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Geophysical constraints on the formation of the volcanic island of Surtsey in 1963-1967 and its internal structure

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Geophysical constraints on the formation of the volcanic island of Surtsey in 1963-1967 and its internal structure

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Dissertation submitted in partial fulfillment of a
Philosophiae Doctor degree in geophysics

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Abstract

The volcanic island of Surtsey, off the south coast of Iceland, was formed by shallow ocean-emergent basaltic volcanism in 1963-1967. There were several episodes of activity, migrating between five vents (Surtur, Surtla, Surtungur, Syrtlingur and Jólnir) to form a discontinuous ~5.8 km-long mostly submarine ridge.

Analysis of data from the rudimentary analog seismic network existing in Iceland in the 1960s reveals that the magnitude of completeness for the Surtsey area was M_L=2.5. Precursory seismicity (ML<3) is detected for nine days before onset of continuous tremor on 12 November 1963, signaling the onset of a 40-hour long submarine eruption, followed by subaerial explosive activity. Earthquakes during the eruption were mostly related to intrusive activity preceding opening of new vents. A complicated connection emerges between seismic tremor and magma flow rate or style of activity. The highest magma flow rates in the first 10–20 days were associated with relatively low tremor; higher tremor was observed in the weeks that followed, after discharge rate had dropped substantially. No correlation is found between minutes-to-hours variations in explosive activity and tremor.

A detailed aeromagnetic survey was conducted in 2021. Spectral analysis, Euler deconvolution and 2.5D forward modeling of selected profiles reveal shallow origin of magnetic anomalies in the area. The subaerial lavas on Surtsey cause the strongest anomalies, while other sources are mostly 0-300 m below seafloor. No indications of significant intrusions are found within and below the structures formed in 1963-1967, confirming that magma fragmentation was dominant in the submarine phases of the Surtsey eruption

Útdráttur

Surtsey myndaðist í eldgosi undan suðurströnd Íslands á árunum 1963-1967. Gosvirkni færðist til nokkrum sinnum og alls gaus á fimm stöðum, í Surti, Surtlu, Surtungi, Syrtlingi og Jólni. Myndanirnar eru samtals um 5.8 km á lengd, mynda breiðan en slitróttan hrygg, að stórum hluta neðansjávar.

Greining gagna úr því frumstæða skjálftamælakerfi sem til var á Íslandi á þessum tíma sýnir að neðri greiningarmörk jarðskjálfta voru M_L=2,5 fyrir Surtsey. Hrina skjálfta <3 varð síðustu níu dagana fyrir gosið, í nóvember 1963. Stöðugur lágtíðniórói hófst upp úr hádegi 12. nóvember og er hann talinn marka upphaf Surtseyjargossins, 40 tímum áður en gosið sást á yfirborði að morgni 14. nóvember. Jarðskjálftar við Surtsey meðan á gosinu stóð voru að mestu tengdir innskotavirkni, dögum eða vikum áður en gosvirknin færðist til. Rannsókn á skjálftaóróa í Surtseyjargosinu sýnir að samband hans við gosvirkni og kvikuflæði var ekki einfalt. Órói var tiltölulega lítill fyrstu 10-20 dagana þegar kvikuflæði var mest. Óróinn var í hámarki vikurnar þar á eftir, þegar verulega hafði degið úr kvikuflæði. Engin fylgni finnst milli sprengivirkni og óróa á skemmri tímaskala (mínútur-klukkustundir).

Flugsegulmælingar í þéttu mælineti voru gerðar 2021. Tvívíð tíðnigreining, Euler-afföldun og líkön af völdum segulfrávikum sýnir að upptök þeirra liggja að langmestu leyti í efstu 300 metrum jarðskorpunnar. Hraunin á suðurhluta Surtseyjar orsaka stærstu frávikin. Engin merki sjást um að bólstraberg hafi myndast í upphafi goss á neinum gosstaðanna. Ekki sjást heldur merki um að umtalsvert magn innskota sé í eða undir túffmyndunum frá 1963-1967. Þessar niðurstöður staðfesta að tvístrun kviku var ráðandi í upphafsfasa gosvirkninnar á sjávarbotni.

Dedicated to My dear Father

Table of Contents

List of Figures ..... *x*

List of Publications ..... *xi*

Acknowledgements ..... *xii*

1 Introduction *1*

1.1 Research aims 4

2 Background *5*

2.1 Surtsey and its growth 5

2.2 Hypotheses on the structure of Surtsey 6

2.3 The SUSTAIN drilling of 2017 7

3 Methods *9*

3.1 Seismology 9

3.2 Airborne magnetic survey 14

4 Paper I: Seismic activity associated with the 1963-1967 Surtsey eruption off the coast of South Iceland *22*

4.1 Summary 22

4.2 Main results 22

5 Paper II: Volcanic tremor associated with the Surtsey eruption of 1963–1967 ..... *24*

5.1 Summary 24

5.2 Main results 24

6 Paper III: Internal structure of the volcanic island of Surtsey and its surroundings, constraints from a dense aeromagnetic survey *27*

6.1 Summary 27

6.2 Main results 27

7 Concluding remarks *30*

References *31*

Paper I *35*

Paper II *62*

Paper III *48*

Appendices *77*

List of Figures

Figure 1. a) The Vestmannaeyjar archipelago off the south coast of Iceland with Surtsey on its southwestern end. b). Map of Surtsey and its surroundings, with the five fissures active during 1963-1967 (Surtur, Surtungur, Surtla, Syrtlingur and Jólnir). 3

Figure 2. The course of events during the Surtsey eruptions in 1963– 1967. a) Onset of the eruption – explosive eruption of Surtur crater, November 1963-January 1964. b) Submarine eruption-Surtla,, December 1963–January 1964. c) Formation of the parasitic cone of Surtungur, January–April 1964 (aerial photo). d) Lava effusion from Surtungur, April–July 1964. e) The temporary island of Syrtlingur, May–October 1965. f) the temporary island of Jólnir, December1965–August 1966. g) Section through the Jólnir–Surtsey–Syrtlingur– Surtla, a 5-km-long discontinuous fissure with the present bathymetry and topography and the approximate outline at the height of activity at each locality (based on data in (Thorarinsson 1966, 1967b, a) and Jakobsson et al. 2009). A perpendicular section through the island of Surtsey is also shown. (Sayyadi et al. 2021). 6

Figure 3. Schematic cross section of Surtsey, showing location of the drillholes from 1979 (SE01) and 2017 (SE02b and SE03), and the main geological units found in the cores, and including different possible minimum and maximum size of the diatreme under the crater Surtur. Constraint on minimum sediment thickness after(Thors and Jakobsson 1982) .Figure 5 in Jackson et al. (2019), https://sd.copernicus.org/articles/25/35/2019/. 8

Figure 4. Distribution of earthquakes during 3.5 years of eruptions. 12

Figure 5. Buildup rate versus tremor intensity for the first 150 days of eruption. a) buildup rate for the first 150 days (Thorarinsson et al. 1964; Ólafsson 2020). b) Tremor intensity for the first 150 days. c) Total duration of visible tremor per day (Fig. 7 in Sayyadi et al. 2022). 14

Figure 6. The aeromagnetic survey lines over Surtsey and the southwesternmost part of the Vestmannaeyjar archipelago. The bathymetry is from the survey of 2007 (Figure 1a and 2 in manuscript 3). 17

Figure 7. Magnetic map from the Helicopter survey in 1965 (based on Sigurgeirsson 1968). The outlines of Surtsey and its submarine outlines, including satellite vents, are indicated (Figure 7b from manuscript 3). 18

Figure 8. Example of Radial average spectrum analysis with explanation of result (Geoosft 2015). 19

Figure 9. Distribution of remanent magnetization in samples of lava from Surtsey.(Figure 3 from manuscript 3) 21

Figure 10. Earthquake activity recorded in association with Surtsey 1963-1967. The central panel shows the complete timeline (1963-1967) while the top panel displays the period end-of-October 1963- May 1964. The bottom panel shows respectively: the onset of the Syrtlingur episodes in May 1964(left); the end of Syrtlingur and start of Jolnir in Octobore-December 1965(center);the end of Jolnir and start of the final effusive phase of the Surtur in June-August 1966(right). 23

Figure 11. Types of observed tremor. a) Harmonic low frequency tremor at REY station. B) Harmonic high frequency volcanic tremor at REY station. C) Spasmodic tremor at SID station. D) Burst of mixture of harmonic high frequency with spasmodic tremor at SID station. 25

Figure 12. Timeline of earthquakes and tremor signals during the 3.5 years of eruptions. The colored areas mark periods where the tremor of the type indicated occurred. Within each period, episodes of tremor alternated with intervals of no visible seismic activity. 26

Figure 13. Total field magnetic map obtained in 2021. The outlines of Surtsey at different times and the main geological features in the area are indicated. (Figure 4 from manuscript 3) 28

List of Publications

Article 1: Sayyadi, S., Einarsson, P., Gudmundsson, M.T., 2021. Seismic activity associated with the 1963–1967 Surtsey eruption off the coast of South Iceland. *Bull. Volcanol.* **83**,54. https://doi.org/10.1007/s00445-021-01481-0

Article 2: Sayyadi, S., Gudmundsson, MT, Einarsson, P., 2022. Volcanic tremor associated with the Surtsey eruption of 1963–1967, *Jökull*, 72, 21-34. https://doi.org/10.33799/jokull2021.72.021

Article 3**:** Sayyadi, S., Gudmundsson, M.T., White, J.D.L., Jónsson, T., Brown, M.C., Jackson, M.D. Internal structure of the volcanic island of Surtsey and surroundings, constraints from a dense aeromagnetic survey - to be submitted to the Journal of Volcanology and Geothermal Research.

Contribution of the author

Article 1: SS was in charge of acquisition of the old data sets (seismic catalogs from Icelandic Meteorological Office), data sorting, analyzing. PE and MTG took part in the interpretation. S.S drafted the manuscript with input from PE and MTG, who also contributed to revising and answering the reviewer's comments.

Article 2: SS did the analysis of the seismic records and resorting the tremor record. MTG performed the analysis of the eruption rate data. SS prepared the figures and drafting of the manuscript. MTG were involved in planning and supervised the work. PE provided critical feedback and helped shape the research, analysis and manuscript and aided in interpreting the results and worked on the manuscript.

Article 3: SS, was responsible for survey and data processing and analysis and performed the numerical computations. SS drafted the manuscript and designed the figures. TJ designed and built the magnetometer bracket for the aircraft and prepared the survey. MCB measured the magnetization of the samples used. JDHW and MDJ contributed to the geological interpretation and discussion. MTG was the leader and supervisor of the project and contributed to the design and implementation of the survey set up and contributed critically through discussion, and revision of the early drafts of the manuscript.

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The multi-disciplinary SUSTAIN project centered around the drilling of three new drill holes 153-354 m long, in Surtsey during August and September 2017. The drill cores, prove that the structure of Surtsey is that of a tuff cone with an underlying diatreme, with the deeper structure having some of the characteristics of a maar volcano.

The PhD project continued through partial funding from the Volcanic hazard (GOSVÁ) Project: Aðferðir við mat á gostíðni í sjó (methods to estimate eruption frequency in oceanic areas).

1 Introduction

Shallow ocean/emergent phreatomagmatic volcanism can involve the eruption of large volumes of basaltic lava. It usually involves fissure eruptions and if it proceeds to effusive, subaerial volcanism, it may create lava deltas, sometimes fed by lava tubes. Vent interaction with external water usually governs the explosivity of these eruptions (Houghton et al. 2015).

The formation of the oceanic island of Surtsey (Fig.1) in a 3.5-year-long eruption (1963–1967) is one of the best examples of basaltic shallow submarine to emergent volcanism to date. Importantly, the eruption was very well monitored and documented (e.g., Thorarinsson et al. 1964; Thorarinsson 1965, 1966, 1967a, b, 1968a,b; Sigtryggsson and Sigurdsson 1966). The term Surtseyjan activity derives from this eruption. On November 14, 1963, explosive hydro-magmatic volcanic activity was observed where ocean depth prior to the eruption was 130 m (Thorarinsson 1968b), in the shallow ocean on the southeastern end of the Vestmannaeyjar archipelago. The first traces of what became the island of Surtsey appeared the following day. Several episodes of the eruption followed over the next 3.5 years. Apart from repeated activity on Surtsey itself (1963, 1964-65, 1966-67), this included the subtle submarine eruption at Surtla Ridge, 2.5 km ENE of Surtsey (1963/64), and the formation of two short-lived islands, Syrtlingur (1965) and Jólnir (1966), which appeared respectively on the NE and SW sides of Surtsey island. Surtla never advanced to become subaerial and the two islands of Syrtlingur and Jólnir were eroded by the ocean in a matter of weeks after activity stopped. The location of vents and the timeline of activity are summarized in Fig. 2.

Surtsey is the remaining subaerial volcanic island, having been reduced in area from 2.66 km^2 in 1967 to 1.25 km^2 in 2019 (Óskarsson et al. 2020). The remnants of Surtla, Syrtlingur, and Jólnir had been eroded to a depth of 35-50 m by 2007 (Jakobsson et al. 2009). Combined, these formations created a predominantly submarine ridge trending ESE with length of approximately 5.8 km (Fig. 1).

In 2008, the inscription of Surtsey as a UNESCO World Heritage confirmed its value and unique setting, offering the opportunity to study the birth of new life using a variety of different scientific views (Baldursson and Ingadóttir 2007).

Surtsey is an island with two tuff cones, the first, Surtur, formed in November 1963-January 1964, and the second, Surtungur, in February-April 1964 (Fig. 1), rising approximately 150 m above sea level. The southern part of the island is a subaerial lava, mostly built on a lava delta, formed in effusive activity in 1964-1965 and 1966-1967. The submarine structure of Surtsey and its satellite formations (Surtla, Syrtlingur, Jólnir) has been a matter of debate (e.g., Thorarinsson 1968b; Jakobsson and Moore, 1982; Jakobsson et al, 2009; Moore 1985; Jackson et al. 2015). Application of geophysical surveying and analysis by modeling is a method that can be used to study the structure of volcanoes and their roots. Gravity modeling of Surtsey was presented by Cameron et al. (1992) and Thorsteinsson and Gudmundsson (1999). The gravity models indicate that the submarine part of Surtsey is predominantly made of hyaloclastite and that no significant volumes of pillow lava are present. No such models exist for the remnants of the satellite islands of Surtla, Syrtlingur and Jólnir; and no studies where magnetic modeling has been applied exist for any of these formations.

A major new chapter in the history of research on Surtsey took place in August-September 2017, with the drilling of three new holes and the extraction of over 600 m of core (Jackson et al. 2019; Weisenberger et al. 2019). This project, SUSTAIN, was funded by ICDP with

contributions from IceSUSTAIN, a Grant of Excellence from the Icelandic Research Fund and several other bodies.

The main body of work in this thesis was firstly analyzing old seismic records and secondly acquisition, processing, and analysis of aeromagnetic data from Surtsey and its surroundings. This included using (1) the list of earthquakes, as published in the catalogues of the Icelandic Meteorological Office, and by (2) analyzing the old records (using seismis.hi.is) to define seismic tremor during the eruption. To study the internal structure, a detailed aeromagnetic survey took place in October 2021. Analysis of the aeromagnetic data has involved a study of the depth to magnetic sources, considered to be crystalline basalts (subaerial lavas, pillow lava, dykes and other intrusive bodies), formed on top of and possibly within what is assumed to be predominantly several hundred meters of oceanic sediment beneath the Vestmannaeyjar volcanics (e.g., Tómasson 1967).

The results of this project are presented in three papers:

Paper I **Sayyadi, S,** Einarsson, P, Gudmundsson, MT. Seismic activity associated with the 1963–1967 Surtsey eruption off the South coast of Iceland – Published in Bulletin of Volcanology in July 2021. https://doi.org/10.1007/s00445-021-01481-0

Paper II **Sayyadi, S,** Gudmundsson, MT, Einarsson, P. Volcanic tremor associated with the Surtsey eruption of 1963–1967 – Published in Jökull, 72, Oct 2022. https://doi.org/10.33799/jokull2021.72.021

Paper III **Sayyadi, S,** Gudmundsson, MT, White, JDH, Jónsson, T., Brown, C, Jackson, MD. Internal structure of the volcanic island of Surtsey and surroundings, constraints from a dense aeromagnetic survey - to be submitted to the Journal of Volcanology and Geothermal Research.

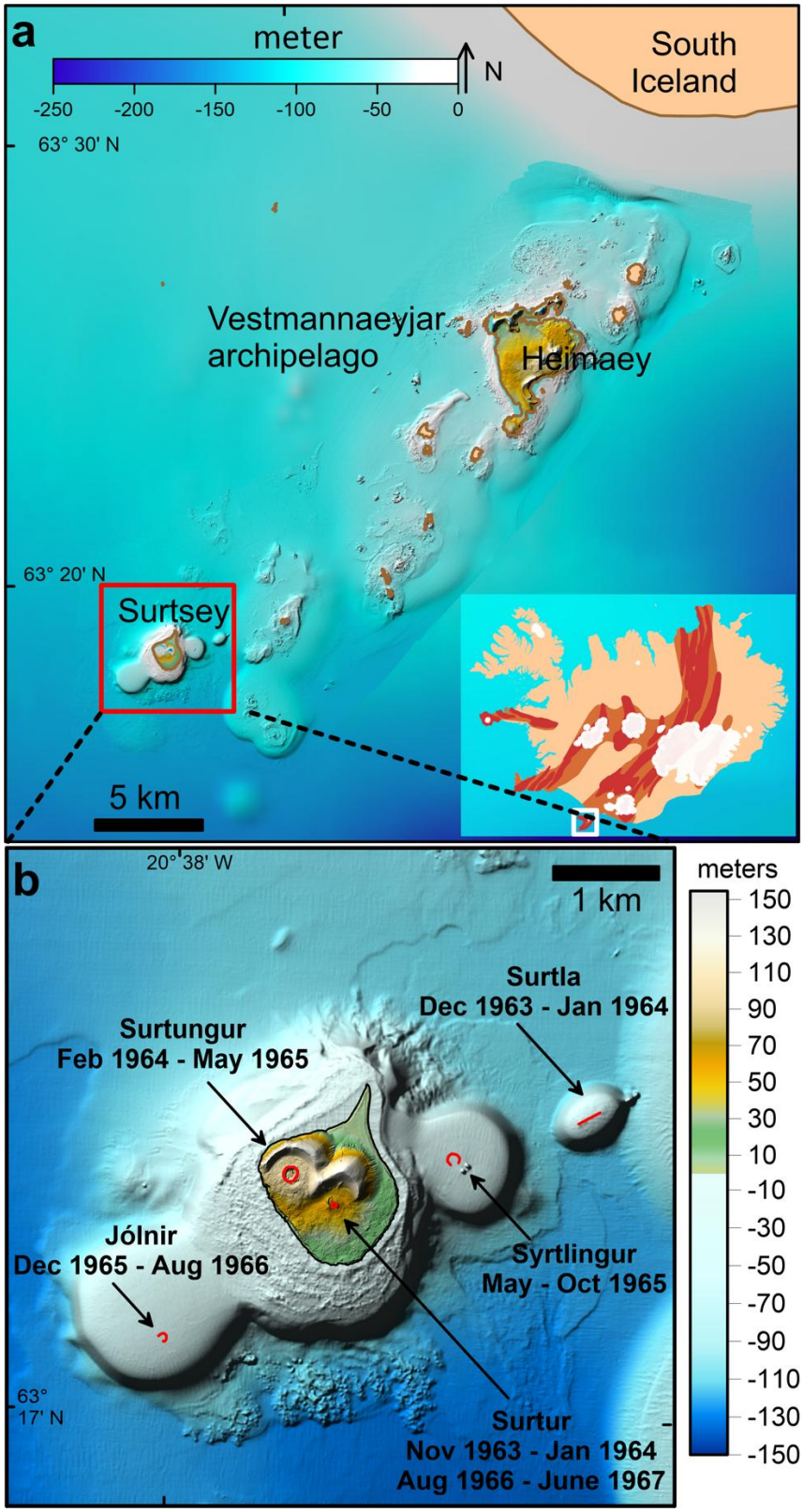

Figure 1. a) The Vestmannaeyjar archipelago off the south coast of Iceland with Surtsey on its southwestern end. b). Map of Surtsey and its surroundings, with the five fissures active during 1963-1967 (Surtur, Surtungur, Surtla, Syrtlingur and Jólnir).

1.1 Research aims

Despite detailed reports of the evolution of the island from first days of the eruption, there are still questions on the subaerial and submarine structures making up the island as well as the beginning of the submarine eruption in the seafloor.

This study focuses on further understanding of subglacial to emergent basaltic volcanism for the type locality of Surtseyan volcanism through applying present-day methods to the study of Surtsey. The purpose is to clarify the eruption mechanisms, study the substructure of the formations created during 1963-1967 and enhance the view of the time-lapse changes from birth to the current state of the island, which is probably the best-known example of a submarine-to emergent volcano in a rift zone setting. For this overarching aim, old analog seismic data are used to link with the timeline of eruption and very high resolution airborne magnetic data was used for exploring the evidence for any intrusions or subvolcanic structures. The principal aims of this PhD project were therefore set as:

1. To refine the history/chronology of the early part of the Surtsey eruption, including defining the onset of submarine eruptive phases, but especially the submarine beginning of the eruption in November 1963. This is addressed through analysis of existing seismic records.

2. To study how variations and trends in the eruption rates throughout the Surtsey eruptions related with seismic tremor recorded by the contemporary Icelandic seismic network.

3. Explore the internal structure of the edifices formed in the eruption area during 1963-1967, in particular looking at indications of shallow intrusions or possible pillow lava formations within and below them, through the analysis of dense aeromagnetic data.

2 Background

2.1 Surtsey and its growth

Surtsey is the remaining subaerial part of the volcanic formations created in 1963-1967. Surtsey, along with remnants of the submarine formation of Surtla, and the temporary islands of Syrtlingur and Jólnir, form what is today to a large extent a broad submarine ridge, approximately 5.8 km long, trending ENE-WSW. Cycles of events over 3.5 years resulted in several different episodes or sub-events. The main sub-events of activity were (see also Fig. 2):

(1) Explosve eruption at Surtur (formerly Surtur I) in November 1963-January 1964;
(2) Surtla, a submarine formation created over several days in December 1963-January 1964;
(3) Surtungur (formerly Surtur II), a parasitic vent to the west of Surtur in February-April 1964. Explosive eruption.
(4) Surtungur turned effusive in April 1964, with eruption ongoing until May 1965.
(5) Syrtlingur. Explosive eruption in the ocean to the NE of Surtur, in May-October 1965, forming a temporary island.
(6) Jólnir. Explosive eruption to the southwest of Surtsey, December 1965 to August 1966.
(7) Effusive eruption at Surtur. This was the final episode, from August 1966 to June 1967. Minor fissures opened on rims of the Surtur tuff cone in December 1966-January 1967 forming minute lava flows.

While the island had attained a surface area of ~22.7 km^2 at the end of the eruption period (Thorarinsson 1968b), coastal erosion, amplified by the harsh weather conditions and wave action in the North Atlantic is still happening on the island and its area has been reduced to less than half its original size. The shape of the island has also been subject to extensive changes since its first emergence. It first emerged as a short ridge, but soon became elliptical in shape, split along its long axis with the volcanic fissure.

The share of tephra/fragmented material in the total volume erupted was much higher than the share of erupted lava. Explosive submarine eruption during November 1963 until January 1964 led to the formation of tephra cones, first on what is now the eastern part and in February-April 1964 on the western side of the island; these are the tuff cones of Surtur and Surtungur.

As outlined above, effusive eruptions happened during different episodes from April 1964 until June 1967. These episodes combined caused the formation of the lava field, 30-100 m thick, which covers the south and the east of the island.

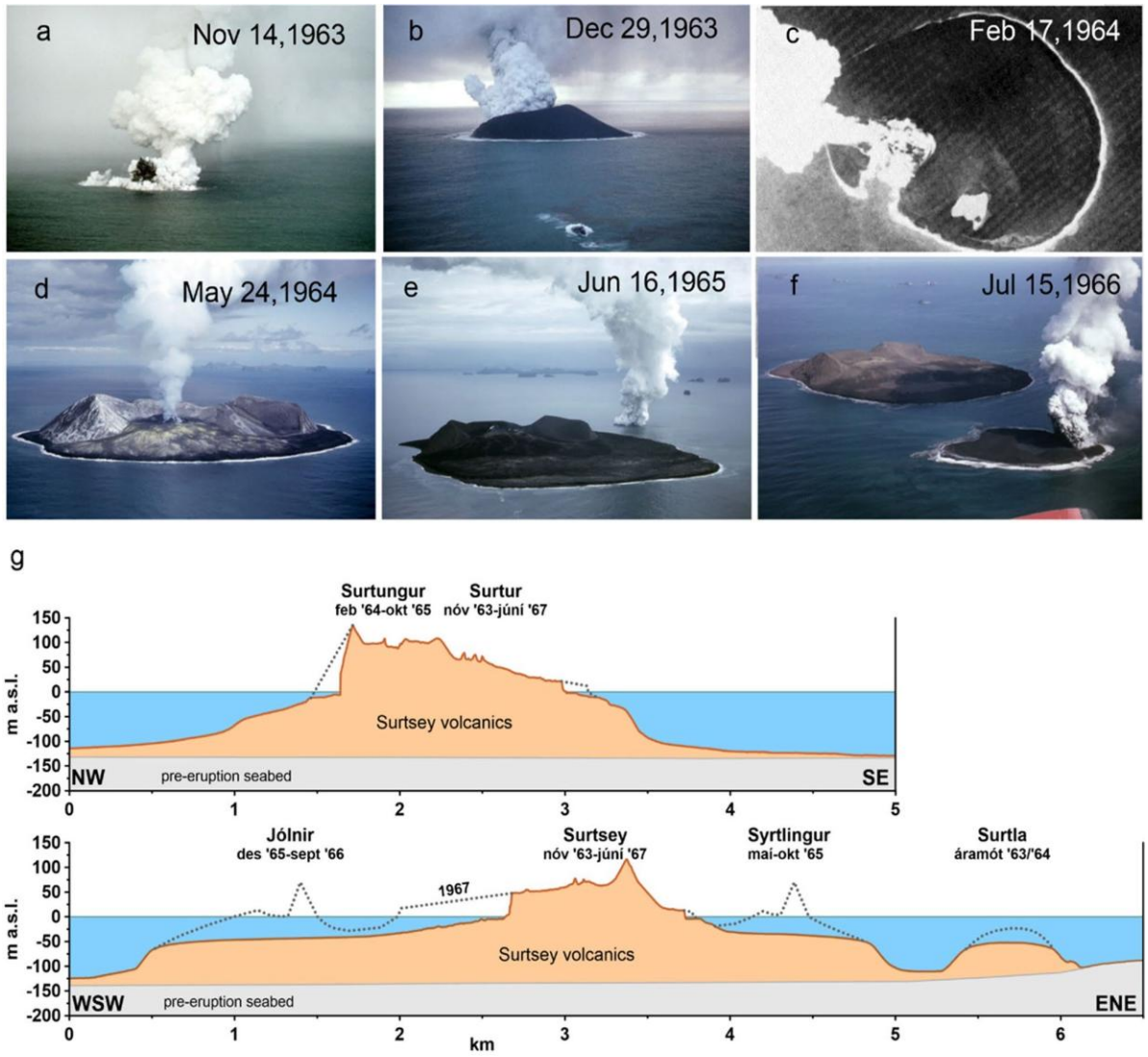

Figure 2. The course of events during the Surtsey eruptions in 1963– 1967. a) Onset of the eruption – explosive eruption of Surtur crater, November 1963-January 1964. b) Submarine eruption-Surtla,, December 1963–January 1964. c) Formation of the parasitic cone of Surtungur, January–April 1964 (aerial photo). d) Lava effusion from Surtungur, April–July 1964. e) The temporary island of Syrtlingur, May–October 1965. f) the temporary island of Jólnir, December1965–August 1966. g) Section through the Jólnir–Surtsey–Syrtlingur–Surtla, a 5-km-long discontinuous fissure with the present bathymetry and topography and the approximate outline at the height of activity at each locality (based on data in (Thorarinsson 1966, 1967a,b) *and* Jakobsson et al. 2009). *A perpendicular section through the island of Surtsey is also shown.* (Sayyadi et al. 2021).

2.2 Hypotheses on the structure of Surtsey

The first hypothesis about structure of the island of Surtsey was the assumption that it was fully built on the pre-eruption seafloor, and did not include a diatreme as a significant part of the structure (e.g. Thorarinsson, 1968a; see also Jackson et al. 2015). Instead, a narrow

conduit is implicit in the model proposed. Apparently, the issue of the conduit and possible excavation of the pre-eruption seafloor was not considered. An issue that people were much more concerned with at this time was whether a mound of pillow lavas had formed at the start of the submarine eruption or later during the eruption. As a result, in Thorarinsson's (1968a) model, the pre-eruption seafloor is seen as relatively intact underneath the volcanic edifice.

Exploratory drilling in Surtsey, on the eastern rim of the explosive Surtur crater (formed during November 1963 – January 1964) took place from June 29 to August 22, 1979, by the Icelandic State Drilling Contractors (Jakobsson and Moore 1982; Moore 1985). A depth of 180.6 m was reached, about 122 m below sea level. The dominant lithology found in the drill hole was basaltic tuff. Analysis of the core revealed that sub-sea-level tuff and the tuff forming the subaerial tuff cones on the island are similar. Also, the lapilli tuff morphology indicated abundant accretionary lapilli and together with the vesicular character of the tuff has been taken to indicate that it was all deposited by subaerial activity (Moore 1985). Importantly, the drilling in Surtsey in 1979 changed the views on substructure of the volcanic island, as no evidence of a pillow mound was found (Jakobsson and Moore 1982).

Another hypothesis was presented in 1985, on the existence of wide funnel-shaped, tephra filled diatreme that extended a few hundred meters into the pre-eruption seafloor (Moore 1985). By considering basaltic tephra recovered from the borehole, Moore (1985) suggested that the long-lasting continuous-uprush explosion style provides a mechanism to quarry a diatreme downward to great depth and simultaneously keep it open to the surface. It was proposed that this downward quarrying was a possible mechanism for the formation of diatremes in some settings. However, as the 1979 drill hole only cored one side of the tephra ring, more information was needed to discriminate between alternative models on the existence of a diatreme.

2.3 The SUSTAIN drilling of 2017

In order to determine the true structure and allow better constraints on eruptive processes, new holes were cored in July to September 2017. In addition to the questions on the early history of the island, various issues of a more general nature for shallow submarine volcanism have remained poorly known. This applies not least to existence of possible intrusive bodies within and below the volcanic formations and when such bodies may have formed. Information from new drillholes in Surtsey were expected to provide results that would also allow for comparison with studies elsewhere.

The SUSTAIN drilling project was supported by the International Continental Drilling Program (ICDP), the Icelandic Research Fund through the IceSUSTAIN project and through contributions from several others (see Jackson et al. 2019; Weisenberger T et al. 2019). Three holes were drilled, all initiated within 10 meters from the 1979 drillhole. The drillholes range in drilled length between 151 and 354 m (Fig. 3). Two of the holes were vertical and one angled. The angled hole intersected the feeder dyke of the 1966-67 effusive and final phase of activity on the island (Jackson et al. 2019; Weisenberger et al. 2022).The analysis of data from the SUSTAIN project is ongoing but has already provided various results on tuff alteration and palagonitization, hydrous geochemistry and rock geochemistry, stratification

revealed by the drill cores and microbiology (Jackson et al. 2019; Weisenberger et al. 2019; Kleine et al. 2020; McPhie et al. 2020; Prause et al. 2020; Bergsten et al. 2021). Lithologic investigations of the drillholes confirmed the existence of a diatreme under the Surtur crater, formed in the explosive phreatomagmatic eruption in 1963-1964 (Jackson et al. 2019).

The drilling data of the Surtsey tephra above and below sea level (Fig. 3) reveal that the structure of Surtsey is best characterized as that of a tuff cone with an underlying diatreme, with the overall structure having some of the characteristics of a maar volcano (White and Ross 2011). Maars are a special type of volcanic structure characterized by circular craters, often filled with water, and surrounded by a ring of pyroclastic deposits (Schulz et al. 2005) with the floor of the crater lying below the pre-eruption ground level. Several studies of maar volcanoes and their characteristics have been reported (Zimanowski 2000; Lorenz 2003, 2007) and the structure of maar-diatremes has been investigated in several cases using geophysical surveying, notably using potential field methods.

