Seismicity in Iceland 1991–2000 monitored by the SIL seismic system

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Abstract — *The SIL seismic system was designed and installed in the South Iceland Lowland in 1989–1990 and was fully operational in automatic mode in June 1991. In 1994 the system was expanded to the northeastern part of Iceland and has been gradually covering larger parts of Iceland since 1996. During the first decade of operation some 160,000 events were recorded and processed. In that period 4 volcanic eruptions and 2 large earthquakes (M_s=6.6) have occurred that have all been monitored by the system.*

INTRODUCTION

Iceland is situated on the Mid-Atlantic Ridge where the ridge is shifted towards east in the vicinity of a mantle plume, centered under the glacier Vatnajökull (Tryggvason *et al.*, 1983; Stefánsson *et al.*, 1988; Wolfe *et al.*, 1997; Allen *et al.*, 2002). Earthquakes with magnitudes up to 7.1 have occurred within the two fracture zones in Iceland (Einarsson, 1979; 1991; Stefánsson and Halldórsson, 1988), the Tjörnes Fracture Zone (TFZ) which connects the Northern Volcanic Zone (NVZ) to the Kolbeinsey Ridge and the South Iceland Seismic Zone (SISZ) which connects the Eastern Volcanic Zone (EWZ) to the Western Volcanic Zone (WVZ) and Reykjanes Peninsula. The TFZ is mostly offshore NE-Iceland, but the SISZ lies within a relatively densely populated agricultural area.

In 1983, the Ad Hoc Committee of Experts on Earthquake Research of the Council of Europe appointed the SISZ as one of 5 test sites in Europe suitable for earthquake prediction research. In 1988 a group of Nordic scientists received funding from the Nordic Council, the science foundations in Sweden, Norway and Denmark as well as the Government of Iceland for a project aiming at designing and building a highly automatic seismic system for monitoring earthquake activity and crustal processes and for collecting high quality data for earthquake prediction research. As medium size and big earthquakes are not very frequent in Iceland, some 6–7 earthquakes of M > 6.0 every 100–150 years in South Iceland Lowland (SIL) and similar in TFZ, these would provide very limited information to monitor crustal processes. Therefore the design criteria for the system were set to detect and locate small earthquakes in order to get almost continuous information about the stress condition in the crust. From the beginning the SIL seismic system has been able to detect events of magnitudes less than 0 in the SISZ, but in other areas the detection threshold is somewhat higher (0.5–1.5) depending on station density. With this sensitivity the system records from ~20 to almost 2000 earthquakes a day, giving approximately 160,000 earthquakes in the database for the first 10 years.

THE SIL SYSTEM

The SIL system is a network of 3-component digital seismic stations and a data processing system, run by the Icelandic Meteorological Office (IMO). It consists of automatic event detection and locations and can thus be used to monitor changes in seismic activity, fault dimensions and other seismic parameters in search of earthquake precursors for prediction research (Stefánsson *et al.*, 1993). The number of stations has grown from 8 stations in 1990 in the South Iceland Lowland to 42 stations at the end of year 2000, mainly covering the seismic zones and the rift zones through Iceland (Figure 1).

