Reviewed research article

The analog seismogram archives of Iceland: Scanning and preservation for future research

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Abstract — *The history of seismography in Iceland began in 1909 with the installation of one horizontal Mainka seismograph in Reykjavík. Following a period of intermittent operation, regular operation was initiated in 1925 with the establishment of the Icelandic Meteorological Office. The number of stations increased gradually over the following decades, and in the sixties, four stations were in operation. The number of permanent stations proliferated following the Heimaey eruption in 1973 and during most of the eighties the number of stations was 40–50. The first digital seismograph stations were installed in 1990 and the analog seismic network was gradually replaced by digital stations over the next two decades. Between 1910 and 1920 the number of seismograms grew to an estimated 300,000. A four-year project to make this record collection accessible on the internet has been initiated and funded. So far around 175,000 seismograms have been scanned and the results are available and free for download on the open website seismis.hi.is. The seismograms are scanned with a resolution of 300 dpi and presented on the website as jpg-, and png-file. The high-resolution files are on the order of 4–8 Mb each. Digitization of the seismic traces has not been attempted since most of the seismograms are from short-period instruments and the waveforms are already lost. In addition to numerous teleseismic body-wave-phases, the record collection contains primary data from various tectonic and magmatic events in Iceland during the last century. This includes eruptions of Hekla in 1947, 1970, 1980–81, 1991 and 2000, Surtsey in 1963–1967, Heimaey in 1973, Askja in 1961, Grímsvötn in 1934, 1983, 1998, and 2004, Gjálp in 1996, rifting episode at Krafla in 1975–1984, persistent seismic activity of the Bárðarbunga and Katla volcanoes, numerous suspected subglacial magmatic events, earthquake swarms on the Reykjanes Peninsula Oblique Rift and within the Tjörnes Fracture Zone, and earthquake sequences in the transform zones of South and North Iceland and adjacent segments of the Mid-Atlantic Ridge.*

INTRODUCTION

All over the world scientists are waking up to the reality that valuable seismological data are being lost. Because storage is costly, large archives of analog data of various nature are taken to the waste dumps (Richards and Hellweg, 2020). The analog-to-digital revolution and the large increase in storage capacities for digital data has brought many benefits to the scientific community. Digital data are becoming readily available to a large generation of scientists, allowing sophisticated analysis and research, unthinkable before. This brings with it the danger of forgetting and ignoring data sets obtained in the pre-digital era. In several branches of science it is essential to have long term data. This includes many branches of earth sciences. The natural systems under investigation operate on time scales of centuries and millennia, much longer than the time periods of available digital data, including volcanic systems, active seismogenic faults, climatic systems (e.g., Sturkell *et al.*, 2006; Sigmundsson *et al.*, 2018). For research in these fields, it is important to extend the period of observation back in time as far as possible in order to appreciate the time-variability of the systems. In earthquake seismology, this is done by studying and interpreting 1) surface effects of prehistoric and historic earthquakes, 2) old documents describing the effects of historic earthquakes, and 3) data from analog seismographs from the early years of seismography.

One of the rules of experimental sciences is that a scientific experiment must be reproducible, i.e., that a repeated experiment shows the same result. This rule is hard to follow in many branches of the natural sciences. We may anticipate future experiments and set up our observational networks to obtain the necessary data. But nature itself determines when the actual experiment takes place and may not agree with our anticipated course of events. The physical and chemical systems at work are complicated and frequently we must design our experiments in retrospect and rely on data that may be available, sometimes by chance. This is particularly evident when dealing with self-destructive systems, like the source area of a large earthquake or an active volcanic system. The next event is almost never a repeat of the last. This situation gets worse the larger the previous event was. As a result the scientific value of a specific data set may not be recognized until long after it was made. In the meantime, the data are in constant danger of being destroyed or lost. The seismological community is responding to this reality of lost data by launching extensive projects to copy analog seismograms into digital formats that can be preserved and used in future research (Richards and Hellweg, 2020).

The first analog seismograph was installed in Iceland in 1909 and the last one was taken out of operation in 2010. The number of instruments varied a lot in the time between these years, reaching a maximum of about 50 stations in the 1980's. These were mostly short-period instruments, suitable for the recording of local earthquakes and for determination of arrival times and magnitudes. The seismograms are primary sources of data on a century of seismic and volcanic activity in the Icelandic crust. The paper seismograms were stored in various insecure locations. A project to preserve the seismograms by digitization was initiated in 2017. The main objectives were twofold:

1. To save the data from destruction, accidental or otherwise.
2. To make the data easily accessible to the scientific community for future studies.

In this paper we give an account of the background of the project and provide guidance to the use of the data.

A HISTORY OF ANALOG SEISMOGRAPHS IN ICELAND

Early decades

The first seismograph in Iceland was set up by German scientists in 1909 in Reykjavík. It was located in the old building of the Nautical School (Stýrimannaskólinn) at Öldugata 23, that still stands (Figure 1). This location was presumably chosen because of the precise time keeping. A visible time mark was given every day from this location for the benefit of navigation of ships in the nearby Reykjavík harbor.

The seismograph was a Mainka seismograph that measured the horizontal N-S component of the ground movement. Another seismograph of the same type was added in 1913. It measured the E-W component. The operation of these instruments did not go very smoothly. It was frequently interrupted and finally stopped in 1914 because of the First World War (Tryggvason, 1951; Garðarsson, 1999). These seismographs were mechanical, i.e., no electronics. The amplification was achieved by connecting rods between the horizontal pendulum and the recording pen. The recording was by a fine needle on smoked paper taped on a rotating drum. The soot on the paper was then fixed in a bath of shellac. The amplification was low, only 100.

The operation of the Mainka seismographs was resumed in Reykjavík in 1925 and 1927, soon after the Icelandic Meteorological Office was founded, at the initiative of Þorkell Þorkelsson, its first director. The instruments were moved to the new Nautical School in 1946 and the operation was continuous until 1952, when improved instruments were installed.

A set of three short-period Sprengnether seismographs was set up in Reykjavík in 1951–1952. These had a much higher amplification than the old instruments but were seriously limited by the high level of microseisms, i.e., continuous tremor originating in the Atlantic Ocean, with a high spectral peak near 6 sec. period. These instruments had an electromag-

Figure 1. Öldugata 23, Reykjavík, the location of the first seismograph in Iceland in 1909. – *Fyrsti jarðskjálftamælir á Íslandi var settur upp 1909 í kjallaranum í húsi Stýrimannaskólans að Öldugötu 23 í Reykjavík.*

netic sensor and recorded with a light beam on photographic paper. The old Mainka instruments were then moved to Akureyri and Vík í Mýrdal, thus forming the first network in Iceland. Some of the largest earthquakes could then be located instrumentally, even though the accuracy was not good.

New stations were set up at Kirkjubæjarklaustur in 1958 and Eyvindará near Egilsstaðir in 1967, consisting of one vertical electromagnetic Willmore sensor. A similar sensor was added to the station in Reykjavík in 1966.