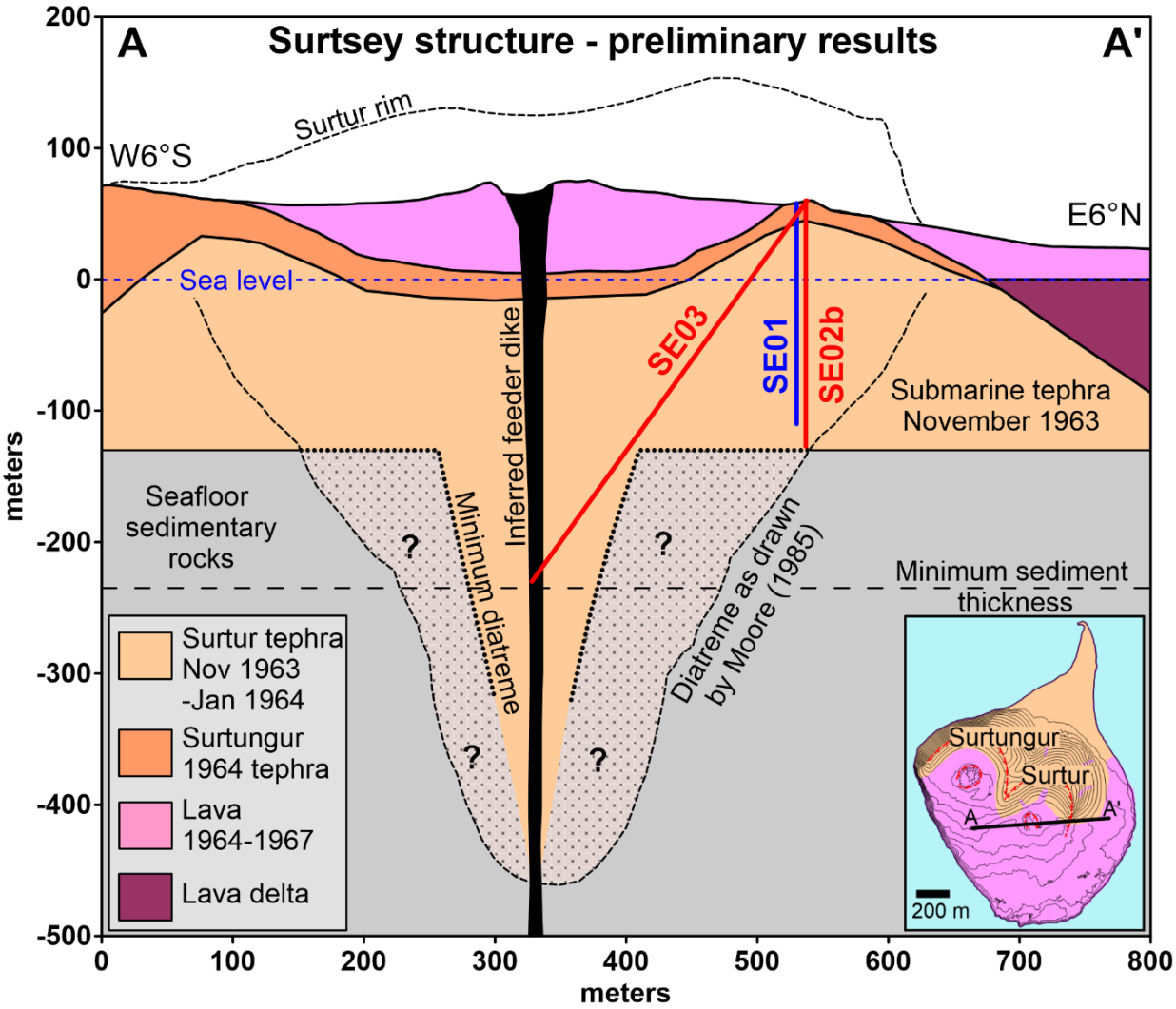

Figure 3. Schematic cross section of Surtsey, showing location of the drillholes from 1979 (SE01) and 2017 (SE02b and SE03), and the main geological units found in the cores, and including different possible minimum and maximum size of the diatreme under the crater Surtur. Constraint on minimum sediment thickness after (Thors and Jakobsson 1982) *.Figure 5 in* Jackson et al. (2019), *https://sd.copernicus.org/articles/25/35/2019/.*

3 Methods

3.1 Seismology

3.1.1 Volcanic seismology

In order to establish a baseline for the precursors associated with each of the main events during the 3.5 years of the Surtsey eruptions and characterize the seismic signals associated with Surtsey activities, a brief description of the special character of the seismic signal originating from volcanic activity, is presented in this section.

Investigation of seismic signals associated with volcanic activities began with the studies of Omori (1912) on Usu-san and Asama in Japan. A classification of volcanic seismicity was presented by Minakami (1974) who defined four different types of signals: (1) high-frequency (A-type) earthquakes, (2) low-frequency (B-type) earthquakes, (3) explosion-quakes or earthquakes followed by an explosive eruption, and (4) volcanic tremors or volcanic pulsations.

Volcanic earthquakes commonly occur in swarms that usually lack the mainshock-aftershock character of tectonic earthquakes (McNutt 1996) and are usually of considerably smaller magnitude. Low-frequency events are discrete signals having an amplitude envelope resembling those of normal earthquakes but spectral features resembling those of tremor (Chouet 1992).

Swarms of low-frequency earthquakes (B-type) are frequent and a brief overview of observations in Iceland is given by Brandsdóttir and Einarsson (1992). The mechanism often invoked to explain these earthquakes is that they are associated with fissures opening at the surface, or through oscillation of fluid-pressurization cracks, shearing and tensile failure, and by attenuation and path effects (Bean et al., 2014). Volcanic tremor has an irregular sinusoid appearance of sustained amplitude, at frequencies within a limited bandwidth, and of considerably longer duration than earthquakes with the same amplitude (Chouet 1992; McNutt 1992).

The driving mechanisms of tremor appear to be quite complicated, and at volcanoes tremors are often associated with interactions of magmatic fluids with the surrounding bedrock. Pressure oscillations during magma transport along a magma-filled fissure that is driven by a pressure gradient along the fissure are commonly invoked as a source mechanism of volcanic tremor (Aki and Koyanagi 1981; Fehler and Chouet 1982; Fehler 1983; Aki 1984; Koyanagi et al. 1987).

Harmonic tremors with dominant frequency of 1-10 Hz are often observed in eruptions before and during explosive phases. Their origin is related to stress variations when magma rises in the earth's crust. They arise during magma movement through conduits, dikes, etc., which produce rupture at the tip of the magma body (Zobin 2012) .

Low and regular tremors at dominant frequencies of 1-5 Hz, sometimes accompanied with low-frequency earthquakes, frequently happen during and before effusive activity. These are

considered to be produced by a phreatomagmatic process in the crater of a volcano and by the movement of lava and pyroclastic flows on its slopes, as well as rockfalls (Zobin 2012). Most tremor looks like an irregular sinusoid with frequencies between 1 and 5 Hz. In contrast, spasmodic tremor consists of pulses of high frequency, usually 5-10 Hz or higher, and has only been recorded in relatively few volcanic areas and no signals like these are known from non-volcanic regions (McNutt 1992).

Since the seismic part of this study is based on 1960s analog seismic data, distinguishing seismic events of volcanic origin and those of tectonic origin is an important problem to consider. Different origins and production processes of volcanic seismic activities from tectonic earthquakes result in different manifestations in seismic records. Distinctions can be recognizable on analog records, on the basis of differences in features such as magnitude, frequency and patterns of occurrence.

3.1.2 Volcanic earthquakes

Available data

Installing seismic stations in the vicinity of volcanoes along with permanent stations, provides better data than can be obtained at distant stations. This helps in characterizing the volcanic seismic signals. In Iceland, monitoring the volcanoes to evaluate possible precursor seismic signals has a long history. Continued observations of volcanic earthquakes by seismographs since 1973 showed that all of the 21 confirmed volcanic eruptions were accompanied by short term precursory seismic activity ranging in duration from of the order of one hour to several days (Einarsson 2018).

During the years 1963 to 1967, seismographs exist from the four permanent stations that were in operation in Iceland: Reykjavik (REY), Kirkjubæjarklaustur (SID), Vík í Myrdal (VIK) and Akureyri (AKU). The seismograph at Akureyri with 291 kilometers distance from Surtsey is not well located to record any seismic activity associated with the eruption. It was equipped with a low magnification Mainka seismic sensor until July 24, 1964, after that a WWNS substituted the old Mainka. During the years 1964 to 1966, some seismic activities were recorded at VIK station (also an old Mainka sensor), 80 kilometers away from Surtsey. However, the most important stations for our study are the REY and SID stations. At Reykjavik, two seismographs were operated, the Sprengether (N component) and a Wilmore sensor with a Z component. At Kirkjubæjarklaustur station, a vertical Wilmore instrument with a maximum magnification of about 16000 for a ground period of 0.1 to 0.7 seconds was in use.

Recently, analog seismic records of Reykjavik (REY) and Kirkjubæjarklaustur (SID) stations have been scanned with a resolution of 300 dpi, available on the website: http://seismis.hi.is/. Digitization of the seismic traces has not been attempted since most of the seismographs are from short-period instruments that do not reproduce well the waveforms. The passband of the

Sprengether (N component) is aproximately 1-6 hz and Wilmore with Z component seismograph in Reykjavik has approximately 1-5 hz passband while being 4-25 Hz for the vertical Wilmore seismograph in SID (Sayyadi et al. 2021).

Analysis of data

Data from the available old analog data (1963-1967) of the permanent seismic network that were in use at this time are considered to have information relevant to determining the initiation time of the first submarine eruption and provide timeline for each of the sub-events. In particular, the aim was to explore how and if the sub-events were associated with earthquakes, from before the onset of the visible eruption in Surtur in Nov 1963 until lava eruption on Surtsey ended on June 5, 1967. The temporal distribution of the earthquakes during the eruption is shown in Fig. 4.

In total 186 earthquakes with magnitudes between 2.1 and 4.3 associated with the Surtsey eruption were recorded in the seismological bulletins of the Icelandic Meteorological Office from this time. The activity mainly occurred as swarms of earthquakes preceding and during changes of vent location or type of eruption. By using the magnitude-frequency relation of Gutenburg Richter, the magnitude of completeness for earthquakes at Surtsey is estimated to have been M_L=2.5.

It is worth mentioning that, the magnitude (M_L) of earthquakes in this study is local magnitude reported in the seismological bulletins of the Icelandic Meteorological Office (Icelandic Meteorological Office 1964a, b, 1970, 1978, 1979a, b, 1980). The magnitude of earthquake of these bulletins are calculated from trace amplitudes and a local magnitude scale. Also, in (Tryggvason 1978) a detailed calibration of the local magnitude scale is described. The M_L scale is based of correlation of the maximum amplitude at the one-component stations in Iceland with the M_S (Surface wave magnitude) determination of the same events at stations in Northern Europe (Tryggvason 1978).

The seismic precursors to the initiation of the first submarine eruption are detected as several seismic events of magnitude M_L<3 during November 3-10, 1963. Continuous tremor started in the early afternoon of November 12, considered to mark the onset of submarine eruption, about 40 hours before the start of the visible subaerial eruption at 06:30 local time on November 14.

Seismologically, the beginning of the eruption was not accompanied with large earthquakes. Magma came to the surface without much seismic activity and then there was a prolonged eruption with mostly minor earthquake activity. The shifts in eruptive activity were accompanied with low frequency earthquakes.

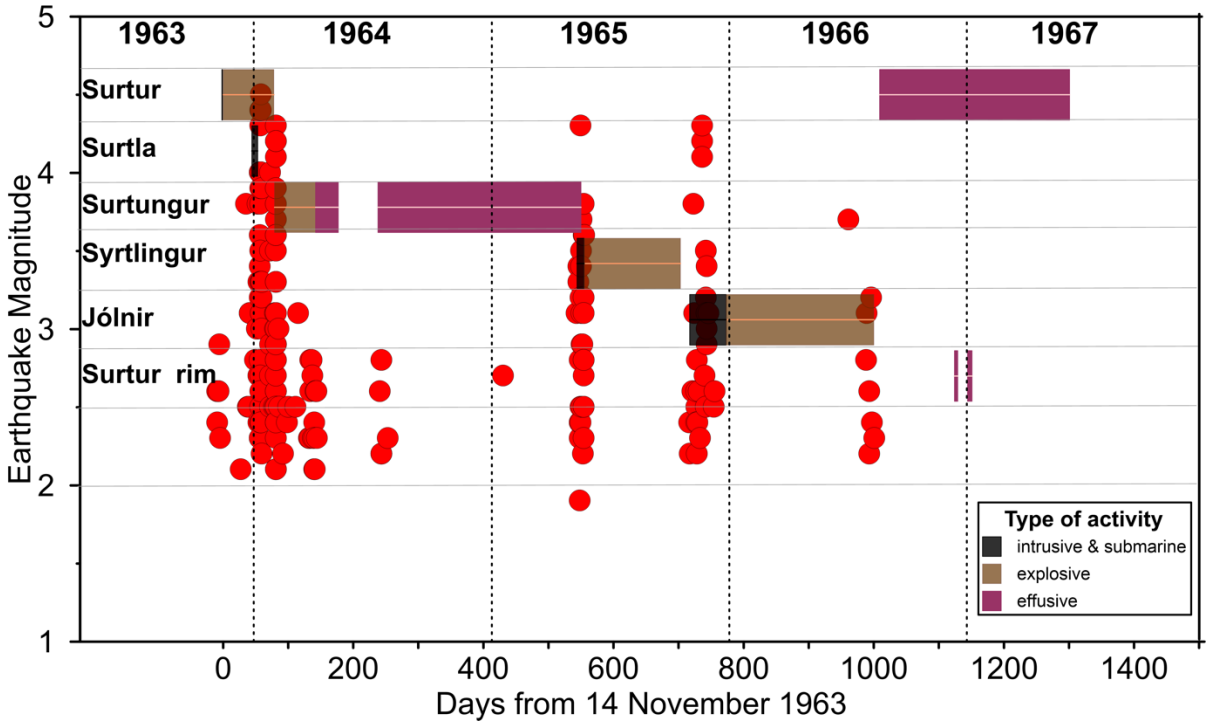

Figure 4. Distribution of earthquakes during 3.5 years of eruptions.

3.1.3 Volcanic tremors

Limitation of data

The available data are paper drum records from a few, distant analog seismic stations of very limited bandwidth and magnification, in no way comparable in quality to present-day digital records. This puts considerable limitations in what information can be obtained from these records.

The limitations imposed by the data imply that it is not possible to apply several of the present-day standard practices in volcano seismology. These include comparison of amplitudes between stations. Given the very limited bandwidth of the analog stations, subtle changes in e.g., dominant frequency of tremor may result in large differences in recorded amplitudes for a signal recorded at two stations where the true amplitudes may have been similar. Comparison of amplitudes between stations are therefore not attempted. For the same reasons, only a first order semi-qualitative estimate can be made of dominant frequencies of tremor.

Digitizing the traces is not feasible, as the time resolution of the drum records is of the order of 1-2 mm/s, possibly allowing wave reconstruction of a signal <2 Hz. In comparison, the signals detected from local earthquakes commonly have the highest amplitude waves at 10-30 Hz.

Eruption rate and tremor intensity

The available data make it possible to describe the overall characteristics of tremor activity and analyze a few well-constrained cases to explore the effects of the style of eruptive activity, notably continuous uprush, periods of cocktail explosions, and gaps in visible eruption during the main explosive phase in November-December 1963.

Eruption rate for several episodes of the eruption can be estimated based on volume of erupted products documented in contemporary descriptions (Thorarinsson et al. 1964; Thorarinsson 1966,1967a, b ,1968a). By using dry bulk density of hyaloclastite formed during explosive phases of 1500 kg/m^3 and for lava a density of 2500 kg/m^3, and a dense rock equivalent density (DRE) of 2700 kg/m^3, an estimate of the time-averaged discharge rate (TADR) is obtained from:

$$TADR = Volume \times \frac{product\ density}{2700 \times duration(seconds)} \quad (1)$$

During the first 150 days, significant amounts of tephra were dispersed outside of Surtsey, with the tephra fallout detected in many parts of South Iceland with estimates of volume of tephra dispersed being in the range 0.1-0.25 km^3 (Thorarinsson 1968b; Ólafsson 2020). The fallout mostly occurred in the first 20 days of the eruption (Thorarinsson et al. 1964) but the variations with time are not well constrained. As a result, TADR cannot be well constrained. However, the buildup rate of the island is an approximate substitute for the values for TADR after the initial 20 days. Fig. 5 shows the buildup rate for the first 150 days of eruption along with tremor intensity during this time. This graph demonstrates that the peak in tremor (December) does not correlate with the peak in magma discharge; the tremor is much weaker in the first 20 days than it was later. On time scales of several weeks to months, a broad correlation exists, with the strongest tremor occurring in the first months, when the eruption rate was higher than later in the eruption when tremor was lower.

The results indicate that magma flow rate is not the main driver of tremor intensity in the explosive eruption of Surtsey. Tremor amplitude and frequency of occurrence broadly correlate with the long-term intensity of activity (days-months) while it does not correlate with short-term variations (minutes-hours) in eruption style during the explosive phases of the eruptions.

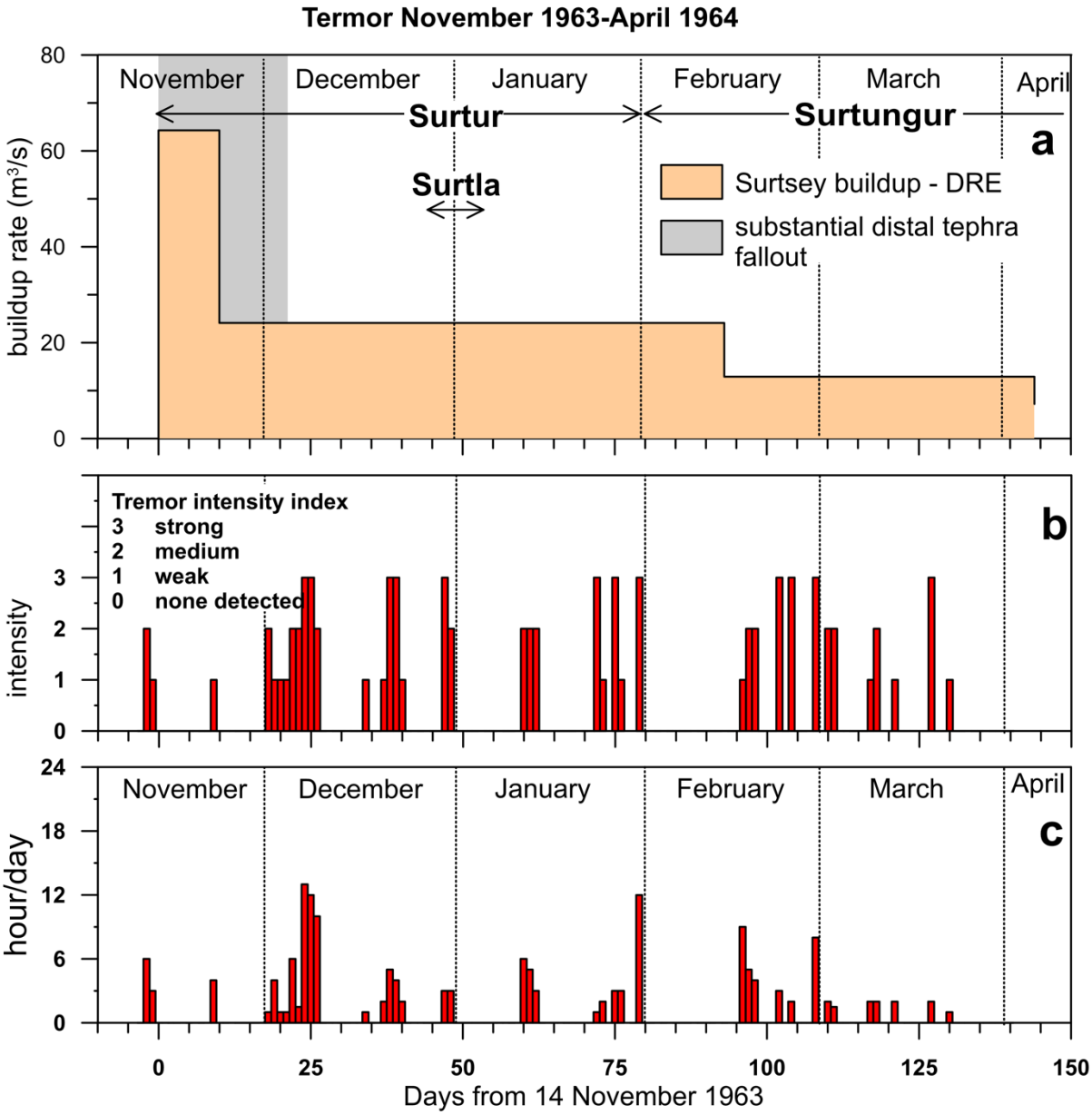

Figure 5. Buildup rate versus tremor intensity for the first 150 days of eruption. a) buildup rate for the first 150 days (Thorarinsson et al. 1964; Ólafsson 2020). *b) Tremor intensity for the first 150 days. c) Total duration of visible tremor per day (Fig. 7 in* Sayyadi et al. 2022).

3.2 Airborne magnetic survey

3.2.1 Surveying

The third paper and the last section of this PhD project is on the results of an aeromagnetic survey over the eruption area of 1963-1967 and its surroundings. A detailed aeromagnetic survey was carried out in October 2021, as a part of the volcanic hazard project GOSVÁ (Sub-project: Methods to define the frequency and magnitude of shallow ocean eruptions). The purpose of the project is to develop methods for estimating the frequency of eruptions in volcanic systems in the submarine setting and explore the potential of a high resolution

airborne magnetic survey for analyzing shallow-ocean volcanic formations in areas such as the Vestmannaeyjar archipelago. In short, the aim is to estimate the total number of remnants of submarine eruptions and use as a proxy for recurrence times of eruptions.

The survey area is shown in Fig. 6. The main aims of this study were to find information on:

- What is the magnetic signature associated with the different vents and edifices built during the 3.5-year-long Surstey eruption?
- Are there signs of pillow lava/magnetic intrusions on the sea floor and buried beneath it?

And more generally, exploring the following questions:

- Can aeromagnetic surveying be used to detect remnants of past eruptions in locations like the Vestmannaeyjar archipelago?
- Can magnetic surveying, through defining deposits of past eruptions, help in defining recurrence times of submarine eruptions?

Magnetometer and aircraft setup

High-quality magnetic data is obtained by the Geometrics MagArrow[1] drone magnetometer, using a laser-pumped cesium vapor sensor. The magnetometer was installed in an aircraft, allowing it to be lowered by 1.2 m below the body of the aircraft while conducting the survey. The study area was 6 by 10 km in area (60 km^2). The flight elevation was 300 feet (90 m) above sea level, with the exception of survey lines over the island of Surtsey itself, that were done at up to 200-300-meter elevation, with a ground clearance of at least 100 m. The distance between profiles was 200 m. With a sampling frequency of 1000 Hz and an aircraft speed of 50 m/s, the MagArrow provides readings every 5 cm.

Other available data sets

Detailed bathymetry data for the area before the first observation of the eruption in Nov 1963 are not available. However, a sparse network of point soundings shows that the average depth was about 130 m (Vésteinsson 2009). The earliest detailed bathymetry map was made in July 1964 after the island of Surtsey had formed but when the lava field had only reached a fraction of the size it had at the end of the eruption in 1967. The 1964 survey shows the slopes of Surtsey but also reveals a submarine knob rising to 74 m below sea level to the SW of the Surtsey island.

A high-resolution bathymetry map for the whole Vestmannaeyjar area was made in 2007 (Jakobsson et al. 2009; Vésteinsson 2009). It is used to show the geological features of the whole study area. The outline of Surtsey island was mapped several times during and after the eruption, including the outlines used for this study, for 1965 and 2016.

During 1965, a magnetic survey via helicopter was performed at a height of 200 meter above sea level, and a total field magnetic anomaly map was made (Sigurgeirsson 1968). This map was digitized (Fig. 7) for comparison with the 2021 survey to explore possible changes after 1965 in sources of magnetic anomalies in the study area.

[1] https://www.geometrics.com/product/magarrow/

3.2.2 Data processing

Sampling

Data processing was done in several steps. First by re-sampling the whole data set, reducing the frequency of measurements from 1000 Hz to 20 HZ by taking an average of 50 measurements. The distance between successive 20 Hz mean values is still only 2.5 m.

Low pass filter

In order to remove aircraft-related noise, a low-pass filter was used (e.g., Allen and Mills, 2004). The low-pass filtering was carried out using Fourier transformation. The low pass filter used had a cutoff frequency of 0.1 Hz. As data with the reduced sampling frequency of 20 Hz are used (2.5 m spacing), this removed wavelengths shorter than ~500 m. This resulted in effective denoising of the data.

Diurnal variation removal

The diurnal effect, caused by the interplay of the solar wind activity and the magnetic field of the earth, must be removed from data. The permanent magnetic observatory at Leirvogur [2] close to Reykjavík records the Earth magnetic's field continuously during the day. This station was used to remove the diurnal changes.

Directional effect

The last step, before gridding, is the removal of any shifts caused by flight path direction, the flight direction effect between the N-S and S-N lines. The value of this effect was found to be 80 nT. After removal of this flight directional effect, all line data were merged to form a final data set ready for gridding of a magnetic map.

3.2.3 Analysis

In order to have a smooth grid, we use the kriging method in the Surfer software (Golden Software 2021) with 100-meter grid spacing for the contoured magnetic map of the area.

Qualitive analysis of the magnetic map

First, the magnetic map was compared with pre-Surtsey geological features in the region. The qualitative analysis of the region around eruption in 1963-1967 indicates:

- The subaerial lavas are a source of strong magnetic anomalies.
- The suspected pillow lava field to the SE of Surtsey appears to create a low amplitude anomaly.
- The remnants of the satellite islands of Surtey (Syrtlingur and Jólnir) have no clear magnetic anomaly associated with them. A weak anomaly is associated with Surtla.

[2] http://cygnus.raunvis.hi.is//~halo/lrv.html

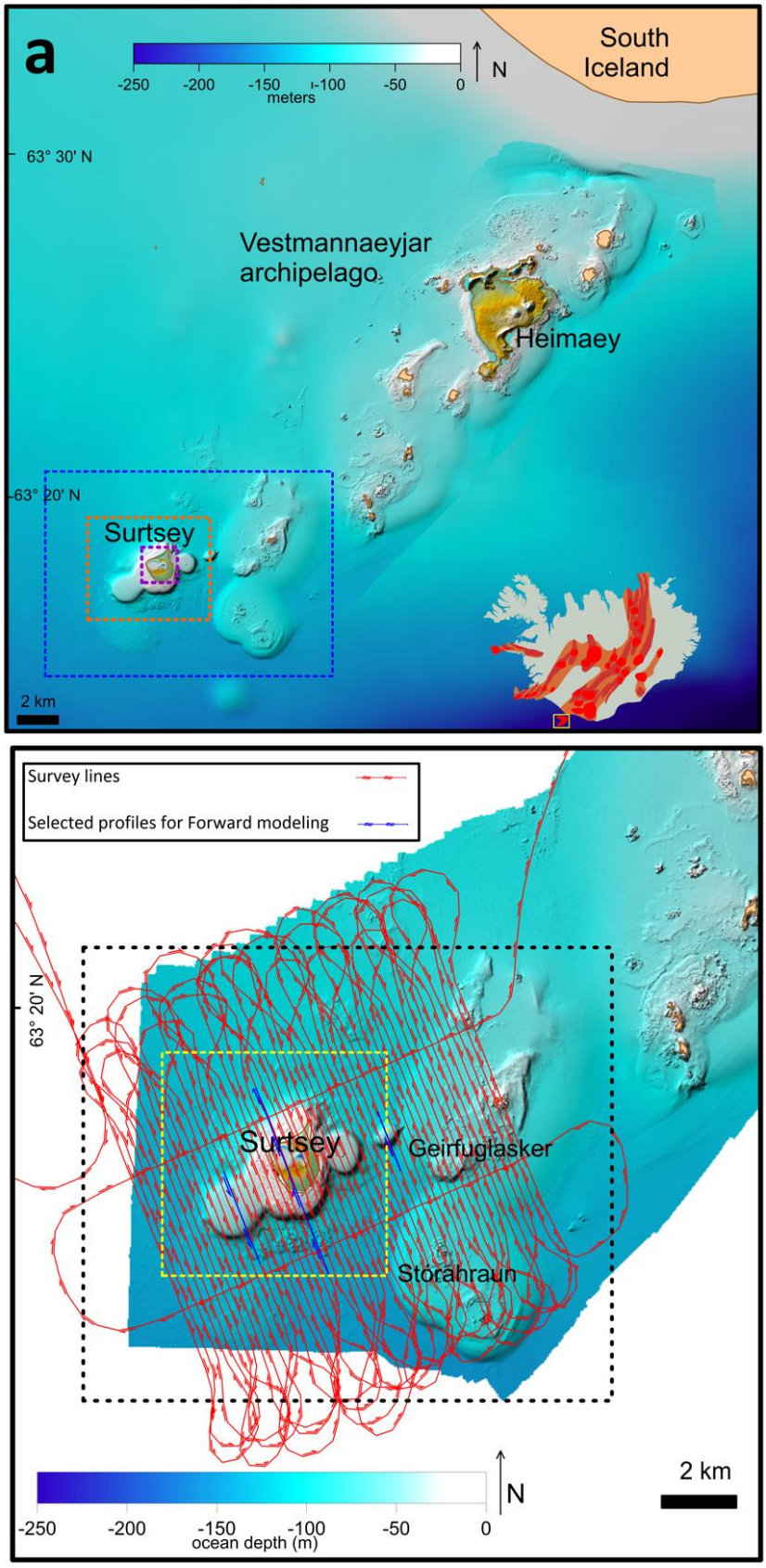

Figure 6. The aeromagnetic survey lines over Surtsey and the southwesternmost part of the Vestmannaeyjar archipelago. The bathymetry is from the survey of 2007 (Figure 1a and 2 in manuscript 3).

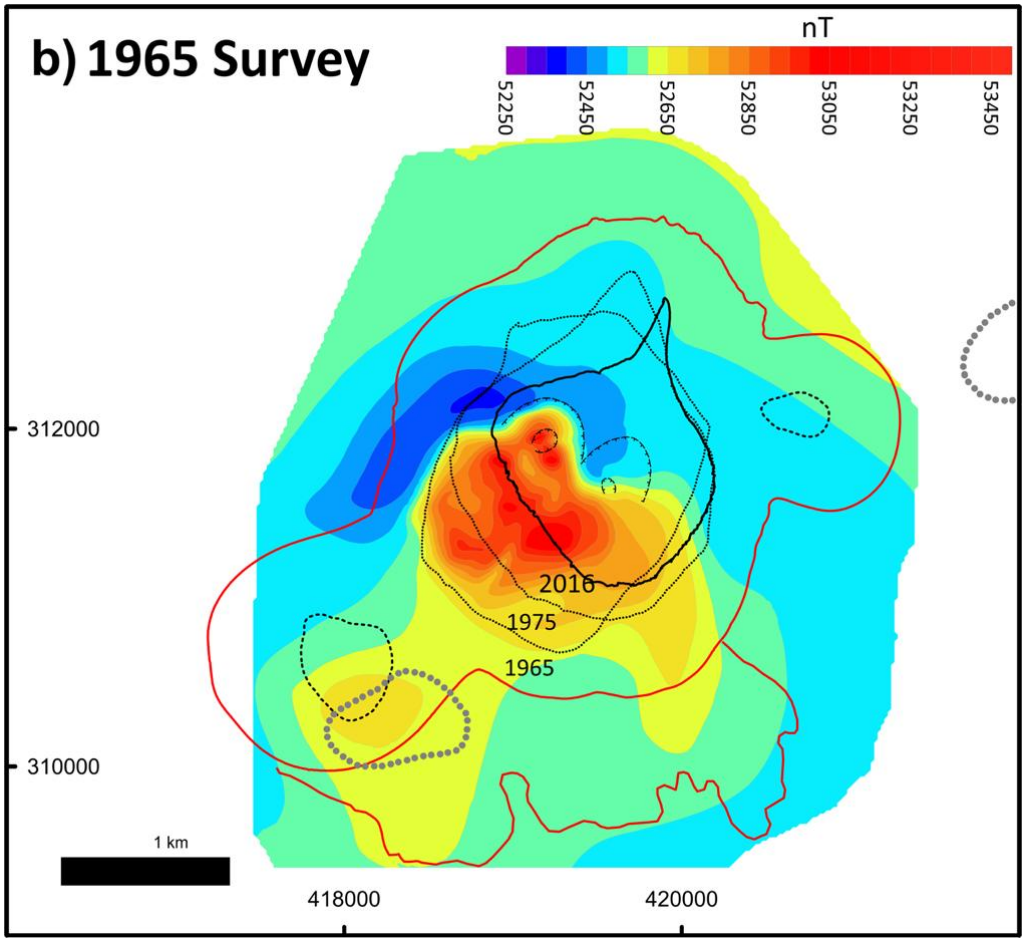

Figure 7. Magnetic map from the Helicopter survey in 1965 (based on Sigurgeirsson 1968*). The outlines of Surtsey and its submarine outlines, including satellite vents, are indicated (Figure 7b from manuscript 3).*

Depth to source Analysis

In order to make full use of the high-resolution magnetic map, quantitative methods to estimate the depth to the magnetic sources were applied. The methods used were power spectrum analysis and Euler deconvolution. Both were carried out using the Geosoft-oasis-montaj software (Geosoft 2015).

Spectral analysis

The Energy Spectral Analysis approach applied to magnetic grid data permits determination of an average depth to ensembles of the causative entities (Spector and Grant 1970; Bhattacharyya and Leu 1977). The 2D spectrum is obtained through a Fast Fourier Transform (Blakely 1995) and the inverse of the energy density spectrum of function $f(x, y)$ based of the wavenumbers and their direction is given by:

$$f(a, b) = \frac{1}{4\pi^2} \iint_{-\infty}^{\infty} f(x, y).\, e^{i(xa+yb)}\, da\, db \qquad (2)$$

Here a and b are wavenumbers in the x and y directions, respectively.

By averaging the energy spectrum of all grid elements for each separate wavenumber, the radially averaged energy spectrum can be calculated. For data in a grid like the magnetic grid map of this survey with several anomalies, the depth to the top of sources can be calculated by the logarithmic value of the radially averaged energy spectrum. The slope of the radially averaged energy spectrum (Spector and Grant 1970) divided by 4π shows the depth of the anomalies in the region.

$$h = -\frac{s}{4\pi} \tag{3}$$

Here S is slope of the plot with 3 or 5 points and h is depth to source of the anomaly. From the radial average spectrum plot, we can estimate the depth of the anomalies from shallow to deep in the region. Fig. 8 shows an example of a spectrum plot for an arbitrary magnetic map.