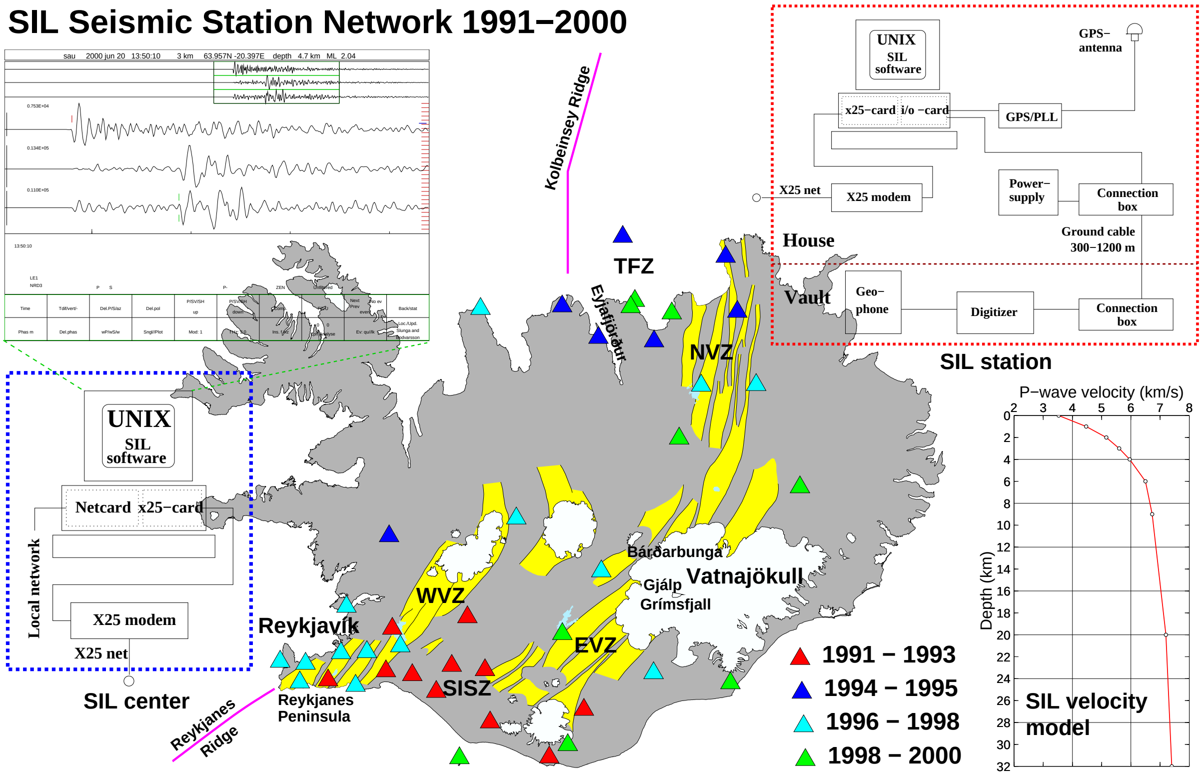

Figure 1. The SIL seismic station network 1991–2000. Also shown are the main tectonic features of Iceland. SISZ is South Iceland Seismic Zone, TFZ is Tjörnes Fracture Zone, WVZ is Western Volcanic Zone, EVZ is Eastern Volcanic Zone and NVZ is Northern Volcanic Zone. The box in the upper right corner shows schematically the components of a SIL seismic station. The velocity model used to locate earthquakes is shown in the right bottom corner. The box to the left represents the SIL center in Reykjavík. – *Myndin sýnir þróun SIL jarðskjálftamælanetsins árin 1991-2000. Sýnd eru gos- og brotabelti landsins. SISZ er Suðurlandsbrotabeltið, TFZ er Tjörnesbrotabeltið, WVZ er vestara gosbeltið, EVZ er eystra gosbeltið og NVZ er norðurgosbeltið. Kassinn í efra horni til hægri sýnir helstu þætti SIL jarðskjálftamælistöðvar. Hraðalíkan sem notað er við staðsetningar á skjálftum er sýnt í neðra horni til hægri. Kassinn til vinstri táknar SIL miðstöðina í Reykjavík.*

The data acquisition is based on waveform analysis and locations of the earthquakes. At every station the data stream from the sensor is digitized and stored in a ringbuffer on the hard drive of a PC-computer at a nearby farm. The incoming signals, exceeding some predefined threshold, are analyzed, the onset time is determined and different parameters are calculated, such as peak-to-peak amplitude, frequency content, coherence and azimuth of the incoming wave and a few additional parameters. All this information is packed into 128b long messages and sent through a communication link (mostly X.25) to a central computer in Reykjavík.

Information from all stations is gathered in the central computer and used to locate all possible earthquakes and estimate their magnitudes. For all locations passing a quality test, requests for waveform data are sent out to the stations which are expected to see the respective event. This means that an earthquake can already be referenced in the automatic bul-