A large step was taken in 1964 when a state-of-the-art seismic station was established in Akureyri, in the basement of the police station. It was a part of the World Wide Network of Standardized Seismographs (WWNSS) that was established and run by the US Geological Survey. The network consisted of more than 120 stations that were distributed throughout the Earth, each one with three long-period sensors and three short-period sensors (Oliver and Murphy 1971). The main purpose of the network was to monitor nuclear explosions, but it also provided the first reliable maps of global seismicity, forming one of the backbones of the Theory of Plate Tectonics. The data from this network were copied and distributed to several data centers, one of which was at the Lamont-Doherty Earth Observatory in New York. Data from the Akureyri station were used in numerous studies of world seismicity and the internal structure of the Earth.

Data from the stations listed so far were analyzed at the Icelandic Meteorological Office (Veðurstofa Íslands). A Seismological Bulletin was issued every year since 1926, listing earthquake epicenters and magnitudes, and other pertinent information. The main results for the three decades from1930 to 1960 were also published in three reports by Tryggvason (1978a, 1978b; 1979).

Electronic revolution

A major advance in seismometry took place in the sixties, mainly due to the invention of the transistor and other electronic components. Measurements using electronic components became reliable and electronic circuits could be designed that did not require connection to the electric mains and could be run outside under field conditions. The eruptions in Surtsey 1963-1967 sparked new interest in earthquake monitoring. A seismograph was operated for a while on Heimaey (Pálmason, 1966) and a grant was obtained to buy and build a seismic system to operate on Surtsey, consisting of a 7-track tape recorder, sensors, and amplifiers (Sigurgeirsson and Stefánsson, 1967; Einarsson, 1974).

The Surtsey eruptions also coincided with the advent of the Plate Tectonics Theory and attracted the interest of the international geoscience community to Iceland. A group from the Lamont-Doherty Earth Observatory came to Iceland in 1967 and brought several portable seismographs with them. The idea was to trace the plate boundary through Iceland by locating microearthquakes that were thought to occur more or less continuously along the boundary. Instead it was discovered that the microseismicity was mostly confined to geothermal areas (Ward *et al.*, 1969; Ward and Björnsson, 1971).

The results of the microearthquake studies led to a major project to monitor the seismicity of the Reykjanes Peninsula, that was showing very high activity at this time (Björnsson *et al.*, 2020). The instrumentation from Surtsey was modified and augmented to establish six semi-permanent stations on the peninsula. In addition, a large field project was launched in the summers of 1971 and 1972 (Klein *et al.*, 1973, 1977).

Three of the portable instruments, that the Lamont-group brought, were set up in South Iceland and "forgotten" over the winters of 1971 and 1972. This was done to test how well these prototype instruments would perform under difficult circumstances and in the care of non-technical people. The best locations were at Skammadalshóll near Katla volcano and Laugarvatn, in the secondary school there. These instruments recorded, among other things, the beginning of the eruption in Heimaey in January 1973 (Björnsson and Einarsson 1974).

Landsnet

The positive experience of operating sensitive seismographs at farms and installations throughout the country prompted the decision to design and build similar instruments and establish a seismic network. Small grants were obtained from the NATO science program for a three-year project for this purpose. The design was based on the prototype instruments from Lamont, but the electronics parts were designed by Marteinn Sverrisson at the Science Institute, University of Iceland. The hardware was made by Karl Benjamínsson in the machine shop of the institute. The work was directed by Sveinbjörn Björnsson and Páll Einarsson (Einarsson and Björnsson, 1987).

The instrument had to be inexpensive, yet robust and easily serviceable by the local people. It had to be sensitive in the frequency band 3–30 Hz for the detection of local earthquakes, yet insensitive in the band of microseisms (0.1–0.2 Hz) from the swell of the North Atlantic Ocean, that seriously limits the sensitivity of island seismographs. The sensor was a geophone of 3 Hz natural frequency. The amplifier had a HP filter selection (at 0.1 or 1 Hz) that could be adjusted according to the level of microseisms activity, also LP filter adjustable between 15 and 30 Hz. The electronics was arranged on five boards that could be individually replaced in case of failure, i.e., power board, preamplifier, amplifier, power amplifier, and time signal receiver (Figure 2). Radio time was put directly on the seismographic trace, thus avoiding using a clock and cumbersome clock corrections. Recording was by pen and ink on paper attached to a rotating drum (Figure 3). Usually, the paper sheet was changed once per day. This allowed a time resolution of 90 mm per minute, one line per 10 minutes on a sheet that is 90 cm long. During days of very high activity the interval between lines was increased to avoid tangling of the lines. Then the sheet had to be changed more often.

The seismograph could be modified for a telemetered version. The power amplifier card was then simply exchanged for a tone modulator and the tone fed into a hand-held radio link. The tone on the receiving end was then de-modulated and amplified in a similar box and fed into the pen-motor of the recorder. The telemetering system required a line of sight and often a repeater station to carry the signal over large distances. This was used for seismic stations on the Reykjanes Peninsula and in the Hengill area near Reykjavík. During the Krafla episode in 1975–1984 several stations were also telemetered to a central recording station in Reynihlíð. A network of telemetered stations was installed in Central Iceland in 1985, funded by Landsvirkjun (the National Power Company), for the monitoring of the active volcanoes around their main power stations. The signals were telemetered over repeater stations on Búrfell and Skarðsmýrarfjall to Reykjavík, where they were recorded on paper at the Science Institute (Figure 4).