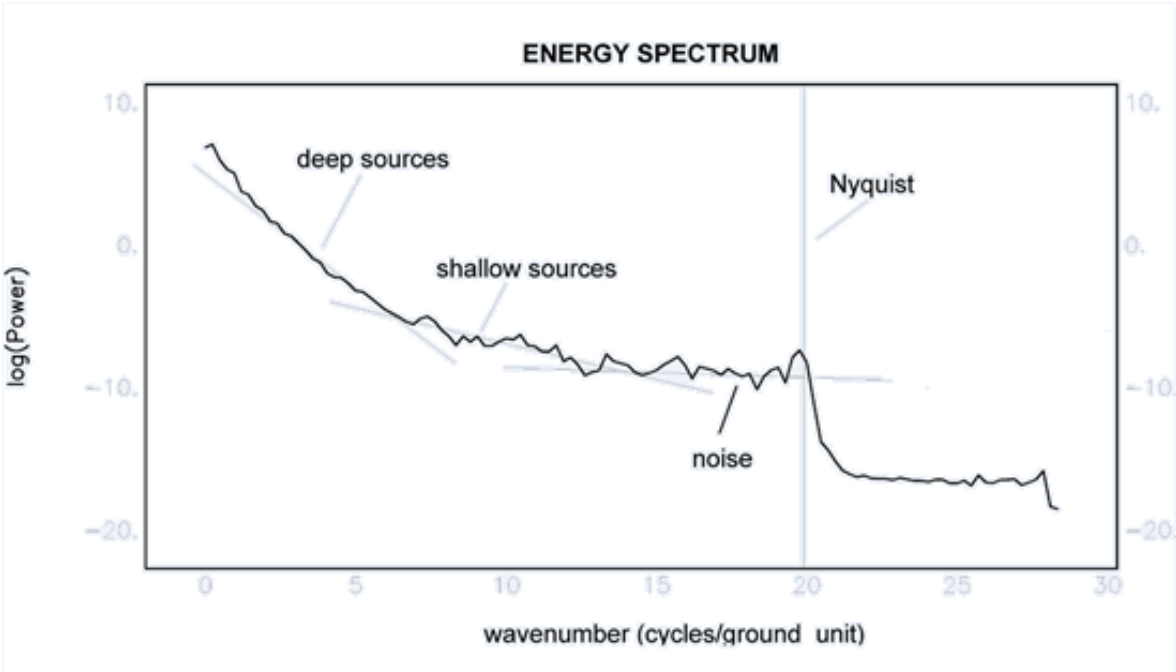

Figure 8. Example of Radial average spectrum analysis with explanation of result (Geosoft 2015).

Euler Deconvolution

The Euler deconvolution method is used to estimate the depth to source and location of the magnetic anomalies over an arbitrary window (number of cells in the grid map) of the study area in a way that covers causative bodies. The window size to use over a region and the structural index are two parameters that need to be defined (Reid et al. 1990). The Euler's equation for a magnetic source at (x_0, y_0, z_0) with total magnetic field, T at the point (x, y, z) is written as (Blakely 1995):

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = N(B - T) \tag{4}$$

Here B is the regional magnetic field and N is called the structural index (SI). Geological characteristics of the study area aid in the decision on what is the most appropriate SI to use. A structural index of 1 (SI = 1) corresponds to sheets and dykes (laterally extensive bodies relative to their depth), SI = 2 applies to pipes or cylinders, while SI = 3 is a body whose dimensions are small relative to the distance, basically a dipole. After the choice of the most appropriate SI, the depth ($z - z_0$) can be calculated to provide depth solution over a defined windows size.

Advantages of the Euler deconvolution is that the approach does not need any assumptions regarding direction of the existing field, the direction of magnetization, or the relative magnitudes of induced and remanent magnetization of the sources. However, choosing the correct structural index plays an important role in the final solution of the Euler deconvolution.

Comparison of 1965 and 2021 magnetic maps - upwards continuation

Since the magnetic survey of 1965 was done at 200-meter height (Fig. 7), for accurate comparison with the 2021 survey, an upwards continuation filter was applied to the magnetic field map of 2021. The upward continuation filter for a potential field (Blakely, 1995) at point $(x, y, z_0 - \Delta z)$ is defined as:

$$U(x, y, z_0 - \Delta z) = \frac{\Delta z}{2\pi} \iint_{-\infty}^{\infty} \frac{U(\alpha, \beta, z_0)}{[(x-\alpha)^2 + (y-\beta)^2 + \Delta z^2]^{3/2}} \, d\alpha d\beta \qquad (5)$$

This filter was applied to the 2021 map when it was compared to the 1965 map. In addition, the change in total field strength between 1965 and 2021 as recorded at the Leirvogur Observatory, 965.3 nT, was added to the 1965 map (Fig. 7). A further 130 nT was added to the 1965 map to get the optimum comparison with the 2021 map.

2.5D forward modeling

Forward modelling has been carried out using three different profiles of the 2021 survey. These are profiles over Surtsey, Surtla and Jólnir. The forward modeling is done using the GravMag software, (Pedley and Busby 1997), a highly interactive modeling program for 2.5D interpretation of gravity and magnetic data. Forward modelling is based on the calculation of magnetic anomalies of finite-length right polygonal prisms. The basic solution is that for infinite two-dimensional polygons striking parallel to the survey line (Talwani and Heirtzler 1962). The finite length of bodies is achieved, providing the 2.5D capability, using the Shuey and Pasquale (1973) method to define models based on the polygons in the X, Y, Z plane and assigned a finite strike length in the third dimension.

To constrain the magnetization of source bodies, results of measurements of magnetic remanence and susceptibility from lab measurements in the palaeomagnetic laboratory at the Institute of Earth Sciences, Univ. of Iceland, were used for 40 samples obtained at 8 locations in Surtsey in 2018 (Fig. 9).

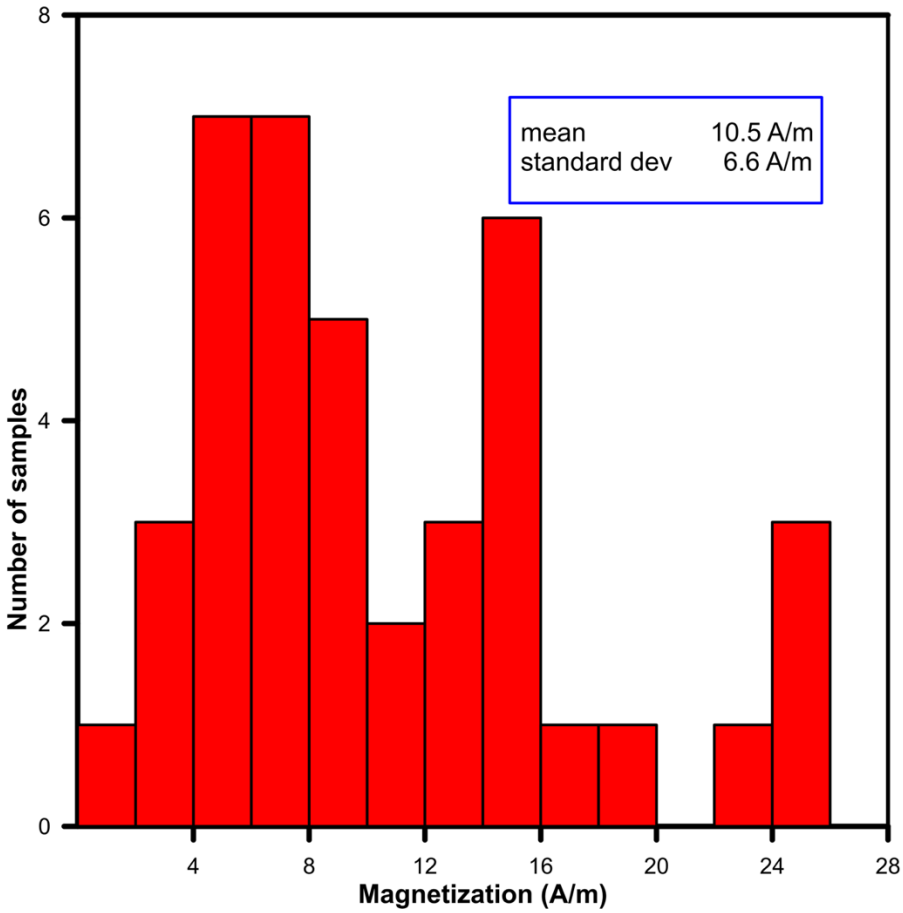

Figure 9. Distribution of remanent magnetization in samples of lava from Surtsey. (Figure 3 from manuscript 3)

4 Paper I: Seismic activity associated with the 1963-1967 Surtsey eruption off the coast of South Iceland

4.1 Summary

The emergence and growth of Surtsey during volcanic activity in 1963–1967, from an oceanic depth of 130 m off the south coast of Iceland, remains one of the best-documented island-forming eruptions to date. By extracting information from seismic bulletins from this period and analyzing archived analog seismic data, principally from seismic station SID, located 140 km from Surtsey and the most sensitive station in the seismic network existing at the time, as well as the REY station, 115 kilometers to the NE, we address key questions on precursors, timing of eruption onset, and duration of the submarine phase.

4.2 Main results

- The results indicate that the magnitude of completeness for earthquakes associated with the Surtsey eruption was M_L = 2.5. Earthquakes smaller than that are likely to have been overlooked by the rather rudimentary seismic network at the time, with only two usable stations in operation, REY and SID, at distances over 100 km.

- Between the permanent stations registering Surtsey-related seismicity, SID, at 140 km distance ENE from Surtsey, was more sensitive than REY and more likely to detect activity associated with Surtsey.

- Five earthquakes of local magnitude 2.4–2.9 with epicentral distance from SID fitting with Surtsey occurred on November 3–7, with additional events of similar magnitude occurring on November 8–10. This activity on November 3–10, 1963, is interpreted as being precursory earthquakes, indicating that a swarm of events with magnitudes less than 3 occurred over at least nine days before the onset of the eruption, the largest of magnitude 2.9 (Fig. 10).

- The submarine eruption is considered to have started in the early afternoon of November 12, when continuous volcanic tremor of dominant frequency 1–2 Hz appears at SID, continuing on November 13. The eruption is considered to have remained submarine for about 40 hours, progressing to an emergent phreatomagmatic eruption by 06:30 on November 14.

- The earthquakes recorded after the onset of the eruption have a strong temporal correlation with shifts in eruptive activity from one vent to another (Fig. 10). The onset of earthquake swarms precedes the opening of new vents by a period ranging from 2 days to a few weeks with the longest period occurring prior to the submarine Jólnir eruption in December 1965.

- This study has provided new insight into the seismicity of this historically important eruption, for the first time providing constraints on the precursory seismicity, eruption onset, and duration of the submarine phase, as well as demonstrating the correlation between seismic activity and changes in vent location. The study also demonstrates how old analog seismic data may contain information on volcanic eruptions of historical and scientific importance that occurred prior to the present age of digital seismometers.

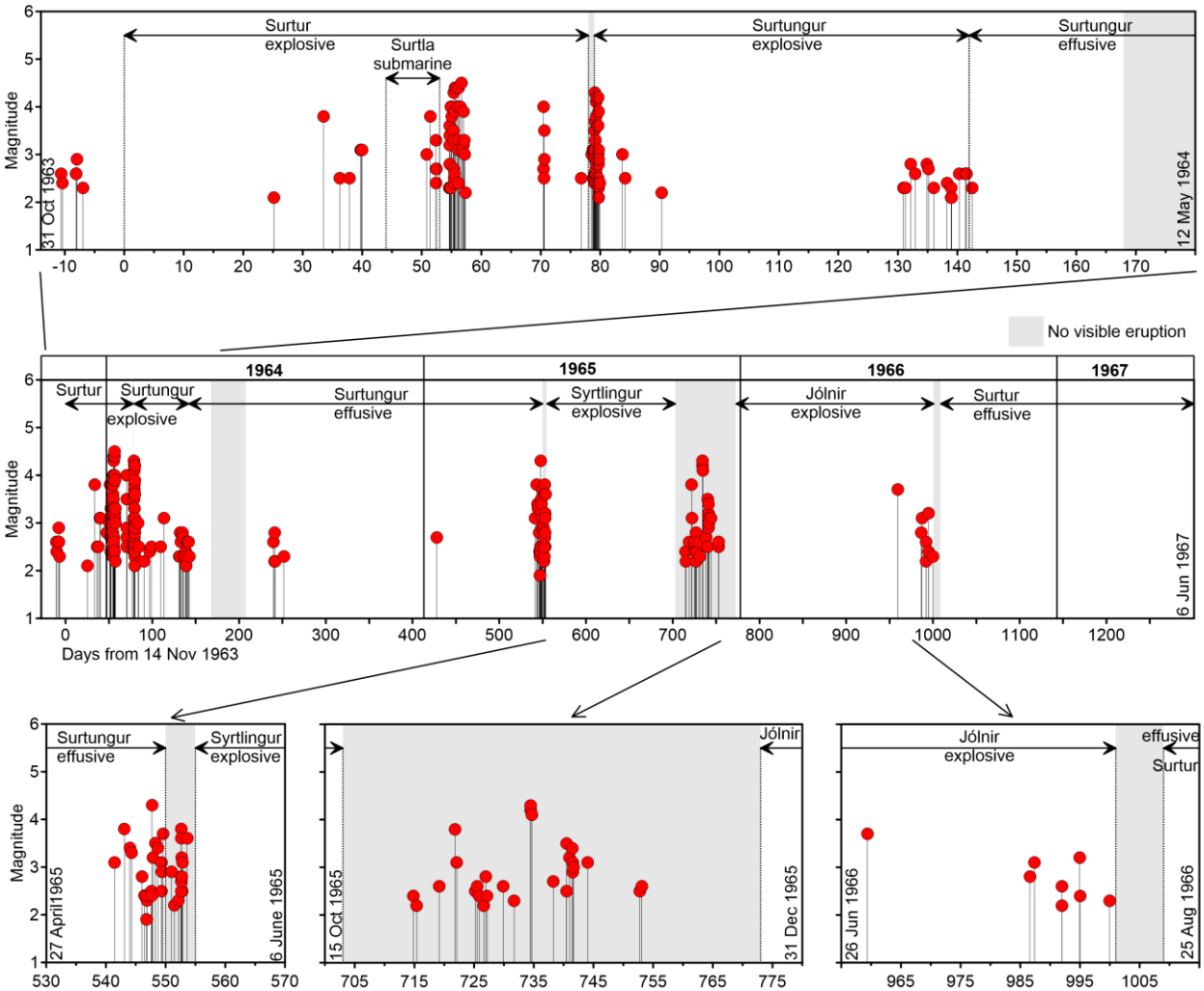

Figure 10. Earthquake activity recorded in association with Surtsey 1963-1967. The central panel shows the complete timeline (1963-1967) while the top panel displays the period end-of-October 1963- May 1964. The bottom panel shows respectively: the onset of the Syrtlingur episodes in May 1964(left); the end of Syrtlingur and start of Jolnir in Octobore-December 1965(center); the end of Jolnir and start of the final effusive phase of the Surtur in June-August 1966(right).

5 Paper II: Volcanic tremor associated with the Surtsey eruption of 1963–1967

5.1 Summary

The eruption of Surtsey volcanic island occurred in several phases involving explosive and effusive activity, including the initial submarine phase on November 12-13, 1963, and continuing until June 1967. The eruptive activity was accompanied by considerable seismic activity, both earthquakes, and volcanic tremor. However, analysis of the seismicity is not straightforward for two main reasons: the offshore location of the activity and the rather rudimentary network of only four permanent seismic stations in Iceland at the time. While two of the stations had old, low magnification seismographs that did not detect tremor, clear signals were detected at the other two, located at distances of 115 and 140 km from Surtsey. Both spasmodic and harmonic tremor were identified, both with low (<3 Hz) and higher (3-5 Hz) characteristic frequencies. Low-frequency and high-frequency harmonic tremors, as well as spasmodic tremors, were observed in Surtsey throughout the activities (Fig. 11). The overall characteristics of the seismic activity during the episodes of the eruption are outlined in Fig. 12.

5.2 Main results

In general, a summary of observations is as follows:

- The discontinuous appearance of tremor on SID in the first several weeks indicates that the magma flow rate and tremor relationship is not simple:
    - The strongest tremor was detected in December and at times in January to March 1964.
    - Little correlation can be seen between tremor strength and shallow vent activity on a time scale of hours.
    - The results indicate that magma flow rate was not the main driver of tremor intensity in the explosive eruption.
- Little tremor is detected during the most vigorous activity in the first 20 days of the eruption, indicating that it is not primarily the magma flow rate that determines the tremor intensity in this explosive part of the eruption; possibly vent conditions are far more influential in determining the intensity of tremor activity than the magma flow rate.
- On timescales of several weeks to months, a broad correlation exists, with the strongest tremor occurring in the first months, when eruption rate was higher than later in the eruption when tremor was lower.

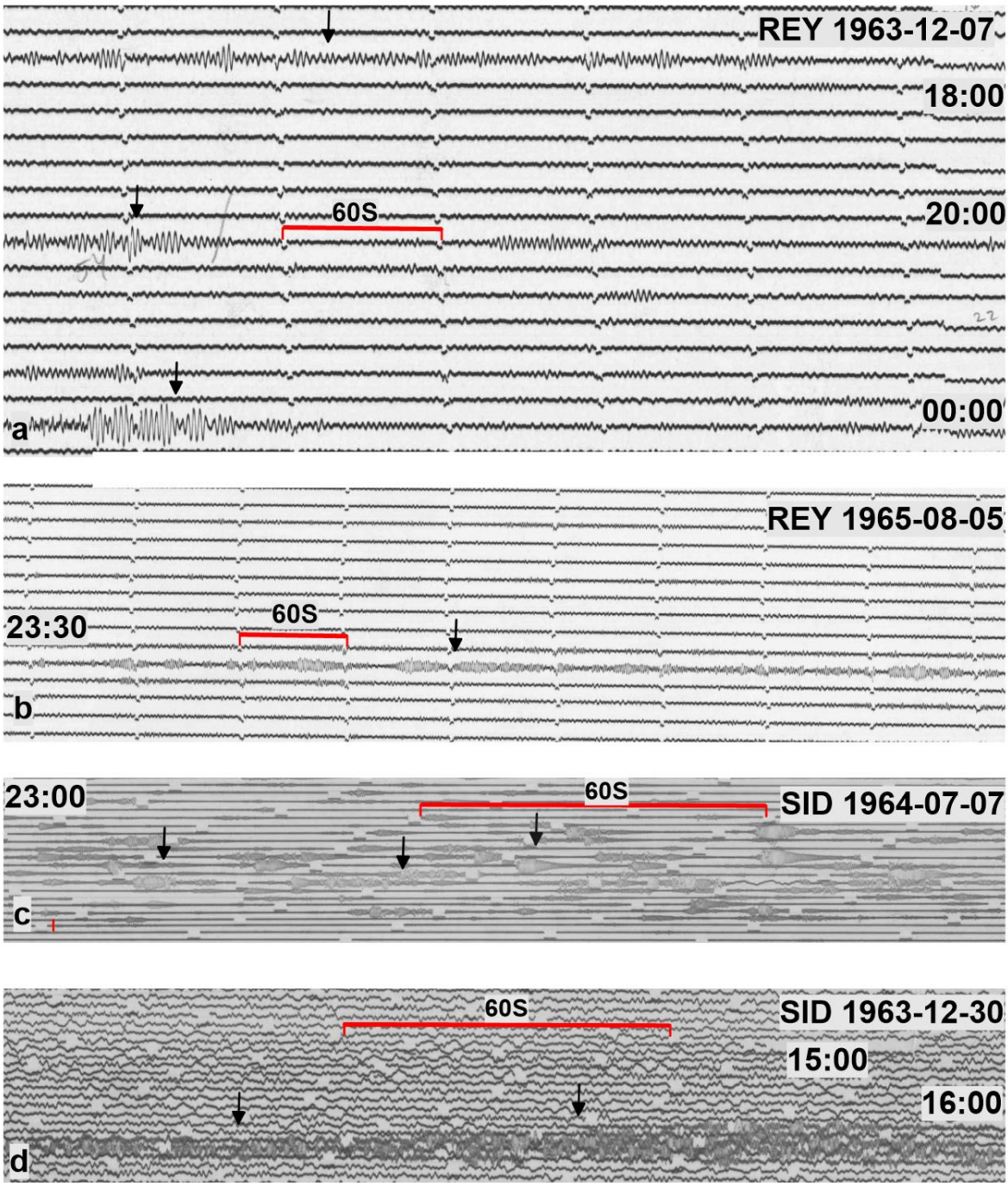

Figure 11. Types of observed tremor. a) Harmonic low frequency tremor at REY station. b) Harmonic high frequency volcanic tremor at REY station. c) Spasmodic tremor at SID station. d) Burst of mixture of harmonic high frequency with spasmodic tremor at SID station.

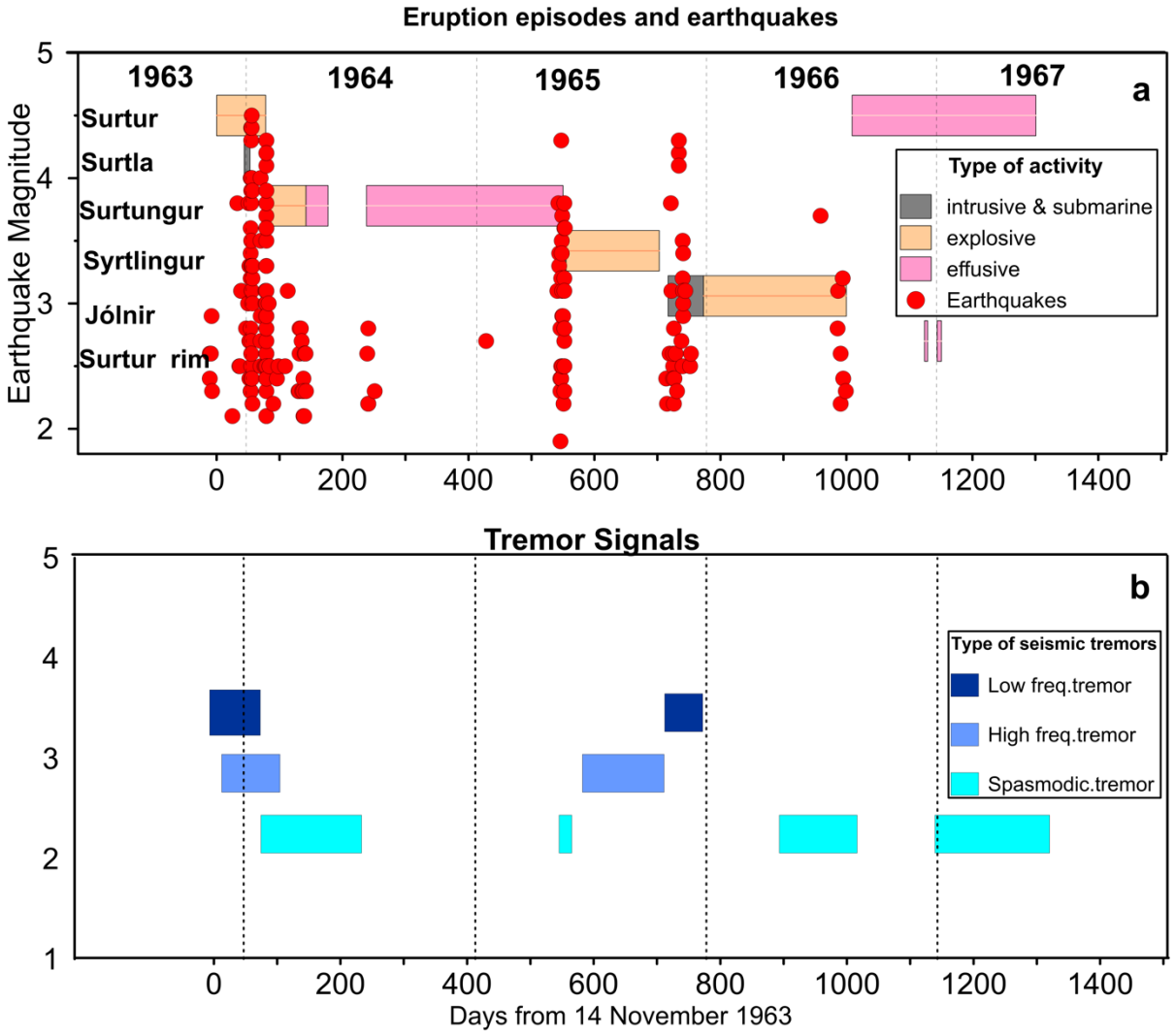

Figure 12. Timeline of earthquakes and tremor signals during the 3.5 years of eruptions. The colored areas mark periods where the tremor of the type indicated occurred. Within each period, episodes of tremor alternated with intervals of no visible seismic activity.

6 Paper III: Internal structure of the volcanic island of Surtsey and its surroundings, constraints from a dense aeromagnetic survey

6.1 Summary

An aeromagnetic survey was completed in October 2021 over the Surtsey area. The survey was carried out using a high precision magnetometer, the Geometrics MagArrow fixed to an aircraft flying at 90 m above the ocean, with over 300 km of survey lines acquired at a spacing of 200 m, covering an area of 60 km^2 in six hours. The aims of this survey were to explore the possible existence or absence of shallow intrusions within and below the edifices formed in the eruption during 1963-1967, to explore whether any signs of pillow lavas can be seen within and adjacent to the edifices formed, and to explore changes that have taken place in extent and amplitudes of the magnetic anomalies since the helicopter magnetic survey of 1965 covering Surtsey. The magnetic map (Fig. 13) reveals anomalies associated with known geological features, and some anomalies that are apparently caused by unknown sub-surface structures.

6.2 Main results

Analysis of the magnetic map has been performed using: (1) qualitative comparison of anomalies observed and known geological features, (2) depth estimates for causative bodies for the observed anomalies using both 2D spectral analysis and Euler deconvolution, and (3) 2.5D forward modelling to constrain size and thicknesses of the bodies that cause the anomalies observed at Surtsey, southeast edge of Jólnir and Surtla. The main findings are the following:

- The depth estimates for the area obtained by 2D spectral analysis and Euler deconvolution indicate that all significant sources of magnetic anomalies, with the exception of the Surtsey subaerial lava field, are located on the sea floor and in the uppermost 200-300 meters of the sea bottom.
- By far the strongest anomaly is associated with the subaerial lava field on Surtsey. The ~700 nT anomaly is best explained by 14-19 A/m magnetization of the subaerial lava flow formed on Surtsey in two episodes in 1964-1967. The magnetic data are not consistent with the presence of any volumes of magnetic rocks at or above the seafloor underneath the vent areas of Surtsey, supporting previous results and inferences that no mounds of pillow lava were formed in the initial phases of the eruption.
- A subtle magnetic high is correlated with the pillow lava field observed to the south of Surtsey. 2.5D modelling indicates that this anomaly is best explained by ~ a ~10-thick layer of pillow lava at the sea bottom, with a magnetization of order 10-15 A/m.

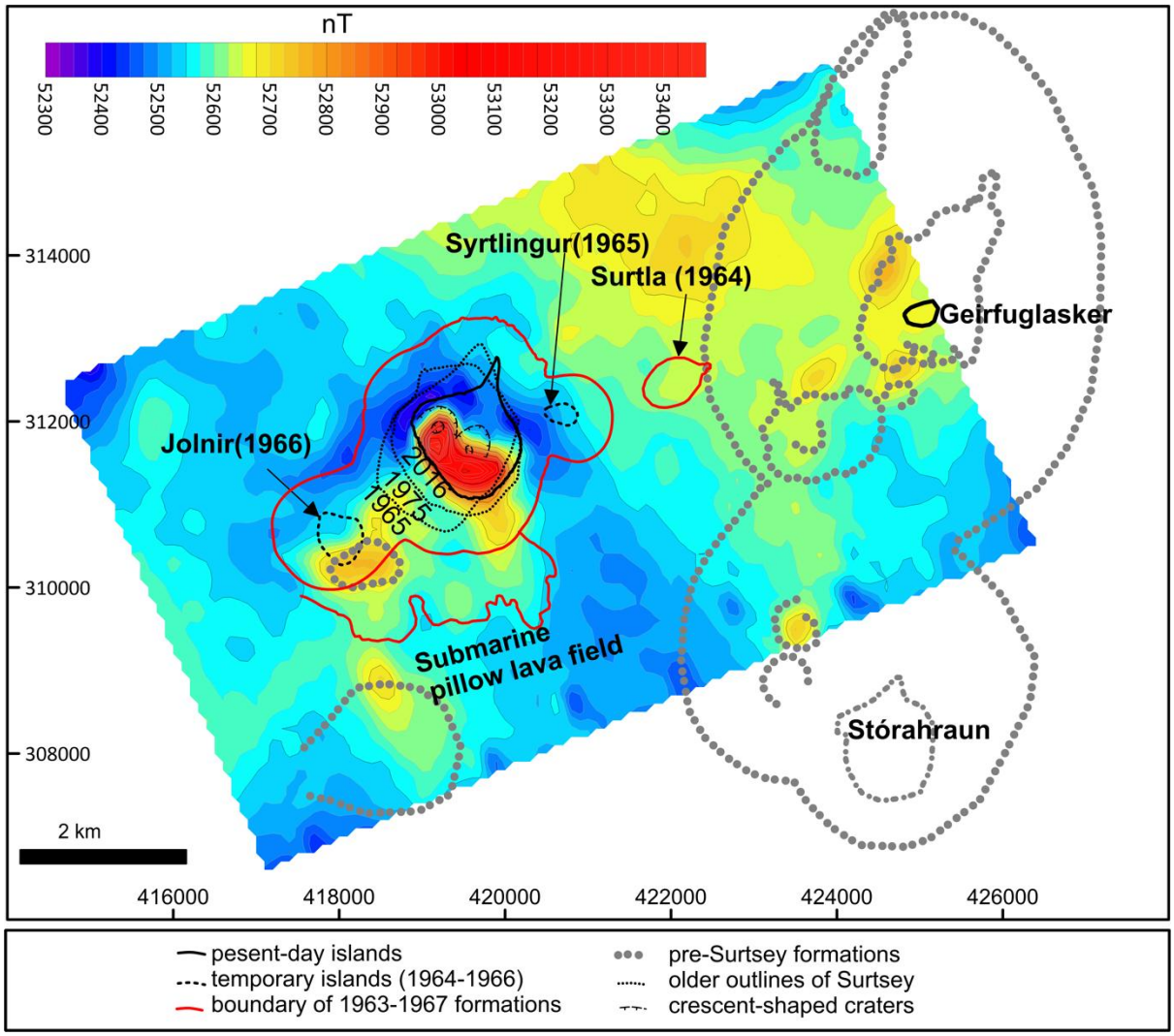

Figure 13. Total field magnetic map obtained in 2021. The outlines of Surtsey at different times and the main geological features in the area are indicated. (Figure 4 from manuscript 3)

- A clear magnetic anomaly is located on the southern edge of the submarine mound that is the remnant of the temporary island Jólnir formed in 1966. Data obtained in 1964 indicates that a 50-m-high submarine knob is the cause of this anomaly. This feature apparently pre-dates the formation of Surtsey as surveys of ocean surface temperature, done in the first days of the eruption, do not indicate any activity at this location at the submarine start of the eruption in November 1963.
- No magnetic anomaly is associated with the mound that is the remnant of the temporary island Syrtlingur, formed in 1965. In contrast, a weak anomaly is associated with mound of Surtla, formed in 1963/64. The Surtla anomaly seems to be best explained by a combination of a narrow dyke along the ridge of Surtla, and that the body of Surtla has weak (<1 A/m) magnetization.
- The differences between the magnetic anomalies for Surtla on one hand and Jólnir and Syrtlingur on the other, may be that the eruption of Surtla was of lower explosive

intensity, never experiencing the powerful phreatomagmatic explosions observed during the explosive phases of Surtsey, Syrtlingur and Jólnir. At Syrtlingur and Jólnir, the explosive Surtseyjan activity may therefore have precluded the preservation of a dyke reaching through the formation, while a dyke was formed and preserved at Surtla.

- No evidence can be found for the presence of sub-seafloor intrusions beneath Surtsey and its satellite islands at a scale sufficient to generate an anomaly detectable by the aeromagnetic survey. This does not rule out intrusions, but their volume and extent would have to be minor compared to the main bodies causing anomalies in this area.

7 Concluding remarks

The results of this PhD project provide a more detailed picture than previously available on aspects of the formation of Surtsey. The results are based on geophysical methods but important first-order constraints are provided by the SUSTAIN drill hole data. The SUSTAIN drilling involved the extraction of three drill cores in August-September 2017. Another important first-order constraint is the recorded course of events during the eruption and the buildup history. This study demonstrates that potential field geophysical modeling methods, in particular for magnetic surveying, can be used to study the substructure of volcanoes, and that historical data on seismic signals can be successfully used to analyze the course of events, which should be useful information for volcanic hazard assessment studies in shallow marine settings.

The observation of the various signals at distant permanent seismic stations from the pre-digital era emphasize the importance of preserving analog seismic data. The results of this project demonstrate that these old and, by present-day standards, low-quality seismic data can be used to define the onset of the submarine eruption and clarify the course of events in the subsequent eruptive phases. The analysis of the continuous record of seismicity preserved as drum plots, demonstrates that the relationship between seismic tremor and eruption rate is complicated and seismic tremor is not a reliable proxy for eruption rate.

The study also demonstrates the usefulness of aeromagnetic surveying and how the investigation of magnetic anomalies in the area provides constraints on the structure of the volcanic islands/submarine edifices built in the various episodes of the Surtsey eruption of 1963-1967. The result also indicate that the combined analysis of ocean bathymetry data and aeromagnetic data are a useful method to assess the characteristics of shallow ocean volcanic areas. They provide evidence on styles of volcanic activity through the varied magnetic characteristics of different formations (effusive versus explosive), and aid in estimating the number of remnants of volcanic formations and in that way the likely recurrence time of eruptions in a region.