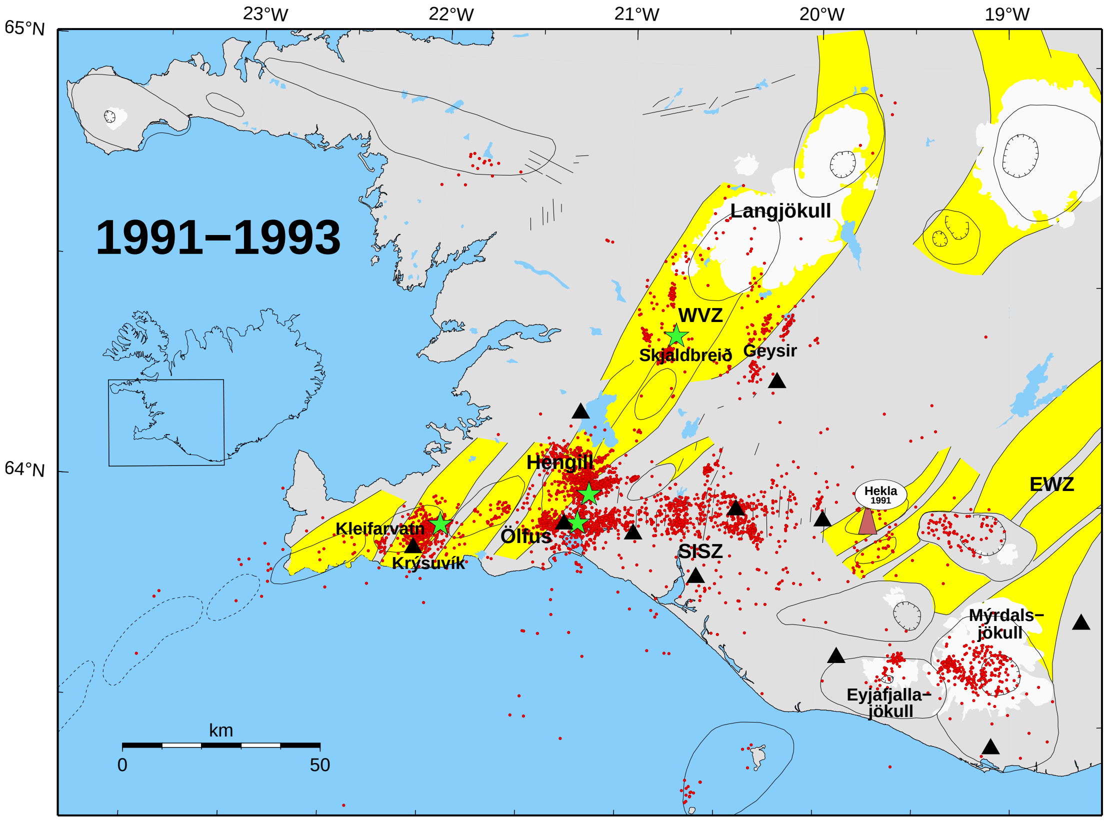

Figure 2. Seismicity in SW-Iceland between 1991 and 1993. The red dots represent earthquakes. The green stars show earthquakes greater than magnitude 4. Black triangles show the location of the SIL stations during this period. – *Jarðskjálftavirkni á Suðvesturlandi árin 1991 til 1993. Rauðu deplarnir tákna jarðskjálfta. Grænu stjörnurnar tákna jarðskjálfta sem eru stærri en 4. Svörtu þríhyrningarnir tákna SIL mælistöðvar á þessu tímabili.*

letin within a few minutes of its occurrence and even before the waveform data have been saved to files on the hard disk. The ringbuffer is overwritten after 10–30 days. A more detailed description of the SIL system can be found in Stefánsson *et al.* (1993), Böðvarsson *et al.* (1996) and Böðvarsson *et al.* (1999). The local magnitude scale M_l, used in the SIL system, is an empirical scale using maximum amplitude and calibrated to give the same magnitudes as those calculated from the older analog instruments. This method gives a fairly good fit to the old local magnitude scale for earthquakes of magnitudes less than 3, but for bigger events it probably underestimates the magnitude. Some work is yet to be done to improve the local magnitude scale. For events larger than 5 the M_s magnitudes from the National Earthquake Information Center (NEIC) are used in this paper.

SEISMICITY IN SW-ICELAND DURING 1991–1993

The SIL database officially started on July 1, 1991. However, some data exist from 1990 and the first half of 1991. The volcanic Hekla eruption on January 17, 1991 was the first big event monitored by the SIL system. The system was still under development at the time and the onset of the eruption was not foreseen, but it was possible to collect and save very valuable data for later research. Several swarms were recorded in SW-Iceland during the first half of 1991 while the system was still not running in a fully automatic mode, including 2 earthquakes larger than magnitude 4. On January 30 an earthquake of M_l=4.6 occurred in the WVZ near Skjaldbreiður south of Langjökull and on June 19 an earthquake of M_l=4.0 was recorded in Ölfus (Figure 2), the largest event in a swarm lasting from June 17 to June 22. The next swarm activity was at Kleifarvatn on November 20, 1992 starting with an M_l=4.0 earthquake preceded with a few earthquakes in the Kleifarvatn area during the night before. On December 27, 1992 an M_l=4.3 earthquake occurred in the Hengill area as the second earthquake in a small swarm. In 1993 there was one swarm recorded near Krýsuvík on Reykjanes Peninsula with 3 earthquakes reaching magnitudes larger than 3.