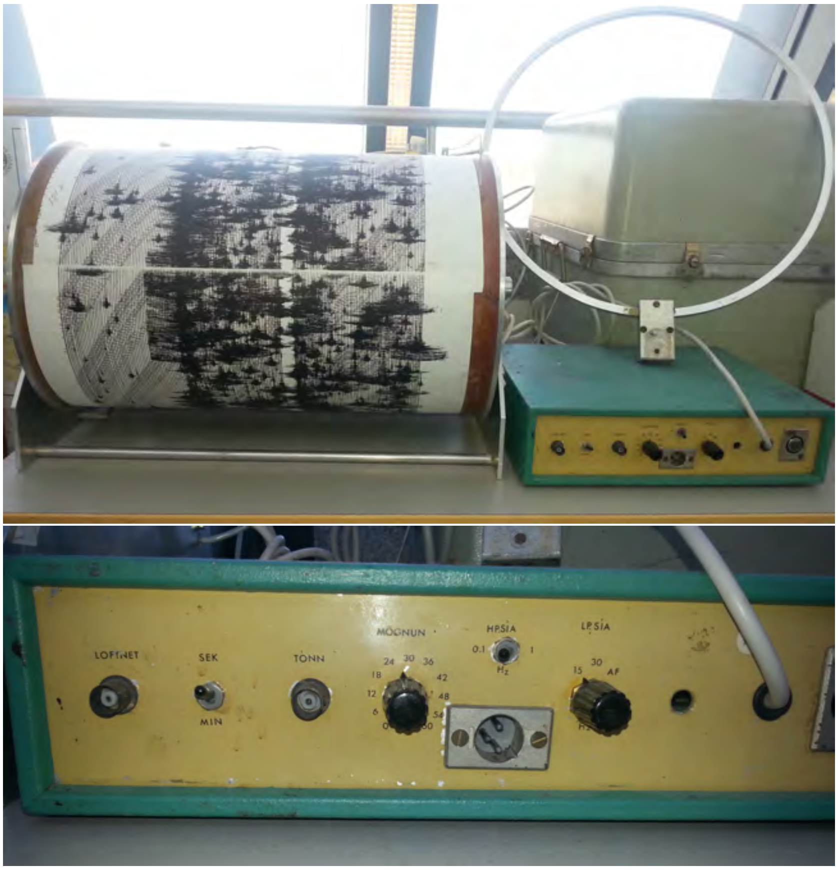

Figure 2. Top: The Landsnet seismograph. Drum recorder with a sheet showing a local recording of an earthquake swarm in the Hengill area, electronics box, and a loop antenna for the reception of the time signal. The grey box was used for the field version of the seismograph. Below: The front of the electronics box: Input for the time signal antenna, seconds filter, tone input for FM modulated signals from a signal receiver, amplifier 0–60 dB, HP-filter, input for geophone signal, LP-filter, 220 VAC power cord, 12 VDC power input. – *Efri mynd: Jarðskjálftamælir Landsnetsins sem hannaður var og smíðaður á Raunvísindastofnun Háskólans. Á tromlunni er skjálftarit frá mælinum við ÍR-skálann sem sýnir jarðskjálftahrinu á Hengilssvæðinu. Einnig má sjá „græna kassann“ sem hýsir rafeindabúnaðinn og hringloftnet til móttöku á tímamerki. Grái kassinn í bakgrunninu var notaður fyrir mælinn þegar mælingar voru gerðar utanhúss. Neðri mynd: Framhlið rafeindakassans: Tengi fyrir tímamerkjaloftnet, sekúndusía, tengi fyrir tón frá móttökutæki þegar skjálftamerki var sent frá fjarlægum mæli, magnari 0–60 dB, háhleypisía, tengi fyrir merki frá skjálftanema, lághleypisía, snúra fyrir 220 VAC rafmagn, tengi fyrir 12 VDC rafmagn.*

The first seismographs of the new network were installed in the autumn of 1973 and summer of 1974 in South Iceland with emphasis on the Katla volcano. In the second phase of the project in 1974–1975 seismographs were installed in North Iceland. These stations showed increased activity around the Krafla volcano, that preceded the first dike injection event of Krafla that began on December 20, 1975 (e.g., Buck *et al.*, 2006; Einarsson and Brandsdóttir, 2021). This led to increased monitoring activity in the Krafla area. Monitoring was also increased in other areas, including the Vatnajökull area and the South Iceland Seis-

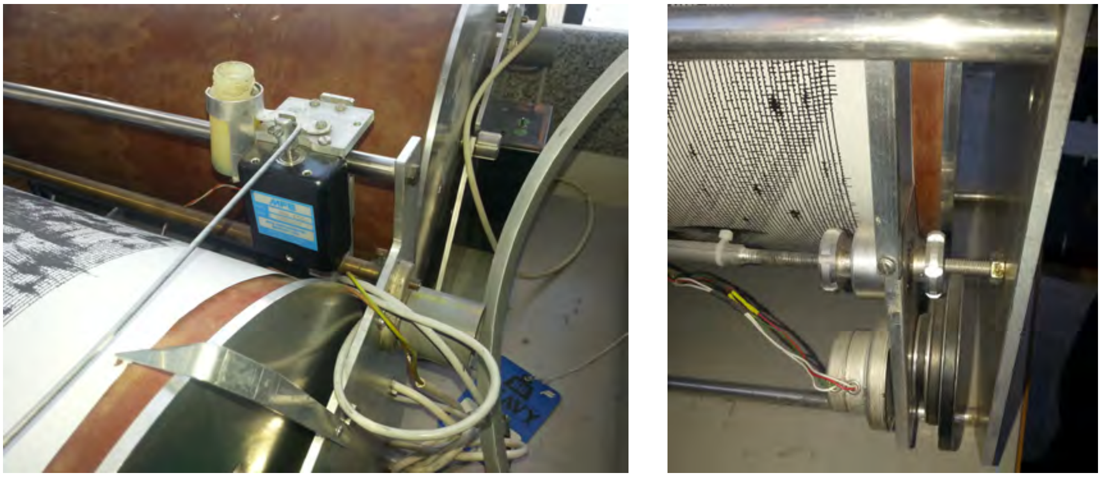

Figure 3. Left: The pen-motor and translation-motor assemblages of the Landsnet seismograph. The pen was made at the SI from a drawing pen tip attached to a syringe pipe. A special recording ink was used, available in different colors, black, red, green and blue. Right: The rotation-motor assemblage of the Landsnet seismograph. It offered three different speeds of rotation. The most used time resolution was 90 mm per minute. – *Vinstri mynd: Pennamótor og færslumótor Landsnestmælisins. Pennarnir voru smíðaðir á Raunvísindastofnun úr oddi af teiknipenna og pípu úr sprautunál. Sérstakt síritablek var notað, sem var fáanlegt í svörtum, rauðum, grænum og bláum lit. Hægri mynd: Sérstakur mótor sneri tromlunni og mátti stilla á þrjá mismunandi hraða. Algengast var að nota hraða sem gaf tímaupplausn 90 mm/mínútu.*

mic Zone. The final phase of the original project was then finished by installing stations around the central highland in 1977. Several stations were then added in the following years when opportunities arose, e.g., around Hengill in 1979. The permanent and semi-permanent stations are listed in Table 1, their names, locations, and operation times. The table will be updated as the scanning project progresses. Figure 5 shows a map of the network stations at the peak of its operation.

The sheets from the Landsnet stations were sent to the Science Institute where a preliminary analysis was carried out. The results were distributed by Skjálftabréf, a pamphlet containing approximate locations and other information, now accessible at https://www.jardvis.hi.is/skjalftabref. The first detailed epicentral maps of earthquakes based on the results appeared in several papers in the eighties and nineties (e.g., Einarsson and Björnsson, 1987; Einarsson, 1978, 1991; Brandsdóttir and Einarsson, 1979; Einarsson and Brandsdóttir, 1980; Foulger and Einarsson, 1980; Björnsson and Einarsson, 1990).

A new digital seismograph system became operational in South Iceland in late 1990, called the SIL-system. This system was expanded in the following years to cover the whole of Iceland. The operation of the old analog network was then gradually phased out as the new, sophisticated network expanded. The last analog seismograph was taken out of service in 2010.