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Paper I

Seismic activity associated with the 1963–1967 Surtsey eruption off the South coast of Iceland

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RESEARCH ARTICLE

Seismic activity associated with the 1963–1967 Surtsey eruption off the coast of South Iceland

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Abstract
The emergence and growth of Surtsey during volcanic activity in 1963–1967, from an oceanic depth of 130 m off the south coast of Iceland, remains one of the best-documented island-forming eruptions to date. By extracting information from seismic bulletins and analyzing archived analog seismic data, principally from SID, the most sensitive station in the seismic network existing at the time (131 km from Surtsey), we address key questions on precursors, timing of eruption onset, and duration of the submarine phase. We estimate the magnitude of completeness for earthquakes at Surtsey to have been $M_L = 2.5$. Several seismic events of magnitude $M_L < 3$ in November 3–10, 1963, with epicentral distance fitting with Surtsey are considered to be precursory earthquakes. Continuous tremor of dominant frequency 1–2 Hz, starting in the early afternoon of November 12, is considered to mark the onset of the submarine eruption, about 40 h before the start of subaerial eruption at 06:30 on November 14. The number of earthquakes larger than the threshold magnitude of 2.5 detected in 1963–1966 was 123, with the largest being of magnitude 4.5. Six earthquakes ranging in magnitude between 3.7 and 4.5 were felt in Heimaey, 22 km to the NE of Surtsey. Changes in vent location occurred five times in 1964–1966. Significant earthquake activity after the eruption start occurred in swarms considerably stronger than observed at the start. These swarms preceded vent migration and lasted days to weeks, apparently caused by intrusive activity prior to eruption at the new vents.

Keywords Submarine volcanism · Eruption precursors · Earthquake swarms · Precursory earthquakes

Introduction

Submarine eruptions constitute a large part of volcanic activity on Earth. This includes shallow marine settings and emergent eruptions. However, there are not many well documented cases of shallow submarine eruptions. This is partly due the fact that such eruptions have not been very frequent in recent decades and partly due to the remote location of many of the known examples.

Eruptions of this nature that have occurred during the present era's instrumental recordings of seismic and other geophysical signals include the Teishi Knoll eruption in 1989 (Yamasato et al. 1991), South Sarigan in May 2010 (Green et al. 2013), El Hierro in 2011–2012 (Martí et al. 2013), Bogoslof in 2016–2017 (Wech et al. 2018), and the submarine eruption of Mayotte in the Indian ocean (Cesca et al. 2020). Prominent shallow submarine and emergent eruptions can pose significant threat to people when they occur near inhabited areas. Therefore, studies of the characteristics of such eruptions are of considerable value for hazard assessment and early warning. The identification and detection of precursors and onset of activity are particularly important. A notable example of shallow submarine/emergent eruption forming an island occurred in 1963–1967 when Surtsey was built in a series of eruptive events lasting 3.5 years between November 1963 and June 1967. The island formed where pre-eruption ocean depth was about 130 m, at the southern end of the Vestmannaeyjar archipelago, off the south coast of Iceland (Thorarinsson et al. 1964; Höskuldsson 2015).

The growth of Surtsey, shift of activity between vents, transition from explosive phreatomagmatic activity to effusive activity and the formation of short-lived islands in explosive eruptions was documented in considerable detail by Thorarinsson et al. (1964) and Thorarinsson (1965, 1966,

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1967a, b, 1968a, b). Aspects of eruption plume activity were documented by Sigurgeirsson (1966), and the Surtsey explosive activity was further analyzed by Kokelaar (1983) and Moore (1985). Drilling campaigns in 1979 (Jakobsson and Moore 1982) and 2017 (Jackson et al. 2019; Weisenberger et al. 2019) have resulted in detailed analyses of the volcanic stratigraphy of the island (McPhie et al. 2020) and analyses of geothermal alteration of the hyaloclastite tuffs (Jakobsson and Moore 1986; Prause et al. 2020). Extensive studies have been carried out to study the island's post-eruption morphological evolution (Jakobsson et al. 2009; Romagnoli and Jakobsson 2015).

In contrast to the visual and volcanological observations, analysis of the seismicity associated with Surtsey has been lacking. A preliminary study of seismicity during the first 2 years of the eruptive activity can be found in Sigtryggsson and Sigurdsson (1966). Pálmason (1966) reported on data obtained from a temporary seismograph in Heimaey, 22 km from Surtsey in January–April 1964. Considerable seismicity is assigned to the Vestmannaeyjar archipelago during the eruption in the seismological bulletins from 1963 to 1967 (Icelandic Meteorological Office, 1964a, 1964b, 1970, 1978, 1979a, 1979b, 1980), based on the existing network of seismic stations in Iceland at the time. Considering present-day standards, these data are of limited quality, recorded on photographic paper by analog instruments of limited bandwidth, at distances of 80–191 km from the eruption site. The accuracy of epicenter location only allows association of seismic events with Surtsey; analyzes of epicentral depth or possible temporal migration of epicenters are not possible. Given these limitations, in the present paper we start by describing the seismic network in Iceland at the time of the eruption and defining the magnitude of completeness for the network to establish the limits of the observations. Then we proceed analyzing the data, exploring in particular the following questions:

Were precursory earthquakes registered by the network in the hours, days or weeks prior to the onset of the visible eruption in the early morning of November 14, 1963?

Can the data constrain the start of the submarine eruption through detection of continuous seismic tremor, as commonly observed for other eruptions?

After the onset of eruption in November 1963, what was the temporal relationship between episodes of earthquakes and changes in the volcanic activity such as shifts in style or changes in vent location?

Background information

Geological setting and the Surtsey eruption

The Surtsey eruption occurred in the ocean at the southern end of the Vestmannaeyjar archipelago which is located at the southern tip of Iceland's Eastern Volcanic Zone (Fig. 1). The archipelago has over 20 islands and a larger number of submarine hills and peaks that presumably are remnants of past eruptions (Mattsson and Höskuldsson 2003). The Surtsey volcanic activity in 1963–1967 lasted for 3.5 years with eruptive activity shifting between five different vents. Three islands were formed but only the main island of Surtsey survived the intensive marine erosion (Fig. 1). The eruption of Surtsey came as a surprise as no eruptions were known to have occurred in the Vestmannaeyjar archipelago in the 1100 years of human settlement in Iceland (Thorarinsson et al. 1964; Höskuldsson 2015).

The course of events during the Surtsey eruption is summarized in Fig. 2. It began as a submarine eruption on the ocean bottom from a depth of 130 ± 5 m, first detected by fishermen at around 06:30 local time in the morning of November 14, 1963, with the first sighting of the emerging island the following morning (Thorarinsson 1965). The eruption built the tuff cone Surtur in November to January 1964, followed by the formation of the second tuff cone Surtungur (previously named Surtur II) in February–April 1964. In December 1963, a new submarine vent, Surtla, was active, but it terminated before it became emergent. On April 5, 1964, the eruption in Surtungur turned effusive and activity on the main island of Surtsey remained that way until the end. A 15-month long gap in activity on Surtsey occurred in 1965–1966. During this period, two smaller islands formed during explosive activity (Syrtlingur and Jólnir), but they were washed away by wave action soon after activity stopped in these craters.

Volcano-induced seismic activity and monitoring in Iceland

Volcanic activity is commonly accompanied by characteristic seismic patterns. Magmatic movement beneath volcanoes (forming intrusions or lava domes) is commonly associated with seismic signals (Brandsdóttir and Einarsson 1992; McNutt 1996; Soosalu et al. 2005; Zobin 2012; Chouet and Matoza 2013; Sgattoni et al. 2016). Seismic activity associated with eruptions is well-documented for many eruptions in Iceland. A network of sensitive, short-period seismographs was installed in Iceland in 1973–1975 (Einarsson and Jakobsson 2021), and considerable effort has been put into detecting and analyzing the precursors of eruptions. Einarsson (2018) studied short-term seismic precursors for 21 confirmed subaerial and subglacial eruptions and several intrusive events between 1973 and 2014. The studies show that all eruptions in Iceland during this period were preceded by swarms of earthquakes.

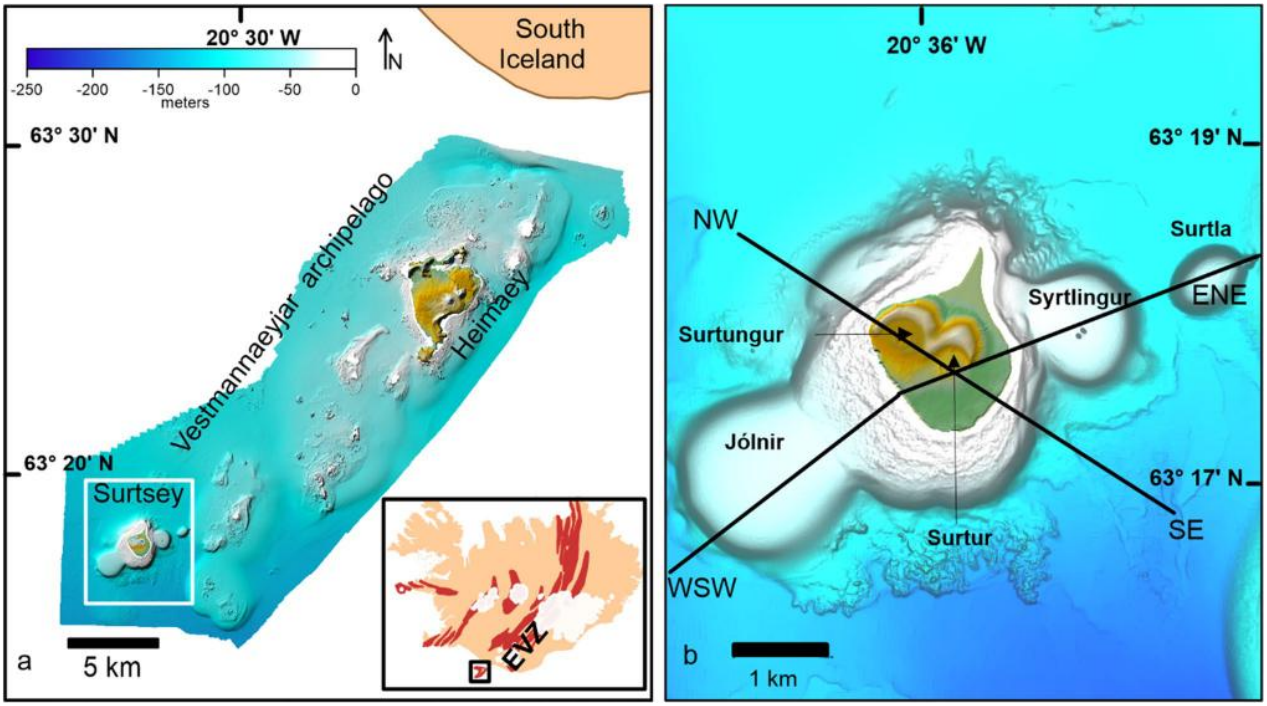


Fig. 1 **a** Bathymetry and topography of the Vestmannaeyjar archipelago off the south coast of Iceland. The inset map of Iceland shows volcanic zones in red (EVZ: East Volcanic Zone). **b** Map of the Surtsey volcano with its five different eruption sites that were active at different times during 1963–1967 (bathymetry: Jakobsson et al. 2009). The solid lines show the location of the cross sections in Fig. 2g

Terminology and classification of volcanic seismic signals

Classification of volcanic seismicity was presented by Minakami (1974), who defined four different types of signals: high-frequency (A-type) earthquakes, low-frequency (B-type) earthquakes, explosion-quakes or earthquakes followed by an explosive eruption, and volcanic tremor or volcanic pulsations. Volcanic earthquakes commonly occur in swarms that usually lack the mainshock-aftershock character of tectonic earthquakes (McNutt 1996; Chouet and Matoza 2013) and are usually of considerably smaller magnitude. In this study, two groups of seismic signals are frequently observed, swarms of earthquakes in the magnitude range 1.9 to 4.5, and volcanic tremor. The existing data mostly do not allow the classification of individual earthquakes into the categories given above.

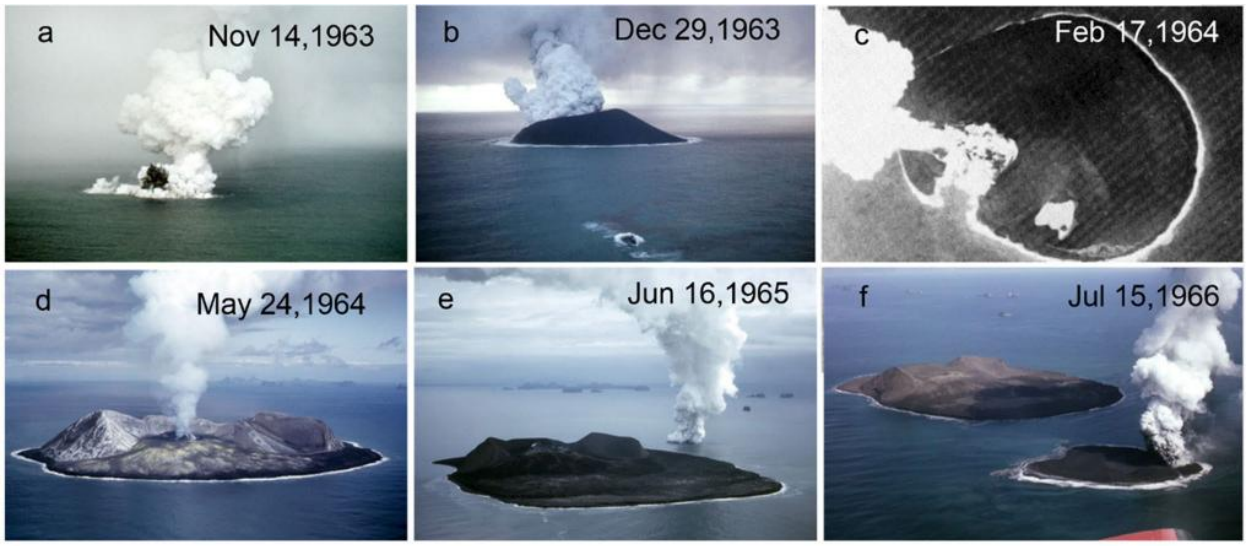
Here we do not attempt to provide a full description of observations of tremor and their mechanism (Dziak et al. 2012). Instead, we limit our discussion to observations of its apparent absence or occurrence preceding the visible eruption in 1963.

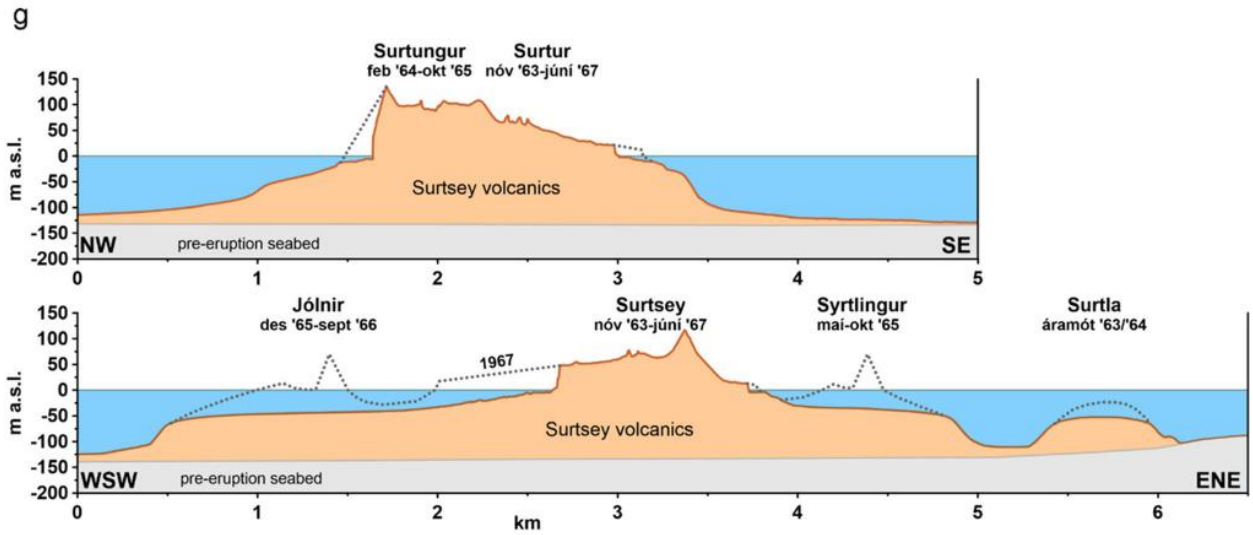
Data and monitoring systems

During the years 1963 to 1967, seismographs from the permanent stations in Reykjavík (REY), Kirkjubæjarklaustur (SID), Vík í Mýrdal (VIK), and Akureyri (AKU) in Iceland were in operation (Einarsson and Jakobsson 2021). Their characteristics, location, and distance from Surtsey are given in Fig. 3a. There was no seismograph in Vestmannaeyjar at the time of the eruption onset.

Seismic station characteristics

The seismographs at AKU and VIK had very low magnification (Fig. 3b). AKU is located 291 km from Surtsey and did not record any seismic activity associated with the eruption, while some was detected at VIK, in 1964–1966, 80 km from Surtsey. Both had old low sensitivity Mainka sensors. The important stations for our study, as they were continuously recording and had a much higher magnification than AKU and VIK, were the station in Reykjavík (REY) and at Kirkjubæjarklaustur (SID). SID only had a vertical Willmore sensor, while REY, equipped with Sprengnether sensors, had


a
Nov 14,1963
b
Dec 29,1963
c
Feb 17,1964
d
May 24,1964
e
Jun 16,1965
f
Jul 15,1966


g
Surtungur
feb '64-okt '65
Surtur
nóv '63-júní '67
m a.s.l.
Surtsey volcanics
NW
pre-eruption seabed
SE
Jólnir
des '65-sept '66
Surtsey
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Syrtlingur
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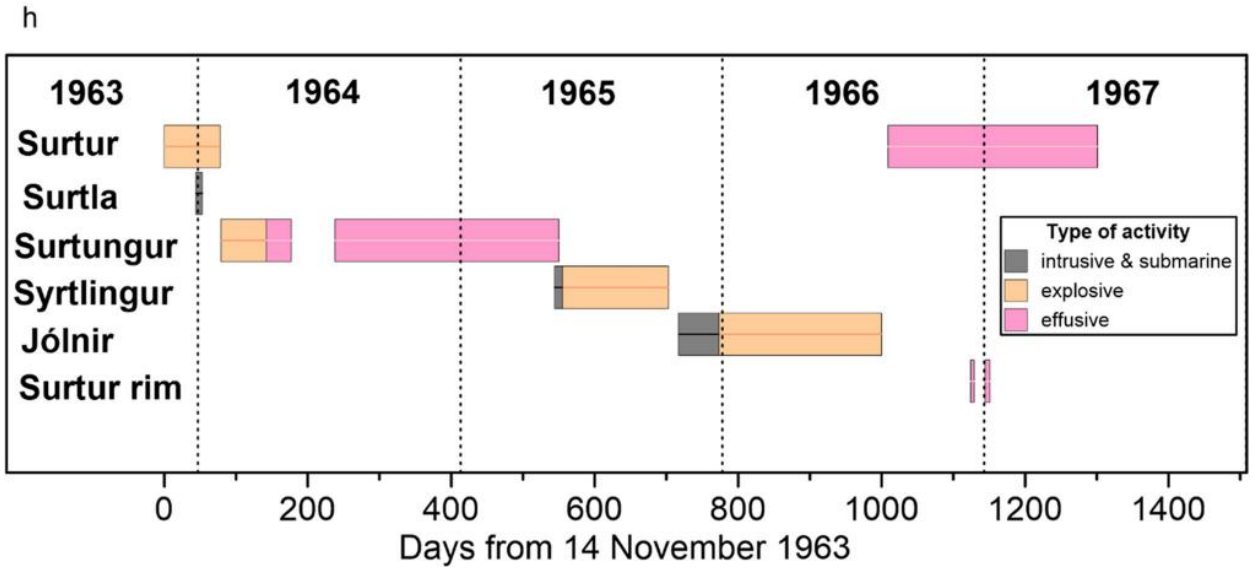
1967
WSW
ENE
km


h
1963
1964
1965
1966
1967
Surtur
Surtla
Surtungur
Syrtlingur
Jólnir
Surtur rim
Type of activity
intrusive & submarine
explosive
effusive
Days from 14 November 1963

◂**Fig. 2** The course of events during the Surtsey eruptions in 1963–1967. **a** Onset of the eruption – explosive eruption of Surtur crater, November 1963-January 1964. **b** Submarine eruption-Surtla, December 1963–January 1964. **c** Formation of the parasitic cone of Surtungur, January–April 1964 (aerial photo). **d** Lava effusion from Surtungur, April–July 1964. **e** The temporary island of Syrtlingur, May–October 1965. **f** The temporary island of Jólnir, December 1965–August 1966. **g** Section through the Jólnir–Surtsey–Syrtlingur–Surtla, a 5-km-long discontinuous fissure with the present bathymetry and topography and the approximate outline at the height of activity at each locality (based on data in Thorarinsson, 1966, 1967a, b, and Jakobsson et al. 2009). A perpendicular section through the island of Surtsey is also shown. **h** Timeline of events during 1963–1967. Photos (**a**), (**b**), (**d**), (**e**), and (**f**) by S. Einarsson and (**c**) from the Icelandic Geodetic Survey

both a vertical and a E-W sensor. In comparisons presented below, we use the Z-component. The seismological bulletins of the IMO for this period (Icelandic Meteorological Office 1964a, 1964b, 1970, 1978, 1979a, 1979b, 1980) present a list of seismic events, with locations if available. In some cases, IMO could use the method generally applied in the pre-digital era of foci determinations based on arrival times from three stations, supplemented by station P- and S-wave arrival time differences. However, for many of the smaller local earthquakes ($M < 3$), detection was limited to a single station, usually SID, with epicentral distance based on the P- and S-wave arrival time difference. For some of these earthquakes detected by a single station, a source area is suggested, but this is usually unconstrained by the data. Given the weak signals and the simple approach, the epicentral distances are considered to have an uncertainty of 10–20 km. The magnitudes (M_L) of earthquakes presented here are from the IMO bulletins, calculated from trace amplitudes and a local magnitude scale (Icelandic Meteorological Office 1978). More details on history of analog seismographs and their progressing in Iceland can be found in Einarsson and Jakobsson (2021).

The higher magnification of SID coupled with higher natural frequency made that station less sensitive to microseisms and more sensitive to the higher frequency volcanic tremor and earthquakes compared to REY (Fig. 3b). Comparison of the seismograms from these two stations shows that on many occasions, when REY is dominated by what are apparently the higher frequency end of the microseisms, SID was much less affected (see Supplementary Material 1), allowing detection of low amplitude signals from earthquakes at distances of 100–150 km, especially for the days before the onset of visible eruption (Sigtryggsson and Sigurdsson 1966; Icelandic Meteorological Office 1970).

The analog seismic records of Reykjavik (REY) and Kirkjubæjarklaustur (SID) have been scanned at a resolution of 300 dpi and made accessible on the website of the Institute of Earth Sciences, University of Iceland (http://seismis.is; see also Supplementary Material 1). Compared to present-day standards, many types of analysis are not feasible (see below). However, the data allow for timing of events and variations with time of relative amplitudes of signals to be estimated.

Analysis of data

The seismological bulletins contain 186 events associated with Surtsey in the period 1963–1967 (see Supplementary Material 2). The largest earthquake of $M_L = 4.5$ happened on January 9, 1964, almost 2 months after the start of the eruption, while the smallest detected event ($M_L = 1.9$) occurred on May 13, 1965. Most of the events were only detected by the two permanent network stations of SID and REY. However, during the period January–April 1964, a temporary and uncalibrated station in Heimaey, 20 km from Surtsey, recorded these earthquakes and several additional events not picked up by SID and REY (Pálmason 1966). The number above does not include five events with magnitude between 2.4 and 2.9 detected at SID between November 3 and 7, with epicentral distance fitting with Surtsey but assigned to the Vatnajökull region (Fig. 3a) in the Bulletin (Icelandic Meteorological Office 1970).

We use the magnitude-frequency relation of Gutenberg-Richter to evaluate the magnitude of completeness (M_c). The curve is approximately linear for local magnitudes (M_L) between 2.4–2.5 and 4, indicating a value of ~ 2.5 for M_c (Fig. 4). We therefore take $M_L = 2.5$ as the lower limit for earthquakes that have a high likelihood of being detected. However, during periods of high winds and in particular strong microseisms, the detection threshold may have been higher. The number of events ≥ 2.5 during the eruption is 140. The Gutenberg-Richter diagram (Fig. 4) indicates a *b* value of 0.5–0.6. Such low values are usually taken to indicate high stress. This will, however, not be considered further here, as the total number of recorded events and the narrow magnitude range are both marginal for reliable statistics (Kulhanek 2005).

A volcanic eruption in the ocean and expected associated intrusive activity may generate earthquakes with P-, S-, surface waves, and possibly T-waves (Wech et al. 2018), as well as various types of seismic tremor. The limitations imposed by the data imply that it is not possible to apply several present-day standard practices in volcano seismology used for digital, broadband data. Digitizing the traces is not feasible, as the time resolution of the drum records is of the order of 1–2 mm/s, possibly allowing wave reconstruction of a signal < 2 Hz. In comparison, the signals detected from local earthquakes commonly have the highest amplitude waves at 10–30 Hz. Thus, spectral analysis is not possible while approximate estimates of the dominant frequency of tremor can sometimes be done. Moreover, given the different sensitivity and bandwidth of the instruments used (Fig. 3b), comparisons of amplitudes

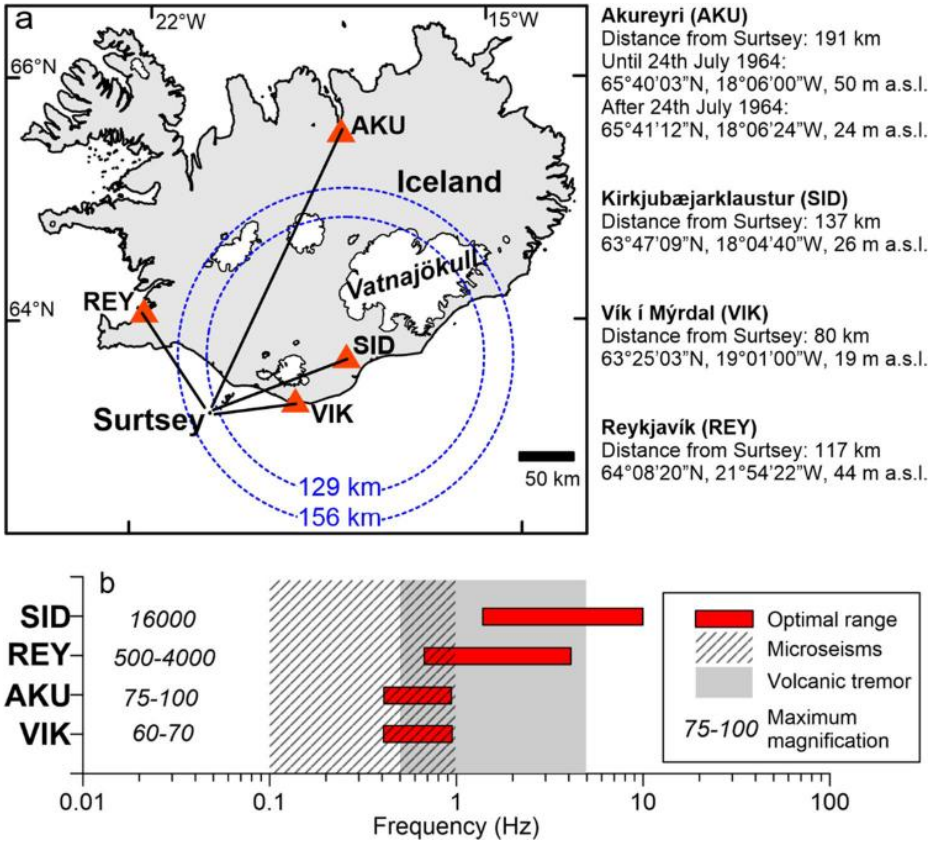


Fig. 3 **a** Location of seismic stations in Iceland 1963–1967 and their characteristics. The blue circles show the epicentral distance of five events recorded at SID (local magnitude 2.4–2.9) on November 3–6, 1963, where epicentral distance could be estimated. **b** Magnification and frequency ranges of the seismic instruments (Sigtryggsson and Sigurdsson 1966; Icelandic Meteorological Office 1970) and how they compare with the characteristic frequency range of oceanic microseisms and volcanic tremor

between different stations are not reliable. No hydrophones or stations of sufficient sensitivity existed on the coast, with the seismograph at the coast (VIK) having very low sensitivity (Fig. 3b). This indicates that if T-waves were generated, they would not have been detected by the system.

The data allow the determination of the temporal distribution and magnitudes of seismic events above the threshold value of $M_L = 2.5$. They also allow a rough estimation of how average wave amplitudes varied at both SID and REY in the days preceding the visible eruption on November 14, 1963. Studies that identify the source areas of microseisms in the North Atlantic include Dahm et al. (2006) and Kedar et al. (2008). Here we follow Kedar et al. (2008) when defining the likely source regions of microseisms and use the ocean wave amplitudes for the region southwest of Iceland to compare with the average noise amplitudes in the seismic records. Although it is known that this region is not the only source of microseisms in the region (Dahm et al. 2006), Kedar et al. (2008) demonstrate that it is the most likely one.

Results

Seismicity associated with the start of the eruption in November 1963

We have investigated the seismological bulletins for the 3-year period 1961 to 1963 to look for possible precursory earthquakes. Moreover, we have analyzed the seismic records for the SID and REY stations over the 12-month period before the onset of the visible eruption to look for possible seismic signals preceding the visible eruption.

Earthquakes preceding the visible eruption

No earthquakes were felt in Heimaey before the Surtsey eruption while several small earthquakes were detected at SID on November 6–8, 1963 (Sigtryggsson and Sigurdsson

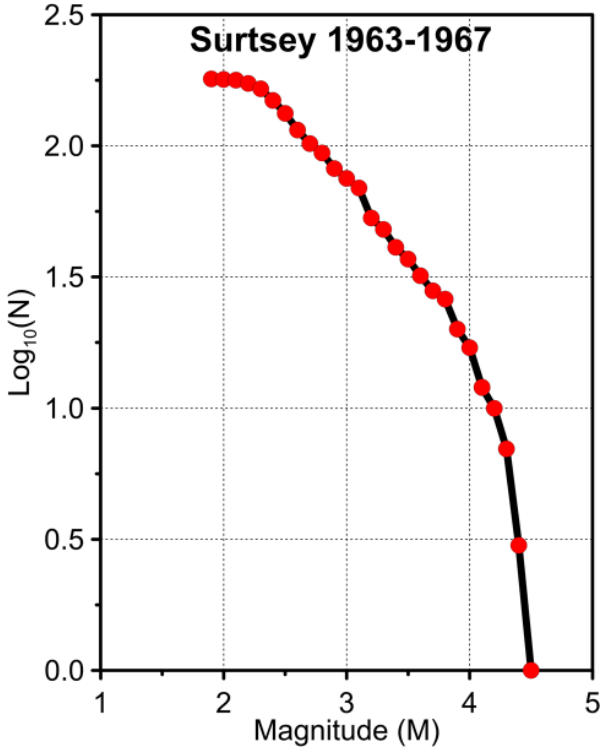


Fig. 4 Gutenberg-Richter plot for the 186 events associated with Surtsey in 1963–1967 in the seismological bulletins of the Icelandic Meteorological Office, suggesting a magnitude of completeness of $M_L = 2.5$. N is the cumulative number of the events of magnitude M and larger

1966). The IMO Bulletin for 1963 (Icelandic Meteorological Office 1970), however, does not assign any earthquakes to Vestmannaeyjar/Surtsey in November. Five earthquakes are assigned to Vatnajökull, located at 129–156 km epicentral distance from SID during November 3–6 (Fig. 5). The epicentral distances are shown as blue circles on Fig. 3a and they fit well with Surtsey. Comparison with records of seismicity gathered over the last few decades (Einarsson 1991; Jakobsdóttir 2008) indicate that the epicentral distances are too long to fit with the seismically active areas in Vatnajökull. We therefore propose that Surtsey is the most likely source area for these earthquakes. Several other events of comparable amplitude occur over this period and again on November 10 where identification of S-waves is uncertain, precluding determination of epicentral distance. The records from REY for the first half of November show no signals that can be interpreted as small earthquakes. REY had a magnification that was about one order of magnitude lower than SID (Fig. 3b). Importantly, the REY records indicate persistent microseism activity throughout this period, while SID was much less affected. This greater sensitivity of REY to microseisms compared with SID is noted by Sigtryggsson and Sigurdsson (1966).

Three earthquakes ($M_c = 2.7$–3.0) of epicentral distances 120–156 km occurred on May 4 and May 26, 1963, only detected at SID, listed in the Bulletin and assigned to the area north of Vatnajökull. In addition, one earthquake ($M_c = 2.8$) occurs on May 12, with epicenter 100 km from REY and 143 km from SID. These four earthquakes are the only events found in the Bulletin that may have been associated with Vestmannaeyjar and occurred in the period January–October 1963.

Seismic tremors preceding the visible eruption

The start of a volcanic eruption is often marked by onset of seismic tremor (Einarsson 2018), and in the case of a fully submarine eruption in relatively shallow waters, vigorous convection above the vents is expected to generate a thermal plume that spreads on the ocean surface, as, e.g., observed in the El Hierro eruption (Martí et al. 2013). To investigate possible tremor signals in the days preceding the visible eruption and how they relate to the activity in the first days of the eruption, we measure the amplitude of the oscillations observed on seismic traces for both SID and REY in the period November 1–15 (Fig. 6a, b). The records do not provide absolute amplitudes of seismic trace oscillations but do allow a relative comparison between different times for each station over this 15-day period. This record is compared with ocean wave amplitudes to the east of the tip of Greenland and southwest of Iceland (using two locations: 58° N, 35° W and 58° N, 40° W), approximating the principal source area for microseisms in the North-Atlantic (Kedar et al. 2008). The comparison shows a broad correlation between the trace amplitudes and the waves. SID and REY follow similar trends in trace amplitudes for most of the time, while a conspicuous peak occurs in SID in the afternoon and evening of November 12, with spikes occurring on November 13 as well. Comparison with the ocean wave amplitudes and wind on the south coast of Iceland indicates that weather and swell near Iceland is an unlikely explanation for this peak, as no storms or high waves occurred during this period. Detection of volcanic tremor over comparable distances has been documented several times in Iceland (Brandsdóttir and Einarsson 1992; Soosalu et al. 2003, 2005).