Except for the first half of 1991, these 3 first years of the SIL system were rather quiet with some 5–20 events detected per day in the SISZ. The first half of 1991 had swarm activity every month with over 100 and up to 500 earthquakes per day, but after June 20 the only days with more than 100 earthquakes detected are mentioned above and the number of events per day never reached 200. At the end of year 1993, after a magnitude ~4 earthquake in Eyjafjörður, the SIL system was expanded with 6 stations in NE-Iceland, which improved the coverage for all of Iceland. Few additional earthquakes were detected in other parts of Iceland during the first three years, but they are not very well located as their epicenters are well outside the network. They are therefore not included here.

EARTHQUAKE EPICENTERS 1994–2000

The map in Figure 3 (page 92) shows epicenters of selected earthquakes with magnitudes greater than or equal to M_l=1 during 1994–2000 as determined by the SIL network. During this period some 145,000 earthquakes were recorded. The majority of the events have their origin in the Hengill-Ölfus area, at the intersection between the SISZ, the Reykjanes Peninsula and the WVZ, where about 85,000 earthquakes were generated in an episode of crustal deformation and high seismic activity during 1994–1998. The Hengill-Ölfus swarm activity culminated with events of M_l~5 in June and November 1998 (Rögnvaldsson *et al.*, 1996; Sigmundsson *et al.*, 1997; Feigl *et al.*, 2000). A large fraction of the seismicity occurred in the TFZ, offshore northern Iceland. The largest earthquake there, M_s=5.3 occurred in February 1994, just after the SIL network was installed in NE-Iceland. The event was accompanied by high seismicity in the period 1994–1997.

Seismicity in connection with eruptions has also been observed during this period. Two eruptions in Vatnajökull, Gjálp in October 1996 (Einarsson *et al.*, 1997) and Grímsvötn in December 1998 were preceded by increased seismic activity and confirmed by pilots that were asked to survey the region. A warning was issued to the National Civil Defence of Iceland prior to both these eruptions. The Gjálp eruption was preceded by an M_s=5.4 earthquake in Bárðarbunga two days earlier. In May 1994 an M_s=5.2 earthquake occurred in Bárðarbunga. The largest event prior to the Grímsvötn eruption was M_l=3.8.

The Hekla eruptions in January 1991 (Gudmundsson *et al.*, 1992; Soosalu and Einarsson 2002) and February 2000 (Stefánsson *et al.*, 2000a) had seismic precursors that were first noticed by the analog highland network operated by the Science Institute, University of Iceland (Einarsson and Björnsson, 1987). Again, a warning was issued to the National Civil Defence of Iceland prior to both these eruptions. The increased seismicity activated the alert system of the SIL network (Böðvarsson *et al.*, 1996) some 50 minutes before the surface rupture. When strainmeters started to show an anomaly, in the same way as known from the Hekla eruption in 1991 some 20 minutes before the onset, a prediction was made with predicted time accuracy within 5 minutes (http://hraun.vedur.is/ja/heklufrettir.html).

Volcanic events in Eyjafjallajökull and Mýrdalsjökull have also been monitored. Eruptions have not been observed directly in these cases, but geodetic measurements confirm uplift at Eyjafjallajökull associated with the seismic activity (Sturkell *et al.*, in press) and a minor magmatic episode in Mýrdalsjökull resulted in the formation of a new cauldron and a jökulhlaup in the river Jökulsá á Sólheimasandi (Einarsson, 2000; Guðmundsson *et al.*, 2000).

In June 2000 two large earthquakes struck near the center of the SISZ (Pedersen *et al.*, 2001; Árnadóttir *et al.*, 2001). The first occurred on June 17 with M_s=6.6 and triggered earthquakes of magnitudes near 5.0 to the west throughout Reykjanes Peninsula. High seismicity was also triggered to the north, activating the area south of Langjökull and near Geysir. The second earthquake struck on June 21 with M_s=6.6. Since then, seismic activity has remained high on the faults of both earthquakes.