The seismograms and time signal

All the analog seismograms are written on drum recorder, i.e., a paper sheet was attached to a rotating drum and the recording element, pen, needle, or light beam was moved sideways with respect to the drum, so that a continuous trace was written on the sheet (Figure 3). When the sheet was removed from the drum the trace formed lines, with time in each line progressing from left to right, like lines in a book. The time resolution of the recording was determined by the rotation speed of the drum, one, two, four or six rotations per hour, producing the same number of lines per hour on the final seismogram sheet.

A time signal was mixed with the seismic signal, a small excursion of the trace superimposed on the

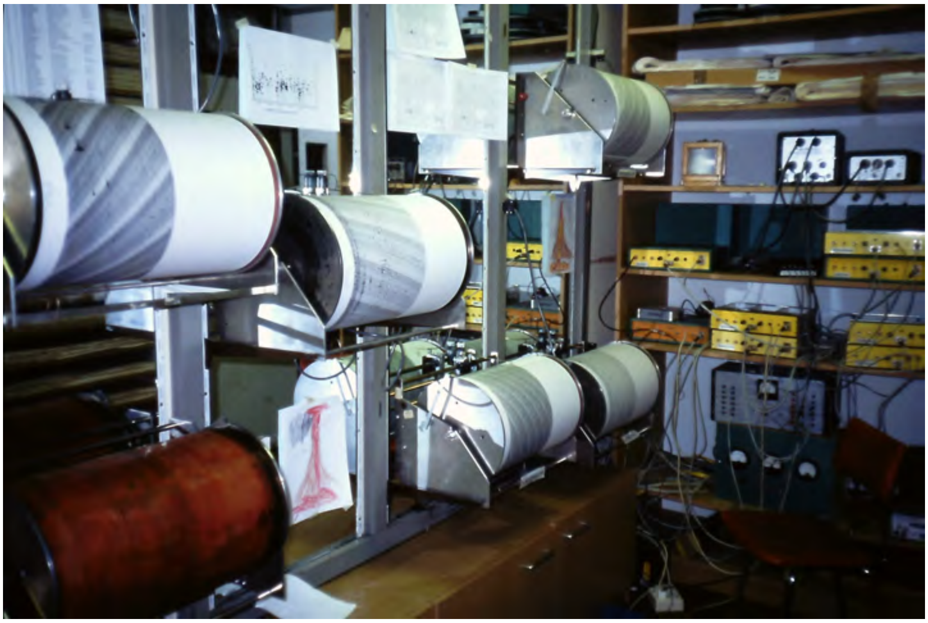

Figure 4. Recorders at the Science Institute of telemetered signals from seismographs in Central Iceland, Grímsfjall, Vonarskarð, Þúfuver, Jökulheimar, Sporðalda, Ljótipollur, and Litla-Hekla. – *Merki frá skjálftamælum á Miðhálendinu var sent til Reykjavíkur þar sem skráning fór fram á Raunvísindastofnun Háskólans.* Photo:/*Ljósm.* Nick Weir.

movements of the ground. Thus, any disturbance of the ground could be timed by measuring its distance from the nearest time signal. On most seismographs a minute mark was considered sufficient, but on the Landsnet seismograph the second marks were used as well, in order to increase the timing accuracy. It was considered important to eliminate the need for clock corrections, so continuous radio time was used directly on the seismogram. The 60 kHz time signal from Rugby in England was used most of the time of operation. Another time signal was used during limited periods, a low-frequency navigation signal for submarines, called Omega, giving only minute marks.

The Rugby time signal was coded after June 1977, which came in very handy when reading the seismograms. The seconds marks came in two sizes, signifying 0 and 1 in a binary code. The date and time were indicated every minute of the seismogram. This made an easily readable pattern on the seismograms because each line was 10 minutes long, i.e., each hour contained six lines. If the time marks were properly aligned the last digit of the time would be the same in all vertical lines across the seismogram. Reading the rest of the code requires a bit of practice but makes the life of the record reader a lot easier. Unnecessary zeros in the front are dropped. So:

0	0000	or 000	or 00
1	0001	001	01
2	0010	010	10
3	0011	011	11
4	0100	100	
5	0101	101	
6	0110	110	
7	0111	111	
8	1000		
9	1001		

Second marks number 17–24 tell the year, no. 25–29 the month, no. 30–35 the day of the month, no. 36–38 the day of the week (Monday no. 1), no. 39-44 the hour (in England), no. 45–51 the minute beginning at the next minute mark. The date and time, Monday the 4th of July 1977 at 1635 would then appear:

$\underline{0111}$	0111	0	$\underline{0111}$	00	$\underline{0100}$	001	01	$\underline{0110}$	011	$\underline{0101}$
7	7	0	7	0	4	1	1	6	3	5

Table 1. Seismic stations, permanent or semi-permanent, with analog recording.