Figure 7 shows parts of the seismograms at SID over 4 days, November 11–14. The first day (Nov. 11) is relatively quiet, while from 13:00 on Nov. 12 signals that are apparently a low frequency tremor of approximately 1–2 Hz begin and remain for the next several hours. The record from Nov. 13 is similar, but of slightly lower amplitude, while a clear burst of tremor occurred between 13:20 and 16:40. By November 14, the overall amplitudes are reduced, and no

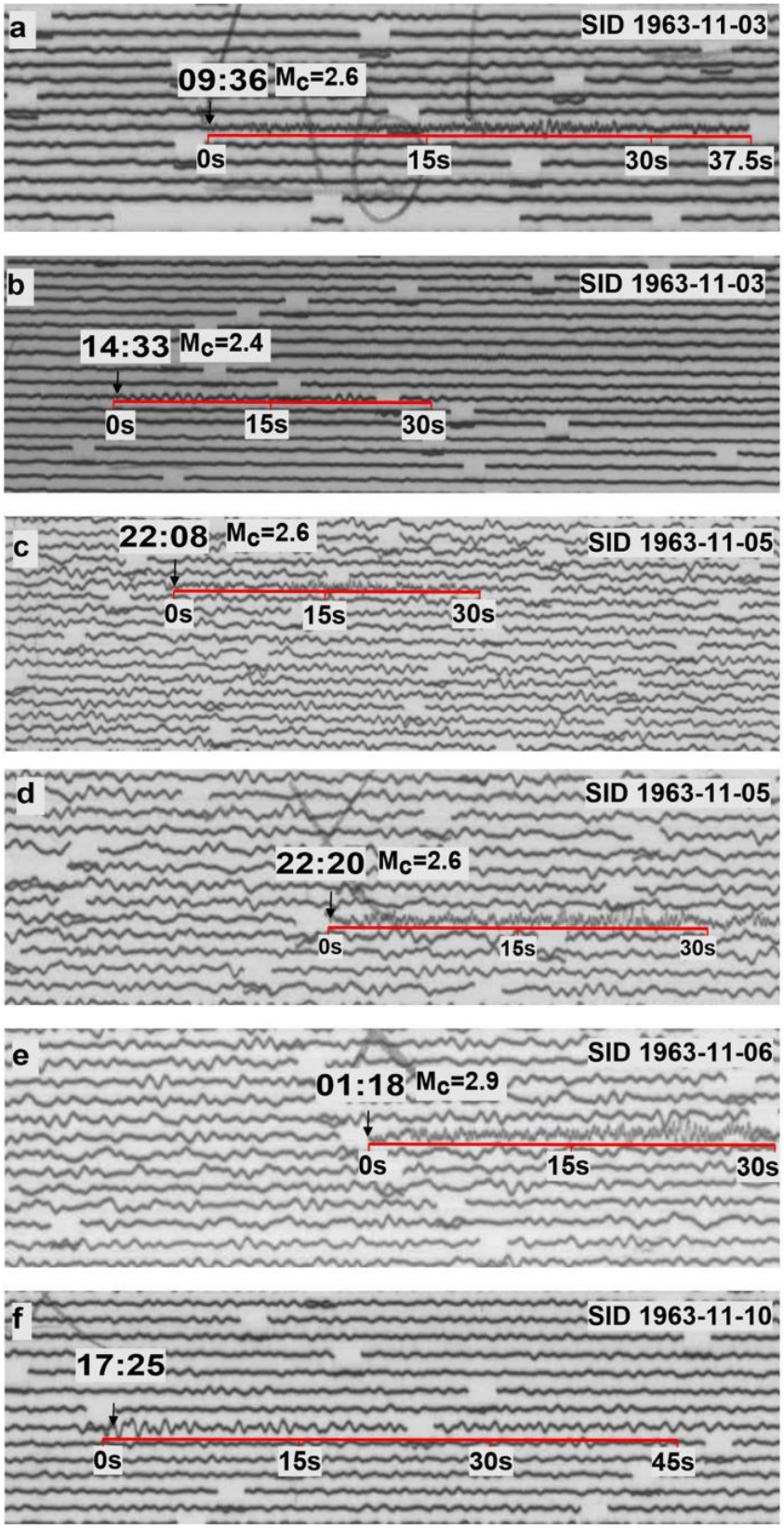


Fig. 5 Examples of seismograms from SID with earthquakes in early November 1963. **a–e** have epicentral distances fitting with Surtsey and magnitudes 2.4–2.9. **f** does not have epicentral distance determined in the seismological bulletin and therefore magnitude is not defined

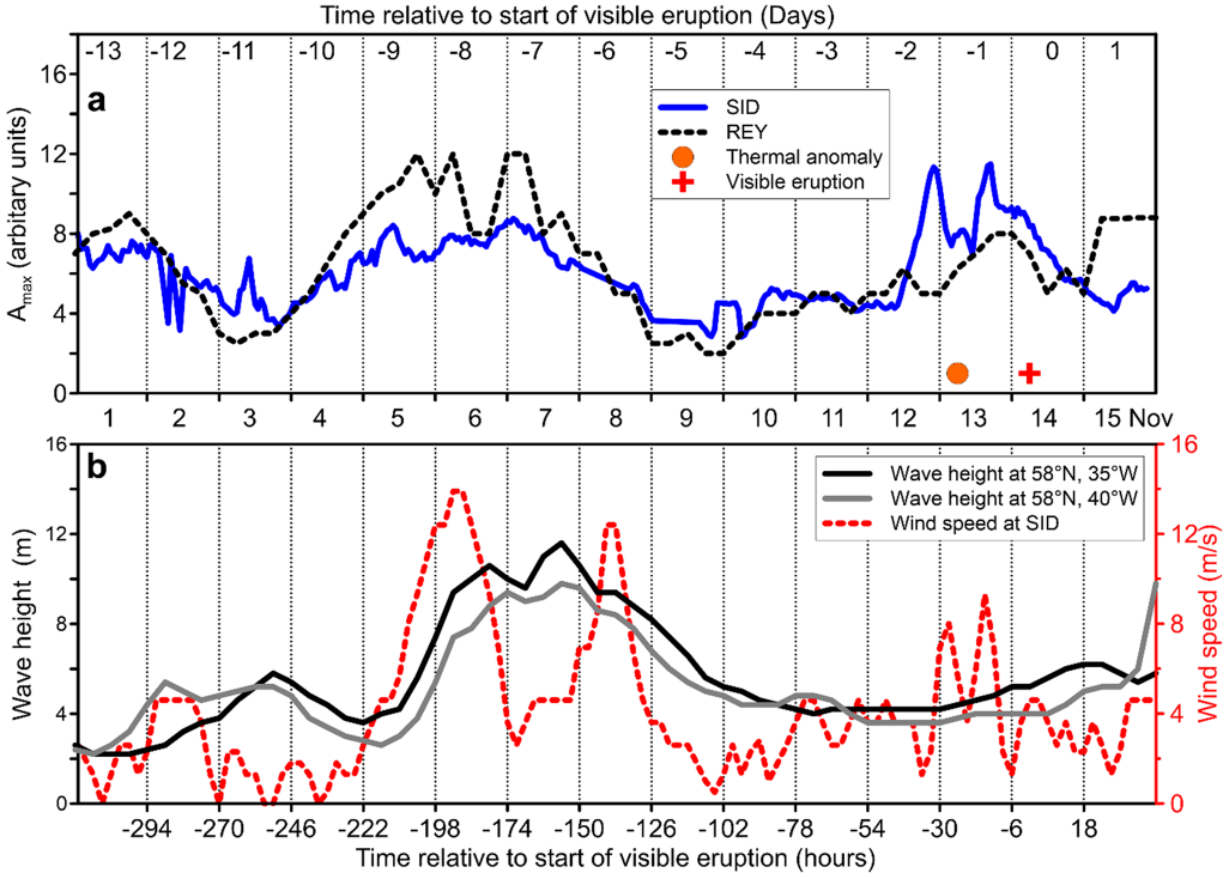


Fig. 6 Comparison of wind strength, ocean wave height, and ambient seismic wave amplitude at SID and REY during November 1–15, 1963. Zero on time axis is set at 06:00 on November 14. **a** Variation of maximum amplitude observed on the seismic records. Approximate time of observation of thermal anomaly on November 13 and the visible eruption are shown. **b** Wave height to the southeast of the tip of Greenland (ECMRWF data), and wind speed at SID (IMO data; see Fig. 1a for location)

seismic signal occurs during the onset of subaerial eruption at or before 06:30.

Thermal anomaly in ocean on November 13

A trawler was searching for herring in the area in the early morning of November 13 (Thorarinsson et al. 1964). The ship was equipped with a thermometer fitted to its side providing continuous readings. A sudden rise in sea surface temperature from about 7 °C to 9.4 °C occurred at a location two nautical miles (3.5–4 km) to the southwest of where the eruption was observed the following day (Malmberg 1965). The width of the area of the thermal anomaly was not measured. The existence of this temperature anomaly indicates a substantial heat source in the ocean, consistent with a submarine eruption already ongoing at this time; the temperature anomaly of ~ 2.4 °C is comparable to the changes observed during the 2011–2012 submarine El Hierro eruption (Hernández et al. 2014). Moreover, the location of the anomaly, 3.5–4 km southwest of present-day Surtsey, indicates that it was carried by a combination of spreading of buoyant warm water on the surface of the ocean and drift by generally southwestward currents in this area of order 0.1 m/s or less (Logemann et al. 2013). Using a maximum current velocity of 0.1 m/s, the minimum transfer time for the plume water to the point of observation is therefore 10 h. This indicates that a submarine eruption had started no later than in the late afternoon or early evening of November 12.

Synthesis, eruption precursors, and eruption onset

The records from SID indicate elevated seismicity at a distance that fits with Surtsey in the period November 3–10. Five of these earthquakes were assigned local magnitudes in the range 2.4–2.9. There are additional 10–15 events that neither have a magnitude estimate nor estimate of epicentral distance (Supplementary Material 1). Given the timing, we propose that these are also precursory earthquakes

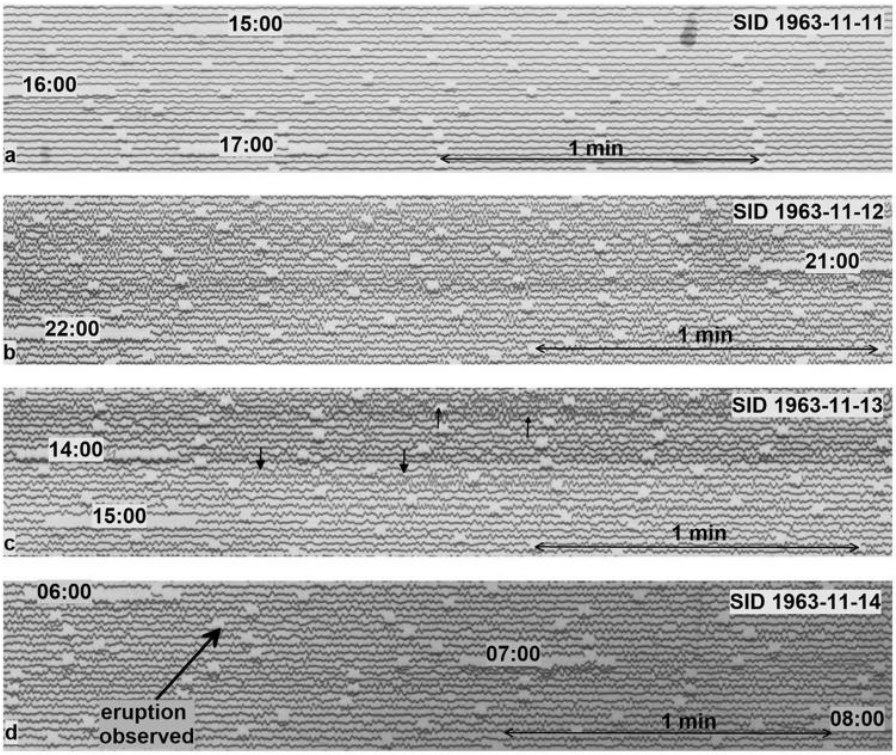


Fig. 7 Seismic records at SID for November 11–14, 1963. **a** November 11: record is relatively quiet with no indications of tremor. **b** November 12: the afternoon and evening is characterized by trains of signals of approximately 1–2 Hz frequency that looks like volcanic tremor. **c** November 13: the record appears similar as the day before, while the bursts of signals that may be tremor are not as sustained. **d** November 14: the signal is slightly less noisy than on November 12–13, and bursts of apparent volcanic tremor as seen the previous day are not obvious. The timing of first visual observation at around 06:30 is marked

for Surtsey. This indicates that the precursory earthquakes may have reached magnitude close to 3 while most events were smaller. This fits with the lack of felt earthquakes in Heimaey prior to the eruption. Further, the data indicate that significant precursory seismicity began on November 3. Occasional seismic events may have occurred for months, as the earthquakes observed in May 1963 and mentioned above may have been related to Surtsey.

On November 12, tremor is weak or non-existent at 12:00 but has gradually set in after 13:00, and by 15:00 there is strong, low frequency tremor. For basaltic eruptions (Einarsson 2018), it is common that earthquake activity usually drops, and tremor picks up with the onset of eruption. We therefore propose that the most likely onset time is between 12:00 and 14:00 on November 12. Given that the eruption had become visible by 06:30 on November 14, this suggests that the duration of the submarine phase was about 40 h.

Seismic activity during eruption

The 3.5 years of eruptive activity in 1963–1967 can be split into different episodes (Fig. 2h), with activity migrating between Surtur, Surtungur, Surtla, Syrtlingur, and Jólnir (Fig. 1). Significant seismic signals were observed over long periods from late 1963 to the end of the eruption in 1967 (Fig. 8).

The largest earthquake occurred at 16:33 on January 9 (Day 56) with a magnitude of 4.5, while Surtur was still active (Fig. 8b). It was felt in Vestmannaeyjar. The smallest felt earthquake had a magnitude of 3.7 (Sigtryggsson and Sigurdsson 1966).

The 186 recorded earthquakes from the bulletins (including 140 with a magnitude ≥ 2.5) are all included in Fig. 8a, with the addition of the five earthquakes of registered magnitude and detected at SID on November 3–7. The earthquakes show clear clustering into swarms. There are the relatively small earthquakes preceding the eruption (M_L range 2.4 to 2.9) followed by no detected earthquakes until December. Six swarms have earthquakes exceeding magnitude 3. These swarms occurred on December 17–23, 1963; January 3–10 and January 31–February 1 in 1964 (Fig. 8b); May 8–20, 1965 (Fig. 8c); October 28 to November 27, 1965 (Fig. 8c); and July 27 to August 8, 1966 (Fig. 8d). In addition, 15 earthquakes up to magnitude 2.9 occurred in the 12 days between March 23 and April 4, 1964.

The course of eruptive events, including timing of individual episodes of the eruptive activity, is provided by Thorarinsson et al. (1964) and Thorarinsson (1965, 1966, 1967a, 1968a, b). The earthquake swarms show a clear correlation with changes in vent location; for the submarine eruption of Surtla (Fig. 8b), the start of the earthquake swarm on December 17 (day 33) preceded the visible activity by 10 days. The largest swarm occurred

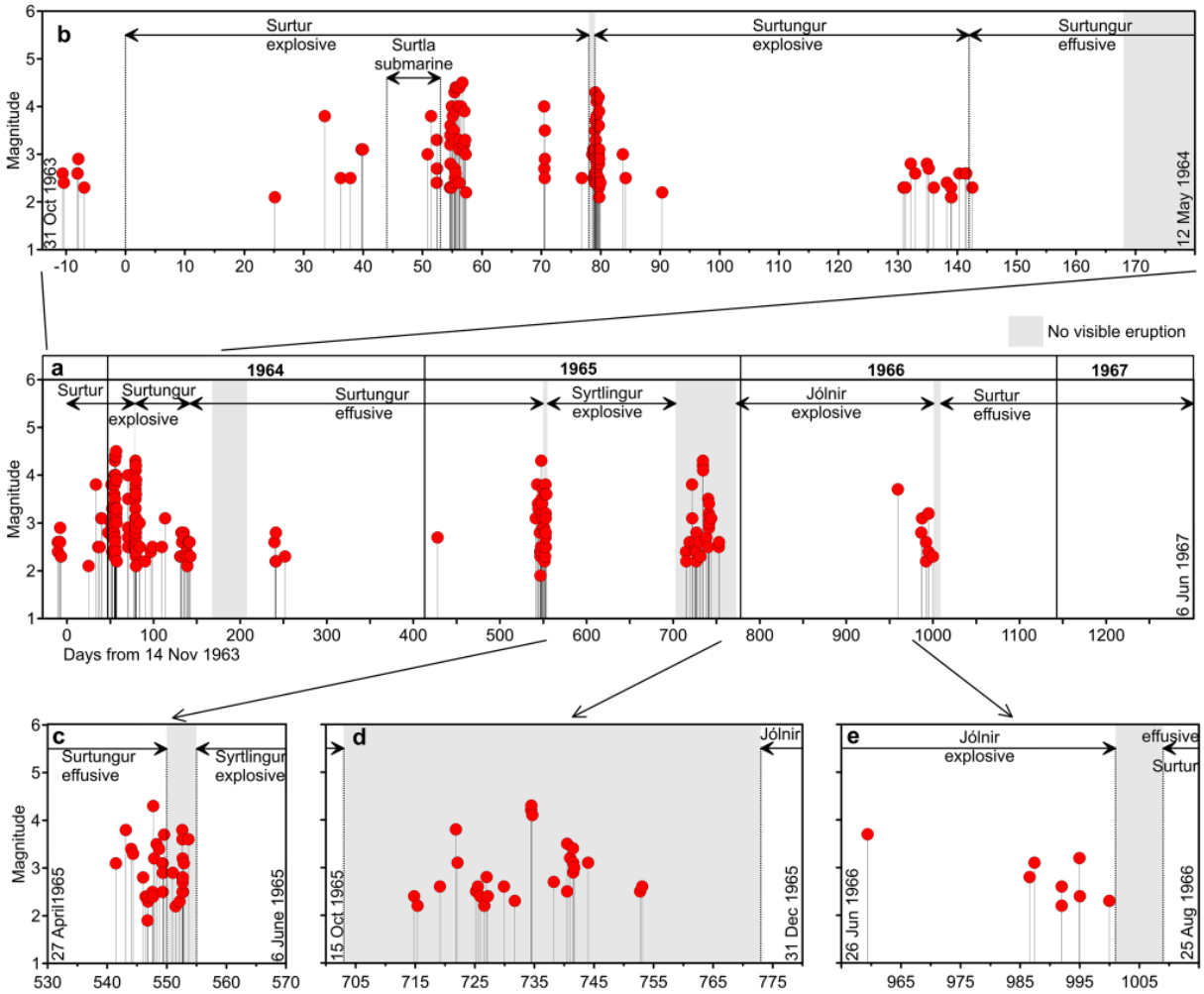


Fig. 8 Earthquake activity recorded in association with Surtsey 1963–1967. **a** The central panel shows the complete timeline (1963–1967), while the **b** top panel displays the period end of October 1963 to May 1964. The bottom panel shows, respectively, **c** the onset of the Syrtlingur episode in May 1964; **d** the end of Syrtlingur and start of Jólnir in October–December 1965; **e** the end of Jólnir and start of the final effusive phase of Surtur in June–August 1966

near the end of the Surtla submarine eruption and continued for 5 days after cessation of visible eruptive activity. The next earthquake swarm occurred at the end of January/beginning of February 1964, starting about 2 days before the onset of explosive activity in Surtungur (Fig. 8b). The cluster in May 1965 (Fig. 8c) began 14 days before and ended 2 days before the Syrtlingur eruption became visible. For the cluster in October–December 1965 (Fig. 8d), the earthquake swarm began 62 days and ended 21 days before the Jólnir eruption became visible. The final swarm in July–August 1966 (Fig. 8d) began 22 days before and ended 9 days prior to the reactivation of Surtur as an effusive vent, starting the final phase of the 3.5-year-long eruption.

Discussion

Our analysis indicates that earthquakes of local magnitude $M_L \geq 2.5$ originating beneath the Vestmannaeyjar archipelago had a high likelihood of being detected by the seismic network in Iceland in 1963. As many smaller earthquakes were at this time only detected at one station (SID), epicenter location is problematic, and the assigning of precursory earthquakes to Surtsey based on these limited data is challenging to assert. However, the occurrence of several events during November 3–10, with epicentral distance fitting with Surtsey, the only such swarm detected in 1963 (Icelandic Meteorological Office 1970), is an indication of a connection to Surtsey. Acknowledging this uncertainty,

our interpretation is that a swarm of precursory earthquakes began no later than November 3 with events detected until November 10. Further, the onset of what is most likely volcanic tremor in the early afternoon of November 12 is considered to mark the start of the submarine eruption. Thus, the indications are that significant precursory seismicity had begun about 9 days before the onset of submarine eruption.

The activity assigned to Surtsey can be compared with the earthquakes observed preceding the Heimaey eruption (Fig. 1) in late January 1973 and the Eyjafjallajökull eruption in March–April 2010. The Heimaey eruption occurred in the Vestmannaeyjar volcanic system, with the vents located on the main island of the archipelago, forcing the emergency evacuation of its 5000 inhabitants. This eruption was preceded by a swarm of over 200 recorded earthquakes of magnitudes less than 3.5 in the last 30 h before the eruption (Björnsson and Einarsson 1974). Eyjafjallajökull in 2010 is another example of an eruption in Iceland within a volcanic system located in a similar tectonic setting where rifting is mostly absent, near the tip of the southwards propagating Eastern Volcanic Zone (Sigmundsson et al. 2010). At the time of the 2010 eruption, a network of seismic stations was in place, allowing detection of events of magnitude $M_L > 1$. The total number of earthquakes detected over a six-month period (January–June 2010) was about 5000, of which about 80% occurred in the 3 weeks prior to the onset of the flank eruption on March 21 (Sigmundsson et al. 2010; Thorkelsson 2012). The largest earthquake in this swarm had a magnitude of 3.0; only 10 had magnitude exceeding 2.5 (Thorkelsson 2012). Given the limitations of the seismic network of the 1960s, the indications are that even though a comparable swarm of several thousand earthquakes and the same distribution of magnitudes likely preceded the Surtsey eruption, the number of detected events would only have been of the order of 10–20, similar to what was observed at SID in early November 1963. This indicates that the Surtsey eruption broadly fits with observations for eruptions in Iceland since 1973, all of which had precursory seismicity (Einarsson 2018), a result that applies generally to eruptions worldwide, with the exception of persistently active, open-vent volcanoes (McNutt and Roman 2015).

The earthquake swarms in December 1963–early 1964 show that seismic activity was quite prominent at times, with several felt earthquakes. Timing of earthquake swarms was strongly correlated with shifts in the location of vents as shown in Fig. 8 (Surtla, shift from Surtur to Surtungur, Syrtlingur eruption, Jólnir eruption, and resumption of activity in Surtur). Apparently, the earthquakes occurred as new pathways for magma were formed. The short distances between the different vents (1–2 km) may indicate that the formation of different magma pathways and the associated seismicity occurred in the shallow crust. The prominent swarm in January 3–10, 1964, may have been caused by migration of magma exploring new pathways to the surface that resulted in intrusive activity while ending before magma reached the surface. A change in vent location occurred roughly 3 weeks later, on January 31, when Surtungur took over from Surtur. We further suggest that the onset of submarine eruption for Syrtlingur and Jólnir coincides with a distinct drop-in seismic activity, respectively, 2 and 20 days before these eruptions broke the ocean surface and became visible (Fig. 8c, d).

The temporal correlation of increased seismic activity with shifts in the eruption sites was already noted by Einarsson (1974) for the shift of eruptive activity in the summer of 1966 from Jólnir to Surtsey. Similar correlation has been seen in other Icelandic eruptions, e.g., for the eruption of Hekla in 1970 (Einarsson and Björnsson 1976). The causal relationship may not always be clear, but it is plausible that the earthquake activity reflects stress changes around the volcano, caused by intrusion of new magma, introduction of fluids into pre-stressed medium, gravitational stresses from load changes, or a combination of these. As no detailed geophysical surveys of the crust beneath and around Surtsey exist, the existence or absence of shallow intrusions relating to the earthquake swarms remains unknown.

Conclusions

Seismic records from the time of the Surtsey eruption off the South Coast of Iceland in 1963–1967 have been analyzed and compared with seismological bulletins for the same period, with the aim of studying the seismic characteristics of the eruption. The results indicate that the magnitude of completeness for earthquakes associated with the Surtsey eruption was $M_L = 2.5$. Earthquakes smaller than that are likely to have been overlooked by the rather rudimentary seismic network at the time, with only two usable stations in operation, REY and SID, at distances over 100 km. Out of the permanent stations registering Surtsey-related seismicity, SID, at 131 km distance ENE from Surtsey, was more sensitive than REY and more likely to detect activity associated with Surtsey.

Five earthquakes of local magnitude 2.4–2.9 with epicentral distance from SID fitting with Surtsey occurred in November 3–7, with additional events of similar magnitude occurring in November 8–10. This activity on November 3–10, 1963, is interpreted as be precursory earthquakes, indicating that a swarm of events with magnitudes less than 3 occurred over at least nine days before the onset of the eruption, the largest of magnitude 2.9.

The submarine eruption is considered to have started in the early afternoon of November 12, when continuous volcanic tremor of dominant frequency 1–2 Hz appears at SID, continuing on November 13. The eruption is considered to

have remained submarine for about 40 h, progressing to an emergent phreatomagmatic eruption by 06:30 on November 14.

The earthquakes recorded after the onset of the eruption have a strong temporal correlation with shifts in eruptive activity from one vent to another. The onset of earthquake swarms precedes the opening of new vents by a period ranging from 2 days to a few weeks with the longest period occurring prior to the submarine Jólnir eruption in December 1965.

This study has provided new insight in to the seismicity of this historically important eruption, for the first time providing constraints on the precursory seismicity, eruption onset, and duration of the submarine phase, as well as demonstrating the correlation between seismic activity and changes in vent location. The study also demonstrates how old analog seismic data may contain information on volcanic eruptions of historical and scientific importance that occurred prior to the present age of digital seismometers.

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Paper II
Volcanic tremor associated with the Surtsey eruption of 1963–1967

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Reviewed research article

Volcanic tremor associated with the Surtsey eruption of 1963–1967

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Abstract — *The formation of the island of Surtsey over 3.5 years, remains one of the best-documented volcanic, island-forming eruptions to date. The basaltic submarine volcanic activity was detected on November 14, 1963, where ocean depth was 130 m prior to the eruption at the southern end of the Vestmannaeyjar archipelago. The eruptions occurred in several phases involving explosive and effusive activity, including the initial submarine phase on November 12–13, 1963. Separate phases of subaerial volcanic activity occurred during November 14, 1963–January 1964, January–April 1964, April 1964–May 1965, May–October 1965, December 1965–August 1966, and August 1966–June 1967. Seismic data quality from this period is inferior compared to that of modern monitoring systems. Four permanent seismic stations were operated in Iceland at the time, whereof only two, located at 115 and 140 km distance, had the sensitivity to record tremor from Surtsey. Nevertheless, the scanned analog seismograms (http://seismis.hi.is/) show that the eruptive activity was accompanied by considerable seismic activity, both earthquakes, and volcanic tremor. Earthquakes were primarily associated with changes in vent location. Both spasmodic and harmonic tremor was identified, both with low (<3 Hz) and higher (3–5 Hz) characteristic frequencies. The results indicate a complicated relationship between tremor and magma flow rate or style of activity. During the explosive eruption, the highest magma flow rates occurred in the first 10–20 days, a period with little observed tremor. The highest tremor is observed in December 1963–March 1964, after the discharge rates had dropped substantially, and on a timescale of hours-to-days, no clear relationship between tremor and eruption style is observed. The same applies to the effusive activity, where no seismic tremor was observed during most of the effusive eruption of Surtungur, despite the fact that magma flow rates were ∼3 times higher than during later phases where some tremor was observed.*

Keywords: Submarine volcanism, eruption precursors, volcanic tremor, precursory tremor, continuous uprush eruptions

INTRODUCTION

Magmatic events, both intrusions and eruptions, are accompanied by characteristic seismic patterns (e.g., Brandsdóttir and Einarsson 1992; McNutt and Roman 2015). Recent studies confirm that all eruptions in Iceland in the last decades have been preceded by swarms of microearthquakes and short-term seismic precursors (Einarsson, 2018). The characteristics of such activity vary and are not the same for all volcanoes. Moreover, individual volcanoes may not always behave in the same way, calling for studies of multiple eruptive cycles to characterize the seismic precursors to an eruption, which may not be feasible where eruptions happen only infrequently (Unglert and Jellinek, 2015). High precision digital records of seismicity, including earthquakes and tremor, exist for various events over the last few decades and great advances have been made in analysis of such phenomena at volcanoes (e.g., McNutt and Roman, 2015 and references therein). However, seismic data collected during some notable events from the early days of seismic analog recordings, although of inferior quality compared to modern-day seismographs,

may also provide useful insight. One such eruption of distinct character, where analog seismic data exist, is the 3.5-year long Surtsey eruption in 1963–1967. The eruption occurred off the south coast of Iceland at the southern end of the Vestmannaeyjar archipelago of Iceland's Eastern Volcanic Zone (Figure 1). Approximately 1.1–1.2 km^3 bulk volume of lava and tephra were erupted (Thorarinsson, 1968; Ólafsson, 2021). The eruption had several eruption episodes at different vents and included shallow to emergent Surtseyan explosive activity and long periods of effusive activity of varying magnitude that was well documented (e.g., Thorarinsson *et al.*, 1964; Thorarinsson, 1968).

There was no seismograph in Vestmannaeyjar at the time of the eruption onset. The four permanent stations operated in Iceland at that time were located at a considerable distance from the eruption site (80–291 km, see below). The network was operated by the Icelandic Meteorological Office, where the seismic records were analyzed, and the results published (Icelandic Meteorological Office 1970,1978,1979a,1979b,1980). Sigtryggsson and Sigurdsson (1966) noted the occurrence of tremor and earthquakes in November and December of 1963. An array of short-period seismograph was installed in Surtsey in the summer of 1966. This array recorded earthquakes swarms associated with the cessation of the last explosive phase of the Surtsey eruptions (Jólnir) and the beginning of the final lava effusion on the island (Einarsson, 1974). In 2017 a drilling program was carried out on Surtsey with multiple aims of detailed studies of the island's structure and evolution under the umbrella of the SUSTAIN project (Jackson *et al.*, 2019; Weisenberger *et al.*, 2019). This work has provided new insight into various aspects of the formation and evolution of Surtsey, including the structure and existence of a diatreme under the main crater (Jackson *et al.*, 2019), the progressive alteration of the volcanic rocks within the edifice (Prause *et al.*, 2020), the geothermal system (Kleine *et al.*, 2020; Perez Romero, 2019) and subsurface microbiology (Bergsten *et al.*, 2021). In this context, analyses of previously poorly studied aspects of the formation of Surtsey and associated volcanic activity can provide useful insight.

Seismicity related to volcanic activity is conventionally divided into earthquakes, i.e., sudden events with clear beginning and end, and volcanic tremor, characterized by sustained vibrations of the ground for minutes, hours or days or longer, without a sharp onset. The seismic activity preceding visible eruption and the earthquakes detected during the Surtsey eruption in 1963–1967 were analyzed and interpreted by Sayyadi *et al.* (2021). The analysis suggests that the eruption was preceded by earthquakes $\geq$M2.5, a week before the beginning of the eruption. Subsequent earthquake swarms were primarily associated with shifts in the eruption sites. The present paper is complimentary to Sayyadi *et al.* (2021) and focusses on the observations of volcanic tremor during the eruption. We explore the relationship between seismic tremor and a few well-constrained cases of the style of eruptive activity, notably continuous uprush, periods of cockscomb explosions, and gaps in visible eruption during the main explosive phase in November-December 1963. This re-analysis of the seismic records is greatly facilitated by the Seismis project, where historic analog seismograms of the Icelandic seismograph station have been scanned and made available through a webpage: seismis.hi.is (Einarsson and Jakobsson, 2021).

PHASES OF THE ERUPTION

Seven episodes of activity for the Surtsey eruption may be identified, based on changes in phases and activities at the five active vents Surtur, Surtla, Surtungur, Syrtlingur, and Jólnir during the years 1963–1967 leading to the creation of the new island of Surtsey (Figure 1):

•Onset of the eruption. – Explosive eruption of Surtur crater, Nov. 1963–Jan. 1964.

•Submarine eruption of Surtla, Dec. 1963–Jan. 1964.

•Formation of the parasitic cone of Surtungur, Jan.–April 1964.

•Lava effusion from Surtungur, April 1964–May 1965.

•Formation of the temporary island of Syrtlingur, May–Oct. 1965.

•Formation of the temporary island of Jólnir, Dec. 1965–August 1966.