DISCUSSION AND CONCLUSIONS

The first decade of the SIL system has been a phase of building up a digital high quality seismic system to cover the active seismic and volcanic zones in Iceland. Large amounts of data have been collected and processed, which in turn has increased the knowledge and understanding of crustal structure and crustal processes. The data have been used to map active faults, monitor stress changes in the crust, monitor swarms in near real-time, develop methods for earthquake prediction and model the velocity structure of the crust by different methods. Four volcanic eruptions have been monitored by the system. All of them have been discovered from the seismic activity recorded by the analog highland network and the SIL system and reported by scientists at the Science Institute and IMO.

Some efforts have been made to find and test methods that might help in predicting earthquakes. Common to all these methods is their focus on monitoring changes in some calculated parameters that are likely to reveal if the stress approaches the breaking point of an asperity. Some examples are the horizontal stress component of microearthquakes, shear-wave splitting (Crampin *et al.*, 1999) and a multiparameter method developed by Slunga (2003). None of these methods have proved to be a robust single parameter prediction tool, but they all give hints that can be included in interpretations leading to predictions. The experience obtained from the SIL system, monitoring earthquakes down to magnitudes less than 0, has shown that many (most) earthquakes greater than M_l=4 are not preceded by heavy seismic activity, which would be helpful in predicting the time factor of expected earthquakes. Accordingly the SISZ earthquake of June 17, 2000 was not predicted on a short-term basis, even though it was predicted on a long-term basis. But the second big earthquake, on June 21, was foreseen and a warning was issued to the National Civil Defence 26 hours before it occurred, stating that an earthquake of magnitude close to M_s=6.5 could be expected any time soon. The expected location almost coincided with the actual rupture (Stefánsson *et al.* 2000b) With all the data now available from these episodes the earthquake prediction research will continue.

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ÁGRIP

Jarðskjálftar á Íslandi 1991–2000 mældir með SIL jarðskjálftamælanetinu.

SIL-kerfið er stafrænt og sjálfvirkt jarðskjálftamælakerfi sem safnar og vinnur upplýsingar úr skjálftamælingum. Forsögu að uppbyggingu kerfisins má rekja aftur til ársins 1979 þegar Evrópuráðið hvatti til aukinna rannsókna á jarðskjálftahættu og jarðskjálftaspám. Árið 1983 útnefndi ráðið að frumkvæði Íslendinga 5 svæði í Evrópu sem tilraunasvæði í slíkum rannsóknum, og var Suðurlandsundirlendið