Name	4-code	2-code	Lat. N	Lon. W	Height	Set up	Closed	Remarks
					m	yyyy mm		
Stórhöfði	ICSH	SH	63.3975	20.2933	120	1973 02		
Skammadalshóll	ICSK	SK	63.4535	19.098	50	1972 09	1989 10	
Hafursey	ICHF	HF	63.5142	18.737	110	1980 01		Telem. to Herjólfsstaðir
Selkot	ICSE	SE	63.549	19.609	180	1973 08		
Snæbýli	ICSB	SB	63.7208	18.621	200	1973 12	1993 08	
Kirkjubæjarklaustur	ICKK	KK/SID	63.785	18.0583	26	1958 08		
Árgilsstaðir	ICAR	AR	63.7883	20.115	90	1974 08		
Svartsengi	ICTH	TH	63.8661	22.4317	80	1984 07	1993 12	
Bjarnastaðir	ICHB	HB	63.9432	21.3027	40	1979 06		
Selfoss	ICSL	SL	63.9438	21.0015	15	1976 12		
Kvísker	ICKV	KV	63.978	16.4383	30	1976 10		
Litla-Hekla	ICHE	HE	64.0057	19.6817	940	1982 03	2003 09	Telem. to SIUI
Móhnúkar	ICMO	MO	64.0252	19.6895	440	2003 08	2008 11	Replacing HE
Hellar	ICHL	HL	64.0107	20.160	100	1976 04	1998 08	
Valahnúkar	ICVA	VA	64.0182	21.8392	137	1971 09		Telem. to SIUI
Ljótipollur	ICLJ	LJ	64.0235	19.0233	600	1985 10	2008 11	Telem. to SIUI
Bjallavað	ICBV	BV	64.0978	19.1580	560	1979	1985	
Vatnsfell	ICVF	VF	64.1993	18.9734	700	1979		
ÍR-skáli	ICIR	IR	64.0418	21.3757	300	1977 02		Telem. to SIUI
Nesjavellir	ICHN	HN	64.1155	21.2573	180	1979 06		
Reykjavík	ICRE	RE	64.1492	21.9492	21	1909	1946 10	Mainka seismogr.
			64.1392	21.9025	41	1946 10	1951 10	Mainka.
			64.1392	21.9025	41	1951 02		Wilmore seismogr.
Laugarvatn	ICLV	LV	64.2155	20.753	100	1972 09	1993 07	
Sporðalda	ICSP	SP	64.2213	19.2483	360	1985 09		Telem. to SIUI
Jökulheimar	ICJO	JO	64.3527	18.2367	790	1985 10	2005 05	Telem. to SIUI
Miðfell	ICMI	MI	64.3983	15.3450	60	1977 06	2000 12	
Grímsfjall	ICGF	GF	64.4153	17.2667	1725	1982	2008 11	Telem. to SIUI
Þúfuver	ICTV	TV	64.5780	18.5967	600	1985 12	1996 12	Telem. to SIUI
Vonarskarð	ICVO	VO	64.6667	17.7670	1017	1985 10	2008 11	Telem. to SIUI
Síðumúli	ICSM	SM	64.7100	21.3800	70	1974 05		
Hveravellir	ICHV	HV	64.8683	19.5683	640	1974 08	1992 09	
Sandbúðir	ICSA	SA	64.9350	17.9900	820			
Aðalból	ICAB	AB	65.0192	15.5817	480	1977 06		
Eyvindará	ICEY	EY	65.2833	14.3833	25	1967 06		Wilmore seismogr.
Svartárkot	ICSV	SV	65.3393	17.2550	405	1978 08		
Lúdent	ICLT	LT	65.5850	16.8183	400	1982 07		Telem. to Reynihlíð
Grímsstaðir	ICGS	GS	65.6433	16.1317	450	1974 10	1991 08	
Reynihlíð	IGRI	RI	65.6467	16.9117	340	1975 07	1994 10	
Akureyri	ICAK	AKU	65.6762	18.0933	53	1954 07	1964 07	Mainka seimogr.
			65.6867	18.1067	24	1964 07	2002 11	WWNSS
Krafla	ICKR	KR	65.6967	16.7817	450	1975 10	1990 12	Teleph. to Reynihlíð
Gæsadalur	ICGD	GD	65.7395	16.9563	430	1976 07		Telem. to Reynihlíð
Sandmúli	ICSU	SU	65.7705	16.7767	610	1982 04		Telem. to Reynihlíð
Húsavík	ICHU	HU	64.0183	17.3250	180	1974 10		
Skinnastaður	ICSS	SS	64.0633	16.4383	80	1974 10		
Hraun	ICHS	HS	64.1117	20.1217	20	1975 09	1996 08	
Siglufjörður	ICSI	SI	64.1550	18.9167	120	1975 08	1994 01	
Leirhöfn	ICLN	LN	64.4063	16.4950	40	1979 08	1992 11	
Grímsey	ICGR	GR	64.5417	18.0117	20	1975 06		

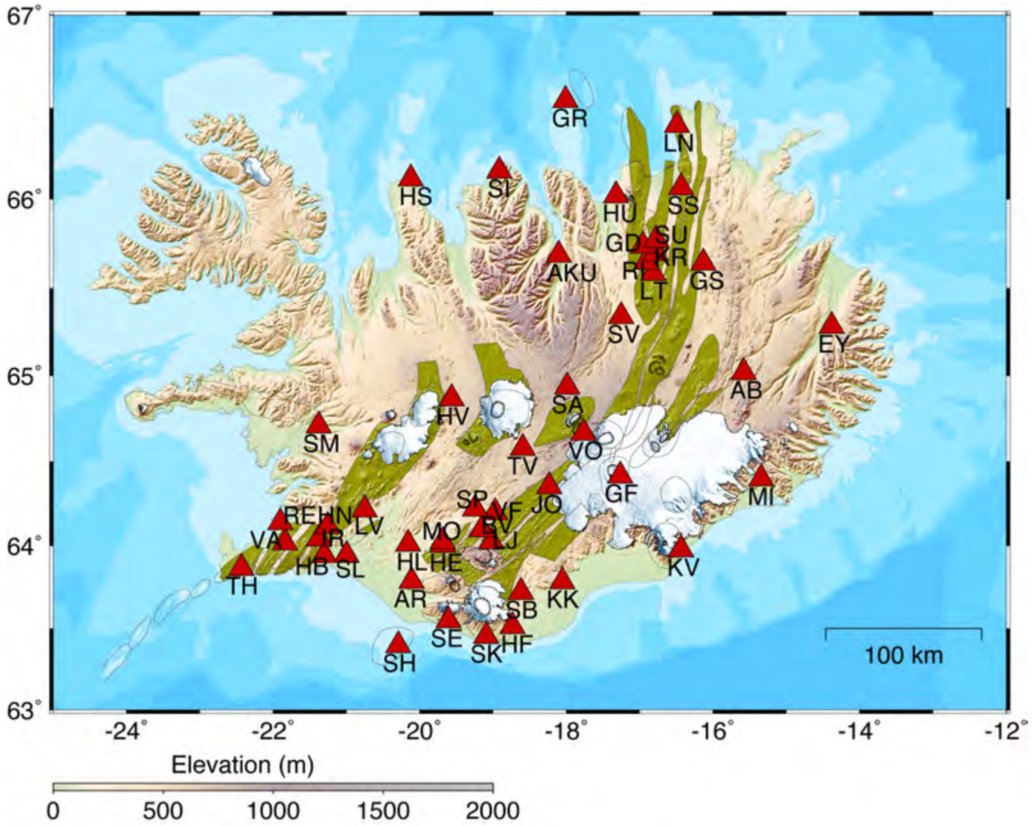

Figure 5. Map of analog seismograph stations at the peak of the network, in the late eighties and nineties. – *Kort af stöðvum Landsnetsins þegar þær voru flestar í gangi, á níunda og tíunda áratug síðustu aldar.*

Magnitude scales for the Landsnet seismographs

The dynamic range of the paper records was limited. The minimum readable amplitude is about 1 mm and the records were designed to clip at about 40 mm to avoid damage to the pen assemblage. It was therefore not practical to use an amplitude-based magnitude scale, such as M_L, to measure magnitude of recorded earthquakes. A scale based on the duration of the seismic signal, M_τ, turned out to be rather practical and give a consistent result for a set of stations recording the same event. Similar scales were used in many seismically active areas of the world, including Hawaii and California (Lee *et al.*, 1972). The stations were calibrated with respect to duration magnitude by plotting log τ against M_L obtained from the Meteorological Office, an average magnitude for events recorded by the older stations in Reykjavík, Akureyri, Síða (Kirkjubæjarklaustur) and Eyvindará. The duration, τ, was determined as the time in seconds from the first P-arrival until the peak-to-peak amplitude last exceeded 1 mm at 36 dB amplification. A best fitting line was then determined for the set of calibration events, which thus was used as a magnitude scale for the respective station.

$$M_\tau = a \log \tau - b$$

The constants a and b are given for the calibrated stations in Table 2. These scales were found to be almost insensitive to the epicentral distance. The number of calibration events ranged between 60 and 200, and the correlation coefficient was above 0.86 for all stations. A representative plot of duration versus local magnitude ML is shown in Figure 6. Most magnitude values in Skjálftabréf are duration magnitudes.