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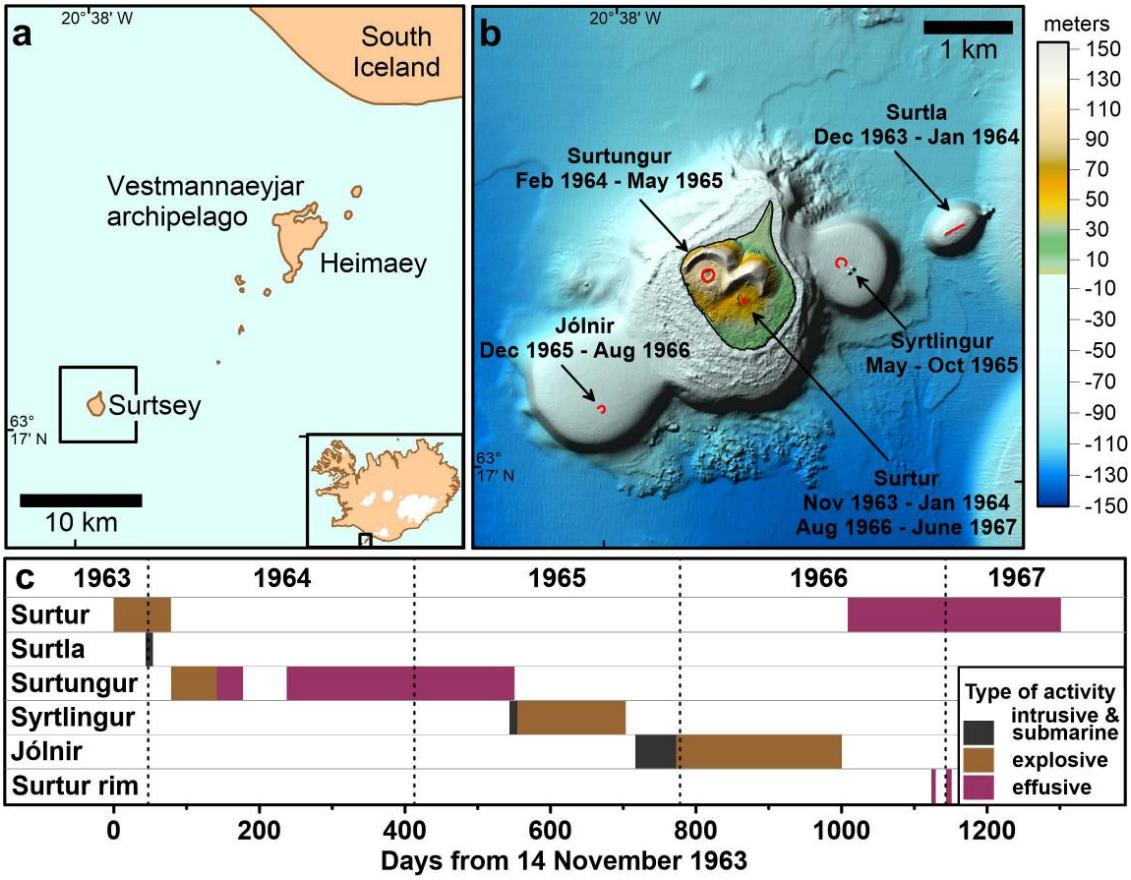

Figure 1. a) The Vestmannaeyjar archipelago off the south coast of Iceland. b) Map of the Surtsey volcano with its five different eruption sites that were active at different times during 1963–1967 (bathymetry: Jakobsson *et al.*, 2009). The two tuff cones (Surtur and Surtungur) and the later-formed effusive craters are indicated. c) The timeline and nature of different phases of the Surtsey eruptions in 1963–1967 (Thorarinsson *et al.*, 1964; and Thorarinsson 1965, 1966, 1967, 1968; Sayyadi *et al.*, 2021). – *a) Kort af Vestmannaeyjum. b) Kort af Surtsey og gosopunum sem voru virk á mismunandi tímum 1963–1967 (dýptarkort: Jakobsson og fl., 2009). Öskugígarnir tveir, Surtur og Surtungur eru sýndir, einnig hraungígarnir sem mynduðust síðar. c) Atburðarás gosanna í og við Surtsey á tímalínu (Thorarinsson og fl., 1964; og Thorarinsson 1965, 1966, 1967, 1968).*

TERMINOLOGY AND CLASSIFICATION OF VOLCANIC TREMOR SIGNALS

Magmatic activity is one of the natural processes that can generate continuous vibrations of the ground. Other processes include e.g., wind, water flow in a river, geothermal activity, waves on a shore, and swell on an open ocean. Magmatic or volcanic tremor has been described and classified by many authors (Brandsdóttir and Einarsson, 1992; Chouet, 1992; McNutt, 1992; Minakami, 1974). Some classification schemes refer to the appearance of the tremor on the seismograms, such as "harmonic tremor", with a narrow frequency band and one characteristic frequency in the range 1-10 Hz, dominating the record. The contrasting example would be "spasmodic tremor", with a broader frequency band and uneven amplitude. "Banded tremor" is characterized by regular temporal amplitude modulation of the tremor, making regular bands on the analog drum seismograms. Other schemes may use the volcanic process at work dur-

ing the respective tremor episode as a basis for the classification, such as "eruption tremor" or "intrusion tremor". Various driving mechanisms have been suggested for the different types of volcanic tremor (Aki, 1984; Aki and Koyanagi, 1981; Dziak, 2002; Fehler, 1983; Fehler and Chouet, 1982; Koyanagi *et al.*, 1987; Sgattoni *et al.*, 2016; Zuccarello *et al.*, 2013) including gas emission, turbulent magma flow, boiling in a geothermal system, and water flow.

Harmonic tremor, according to Zobin (2012), is often observed during eruptions before and during explosive phases and may be related to stress variations when magma rises in the earth's crust. Low-frequency earthquakes frequently accompany tremor at dominant frequencies of 1-5 Hz. Phreatomagmatic processes produce these in the crater of a volcano and by the movement of lava and pyroclastic flows on its slopes, as well as rockfalls (Zobin, 2012) . Most harmonic tremor looks like an irregular sinusoid with frequencies between 1 and 5 Hz.

Spasmodic tremor consists of pulses of higher frequency, usually 5–10 Hz or higher. It has only been recorded in relatively few volcanic areas, and no signals like these are known from non-volcanic regions (McNutt, 1992). During the Krafla volcano-tectonic episode in Iceland 1975–1984, spasmodic tremor was observed during intrusive activity when dikes propagated away from the central volcano's magma chamber (Einarsson and Brandsdóttir, 2021). It may be the expression of a very dense swarm of small earthquakes associated with the tip of a propagating dike. In contrast, harmonic tremor was observed at Krafla when the magma reached the surface in effusive eruptions (Brandsdóttir and Einarsson, 1992). At Krafla the amplitude of the eruption tremor reflected the intensity of the eruption. Several tremor signals recorded by seismic and acoustic networks during submarine eruptions suggest that other mechanisms may be responsible for its generation, for example, banded tremor in the Izu- Oshima eruption of 1986 (Hashimoto *et al.*, 1989) and harmonic tremor on the Volcano Islands arc south of Japan (Dziak, 2002).

Banded tremor is not observed in the records associated with the Surtsey eruption during 1963–1967 and is not considered further here.

DATA AND MONITORING SYSTEM

The four permanent seismic stations in Iceland during the eruption were in Reykjavík (REY), Kirkjubæjarklaustur (SID), Vík í Mýrdal (VIK), and Akureyri (AKU). The location of each station, distance from Surtsey, and the characteristics of the instruments used are summarized in Figure 2 (Icelandic Meteorological Office, 1970; Sigtryggsson and Sigurdsson, 1966).

Seismic station characteristics

The two stations in Reykjavík (REY) and Kirkjubæjarklaustur (SID) had a much higher magnification than the two older stations (Figure 2). The analysis presented here is based on information obtained from REY and SID. The older stations (AKU and VIK) with early 20th century Mainka seismographs (Sigtryggsson and Sigurdsson, 1966; Sayyadi *et al.*, 2021) of low magnification, do not contain signals useful for this project. The seismograms were written on paper sheets fastened on rotating drums, giving time resolution of 1 mm/second. The dynamic range of such records is low and for the observed tremor during first 150 days of eruption is estimated in the range 6 dB (low frequency) to 12 dB (high frequency and spasmodic). Moreover, resolving frequencies above 1 Hz is not possible. The waveforms at high frequencies of local earthquakes are therefore lost, even though arrival times of body waves and magnitude of the earthquakes can be determined with fair accuracy. For volcanic tremor only low-frequency (1–5 Hz) or harmonic tremor can be resolved on the seismograms. The high-frequency waveforms are already lost in the recording process, so they cannot be reconstructed from these records. The type of tremor and the dominant frequency can, however, be determined. Considering the passband of seismographs, the course of events and relative wave amplitude can be assessed. The Wilmore seismograph at SID station had a wide passband (4–25 Hz) compared to the Sprengnether sensors in Reykjavík, both N-S and Z components. For more details on the seismic network at this time see Sayyadi *et al.* (2021) and Einarsson and Jakobsson (2020).

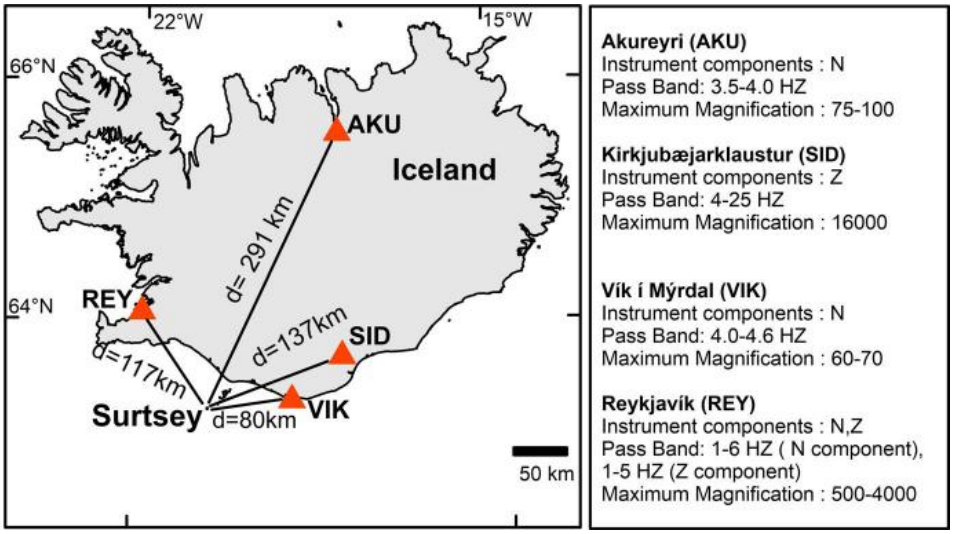

Figure 2. Seismic stations operating in 1963–1967, their characteristics, location, and distances from Surtsey (Icelandic Meteorological Office, 1970; Sigtryggsson and Sigurdsson, 1966). Modified from Sayyadi *et al.* (2021). – *Skjálftamælistöðvar á tímabilinu 1963–1967, eiginleikar mælanna, staðsetning og fjarlægð þeirra frá Surtsey (Sigtryggsson og Sigurdsson, 1966; Veðurstofa Íslands, 1970). Mynd frá Sayyadi og fl., (2021) með breytingum.*

THE RELATIONSHIP BETWEEN SEISMIC TREMOR AND EPISODES IN THE ERUPTION

Tremor was repeatedly recorded during the eruptions. The types of tremors observed, and their domain of frequencies are categorized in three groups (Table 1). The dominating tremor frequency changed during the eruptions and different types of tremors were observed (Figure 3), which can be related to different sources. Many cases are known where magma emplacement within conduits or formation of lava domes has produced volcanic tremor of medium to high amplitude that is strong enough to be observed at stations farther from source than the 137 km between Surtsey and the SID station (e.g., Arámbula-Mendoza *et al.*, 2016; Brandsdóttir and Einarsson 1992; Einarsson 2018).

The onset of seismic disturbance with the characteristics of low frequency volcanic tremor, detected on November 12 at SID between 12:00 and 14:00, is considered to mark the onset of submarine volcanic activity, about 40 hours before the eruption was first observed at the surface (Sayyadi *et al.*, 2021). During the submarine eruption on November 13, low frequency (<3 Hz) harmonic tremor was observed, but only minor indications of tremor were detected from the seismogram of the following day despite the onset of explosive subaerial activity (Figure 4).

Table 1. Types of tremor and their domains of frequency. – *Tegund óróa og tíðnisvið.*

Type of tremor		Frequency domain	Amplitude
Harmonic	Low frequency	$\leq$3 Hz	Slowly varying
	High frequency	3–5 Hz	
Spasmodic (Broad band)		5–15 Hz pulses of high frequency, 5–10 Hz periodic bursts separated by quiescence of uniform duration $\geq$10 Hz	Rapidly varying

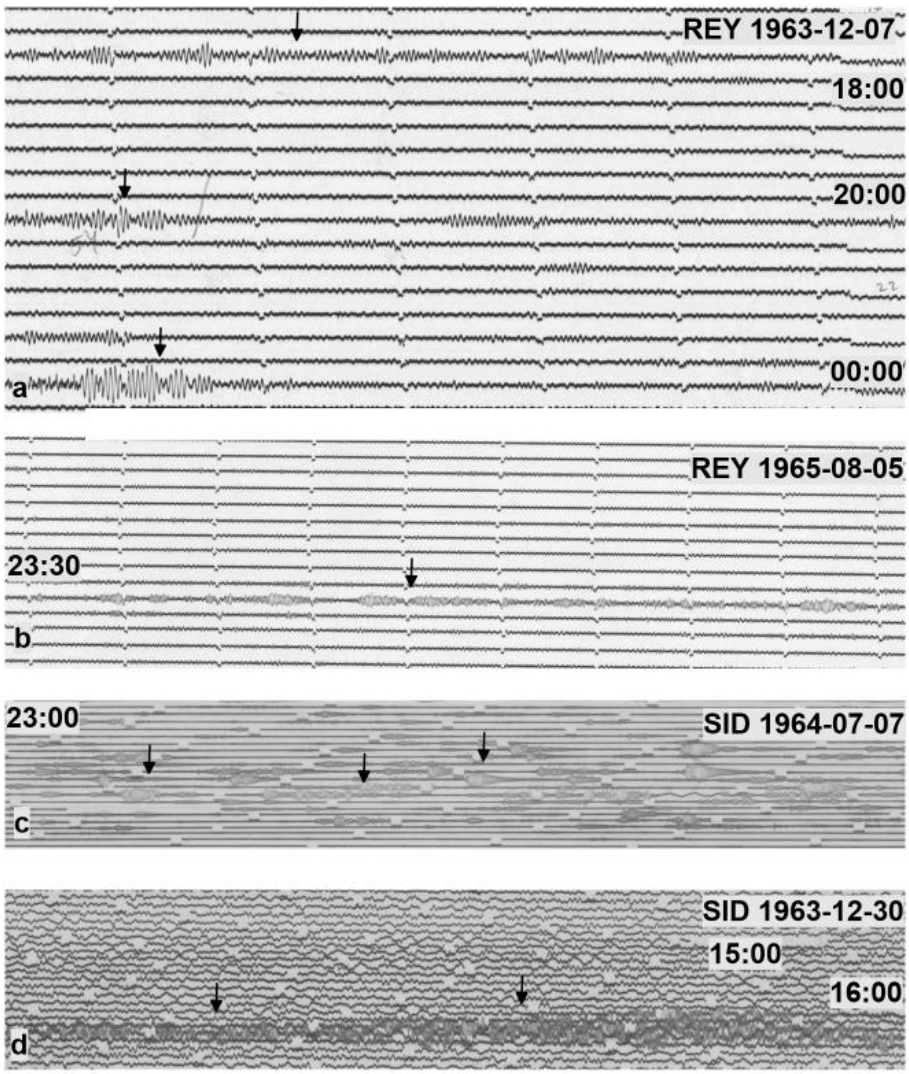

Figure 3. Types of observed tremor. a) Harmonic low frequency tremor at REY station. b) Harmonic high frequency volcanic tremor at REY station. c) Spasmodic tremor at SID station. d) Burst of mixture of harmonic high frequency with spasmodic tremor at SID station. – *Tegundir óróa. a) Hreintónaórói með lágri megintíðni á skjálftariti frá Reykjavík. b) Hreintónaórói af hárri tíðni á skjálftariti frá Reykjavík. c) Krampaórói á skjálftariti frá Kirkjubæjarklaustri. d) Blandaður órói, bæði krampa- og hreintóna á skjálftariti frá Kirkjubæjarklaustri.*

The next burst of low-frequency tremor after the eruption broke through the ocean surface on November 14 was recorded some hours before and after the time of continuous uprush at the vent at 15:00 on November 23 (day 9). A few days later, on December 1 (day 17), high-frequency tremor appeared on the SID records while an explosive eruption at Surtur was going on. Tremor continued throughout the period of activity at Surtla in December 1963.

As the active vent switched to Surtungur on February 1, 1964 (day 79), low-frequency tremor disappeared, and spasmodic tremor was first observed. During the period April 29–July 9, 1964, no surface flow of lava was observed in Surtungur although a lava pond with some activity remained in the crater (Thorarinsson 1967a). Spasmodic tremor continued through this period of no surface flow but disappeared on July 9, 1964 (day 238), when the surface effusive eruption began again from Surtungur (Figure 5).

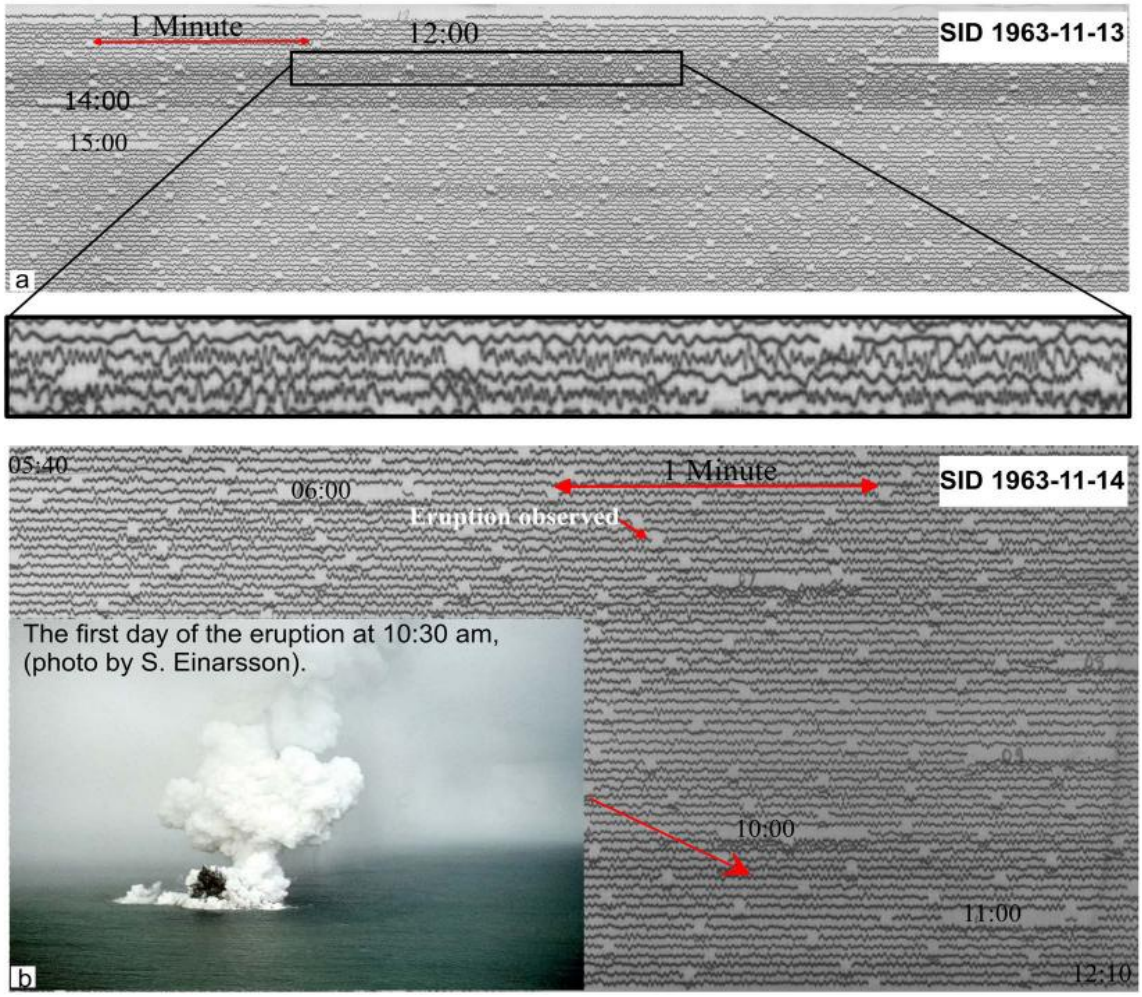

Figure 4. a) Bursts of low frequency harmonic tremor at SID on November 13, 1963, between 13:20 and 16:10 UTC, around 17 hours before the first observation of eruption in the sea and about 22–23 hours after tremor was first detected in the early afternoon of November 12, considered to mark the start of submarine eruption (Sayyadi *et al.*, 2021). b) Seismic records on the first day of the eruption at SID station. The inset shows the eruption at 10:30 AM on November 14. – *a) Hviður af hreintónaóróa af lágri tíðni sjást á skjálftariti frá Kirkjubæjarklaustri 13. nóvember 1963, milli klukkan 13:20 og 16:10, um það bil 17 klukkustundum áður en gosið sást á yfirborði sjávar, Sayyadi og fl. (2021). Nokkuð samfelldur órói hófst þó fyrr, eða stuttu eftir hádegi 12. nóvember og markar hann að líkindum byrjun neðansjávargossins. b) Skjálftarit frá Kirkjubæjarklaustri fyrsta gosdaginn. Ljósmynd S. Einarssonar er tekin klukkan 10:30, 14. nóvember.*

Effusive activity at Surtungur continued until May 10, 1965 (day 543). This 10-month long phase was one of seismic tranquility; there is no record of any seismic activity between the end of July 1964 and May 10, 1965 (day 543), when lava effusion ended at Surtungur.

The intrusive phase of the Syrtlingur eruption was characterized by spasmodic tremor, first observed on May 17, 1965 (day 550). However, the explosive activity during the Syrtlingur eruption, was mainly accompanied by high-frequency tremor (Figure 5). Eruptive activity in Syrtlingur ended on October 18,

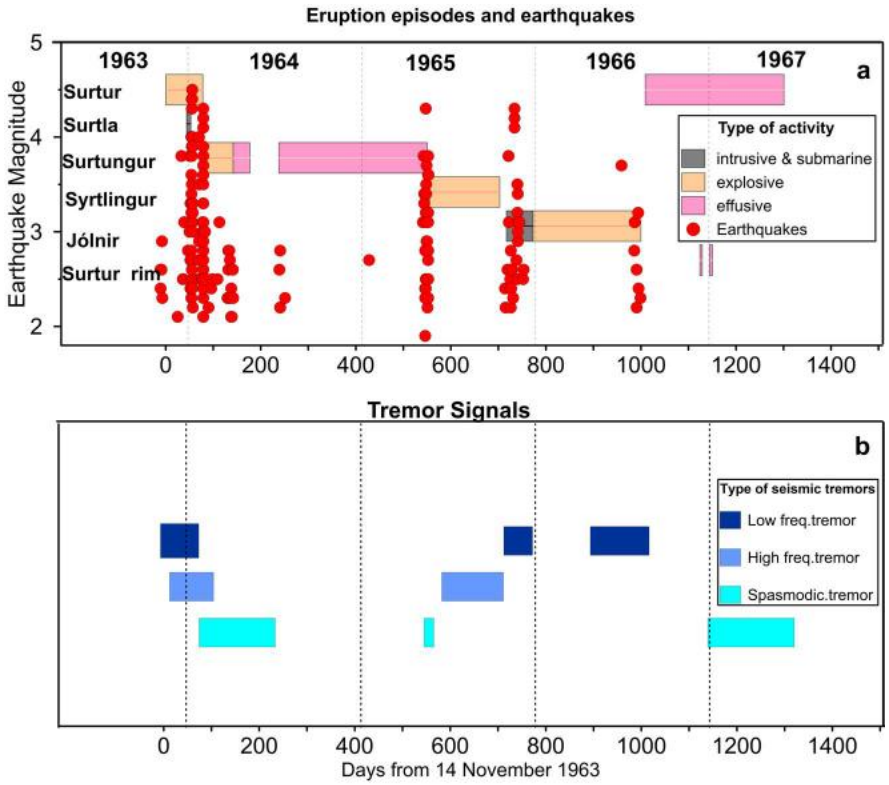

Figure 5. Timeline of earthquakes (a) and tremor signals (b) during the 3.5 years of eruptions. The colored areas in (b) mark periods where the tremor of the type indicated occurred. Within each period episodes of tremor alternated with intervals of no visible seismic activity. Earthquake data from Sayyadi *et al.* (2021). – *Tímalína jarðskjálfta (a) og óróa (b) meðan á gosum stóð 1963–1967. Lituðu reitirnir í (b) sýna hvers konar órói mældist. Jarðskjálftagögnin eru samkvæmt Sayyadi og fl. (2021).*

1965 (day 704) and the island soon disappeared. In the 70 days that followed (days 703–773) no volcanic activity was observed on the surface. During this period earthquakes were detected, considered to mark the intrusive and/or submarine volcanic activity preceding the visible eruption at Jólnir that reached the ocean surface around December 26, 1965 (Thorarinsson, 1966; Sayyadi *et al.*, 2021). Moreover, low-frequency tremor was seen during the intrusive and submarine eruption (days 713–772). Spasmodic tremor was occasionally observed during the explosive eruption that followed at Jólnir and in the days after cessation of explosive activity on August 10 (day 1000). Compared to the Syrtlingur activity, seismic signals during the Jólnir eruption were of slightly lower intensity.

On August 19, 1966 (day 1009), the third phase of effusive activity started at the eastern crater, Surtur, forming lava. Bursts of spasmodic tremor were observed and continued until August 31 (day 1021). From January 1 to 8, 1967 (day 1144–1151), the effusive eruption was briefly intensified by the opening of new minor fissures at the rims of the Surtur tuff cone. On January 27 (day 1170), two minor vents opened along short concentric fissures on the inner wall of the Surtur tuff cone. These rim-fissures were short-lived and produced minor amounts of lava. Finally, June 7, 1967 (day 1301) was the last day when molten lava was observed on the island. Occasional bursts of spasmodic tremor were detected from January 1 until June 31, 1967 (day 1144 to 1325).

Tremor signals and style of explosive activity

During the 4.5 months of explosive activity 1963–64, no instruments could be deployed on the island and direct observations could only be made from ships or aircraft. Visual observations were as a result not continuous and depended on weather. This limits the possibility of comprehensive analysis. However, the main characteristics of activity could be identified and some periods exist where timing and styles of activity were recorded (Thorarinsson *et al.*, 1964).

Two types of volcanic activity were frequently observed during the explosive phases: tephra-finger (cock's tail) explosions and "continuous uprush" explosive eruptions (Thorarinsson *et al.*, 1964). Tephra finger explosions occurred when there was easy access for water to vents. Sometimes when the access of the sea to the vent was restricted with the formation of a thick tephra wall, continuous uprush eruptions appeared. They could go on continuously for several hours. Apparently, as the uprush eruption progressed, the pressure exerted on the conduit walls from the magma decreased, increasing the risk of the conduit collapsing inwards (Moore, 1985).

Continuous uprush eruptions were sometimes followed by gaps in activity lasting several minutes to hours. Thorarinsson *et al.* (1964) gave some timings of the abrupt end of uprush, the length of time which the following inactivity lasted and the gradual onset of explosive activity following such a gap. Moore (1985) also indicates some of the continuous uprush events based on available photos.

Characteristic maximum amplitude of SID records was analyzed for three periods in Nov.–Dec. 1963 (Figure 6), during the explosive phase of Surtur. On 16–18 December, at 772–776 hours (time since visible start of the eruption on November 14), a continuous uprush event with a duration of 3–4 hours occurred (Figure 6c). This was followed by 17 hours of no visible activity. As the graph shows, there does not appear to be any correlation between the uprush activity and the seismic wave amplitude at SID over the period studied. The tremor bursts were observed at 766 hours and during the quiet period at 783–790 hours, showing no apparent correlation with the explosive eruption style. The same lack of correlation is apparent for the other two episodes, 23–28 November, and 1–3 December 1963 (Figures 6a and 6b).

Seismic tremor and eruption rate

Although the observation of tremor was not continuous, when observed, the highest amplitudes occurred in the first 150 days, with all of the three types of tremor bursts detected at Surtsey observed in this period (low frequency, high frequency and spasmodic). After July 9, 1964 (day 238), a significant gap occurred with no observed tremor. The tremor was observed again on May 17, 1965 (day 550), by the end of effusive eruption at Surtungur and the onset of the Syrtlingur eruption. By this time the occurrence of detected tremors had decreased, and for long periods it was hardly observed continuously. Thorarinsson *et al.* (1964) and Thorarinsson (1966, 1967b, 1968) estimated the average eruption rates for different periods of the eruption, noting a slow decline with time. By using lava bulk density of 2500 kg/m^3 and the bulk density of the piles of pyroclasts formed during the explosive phases of 1500 kg/m^3, Thorarinsson's estimates can be converted to approximate time-averaged discharge rates (TADR) using a dense rock equivalent (DRE) of 2700 kg/m^3. Values obtained for TADR (Figure 7a) being 65 m^3/s for 12–24 Nov. 1963, 25 m^3/s for 24 Nov. 1963-1 February 1964, 13 m^3/s for 1 Feb.–4 April 1964, 7–8 m^3/s for April 1964-May 1965, and varying between 2 and 3 m^3/s for the period May 1965-June 1967 (Syrtlingur, Jólnir, Surtur). Note that the TADR values for the first 15–20 days are only displaying a part of the total eruption rate, as they do not include the airborne tephra fallout outside the island which was quite significant in November-December 1963 (Thorarinsson *et al.*, 1964; Ólafsson, 2021).

Duration and approximate amplitude plots of the tremor in the first 150 days (Figures 7 b and c) show discontinuous appearance of tremor in these first several weeks which indicates that magma flow rate and tremor relationship is not simple. Little tremor is detected during the most vigorous activity in the first 20 days of the eruption (Figure 7). In contrast, the strongest tremor is detected in December and at times in January to March 1964. This indicates that it is not primarily the magma flow rate that determines the

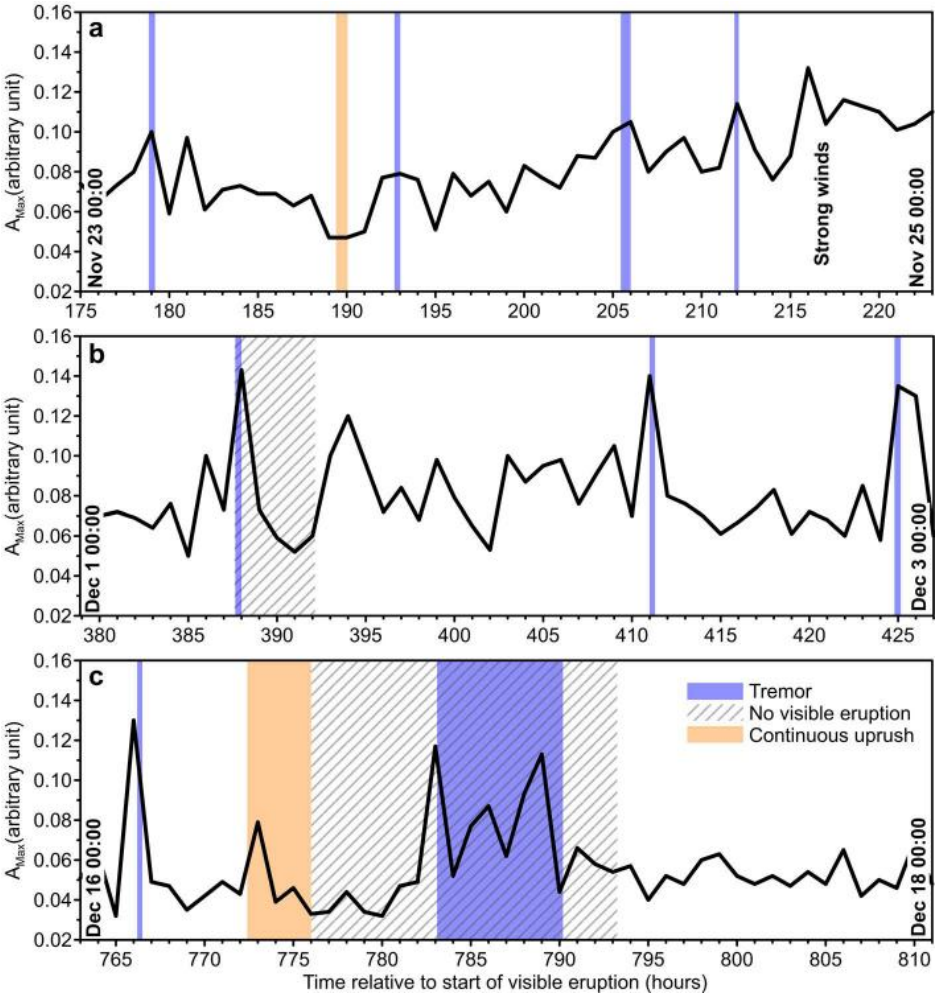

Figure 6. Variation of characteristic seismic maximum amplitude (the wave-amplitude observed on the seismograms excluding earthquakes) during selected periods in November–December 1963. a) 23–25 November. b). 1–3 December. c) 16–18 December; period with the occurrence of continuous uprush, 17 hours of no visible activity followed by gradually increasing explosive activity. – *a) Breytingar á mesta útslagi óróa 23.–25. nóvember, 1963. b) Breytingar á mesta útslagi óróa 1.–3. desember 1963. c) Breytingar á mesta útslagi óróa 16.–18. desember 1963. Á þessum tíma var first sígos, þá goshlé í 17 klukkustundir, og síðan hægt vaxandi sprengivirkni.*

tremor intensity in this explosive part of the eruption, possibly vent conditions (geometry, magma-water interaction, or the absence of it, etc.) are far more influential in determining the intensity of tremor activity than the magma flow rate.