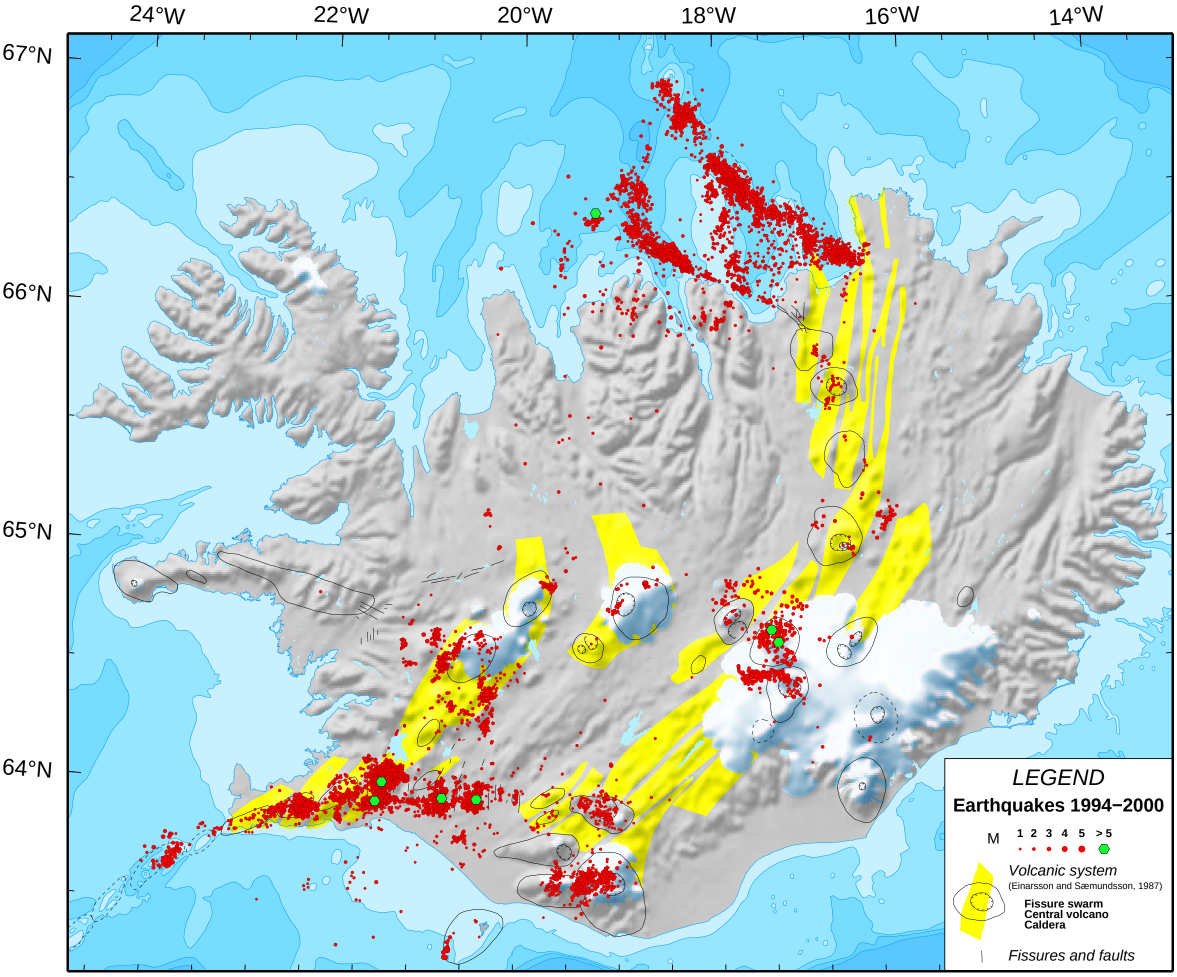

Figure 3. The map shows epicenters (red dots) of earthquakes equal to and greater than magnitude 1 during the period 1994–2000 as monitored by the SIL seismic network. Earthquakes greater than 5 are represented by green hexagonals. Also shown are tectonic and volcanic systems in Iceland (Einarsson and Sæmundsson, 1987). – *Upptök jarðskjálfta (rauðir deplar) á Íslandi sem eru stærri eða jafnt og 1 að stærð og SIL jarðskjálftamælakerfið mældi á tímabilinu 1994–2000. Jarðskjálftar stærri en 5 eru táknaðir með grænum sexhyrningum. Einnig eru brota- og gosbeltin sýnd (Einarsson og Sæmundsson, 1987).*

eitt þessara svæða. Jarðskjálftafræðingar á Norðurlöndum brugðust skjótt við og komu af stað norrænu rannsóknarverkefni á sviði jarðskjálftaspár. Árið 1988 fékkst fjárveiting frá Norrænu ráðherranefndinni, norrænu vísindasjóðunum og íslenska ríkinu til verkefnisins. Verkefnið fékk nafnið SIL-verkefnið (dregið af Södra Islands Lågland, Suðurlandsundirlendi). Það var mat vísindamannanna að grundvöllur þess að ná árangri í jarðskjálftaspárannsóknum væri að rannsaka spennuaðstæður og ferla í jarðskorpunni sem leitt gætu til stórra jarðskjálfta. Það var einnig þeirra mat að bestu upplýsingar um slík ferli fengjust úr fjölda smáskjálfta sem stöðugt verða í skorpunni á jarðskjálftasvæðum. Því var meginmarkmið verkefnisins að byggja upp jarðskjálftamæla- og úrvinnslukerfi sem næmi og túlkaði slíkar upplýsingar. Byggt var 8 stöðva kerfi á Suðurlandsundirlendinu, SIL kerfið. Næmni kerfisins var miðuð við að ná sem flestum smáskjálftum á svæðinu sem gætu veitt gagnlegar upplýsingar. Vegna þess mikla fjölda skjálfta sem þurfti að mæla og túlka varð kerfið að vinna sjálfvirkt að mjög miklu leyti. Þetta var síðan grundvöllur þess að byggja viðvörunarkerfi við SIL-kerfið.

Gagnasöfnun í SIL-kerfinu hófst árið 1990. Um mitt ár 1991 hófst sjálfvirk skammtímaúrvinnsla í kerfinu og var miðstöð hennar á Jarðeðlissviði Veðurstofu Íslands, sem frá byrjun var miðstöð SIL-verkefnisins. Um áramótin 1993–1994 voru 6 stöðvar á Norðurlandi tengdar við kerfið. Í lok árs 2000 voru 42 SIL-stöðvar í rekstri á landinu (sjá 1. mynd). Á hverri SIL-stöð er bylgjuhreyfingin mæld með þriggja ása jarðskjálftanema, þar sem einn ásinn nemur lóðrétta hreyfingu og hinir nema lárétta hreyfingu í tvær áttir. Mæliröðin er sett á stafrænt form þegar úr nemanum kemur og tímasett af mikilli nákvæmni (nú með GPS tímamerkjum). Tölva á stöðinni vinnur ákveðnar upplýsingar úr hreyfingunni og metur hvort hugsanlega sé um jarðskjálftabylgju að ræða. Þessar upplýsingar eru sendar til miðstöðvarinnar í Reykjavík, sem metur sjálfvirkt með samanburði við upplýsingar frá öðrum stöðvum hvort um jarðskjálftahreyfingu sé að ræða eða einhvers konar truflun. Á þessu stigi fer fyrsta staðsetning skjálfta fram, aðeins nokkrum tugum sekúndna eftir að skjálfti verður. Þegar um raunverulega skjálfta er að ræða sendir miðstöðin nú skeyti til útstöðvanna og biður um ítarleg gögn um hann. Upplýsingasamskiptin fara að mestu fram um flutningsnet Símans. Í SIL-miðstöðinni í Reykjavík fara starfsmenn Jarðeðlissviðs Veðurstofunnar svo yfir hinar sjálfvirku mælingar, og leiðrétta ef þarf. Í framhaldinu er gerð endanleg staðsetning, brotahreyfing skjálftans metin o.fl., og upplýsingarnar settir inn í SIL gagnagrunninn.

Hér er gerð grein fyrir jarðskjálftavirkni á Suðvesturlandi fyrir tímabilið 1991–1993 og fyrir allt landið árin 1994–2000. Myndir 2 og 3 sýna upptök jarðskjálfta á þessum tímabilum. Á kortin eru valdir vel staðsettir skjálftar stærri en 1 á Richterskvarða. Þann 17. janúar 1991 hófst Heklugos og í kjölfarið, næstu mánuði á eftir, fylgdu nokkrar skjálftahrinur á Suðurlandi og í vestara gosbeltinu. Mjög mikil skjálftavirkni var á Hengilssvæðinu og í Ölfusi á árunum 1994–1998. Á þessu tímabili voru staðsettir um 85.000 skjálftar á þessum svæðum. Virknin þar dróst saman eftir 2 skjálfta $M_l \simeq 5$ sem urðu í júní og nóvember 1998. Í febrúar 1994 varð skjálfti af stærð M_s=5,3 norðan við Siglufjörð á Tjörnesbrotabeltinu. Í framhaldi af honum og allt fram til ársins 1997 urðu margar stórar hrinur úti fyrir Norðurlandi. Mikil skjálftavirkni var í tengslum við 2 eldgos undir Vatnajökli. Á undan Gjálpargosinu í október 1996 var mikil skjálftahrina í Bárðarbungu þar sem stærsti skjálftinn mældist M_s=5,4. Á undan Grímsvatnagosinu í desember 1998 var einnig skjálftahrina. Smáskjálftahrina kom fram á mælum um klukkustund fyrir Heklugosið í febrúar árið 2000. Hún ásamt þenslumælingum varð til þess að afgerandi viðvörun um yfirvofandi eldgos var gefin út áður en gosið braust upp. Nokkrar jarðskjálftahrinur voru undir Eyjafjallajökli og einnig var viðvarandi haustskjálftavirkni undir Mýrdalsjökli en mismikil eftir árum. Í júní 2000 voru tveir stórir jarðskjálftar á Suðurlandi. Fyrri skjálftinn (M_s=6,6) varð þann 17. júní og átti upptök í Holtunum. Í kjölfar hans fylgdu skjálftar til vesturs, út eftir Reykjanesskaganum og einnig norður til Geysis og Langjökuls. Seinni skjálftinn (M_s=6,6) varð þann 21. júní og átti hann upptök við Hestvatn.

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