Table 2. Duration magnitude scale for analog stations, $M_\tau = a \log \tau - b$.

Station	4-code	a	b	R	N
Skammadalshóll	ICSK	2.1	0.5		
Hafursey	ICHF	2.4	0.9		
Selkot	ICSE	2.6	1.2		
Snæbýli	ICSB	2.2	0.5		
Árgilsstaðir	ICAR	1.8	0.4		
Selfoss	ICSL	2.3	1.3		
Kvísker	ICKV	2.39	0.56	0.89	49
Litla-Hekla	ICHE	2.8	2.6		
Hellar	ICHL	2.7	1.2		
Svartsengi	ICTH	2.5	1,2		
Valahnúkar	ICVA	2.3	1.6		
ÍR-skáli	ICIR	2.9	2.4		
Laugarvatn	ICLV	2.3	0.1		
Ljótipollur	ICLJ	2.0	0.5		
Sporðalda	ICSP	2.2	0.3		
Jökulheimar	ICJO	2.2	0.6		
Vonarskarð	ICVO	2.5	1.1		
Hveravellir	ICHV	2.2	0.6		
Miðfell	ICMI	2.54	0.68	0.96	61
Aðalból	ICAB	2.40	0.56	0.93	65
Svartárkot	ICSV	2.75	1.09	0.91	96
Grímsstaðir	ICGS	2.29	0.44	0.96	34
Reynihlíð	ICRI	3.00	1.66	0.93	86
Húsavík	ICHU	3.0	2.1		
Skinnastaður	ICSS	2.46	0.75	0.89	67
Hraun	ICHS	3.30	2.11	0.90	66
Siglufjörður	ICSI	3.17	1.86	0.93	85
Leirhöfn	ICLN	3.36	2.47	0.88	66
Grímsey	ICGR	2.75	1.26	0.87	59

THE SCANNING PROJECT

The purpose of the scanning project was mainly twofold: 1) to preserve the seismogram archives, and 2) to make the seismograms accessible to researchers for studies. On more than one occasion, collections of seismograms had been close to destruction when colleagues were re-organizing store rooms and offices. The threat of flooding or fire was also considered. The seismograms had been stored in the archives of the institutes that collected them and the National Archives, but they had never all been stored in the same place. Finding records of a particular event was almost an impossible task. Having all the seismograms accessible on an open website would greatly facilitate research on seismicity and volcanism. An initiative by the Institute of Earth Sciences was well received and a decision was made in early 2017 to join forces and start a four-year program to scan and computerize all available analog seismograms. The participating institutions were: Institute of Earth Sciences, Science Institute, University of Iceland, Icelandic Meteorological Office, Natural Catastrophe Insurance of Iceland, National Power Company of Iceland, Reykjavík Energy, Icelandic National Archives, Rannís, the Icelandic Centre for Research, and The Eggert Briem Fund, University of Iceland.

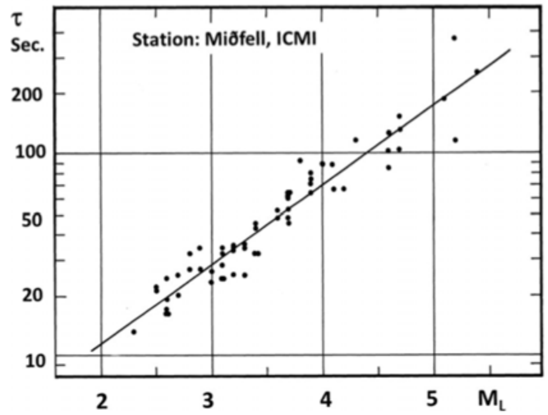

Figure 6. Duration of selected earthquakes at the Miðfell station plotted against the local magnitude derived from the calibrated stations in Reykjavík, Akureyri, Sida and Eyvindará. – *Stærð skjálfta sem komu fram á mælum Landsnetsins mátti ákvarða út frá varanda hreyfingarinnar, τ, þ.e. tímanum sem leið frá fyrstu bylgju og þangað til hreyfingin dó út. Mælarnir voru kvarðaðir með tilliti til eldri mæla, í Reykjavík, á Akureyri, Kirkjubæjarklaustri og Eyvindará. Myndin sýnir hvernig varandi á mælinum á Miðfelli var háður stærð. Línan er kvörðunarkúrfan sem felld er að mæligögnunum.*

Several criteria were set for the project:

1. The quality of the scanned records should be comparable to that of the originals.
2. The scanned records should be available and easily accessible to everyone interested.
3. The scanning files should be of manageable size to allow a quick overview of their content.

The scanning began in late 2017 in the facilities of the National Archives with a large-format scanner provided by the Eggert Briem Fund. The work was performed mostly by students of the University of Iceland. The scanning operation was later moved to the Institute of Earth Sciences, University of Iceland.

THE DATA AND RESEARCH POSSIBILITIES

The new data archive opens several lines of research into the activity of the crust in Iceland, both volcanic and seismic. The installation of seismographs in Iceland has often happened in response to large events. The large earthquakes in the transform zones of Iceland in 1910 and 1912, for example, without doubt attracted the attention of the international seismological community to Iceland and the high activity there and led to the installation of the first seismograph. The increase in the number of instruments in the fifties was influenced by the general belief that Katla, the feared volcano of South Iceland, was likely to erupt around 1960 (Thorarinsson, 1960), an opinion based on its previous eruption pattern. Otherwise, the central part of the twentieth century was rather quiet if compared to previous centuries. This changed in the sixties with the eruption of Askja in 1961, the large earthquake of Skagafjörður in 1963, and the prolonged eruptive activity of Surtsey 1963–1967 (e.g., Sayadi *et al.*, 2020). Portable seismographs became available and were used to study the eruptions of Hekla in 1970 and Heimaey in 1973.

The new analog seismograph system, Landsnet, came just in time to record the beginning of the Krafla rifting episode 1975–1984 with its 20 diking events and 9 eruptions. Several papers are based on data from these events, but considerable part of the data set still has not been analyzed to its full capacity. An example of the data is shown in Figure 7, that displays the beginning of the last and largest Krafla eruption on September 4, 1984, as recorded at the Skinnastaður station, 30 km from the eruption site (Einarsson, 2018). The seismogram shows the precursory seismic activity that began about three hours before the eruption, and the characteristic low-frequency earthquake about 9 minutes before the eruption. The earthquakes then decrease as soon as the intruding dike reaches the surface and feeds the eruption.