The complicated relationship between eruption rate and tremor is further highlighted by the lack of observation of tremor during the effusive eruption between July 1964 and May 1965, when the TADR was 7–8 m^3/s, while it was observed in the final year of effusive eruption when the TADR was only 2–3 m^3/s.

In the short term (hours-days), apparently no correlation is observed as demonstrated above for the episodes of explosive activity in November-December 1963 (Figure 6). This lack of correlation for e.g., 16–18 December 1963 may indicate that during the ex-

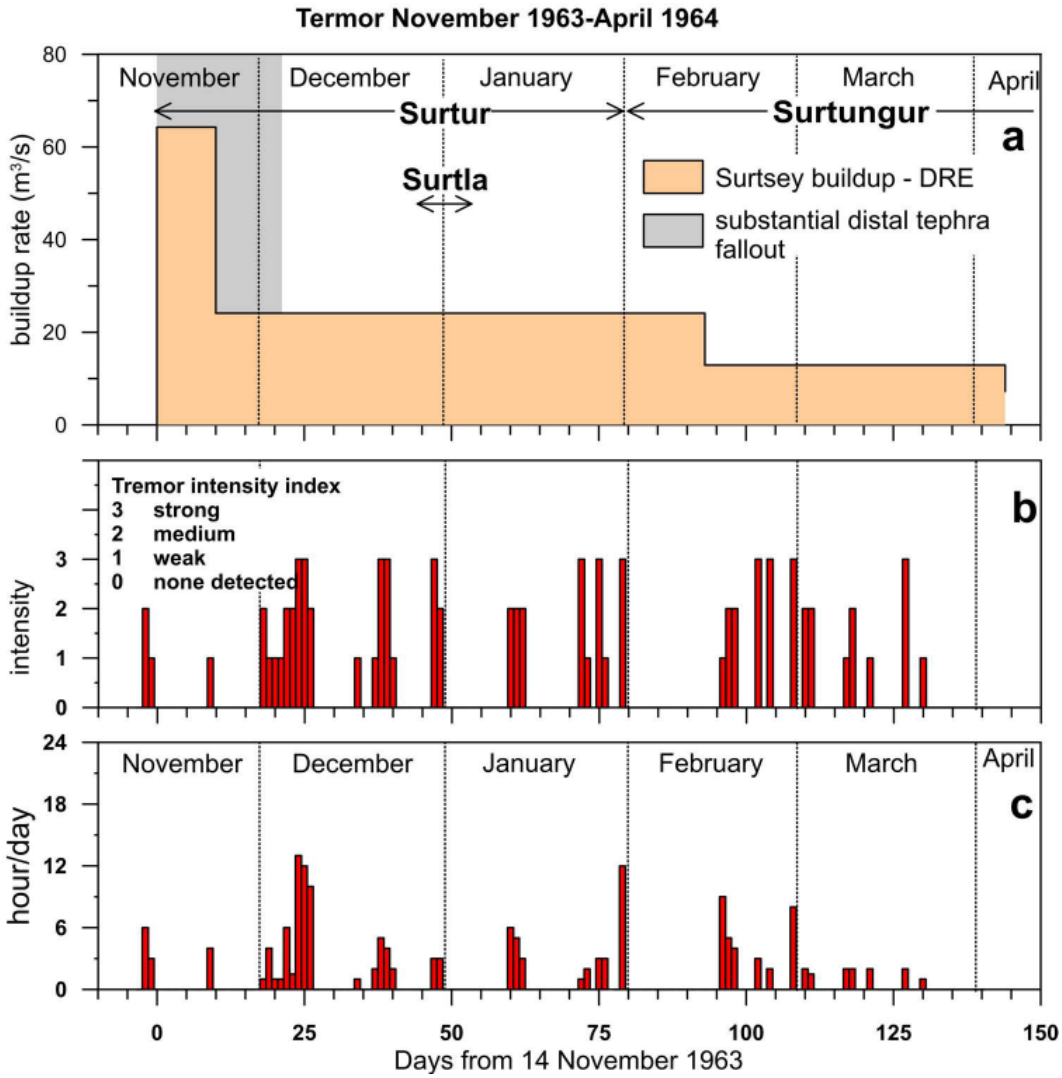

Figure 7. Eruption rate versus tremor intensity for the first 150 days of eruption. a) buildup rate for the first 150 days (Thorarinsson *et al.*, 1964; Ólafsson, 2021). A DRE-equivalent volume is used assuming loose tuff density of 1500 kg/m^3, lava density of 2500 kg/m^3 and DRE density of 2700 kg/m^3. b) Tremor intensity for the first 150 days of eruption. c) Daily tremor duration during first 150 days of eruption, in hours per 24 h. – *Framleiðni gosefna og óróinn fyrstu 150 daga gossins. a) Upphleðsluhraði, reiknaður út frá eðlismassa móbergstúffs 1500kg/m^3, eðlismassa hrauns 2500 kg/m^3, og DRE 2700 kg/m^3. b) Styrkur óróa. c) Varandi óróa á sólarhring, í klukkustundum.*

plosive eruption magma was continuously rising in the conduit despite gaps in activity on the surface. Throughout the continuous uprush episodes, the conduit is apparently excavated to progressively deeper levels while there remains external water access to magma. This may suggest that the uprush activity eventually stops when either (1) the water in the conduit dries up, and therefore no longer has access to the magma, resulting in cessation of phreatomagmatic fragmentation, or (2) the conduit is flooded by water after a period of progressively deeper excavation of the magma, resulting in a sudden increase in confining pressure exerted on the magma-water interface from the overlying water column. Such a sudden in-

crease in water pressure may inhibit magma-coolant interaction and therefore temporarily prevent energetic fragmentation (e.g., Zimanowski and Buttner, 2003) In this case, magma needs to rise in the conduit to near the surface before the hydrostatic pressure has become sufficiently small to allow for explosive phreatomagmatic fragmentation to begin again. Both of these processes (1 and 2) can be reconciled with continuous flow of magma from below. However, the second hypothesis seems more plausible, since, as pointed out by Moore (1985), it is difficult to see how a hundreds-of-meters deep conduit, dammed by a permeable pile of pyroclastic material, can remain water free for extended periods in this oceanic setting.

SUMMARY AND CONCLUSIONS

The inherent limitations of our observations of old analog data preclude a detailed interpretation of the tremor signal in terms of eruption dynamics. However, they provide useful lessons on the relationship between eruption behavior and tremor signals.

•The strongest tremor signals occur during the early periods of activity, when eruption rate was highest, indicating a broad correlation between tremor intensity and eruption rate. Due to the limited bandwidth and analog nature of the instruments, any connection between tremor amplitude and frequency content is difficult to assess.
•On shorter timescales of minutes to hours, correlations between eruption rate and style of eruption are not apparent.
•During the explosive phase of Surtur, comparisons between seismic tremor occurrence and visible activity indicate that magma flow from below was more or less continuous. Gaps in visible activity sometimes following episodes of continuous uprush may have been caused by seawater entering a partly excavated conduit, temporarily preventing powerful phreatomagmatic fragmentation.

Thus, the tremor was at least at times not correlated with shallow vent-processes. This illustrates the complicated nature of seismic tremor in volcanic eruptions.

Acknowledgements

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Eldvirkniórói í Surtseyjargosinu 1963–1967

Af þeim neðansjávargosum sem myndað hafa eyjar er Surtseyjargosið líklega einna mest rannsakað. Neðansjávargossins varð fyrst vart 14. nóvember 1963. Gosstaðurinn var á um 130 m hafdýpi sunnan Vestmannaeyja. Á þeim 3½ árum sem gosvirknin stóð mynduðust þrjár eyjar en tvær þeirra eyddust fljótt vegan sjávarrofs og eftir stóð Surtsey ein. Gosvirknin var kaflaskipt og skiptust á sprengigos og hraungos. Fyrsti kafli var neðansjávargosið en bæði óróinn og hitafrávik í sjónum (Sayyadi og fl., 2021) benda til þess að það hafi hafist 12. nóvember, þ.e., nokkru áður en gosið sást upp úr sjó. Aðrir kaflar stóðu frá 14. nóvember 1963 til janúar 1964, frá janúar til apríl 1964, frá apríl 1964 til maí 1965, frá maí til október 1965, desember 1965 til ágúst 1966, og ágúst 1966 til júní 1967. Gosunum fylgdi talsverð skjálftavirkni, bæði jarðskjálftar og eldvirkniórói. Rannsóknir á skjálftavirkninni eru nokkrum erfiðleikum bundnar af tvennum orsökum: Skjálftamælakerfi landsins var ennþá fremur frumstætt og atburðirnir gerðust utan mælanetsins. Fjórir skjálftamælar voru á landinu og einungis tveir þeirra voru nógu nálægt til þess að sýna virknina greinilega. Gögn frá þessum mælum eru nú aðgengileg á vefsíðunni http://seismis.hi.is/ og voru notuð til rannsóknar á skjálftavirkninni. Jarðskjálftar urðu flestir í tengslum við breytingar á gosinu, þegar virknin hætti á einum stað og tók sig upp á nýjum.

Eldvirkniórói sást á mælunum í Reykjavík, í 140 km fjarlægð frá Surtsey og á Kirkjubæjarklaustri í 115 km fjarlægð. Órói af að minnsta kosti tveimur gerðum mældist, annars vegar svokallaður krampaórói (spasmodic tremor) sem gjarnan fylgir innskotavirkni, og hins vegar hreintónaórói (harmonic tremor) sem oft mælist þegar gos er uppi. Bæði mældist hreintónaórói með lágri megintíðni (< 3 Hz) og hærri (3–5 Hz). Ekki var hægt að greina einfalt samband milli útslags óróans og virkninnar í gosinu, hvorki í sprengigosunum né hraungosunum. Í fyrsta sprengigosakaflanum var framleiðni gosefna mest fyrstu 10–20 dagana, en þá mældist lítill órói. Mestur órói mældist frá desember 1963 til mars 1964 en þá hafði talsvert dregið úr framleiðni gossins. Ekki var heldur hægt að sjá tengsl óróans við hegðun gossins frá degi til dags. Svipaða sögu er að segja af hraungosaköflum. Enginn órói mældist í tengslum við hraungos í Surtungi 1964-1965 þó framleiðni gossins þar væri þrisvar sinnum meiri en í síðari hraungosaköflum, þegar órói var greinilegur.

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Paper III

Internal structure of the volcanic island of Surtsey and surroundings, constraints from a dense aeromagnetic survey

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Internal structure of the volcanic island of Surtsey and surroundings, constraints from a dense aeromagnetic survey

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Abstract

An aeromagnetic survey was carried out in October 2021 over a 60 km^2 area including the volcanic island Surtsey off the south coast of Iceland. The island was built by volcanic activity in 1963-1967 from an ocean depth of 130 m. The aim of the survey was to explore the internal structure and the possible existence of intrusions associated with the five vents active at different times over the 3.5 years of activity. Survey line spacing was 200 m and the flying altitude was generally 90 m a.s.l. The results show that some of the magnetic anomalies mapped outside Surtsey have a clear connection with submarine volcanic structures while the subaerially-formed lava field on Surtsey generates the strongest signal, a ~700 nT magnetic high. 2D spectral analysis and Euler deconvolution indicate that the causative bodies of anomalies outside Surtsey itself are shallow, located in the uppermost 300 m of the seafloor. Forward 2.5D modeling of selected profiles is consistent with an absence of pillow lava having formed at the seafloor during the early submarine phases of the vents. Volumetrically significant intrusive bodies also appear to be absent from the edifices formed. Magma fragmentation apparently dominated the submarine activity from initiation of activity. The only location where a dyke is detected within a submarine formation is at Surtla, known to have been active for about 10 days in 1963/64. Activity at Surtla remained subaqueous with weak or moderate explosive activity that apparently allowed a dyke to be preserved within the submarine mound. In contrast, the more violent surtseyan activity at other vents precluding the preservation of a magnetically resolvable dyke. Indications of

magnetized rocks of unknown age but predating the Surtsey eruption are found under the southeast margin of Jólnir; earlier volcanism produced the magnetized rocks at this location long before Surtsey was formed.

1. Introduction

Submarine-to-emergent volcanism forms volcanic islands in the ocean and in lakes. It often leads to explosive eruptions influenced by magma-water interaction. Such eruptions can be a hazard, forming eruption clouds and tephra fallout. They can also build unstable islands that collapse causing tsunamis (e.g., Somoza et al. 2017). Observations of eruptions in such settings inform our knowledge on the style of activity, their influence and potential hazard. A notable example is the well-known formation of the volcanic island of Surtsey, off the south coast of Iceland in 1963-1967 (e.g., Thorarinsson et al. 1964; Thorarinsson 1967a; Moore 1985).

Although various studies of submarine to emergent volcanism have been carried out, it is rare that the details of the observed eruptive activity and studies of the internal structure of an ocean island volcano and the formations created, can be studied and compared. The detailed studies that have been carried out at Surtsey, establishing the timeline of its formation (Thorarinsson 1965, 1966, 1967a, 1968b; Baldursson and Ingadóttir 2007). The coupling of the timeline with stratigraphic information obtained from cores extracted from the young volcanic island in 1979 and in 2017 (Jakobsson and Moore 1982; Jackson et al. 2019; Weisenberger et al. 2019) make Surtsey an ideal site for studying the internal structure of a submarine to emergent monogenetic volcano. A large part of the volcanic formations created in 1963-1967 are submerged, and that puts limits to the extent that geological mapping and various geophysical methods can be applied to study the internal structure of the volcanic formations or assess the possible existence of diatremes or subvolcanic intrusions. A method that is not hampered by the ocean-island setting is aeromagnetic surveying. Important constraints on internal structure, intrusion, and development of submarine volcanoes may result from using modeling of airborne magnetic survey results, which can be employed to image subsurface geological features (e.g., Finn and Morgan 2002; Blanco-Montenegro et al. 2007; Okuma et al. 2009; Paoletti et al. 2009).

The typically magnetic basaltic crystalline rocks such as dykes and pillow lava, contrast sharply with the essentially non-magnetic pyroclastic rocks/hyaloclastite that are the principal

products of the explosive, hydromagmatic, activity at Surtsey (Kristjansson 1982; Behrendt et al. 1995).Thus, the various magnetic bodies of crystalline rocks, if present, give rise to anomalies in magnetic surveys. Studies of these anomalies give insight into the geological features of the region and may reveal the existence of various volcanically formed bodies, exposed or buried volcanic vents, and possible tectonic characteristics of the region (Blanco-Montenegro et al. 2008; Okuma et al. 2009).

In October 2021, a six-hour aeromagnetic survey with a high-resolution magnetometer was completed over the Surtsey area. The main aim of the survey was to look for signs of shallow intrusions and possible pillow lava formations within and below the edifices of the Surtsey complex built in 1963-1967. This includes the subaerial Surtsey island, the submarine vents and edifices created at the same time, it also may reveal possible signs of local tectonic structures.

Specifically, we aim to investigate the magnetic signature associated with the different vents and edifices built during the 3.5-year-long Surstey eruption, and the role of pillow lavas and/or magnetic intrusions on the sea floor and buried beneath it in forming that signature.

A more general aim was to explore the feasibility of aeromagnetic surveying for detecting remnants of past eruptions in locations like the Vestmannaeyjar archipelago, and whether magnetic surveying can help in defining recurrence times of submarine eruptions through defining deposits of past eruptions.

2. Use of aeromagnetic surveying for submarine settings

Aeromagnetic surveys have been used to study hydrovolcanic craters and conduits elsewhere, including studies of maar volcanoes in Auckland, New Zealand (Cassidy et al. 2007). Those authors inferred that observed magnetic anomalies are related to coherent basaltic rocks formed in shallow-depth magma conduits and did not find signals supporting the existence of diatremes associated with these maars. Another example is that of the Aeolian Islands, Italy, including Stromboli. Okume at al. (2009) carried out two helicopter aeromagnetic surveys over the islands. Some shallow magnetic structures were detected. A third example is that of submarine volcano, Izu-Oshima in 1986 and in 1997 (Ueda 2007). The comparison of 3D magnetic models of the two surveys illustrates the shift of the vents within the volcanic edifice and the ridge spreading system of Izu-Oshima Volcano. One more example is a 1993 aeromagnetic survey of the Canary Archipelago that was analysed by Blanco-Montenegro et

al. (2020) with 3D inversion modelling. This study provided new insights on intrusions associated with the tectonic framework underlying the substructure of the submarine Canary Archipelago.

Aeromagnetic surveys facilitate the study of offshore and remote volcanic areas by allowing coverage of large and inaccessible areas while also being very cost-effective because large areas can be covered in a short period of time. Nishinoshima in Japan is a good example of a study where constraints on volcanic processes occurring while islands are formed (Tada et al, 2021). Comparison of results from two aeromagnetic surveys (2018 and 2019) revealed two newly formed shallow magnetized, formed in the period between the surveys, interpreted to indicate emplacement of large magma bodies beneath the crater (Tada et al, 2021).

3. Surtsey, geological setting

The Vestmannaeyjar Archipelago with 17 islands of the south cost of mainland Iceland is an early-stage volcanic system, with an area of more 800 km^2 (Fig.1). It can be categorized as a monogenetic volcanic field (e.g., Walker 2000; Mattsson and Höskuldsson 2003). The geological record indicates that over the last few tens of thousands of years, numerous eruptions have taken place, as demonstrated by several tens of remnants of vents that are spread over an area that is ~40 km long (SW-NE) and 30-35 km wide (NW-SE) (Jakobsson 1979; Mattsson and Höskuldsson 2003; Sigurdsson and Jakobsson 2006). Compared to the more productive volcanic systems in Iceland, the Vestmannaeyjar volcanic system is not very active, with the eruptions in Surtsey in 1963-67 and Heimaey in 1973 being the only known eruptions for over 1000 years (Thorarinsson et al. 1964; Höskuldsson 2015). Episodes of volcanic activity occurred in early Holocene time and during the last glacial period (<100kyr) (e.g., Jakobsson, 1979; Mattson and Höskuldsson, 2003). Drilling in Heimaey, the largest and only inhabited island, revealed that the volcanics, including consolidated hyaloclastite, are only 180 m thick, and overlie 600 m of mostly seafloor sediment, partly tuffaceous, considered to be derived from mainland Iceland (Tómasson 1967) .

Volcanic activity was observed in the Vestmannaeyjar archipelago (Southern part of the Eastern volcanic zone) of Iceland, at a site where ocean depth was 130 m, in November 1963 (Thorarinsson et al. 1964). This was the start of the Surtsey eruption, with the submarine

eruption starting on 12 November 1963 and becoming subaerial on 14 November (Sayyadi et al., 2021; Thorarinsson et al., 1964). Eruptive activity continued until July 1967 (Thorarinsson 1968b). Over this 3.5-year-long period, a volcanic island, Surtsey, and its temporary satellite edifices (Surtla, islands of Syrtlingur, and Jólnir) were created (Fig.1). The main phases of the 3.5-year-long eruption were:

- Eruption of Surtur, November 1963-January 1964. Surtur I: Explosive, subaerial eruption preceded by ~40 hours of submarine eruption (Sayyadi et al. 2021).
- Surtla – submarine – late December 1963-early January 1964.
- Surtur II (Surtungur), explosive: February-April 1964, effusive: April 1964-May 1965.
- Syrtlingur, explosive; May-October 1965.
- Jólnir, explosive: December 1965-August 1966.
- Surtur I, effusive: August 19, 1966 - June 5, 1967.

4. Survey setup

The aeromagnetic survey was conducted on 30 October 2021, using a MagArrow Geometrics magnetometer, designed for drone surveys. It was set up with the MagArrow fastened by two rigid aluminum poles to the bottom of the Partenavia Observer II aircraft, allowing the MagArrow to be lowered 1.2 m below the aircraft while surveying.

The survey area (Fig. 2) is 6 x 10 kilometer in size (60 km^2) and was covered in 6 hours. The area includes Surtsey and the its surroundings, e.g., the island of Geirfuglasker and several places to the east and northeast of Surtsey with undulations in the seabed that are considered traces of past eruptions in the area.

Flightlines had a spacing of 200 m, similar to the mean depth from aircraft to the sea bed for lines outside the island of Surtsey. They were flown either NNW or SSE, at an elevation of 90 m (300 feet) above sea level, with two tie-lines flown at right angles (ENE and WSW) to the main survey line directions.

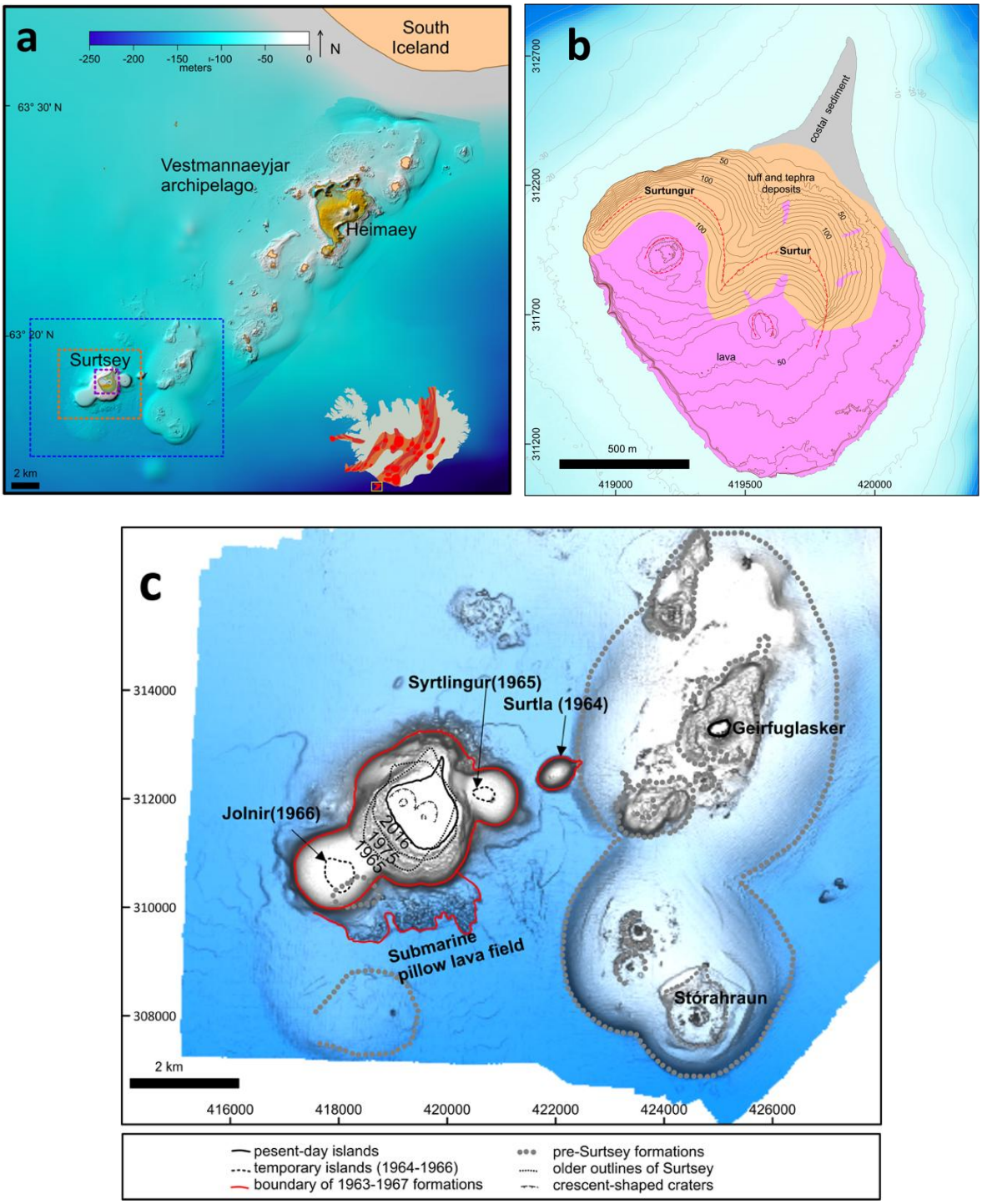

Figure 1. a) Bathymetry of the Vestmannaeyjar archipelago. The dotted quadrangles show the outlines of the maps in Figure 1b (inner), 4 and 7 (outer), and Figure 7 (middle) are indicated. b) A geological map of Surtsey showing the location of the lava field on the southern part and the tuff cones formed in 1963-64 on the northern side (Jakobsson et al. 2009). *c) Shaded relief bathymetry map of Surtsey and its surroundings based on a 2007 survey* (Jakobsson et al. 2009). *The volcanic formations built during the Surtsey eruption in 1963-1967, including outlines of the temporary islands of Syrtlingur and Jólnir, are shown as*

well as that of Surtsey at different times. Outlines of older formations of unknown age are also shown.

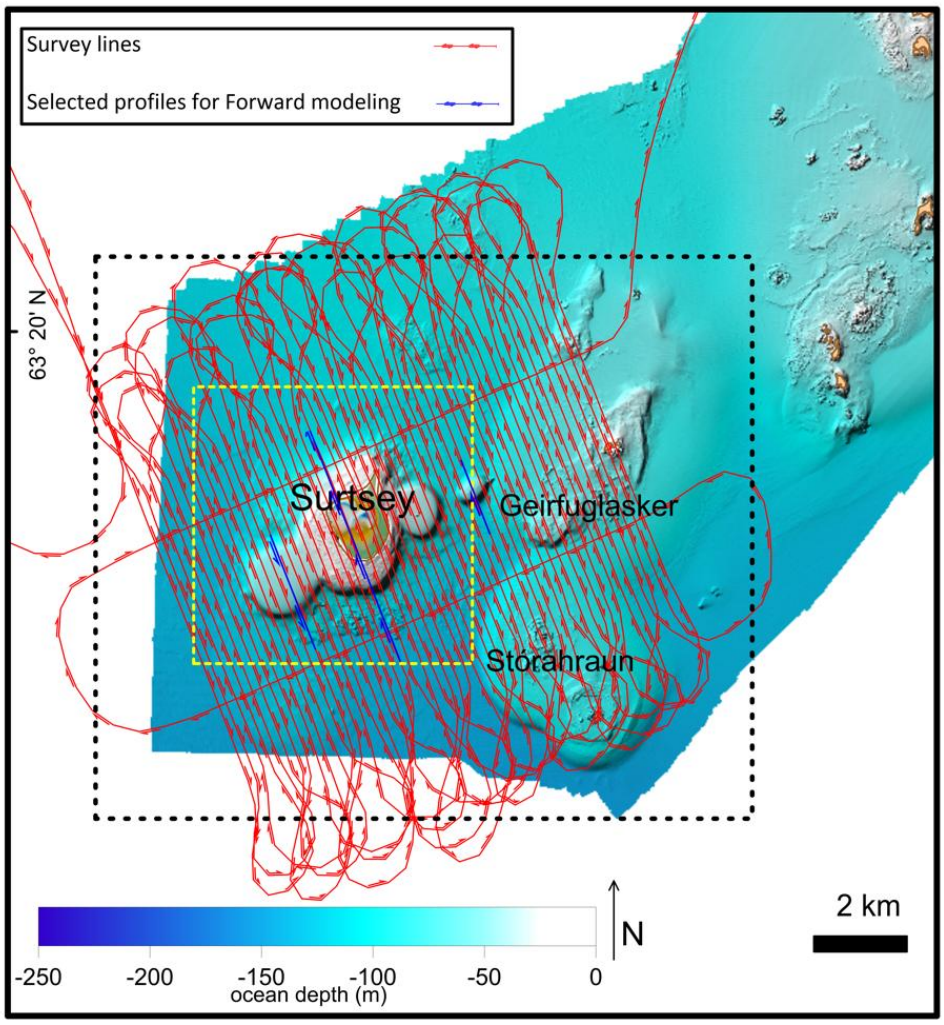

Figure 2. a) The October 2021 aeromagnetic survey. The colour scale show ocean depth. The blue dotted in outline defines the mapped area shown in Figures 4 and 7.

5. Data processing and the magnetic map

The MagArrow has a sampling rate of 1000 Hz. The speed of the aircraft was close to 50 m/s, so the distance between individual measurements was 5 cm. The processing involved the following steps: (1) Resampling. A moving average was used to reduce the data density to 20 Hz (point spacing of 2.5 m). (2) A low pass filter with a frequency of 0.1 Hz was applied, effectively removing wavelengths less than 400-500 m. This removed high frequency noise associated with the aircraft from the data while preserving anomalies arising from sources at >200 m below it.

Temporal variations were removed (3) using the record from the Leirvogur Magnetic Observatory, 110 km NE of Surtsey (http://cygnus.raunvis.hi.is//~halo/leirvogur.html). Apart from the diurnal (a few nT), the geomagnetic field was quiet at the time of the survey. (4) A static shift in the magnetic field strength of about 50 nT was observed, depending on flight direction (NNW versus SSE). This effect was removed. The corrected data were used to create a magnetic map with 100 m grid spacing, using kriging (Golden Software 2021). The final total-field magnetic map is shown in Fig. 4.

5.1 Magnetic properties

The main types of geological formations found in Surtsey and its surroundings are all basaltic (e.g., Jakobsson 1979). These are hyaloclastite tuffs, pillow lava, subaerial lava, submarine lava breccias, minor intrusions (dykes, sills, peperites) and seafloor sediments and sedimentary rock. When it comes to magnetic properties, they are highly contrasting. The hyaloclastites have close to zero magnetization as do the seafloor sediments, while the recently formed and unaltered, predominantly crystalline rock formatonis: the subaerial lavas, pillow lavas and intrusions are expected to have quite high magnetization (e.g., Kristjansson 1982; Gudmundsson and Milsom 1997; Kristjánsson 2013). Thus, magnetic anomalies are expected to arise from lava flows, pillow lavas and intrusive rocks.

The lava field formed during subaerial effusive activity at Surtsey in 1964-1965 (Surtur II) and 1966-1967 (Surtur I) is in most places 30-100 m thick (Thorarinsson 1968a). The magnetization of these lavas was studied using 40 samples taken in 2018 (Appendix E). The remanent magnetization of the samples ranges from 1.5 to 25.6 A/m, has a mean of 10.5 A/m and a standard deviation of 6.6 A/m. The average susceptibility is 0.02. This is equivalent to induced magnetization of about 0.8 A/m. Overall, these measurements confirm relatively strong magnetization of Surtsey lavas, but the large range does not support a single average value.

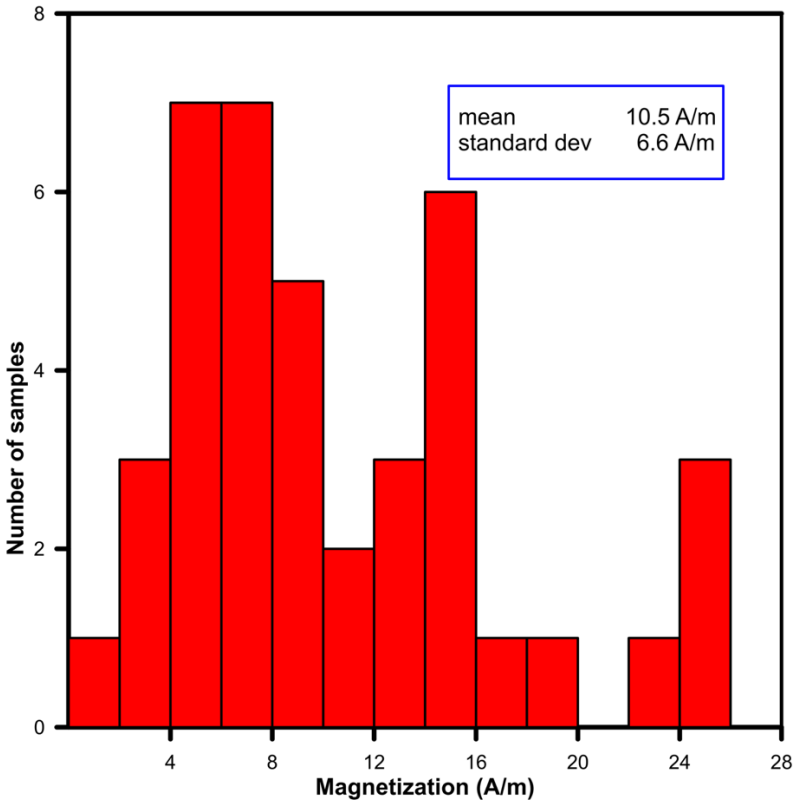

Figure 3. Magnetization measurement distribution over lava samples (Complete data set in the Appendix E).

6. Results

6.1. Correlation between geological features and magnetic anomalies

The magnetic map in Fig. 4 shows several anomalies that appear to be associated with known geological features, while others do not have an obvious connection. Their sources are apparently unknown sub-surface structures. By far the most prominent magnetic anomaly is over the southern part of Surtsey, and closely correlates with the subaerial lava shield. Other geological features associated with Surtsey that have a magnetic anomaly are the now submerged edifices of Jólnir (formed in 1966), and Surtla (1963/64). A suspected pillow lava field on the sea floor extending about 500 m to the south of Surtsey (Sigurgeirsson 1966; Jakobsson et al. 2009), is correlated with a low-amplitude magnetic anomaly high.

Southwest of Surtsey, a magnetic high (~200 nT) correlates with the southeastern edge of submarine remnant of Jólnir. Its location does not fit with that of the vent which built up the island. However, it fits with the location of a knob seen on bathymetric maps made in 1964, prior to the eruption of Jólnir (Jakobsson et al. 2009), and on a seismic reflection profile surveyed in 1980 (Thors and Jakobsson 1982), where it is seen rising as a structure through Jólnir. In contrast, no anomaly is associated with the former island of Syrtlingur (1965). A weak anomaly (~25 nT) is seen on the three lines that cross the submarine remnants of Surtla. This anomaly was previously detected by a single boat traverse with a magnetometer in 1965 (Sigurgeirsson 1966).

Around the apparent craters associated with Geirfuglasker and Stórahraun, formations much older than Surtsey but of unknown age, a wrapped anomaly indicates magnetized bodies, possibly pillow lavas, subaerial lavas formed at times when sea level was lower than today, or other shallow sub-volcanic structures.

6.2 Magnetic map analysis, depth to sources

As Fig. 4 shows, the 60 km^2 area surveyed has numerous anomalies of varying amplitude. The total magnetic field map shows a pattern of magnetic anomalies of mostly short wavelengths (<1 km). This suggests relatively shallow sources being the main causes for observed magnetic anomalies. In order to explore the depth of the sources we perform a 2D spectral analysis and Euler deconvolution. The reference surface is sea level, thus, a depth of 100-150 m outside Surtsey itself corresponds a source at or very close to the sea floor.

The surface of the Surtsey lava field lies at 20-100 m above sea level indicating a spacing between aircraft and source of ~200 m and should therefore correspond to a depth of ~100 m in these and subsequent calculations.

6.3 Spectral analysis

A radially averaged 2D power spectrum (Spector and Grant 1970) for the area is shown in Fig. 5, obtained by applying the Geosoft software (Geosoft 2015). Being radially averaged, it is independent of any linear or other trends that may be present in the data. The decay of the spectrum function (the slope) within a comparable frequency range indicates the depth of the causative bodies but does not provide information on location of individual bodies.

From Fig. 5, we can characterize the region from high to low wavenumbers with depth estimation. The highest wavenumber signal, which corresponds to noise, is part of the spectrum, along with low frequency and medium frequency signals. The first part of the spectrum graph (wavenumber <1) refers to the deepest bodies that may be present, while wavenumbers in the range 1-4 km^{-1} dominate the middle to low frequency region. The average depth to the shallower sources is calculated by the slope for this wavenumber range (Reid et al. 1990). Wavenumbers >4 km^{-1} represent noise.

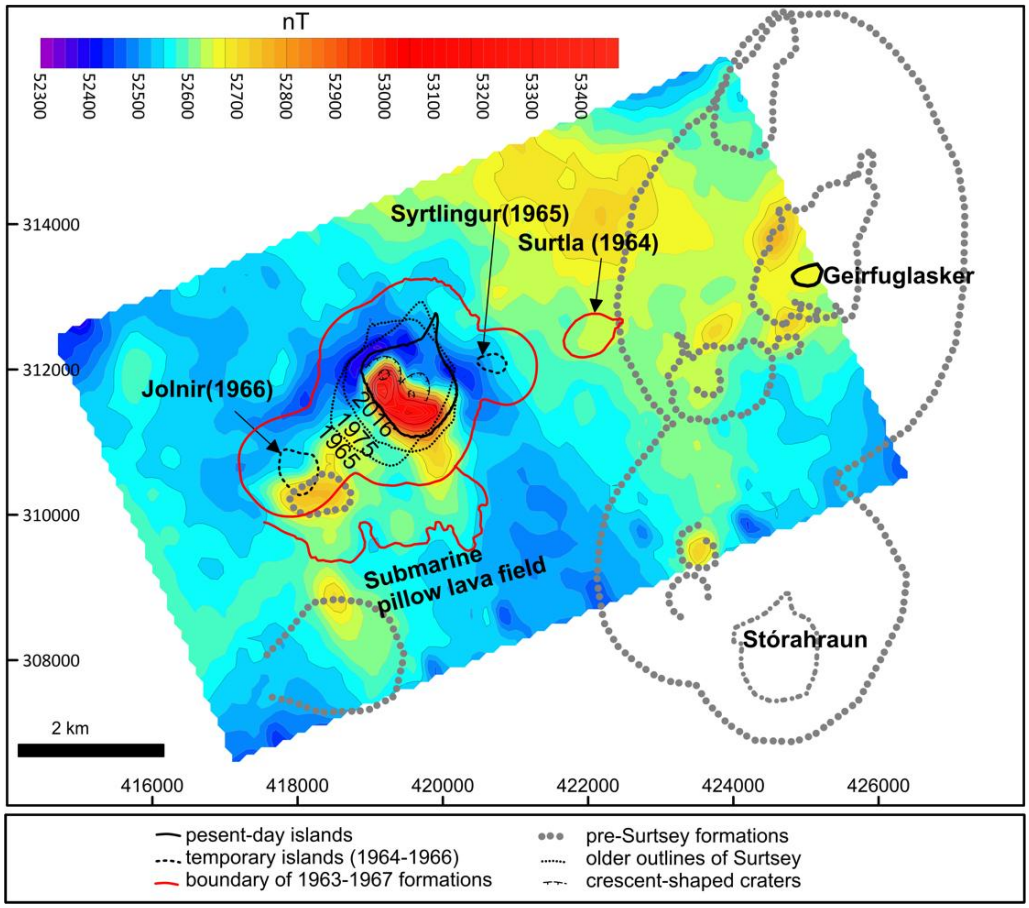

Figure 4. A total field magnetic map from the 2021 survey, contour interval 25 nT. Coordinates: INS93 Lambert in meters.

The spectrum (Fig. 5) indicates that most of anomalies observed arise from shallow bodies, at depth 100-400 m below the ocean surface, or in the uppermost 300 m of the seafloor, with the shallowest sources being most prominent.

6.4 Euler deconvolution methods

To further analyze the depths and how they vary over the area, we apply Euler deconvolution (Reid et al. 1990). Euler deconvolution requires neither information on magnetization

direction of the field nor of the sources (Mushayandebvu et al. 2001). The shape and extent of the anomalies varies with the form of the causative bodies. The depths values obtained depend on the body form chosen, and in the absence of other data constraining this, Euler deconvolution is applied to different shapes of bodies, with the shape of the bodies modelled indicated by the structural index (SI). For dykes and sheets SI=1, for vertical pipes SI=2, while bodies that are spatially very small compared to depth and therefore resembling dipoles, SI=3 (Reid et al. 1990).

We use Geosoft software (Geosoft Inc. 2015) for calculation of the 3D-Euler deconvolution for the magnetic grid (Fig. 4). Three structural indices are used (SI=1, 2 and 3). The results are show in Fig. 6.

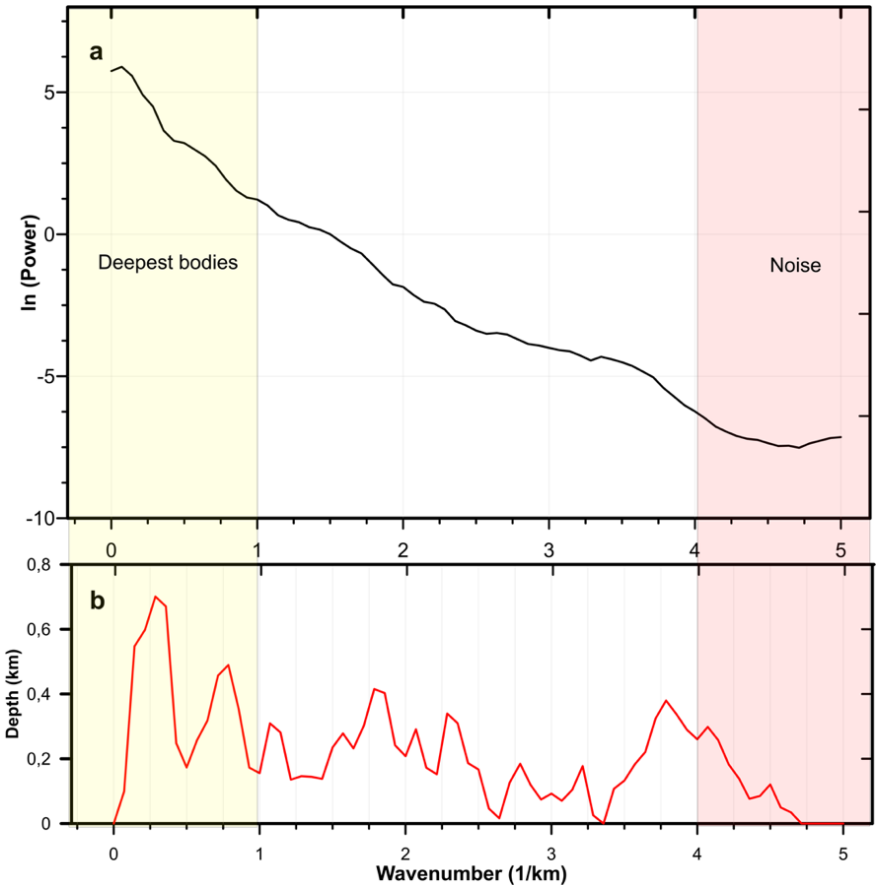

Figure 5. Radially averaged power spectrum and depth estimation of anomalies in the study area. The spectra is obtained using Geosoft software (Geosoft 2015) *and indicates a dominant source depth in the uppermost 300 m of the seafloor.*

Depth is relative to the sea surface, as before, and the results indicate that SI in the range 2 to 3 is most plausible for the Surtsey area. Structural index 1 (dikes) calls for unrealistically

shallow sources, forcing more than 50% of solution above the sea floor, which is not physically plausible. For SI=2 about 25% are forced above the sea floor while SI=3 (dipole-like sources) appears most realistic, with all the sources at or below the sea floor. Note, however, that the lava field on Surtsey with an approximate length of 1.5 km (NNW-SSE) and a width of 750 m (ENE-WSW), would be better represented by a sheet with SE=1. It should also be noted, the overall results from the Euler deconvolution are in agreement with the 2D spectra, in that most sources appear to be located in the uppermost 200-300 m of the sea floor.

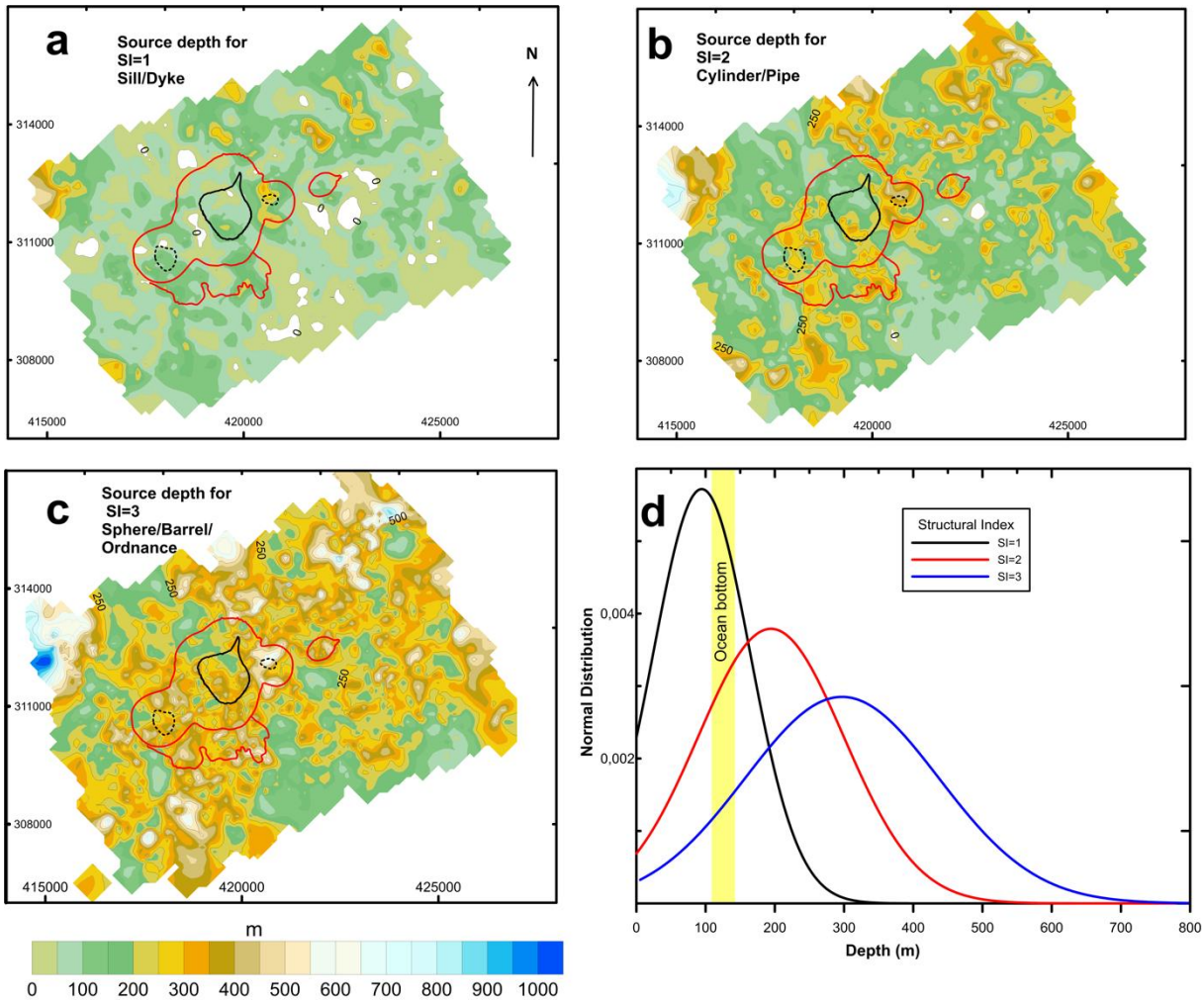

Figure 6. Depth estimation relative to the ocean surface for causative bodies according to 3D-Euler deconvolution of the magnetic map for different structural index (a) sheet; SI = 1, (b) vertical pipe; SI = 2 and (c) sphere; SI = 3. d) depth distribution of sources for each SI. Coordinates: INS93 Lambert in meters.

The depth to source analyses using two methods of spectral analysis and Euler deconvolution for the magnetic grid map provide essentially identical results, indicating that the principal sources for magnetic anomalies in the Surtsey region arise from shallow sources. In the sections that follow, we analyse the data in 2 ways. (1) We compare the 2021 survey with a previous survey done over Surtsey in 1965, exploring changes that have happened. (2) To further study three selected anomalies (over Surtsey, Jólnir and Surtla), we use forward modelling to place constraints on extent, thickness, and magnetization of the causative bodies. Constraints available from the contemporary monitoring of the Surtsey eruption are used where possible.

6.5 Comparison with the 1965 helicopter survey

A helicopter survey with a proton precession magnetometer was done at 200 m elevation above sea level on 31 August 1965, covering Surtsey and extending 1-1.5 km beyond its shores at this time (Sigurgeirsson 1968). Importantly, this survey was done after the eruption of Surtur II (1964-65) but before the formation of Jólnir and the effusive eruption of Surtur I. On Fig.7 the results of this survey are compared with the 2021 survey. We use data from Leirvogur Magnetic observatory to compensate for the observed changes in total field strength between 1965 and 2021. An additional 130 nT was added to the 1965 survey map to remove a remaining shift between the two maps outside of Surtsey. This discrepancy is probably due to the shifts applied to the data sets when directional effects are removed, as described in Section 5 above. Since the survey in 1965 was done at 200-meter height, an upward continuation filter (Blakely 1995) has been applied to the magnetic grid map of 2021 (Fig. 4) lifting it by 100 meters.

Comparison of the two surveys (Fig. 7c) shows large changes in the anomalies associated with Surtsey. The field strength has dropped where erosion has removed the subaerial lava, confirming that the lava field is the principal source of the positive anomaly over Surtsey. The anomaly over the remaining subaerial lava has increased between 1965 and 2021, especially where the Surtur I lava field was formed in 1966-67. A contributing factor to increase in anomaly strength in the western part of the lava field, formed in the 1964-65 Surtur II effusive activity, may be that it had not yet acquired full magnetization in 1965 because the lava stack had not everywhere cooled through its Curie point.

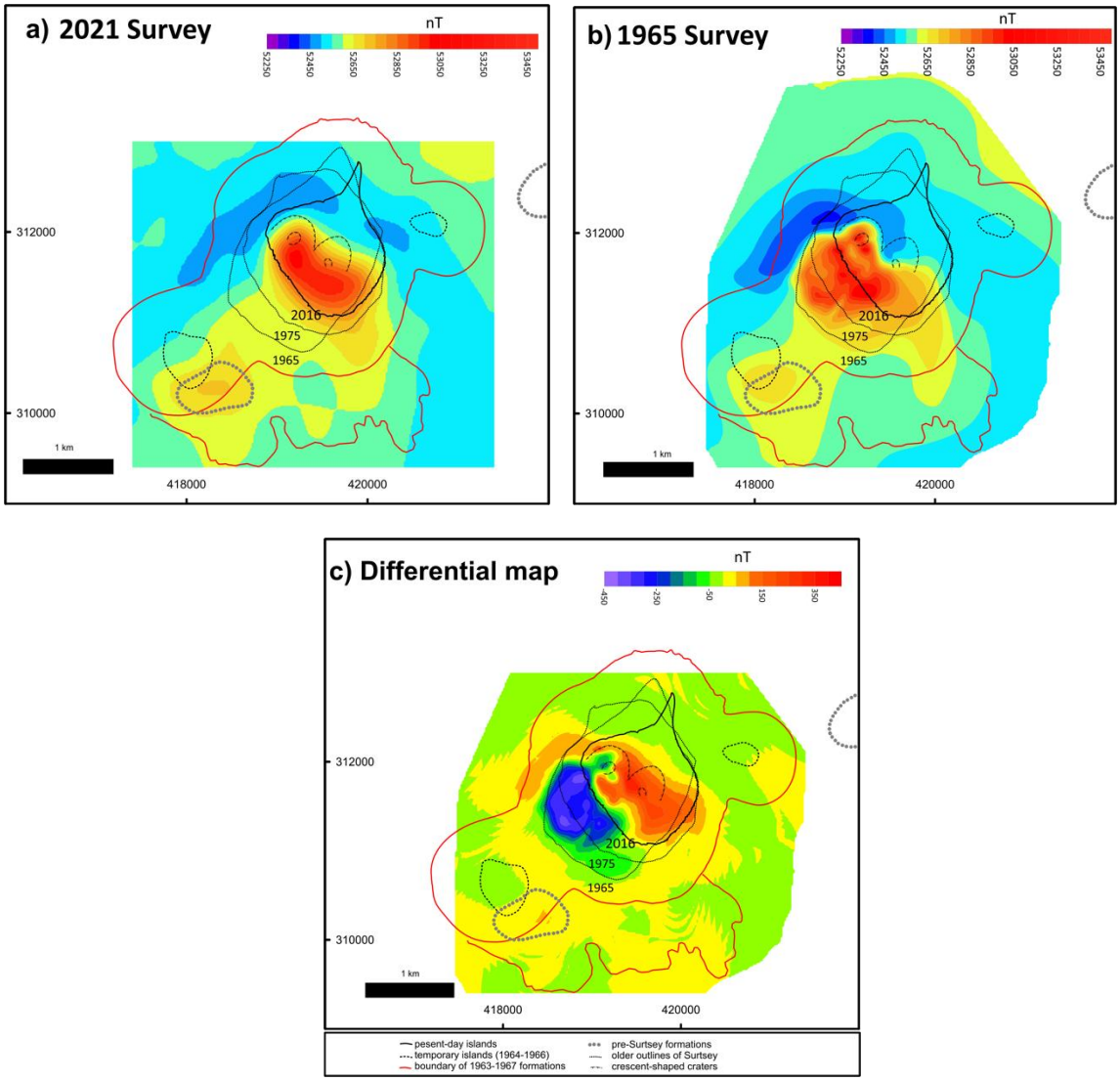

Figure 7. a) The 2021 map, upwards continued to 200 m above sea level. b.) The magnetic map from the 1965 survey has been shifted upwards by 1095 nT to remove a static shift, mostly caused by changes in average field strength in Iceland between the dates of the two surveys (see text). c) Differential map, the change between 1965 and 2021. Coordinates: INS93 Lambert in meters.

No apparent change can be seen between the two surveys, 1965 and 2021 (Fig. 7a and 7b) over the ocean bottom pillow lava field to the southeast of Surtsey. It was therefore already formed and cooled by this time, consistent with it being formed in the spring of 1964.

The anomaly associated with the knob under the SE side of Jólnir is visible in the magnetic maps. The knob is also visible on the bathymetric map made in 1964 (Jakobsson et al. 2009; Vésteinsson 2009). It therefore already existed when the Jólnir eruption took place in 1966. A question arises whether this knob could represent a submarine lava mound formed in the

first days of the Surtsey eruption in November 1963. The eruption is considered to have started on the ocean floor in the afternoon of November 12, based on seismic tremor (Sayyadi et al. 2021). Thermal anomalies were detected 3-4 miles to the southwest of Surtsey on the morning of the November 13, 1963, and in the vicinity of Surtsey on the November 14 (Malmberg 1965). Further measurements of sea surface temperatures were made around Surtsey on November 15 and 16, one and two days after the eruption became visible (Malmberg 1965).The measurements were made along N-S and E-W lines with Surtsey in the middle, with the closest observations made 300 m from the emerging island, with no anomaly at the site of the knob. This suggests that no significant heat sources were present on the sea floor after Surtsey emerged on the November 15, indicating that this knob existed before the onset of the Surtsey eruption. Had a basaltic lava edifice of this size been present and only a few days old on 16 November, it would have been releasing significant heat to the water column. Thus, it seems very likely that this knob existed before the eruption.

6.6 2.5D Forward Modelling

In order to explore the size, and place constraints on the geometry, of sources for the anomalies associated with (1) Surtsey and the pillow lava field to its south, (2) the knob beneath Jólnir and (3) the Surtla, we apply 2.5D forward modelling (Figs. 8-10). The modelling is done using the GravMag software (Pedley and Busby 1997). 2.5D forward modelling is based on the calculation of magnetic anomalies of right polygonal prisms of finite half-strike length (Shuey and Pasquale 1973).

6.6.1 Surtsey forward model

A profile along Surtsey (see Fig. 2 for location) is used for forward modelling which crosses the Surtsey island and the suspected pillow lava field to its south. The geometry of the island at the time of the survey and the topography of the island at the start of effusive activity (Thorarinsson 1967c) are used to define the geometry of the lava bodies (bodies 1 and 2 in Fig. 8) and the boundary between hyaloclasite tuffs from the explosive eruption and the lava delta formed in 1965-1967. A zero magnetization is assigned to the hyaloclastites. The best fit is obtained by assigning a magnetization of 14 A/m to the lavas from Surtur II and 19 A/m to those of Surtur I. These values are somewhat higher than the measured mean for the samples, falling to the range of one standard deviation. These bodies are the principal source for the large ~700 nT anomaly observed. The model indicates that hyaloclastite tuffs dominate the submarine part of Surtsey, both for Surtur I and Surtur II. This is consistent

with results of drilling done in 1979 and 2017 (Jakobsson and Moore 1982; Jackson et al. 2019), which reveal only minor amounts of coherent crystalline rock (dykes and other intrusions) within the tuffs. A substantial pile of pillow lava on the sea floor at either eruption site would be difficult to reconcile with the magnetic anomalies because inclusion of such a body leads to a broader anomaly than observed. The lava delta is inferred to consist of largely glassy deposits having only minor amounts of crystalline magnetized rock (e.g. Watton et al. 2013), and is assigned only minor magnetization in the model.

The pillow lava field was assigned a magnetization value similar to that of the lavas and a thickness of around 10 m. There is of course a trade-off between thickness and magnetization. The same result would be obtained for a 20-m-thick pillow lava field with magnetization of 7 A/m.

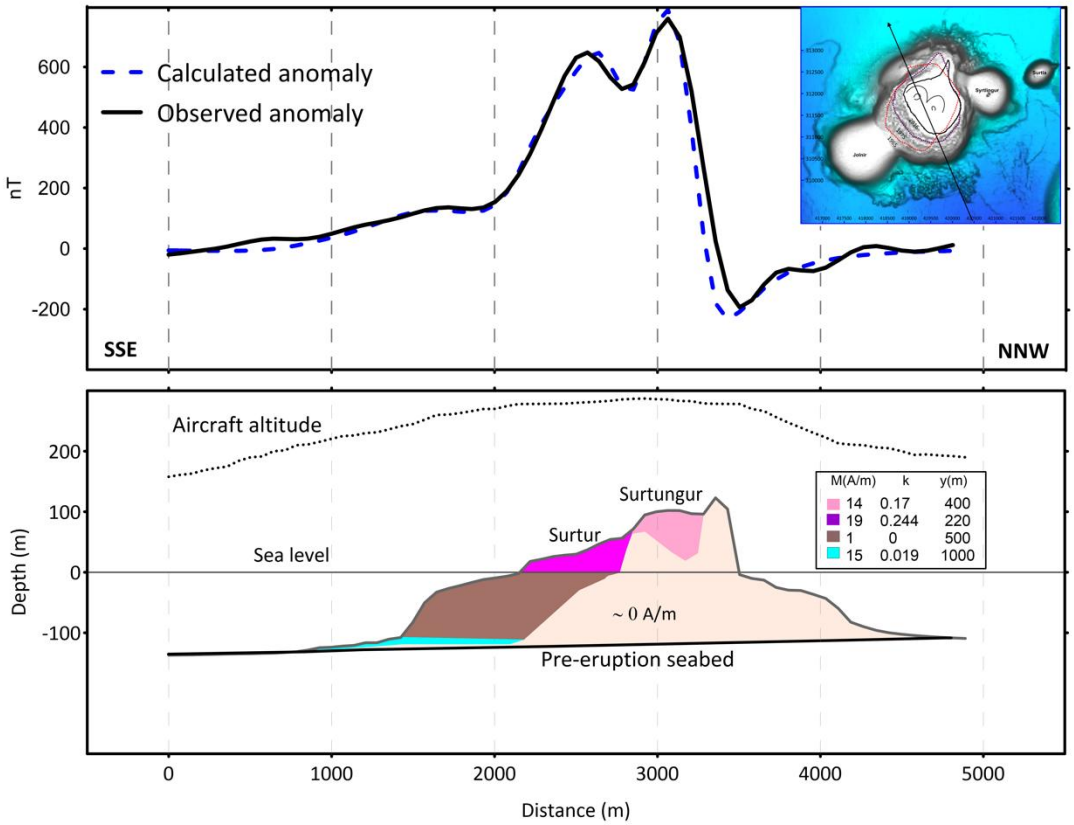

Figure 8. A 2.5D forward magnetic model of Surtsey and the sea floor to its south created with the GravMag software (Pedley and Busby 1997). *The table shows the magnetization of bodies (M), the susceptibility used (k) and the half strike lengths (y) of the individual bodies.*

6.6.2 Surtla forward model

The forward model for the short profile over Surtla is shown in Figure 9 (see Fig. 2 for location). Surtla was formed in a submarine eruption at the end of December 1963 and first days of January 1964. A dyke, modelled as 2 m wide, is inserted along the axis of the formation, based on evidence of crystalline rocks that were found at the ridge (Kokelaar 1983; Jakobsson et al. 2009). The dyke, however, is not needed to explain the anomaly, the assigning of minor magnetization (<1 A/M) to the edifice is required to approximate its form. This could be explained by the presence of peperites and/or dispersed small coherent crystalline intrusions.

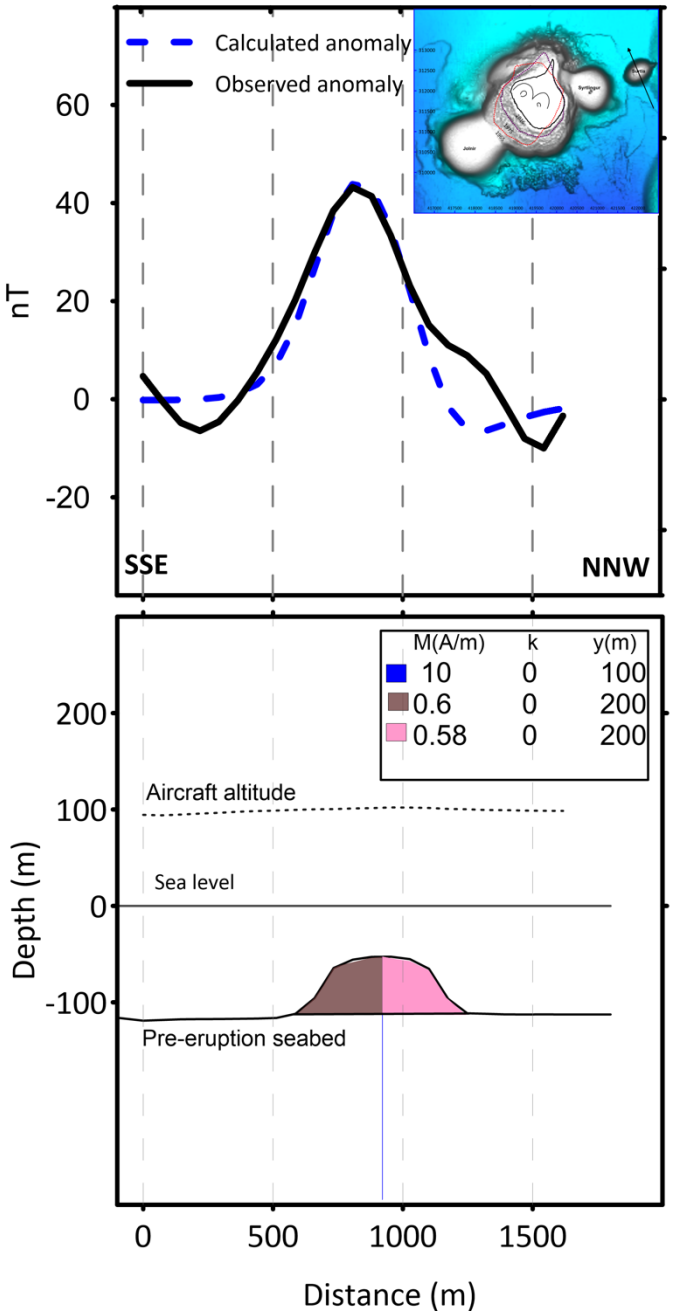

Figure 9. Surtla 2.5D forward model. Results from GravMag software (Pedley and Busby 1997). *The table shows the magnetization of bodies (M), the susceptibility used (k) and the half strike lengths (y) of the individual bodies.*

6.6.3 Jólnir forward model

A 2.5D forward model for Jólnir is shown in Figure 10 (see Fig. 2 for location). The most prominent feature is the knob seen both in the seismic reflection profile from 1980 (Thors and Jakobsson 1982) and the 1964 bathymetric survey (Vésteinsson 2009) and these profiles are used to constrain the thickness of the body modelled. It is up to 30-40 m thick and the magnetization required to explain it is 11 A/m. A thinner body, possibly pillow lava, extends to the south. Apparently, the main edifice of Jólnir has essentially zero magnetization, consistent with it being made up of hyaloclastite with negligible amounts of crystalline, magnetized rocks.

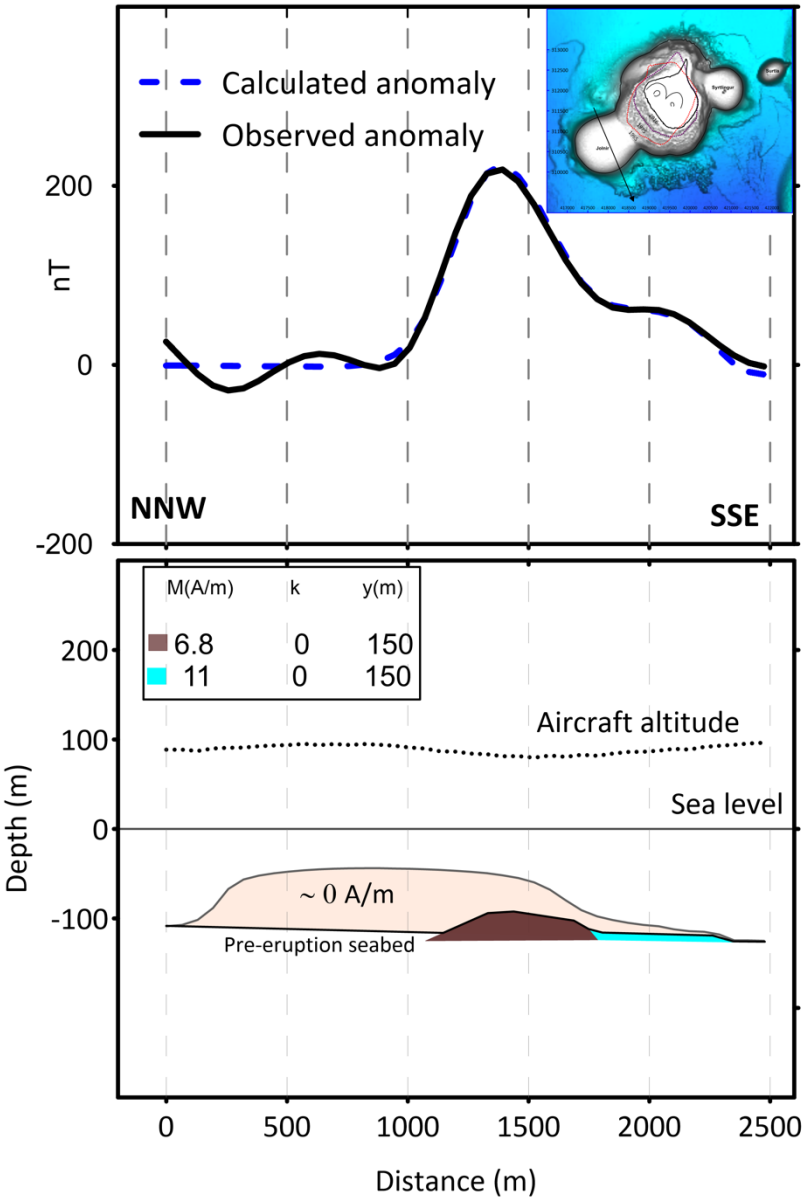

Figure 10. A 2.5D forward magnetic model of Jolnir. Result from GravMag software (Pedley and Busby 1997). *The table shows the magnetization of bodies (M), the susceptibility used (k) and the half strike lengths (y) of the individual bodies.*

7. