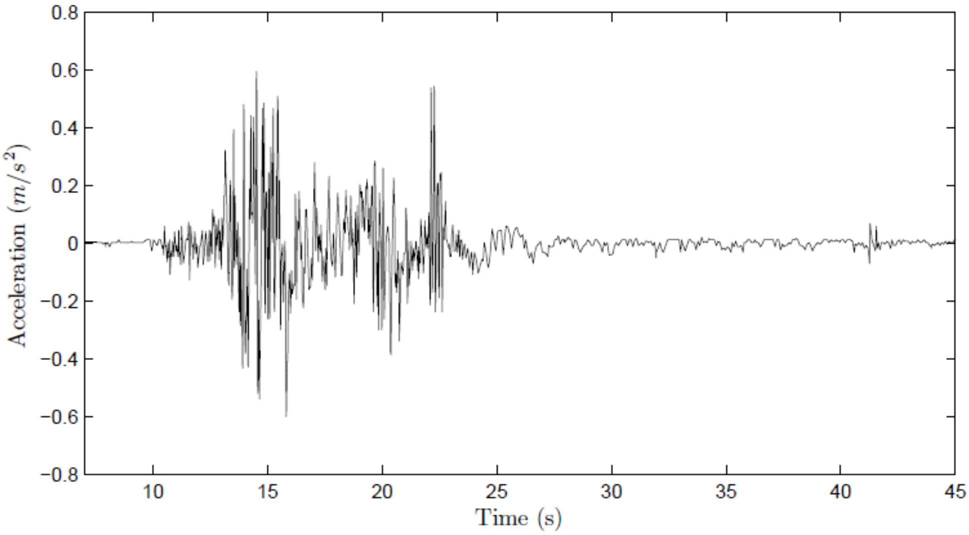

Figure 6. Ground acceleration recorded at the Hveragerði Church during the 21 June 2000 Earthquake. Uncorrected acceleration obtained from ISESD (Ambraseys et al., 2002; 2004) is shown.

The 29 May 2008 Ölfus Earthquake

The 29 May 2008 Ölfus Earthquake occurred on two nearby faults rupturing almost simultaneously (Halldorsson and Sigbjörnsson, 2009). The overall behaviour was similar to the June 2000 Earthquakes. However, some additional features surfaced. These observations are the following: The initial motion started on the eastern causative fault and rupture propagation was most-likely southwards, producing clear forward-directivity pulses (see Rupakhety et al., 2011) at recording stations located south of the epicentre, e.g. at Selfoss. Towards north, on the other hand, distinct forward-directivity pulses were not observed and the motion was in general characterised by low amplitude. A moment later (1-2 s), another rupture began on the western fault. The effects of this rupture resulted in strong near-fault pulses in Hveragerdi located towards the northern end of the second causative fault, while towards south the motion was apparently much smaller. These observations are in accordance with the simplified 'bookshelf' kinematics described earlier. The overall co-seismic behaviour is a shear deformation of the counter-clockwise rotating blocks. The kinetics on the other hand reveals reactive rupture propagation corresponding to a clockwise rebound resulting in a clockwise 'back' spin. Hence, the forward-directivity pulses observed in Selfoss and Hveragerdi, respectively, are in accordance with the simplified model described above.

DISCUSSION AND CONCLUSIONS

Strong ground motion models in engineering seismology are commonly based on the assumption of a single event in the sense that predicted ground motion parameters are considered to be caused by rupture on a single fault. This assumption, although not implicitly declared, manifests itself in engineering applications, for example in calibrating and using empirical ground motion prediction equations (GMPEs). The source-site distance parameter used in such equations refers either to an epicentre or a causative fault. In the tectonic environment of SISZ, where multiple events, sometimes occurring almost simultaneously, contribute to ground motion at a site, neither a single epicentre nor a single causative fault is unambigiously defined. A direct consequence of this is ambiguity in defining source-site distance to be used in GMPEs (see Sigbjörnsson et al., 2009). Stochastic modelling of strong ground motion relies heavily on earthquake source spectra, and the spectral models in use are attributed to a single source. When ruptures on multiple nearby faults overlap in time, the resulting source spectra might depend on factors such as relative energies released on the individual faults, and the time sequence of occurrence of rupture. These effects are likely to be important while modelling strong ground motion in the SISZ. Apart from this, estimates of earthquake magnitude based on the assumption of a single source might be biased when energy is released by ruptures on multiple faults occurring almost, but not exactly, simultaneously. The bookshelf mechanism with rupture on multiple nearby faults also affects the distribution of near-fault directivity effects in the epicentral area. For example, if the rupture propagation in the two nearby parallel strike-slip faults are in opposing directions, forward-directivity effects can occur on areas located near both ends of the faults. The presence of rupture on multiple faults might also enlarge the area where forward-directivity effects become significant. From hazard modelling perspective, the feature of SISZ where earthquakes happen on roughly parallel faults of comparable lengths, and the lack of earthquakes on the much longer tectonic plate boundry, could result in a characteristic earthquake recurrence in the region. This would imply that earthquakes of certain magnitude, which are consistent to the dimensions of north-south oriented parallel faults in the region, might occur more frequently. This might also result in a situation when tectonic strain is released in two or more characteristic earthquakes rather than on a single large earthquake. The earthqukes sequences of 1986 and June 2000 provide empirical evidence of this phenomenon. The vailable data, in terms of earthquake catalog and recorded strong ground motion, is currently not sufficient to quantitatively model the effects of these phenomenon in engineering design. Nevertheless the empirical observations indicating their relevance are piling up. With more observations and recordings, some engineering modelling might be feasible in the future. Nevertheless, it is important to be aware of these phenomenon in analyzing seismic hazard in the region.

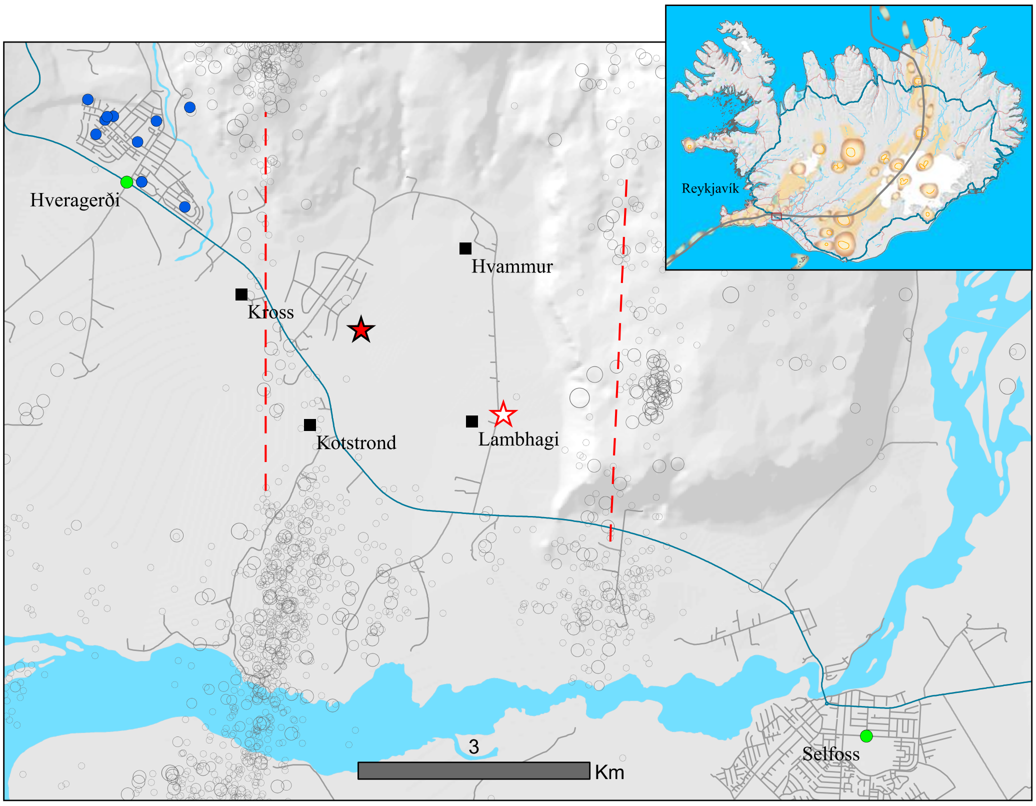

Figure 7. The 15:45 UTC 29 May 2008 Ölfus Earthquake originated on two causative faults. The main picture displays the seismicity distribution for the period of 23 May to 31 June 2008; open circles denote earthquake epicentres and the location of the two causative faults are approximated by the red dashed lines. The solid star indicates the macroseismic epicentre and the hollow star indicates the epicentre estimated from strong-motion data of the Ölfus Earthquake (see, Sigbjörnsson et al., 2009). The blue circles in Hveragerdi indicate the locations of the recording stations of the ICEARRAY. The top right inset picture shows Iceland with the Mid-Atlantic Ridge (grey curve). The solid red rectangle on the inset map indicates the area shown in the main picture.

ACKNOWLEDGEMENTS

This study was co-financed by the EU - Civil Protection Financial Instrument (**U**rban disaster **P**revention **Strat**egies using **MA**croseismic Fields and **FA**ult Sources - UPStrat-MAFA, Grant Agreement N. 23031/2011/613486/SUB/A5). We also acknowledge the support from University of Iceland research fund.

REFERENCES

Ambraseys NN, Sigbjörnsson R (2000) Re-appraisal of the seismicity of Iceland. *Polytechnica - Engineering seismology*, Earthquake Engineering Research Centre, University of Iceland, Selfoss; ISBN 9797-989-91-4X: 196 pages.

Ambraseys NN, Smit P, Sigbjörnsson R, Suhadolc P, Margaris B (2002) *Internet-Site for European Strong-Motion Data*. Brussels: European Commission, Research-Directorate General, Environment and Climate Programme. URL: http://www.ised.hi.is [Date visited: 30 April 2006].

Ambraseys NN, Douglas J, Sigbjörnsson R, Berge-Thierry C, Suhadolc P, Costa G, and Smit, P (2004) *European Strong-Motion Database* (Vol. 2). London: Imperial College of Science, Technology and Medicine

Angelier J, Bergerat F, Bellou M, Homberg C (2004). Co-seismic strike-slip fault displacement determined from push-up structures: the Selsund Fault case, South Iceland. Journal of Structural Geology, 26:709–724

Bergerat F, Angelier J (2000) The South Iceland Seismic Zone: tectonic and seismotectonic analyses revealing the evolution from rifting to transform motion. *J. Geodynamics*, 29:211–231

Bergerat F, Gudmundsson A, Angelier J, Rögnvaldsson A Th (1998) Seismotectonics of the central part of the South Iceland Seismic Zone. *Tectonophysics*, 298:319–335.

Einarsson P (2008) Plate boundaries, rifts and transforms in Iceland. *Jökull*, 58:35–58

Einarsson P (2010) Mapping of Holocene surface ruptures in the South Iceland Seismic Zone. *Jökull*, 60:117–134

Einarsson P, Björnsson S, Foulger G, Stefánsson R, Skaftadóttir Þ (1981) Seismicity pattern in the South Iceland seismic zone. *In*: D. Simpson and P. Richards, eds., *Earthquake Prediction – An International Review*, Am. Geophys. Union, Maurice Ewing Series 4, 141–151

Gudmundsson A, Brynjolfsson S (1993) Overlapping rift-zone segments and the evolution of the South Iceland Seismic Zone. *Geophys. Res. Lett.* 20:1903–1906.

Gudmundsson A (2007) Infrastructure and evolution of ocean-ridge discontinuities in Iceland. *Journal of Geodynamics*, 43:6–29

Halldorsson B, Sigbjörnsson R (2009) The Mw 6.3 Ölfus earthquake at 15:45 UTC on 29 May 2008 in South Iceland: ICEARRAY strong-motion recordings. *Soil Dynamics and Earthquake Engineering*, 29(6):1073–1083

Halldorsson B, Sigbjörnsson R (2009). The Mw 6.3 Ölfus earthquake at 15:45 UTC on 29 May 2008 in South Iceland: ICEARRAY strong-motion recordings. *Soil Dynamics and Earthquake Engineering*, 29(6):1073–1083

Halldrosson P (2005) Re-evaluation of the historical earthquakes in light of the new observations. PREPARD-third periodic report, Report no. 06008, VÍ-ES-05, Veðurstofa Íslands, Reykjavik.

Rupakhety R, Sigurdsson SU, Papageorgiou AS, Sigbjörnsson R (2011) Quantification of ground-motion parameters and response spectra in the near-fault region. *Bulletin of Earthquake Engineering*, 9(4):893–930

Rupakhety R, Sigbjörnsson R (2014) Quantification of loss and gain in performance using survey data: a study of earthquake-induced damage and restoration of residential buildings. *Natural Hazards*, Online first (20 June 2014), DOI 10.1007/s11069-014-1279-0

Sigbjörnsson R, Olafsson R (2004) On the South Iceland earthquakes in June 2000: strong-motion effects and damage, *Bollettino di Geofisica ed Applicata*, 45(3):131–152

Sigbjörnsson R, Rupakhety R (2014) A saga of the 1896 South Iceland earthquake sequence: magnitudes, macroseismic effects and damage. *Bulletin of Earthquake Engineering*, 12:171–184

Sigmundsson F, Einarsson P, Bilham R, Sturkell E (1995) Rift-transform kinematics in south Iceland: deformation from Global Positioning system measurements, 1986 to 1992. *Journal of Geophysical Research*, 100(B4): 6235–6248

Stefansson R, Guðmundsson GB, Halldórsson P (2003) The South Iceland earthquakes 2000 a challenge for earthquake prediction research. Veðurstofa Íslands, Report 03017, www.vedur.is/media/vedurstofan/utgafa/greinargerdir/2003/03017.pdf (last accessed 6 July 2014)

Stucchi M, Rovida A, Gomez Capera AA, Alexandre P, Camelbeeck T, Demircioglu MB, Gasperini P, Kouskouna V, Musson RMW, Radulian M, Sesetyan K, Vilanova S, Baumont D, Bungum H, Fäh D, Lenhardt W, Makropoulos K, Martinez Solares JM, Scotti O, Živčić M, Albini P, Battlo J, Papaioannou C, Tatevossian R, Locati M, Meletti C, Viganò D, Giardini D (2012) The SHARE European Earthquake Catalogue (SHEEC) 1000–1899 "*Journal of Seismology*, doi: 10.1007/s110950-013-9335-2

Thoroddsen Th (1899). Jordskjaelvene i efteraaret 1896. *Dansk Geogr. Tidskr.*, 14:93–113. (in Danish)

Thoroddsen Th (1925) Die Geschichte der Isländischen Vulcane, D. Kgl. Danske Vidensk. Selsk. Skrifter, Naturvidensk. og Matem. Afd., 8. Række, IX, 380-458 (in German).

Tryggvason E (1973) Seismicity, earthquake swarms and plate boundaries in the Iceland region. *Bulletin of Seismological Society of America*, 63:1227–1348