The Grímsvötn volcano erupted in 1983 after several decades of quiescence, showing typical precursory activity, earthquake swarm and eruption tremor (Einarsson and Brandsdóttir, 1984). Soon after that the analog network was expanded into the central highland of Iceland in order to increase the monitoring capabilities for the volcanoes there. This network showed the background activity of Bárðarbunga and Grímsvötn volcanoes, in addition to the Loki Ridge, the source area of jökulhlaups into the Skaftá river (Björnsson and Einarsson, 1990). The enigmatic bursts of tremor following the jökulhlaups were also recorded by the network (Figure 8). The bursts normally last a few tens of minutes and occur at the end of the water release from the glacial cauldrons that feed the floods. The similarity of the tremor to eruption tremor from Grímsvötn led Björnsson and Einarsson (1990) to suggest that they signified small, subglacial volcanic eruptions, triggered by the sudden pressure drop when the water was released from the overlying ice cauldron. Other authors suggest that the tremor may be caused by flash boiling of the geothermal system beneath the cauldron (Björnsson, 2003; Eibl *et al.*, 2020). Seismicity in connection with eruptive activity in Grímsvötn 1998 and 2004 was recorded by the network, also the seismicity of Bárðarbunga volcano leading up to the Gjálp eruption in 1996 (Einarsson *et al.*, 1997).

In addition to the seismicity within Iceland, the network also recorded seismic activity on adjacent sections of the plate boundary. An example is shown in Figure 9 of a large earthquake swarm in 1990 on the Reykjanes Ridge, SW of Iceland, reported by Einarsson (1993). The swarm originated at latitude 63°N, about 180 km away from the seismograph station at Bjarnastaðir. Hundreds of events were recorded within the next two days, at least 14 of magnitude 4 and larger.

The examples above are only a few selected samples from a list of remarkable events during the century of analog seismographic coverage of Iceland. A comprehensive list is available on the website seismis.hi.is.

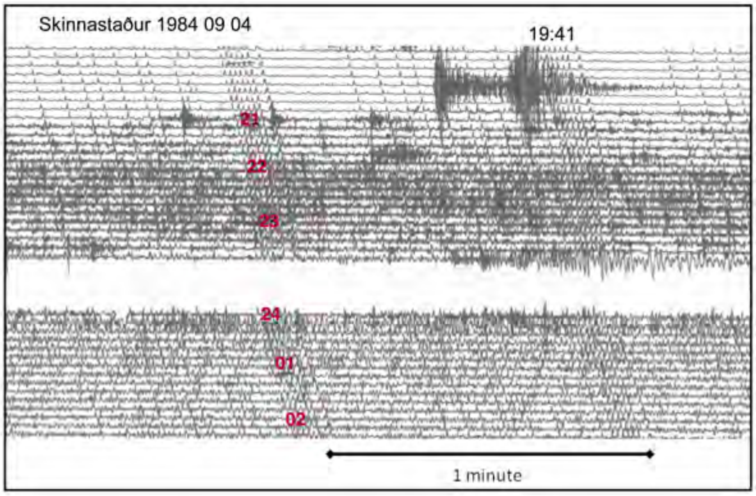

Figure 7. Section of a seismogram from the seismograph at Skinnastaður in N-Iceland on September 4 1984, showing precursory activity and the beginning of the last eruption of the Krafla rifting episode 1975–1984. The earthquake near the top of the seismogram was a magnitude 2.9 (M) event in the Tjörnes Fracture Zone in Fljót, unrelated to the eruption. At this station high-frequency tremor mixed with earthquakes is seen at 22:50. The beginning of the eruption at 23:49 is not accompanied by a significant seismic event. The eruption was accompanied by low-frequency tremor, but very few earthquakes. – *Hluti af skjálftariti frá mælinum á Skinnastað í Öxarfirði 4. september 1984, sem sýnir aðdraganda eldgossins í Gjástykki, síðasta og stærsta gossins í Kröflueldum 1975–1984. Á ritinu sést jarðskjálfti að stærð 2.9 (M) sem átti upptök í Fljótum og er gosinu óviðkomandi. Hátíðnióról blandaður smáskjálftum sést kl. 22:50. Gosið byrjaði kl. 23:49 en engin sérstök jarðskjálftavirkni virðist fylgja gosbyrjuninni. Hátíðnióróinn hættir og við tekur lágtíðnióról, gosórói.*

ÁGRIP

Saga skjálftamælinga á Íslandi nær allt aftur til ársins 1909. Þá var settur upp skjálftamælir í húsi Stýrimannaskólans við Öldugötu í Reykjavík (1. mynd). Staðarvalið réðst líklega af því að þar var nákvæmasta klukka landsins, sem skipstjórnarmenn í Reykjavíkurhöfn stilltu klukkur sínar eftir. Mælirinn var ekki sérlega næmur og skráði einungis einn þátt hreyfingar jarðarinnar, í N-S stefnu. Öðrum sams konar mæli var bætt við 1913 og skráði hann A-V þátt hreyfingarinnar. Rekstur mælanna gekk nokkuð skrykkjótt, og lagðist alveg af á tímum fyrri heimsstyrjaldarinnar. Reglulegar skjálftamælingar hófust síðan aftur 1925 á vegum hinnar nýstofnuðu Veðurstofu Íslands að frumkvæði Þorkels Þorkelssonar, fyrsta Veðurstofustjórans. Aðeins stærstu skjálftar komu fram á þessum fremur frumstæðu mælum. Framfarir urðu 1951 þegar næmari mælar voru settir upp í Reykjavík og gömlu mælarnir færðir til Akureyrar og Víkur. Eftir þetta fjölgar mælum hægt næstu tvo áratugi. Mikil fjölgun varð á áttunda áratugnum í kjölfar tækniframfara. Þá var hannaður skjálftamælir á Raunvísindastofnun sem hentaði til mælinga víða um land og í umsjá heimamanna (myndir 2–4). Fjöldi slíkra mæla var smíðaður og um 1980–1985 voru skjálftamælistöðvar á landinu orðnar um og yfir 40 (5. mynd, tafla 1). Þessir mælar skrifuðu gögn sín á síritatromlur, með penna á pappír, eitt skjálftarit á sólarhring. Framfarir í tölvutækni leiddu af sér nýja kynslóð mæla sem skráðu stafræn gögn sem hægt er að vinna úr að talsverðu leyti í tölvu. Uppbygging stafræns skjálftamælakerfis hófst um 1990 og leysti smám saman gömlu papírsskrifarana af hólmi. Síðasti pappírsskrifarinn var tekin úr notkun 2010. Skjálftaritasafnið sem varð til á tímabilinu 1909–2010 er þýðingarmikil frumheimild um skjálftavirkni í landinu í heila öld og ómetanlegt við rannsóknir á skjálftavirkni, eldvirkni og innri gerð jarðarinnar. Jarðskjálftafræðing-

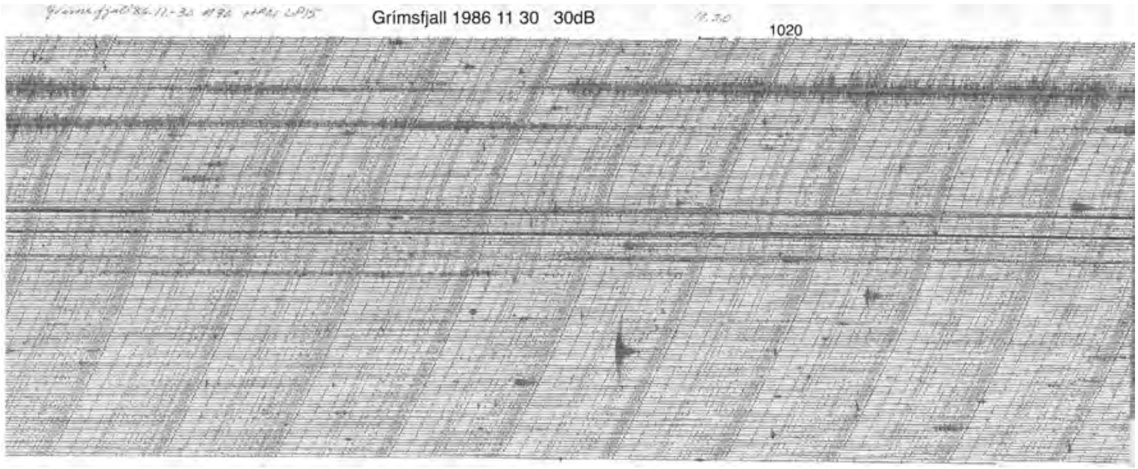

Figure 8. Seismogram from the seismograph at Grímsfjall, the caldera rim of Grímsvötn volcano, on November 30, 1986, showing two bursts of continuous tremor following a jökulhlaup from the eastern Skaftá cauldron at a distance of 15 km. The recording starts at the 10:20 time mark. – *Skjálftarit frá skjálftamælinum á Grímsfjalli, á öskjubarmi Grímsvatna, 30. nóvember 1986. Fyrsta tímamerkið er kl. 10:20. Á ritinu má sjá tvær óróahviður sem komu í kjölfar Skaftárhlaups úr Eystri Skaftárkatlinum, um 15 km norðvestan Grímsvatna. Enn eru skiptar skoðanir á því hvað veldur slíkum óróahviðum eftir að allt vatn er farið úr Skaftárkötlunum. Er það hrun íssins í sigkatlinum, hvellsuða í jarðhitakerfinu undir katlinum, eða hugsanlega lítið eldgos við botn jökulsins?*

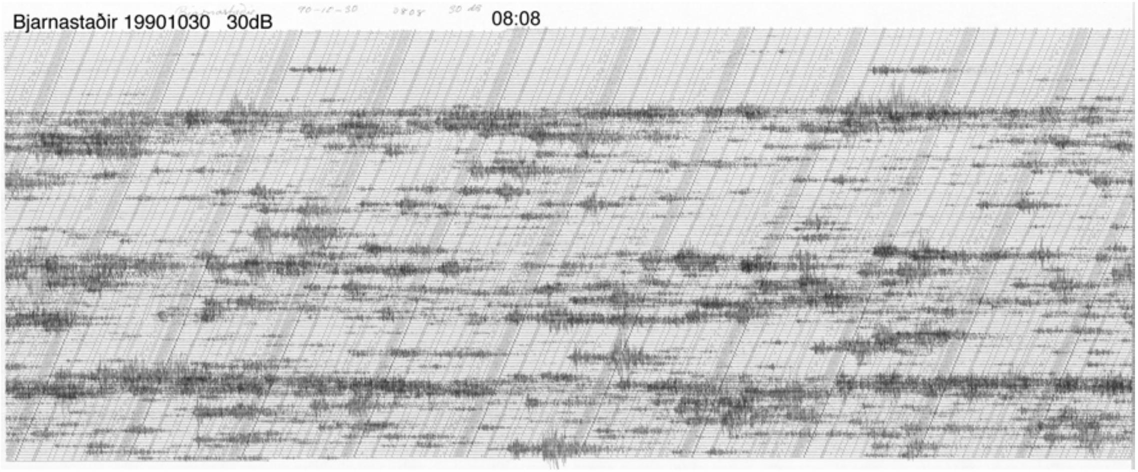

Figure 9. Seismogram from the seismograph at Bjarnastaðir in SW-Iceland, showing the beginning of a large earthquake swarm originating on the Reykjanes Ridge on October 30 1990. The record starts at time mark 08:08. – *Skjálftarit frá mæli á Bjarnastöðum í Ölfusi, 10. október 1990. Fyrsta tímamerkið er kl. 08:08. Sjá má stóra skjálftahrinu sem á upptök á flekaskilunum á Reykjaneshrygg suðvestan Íslands, við 63°N. Fjarlægð frá Bjarnastöðum var um 180 km. Hundruð skjálfta komu fram á mælum og a.m.k. 14 af þeim voru af stærðinni 4 eða stærri.*

ar um allan heim hafa verið að vakna til vitundar um að víða liggja slík gagnasöfn undir skemmdum. Því er víða hafið átak til að tryggja varðveislu gagnanna með því að skanna skjálftaritin og gera þau aðgengileg í tölvukerfum. Fjögurra ára verkefni í þessu skyni hófst hér á landi 2017. Um 175 000 skjálftarit hafa þegar verið skönnuð og vefsíða opnuð til að gera þau aðgengileg hverjum sem áhuga hefur. Veffangið er seismis.hi.is. Skjálftaritin eru skönnuð með upplausn 300 dpi og birt á vefsíðunni sem jpg- og png-skrár. Hvert skjálftarit er 4–8 Mb að stærð. Ekki hefur verið reynt að breyta skjálftaritunum í stafræn skjálftarit sem sýna bylgjuformin. Flest skjálftaritin eru úr hátíðnimælum með litla tímaupplausn þar sem upphaflegu bylgjuformin eru illa varðveitt. Á skjálftaritunum má sjá margs konar bylgjur, bæði frá fjarlægum, stórum skjálftum, og nálægum skjálftum. P-bylgjur frá fjarlægum skjálftum gefa upplýsingar um gerð dýpri laga jarðarinnar undir Íslandi, t.d. möttulstrókinn fræga sem fóðrar eldstöðvar íslenska heita reitsins. Nálægir skjálftar gefa upplýsingar um virkni í jarðskorpunni, flekahreyfingar, ferðir kviku um skorpuna, aðdraganda eldgosa (7. mynd) og fleira áhugavert. Á tímabilinu sem skjálftamælingarnar ná til urðu til dæmis eldgos í Heklu 1947, 1970, 1980–81, 1991 og 2000, Surtsey 1963–1967, Heimaey 1973, Öskju 1961, Grímsvötnum 1934, 1983, 1998 og 2004, og Gjálp 1996. Þá má nefna umbrotin við Kröflu 1975–1984, þráláta skjálftavirkni við Bárðarbungu og Kötlu, fjölda óstaðfestra gosa eða kvikuatburða undir jöklum (8. mynd), jarðskjálftahrinur á Reykjaneshrygg (9. mynd), á Reykjanesskaga og á Tjörnesbrotabeltinu, og aðrar skjálftarunur á skjálftabeltum Suðurlands og Norðurlands, sem og aðliggjandi hryggjarstykkjum Atlantshafshryggjarins.

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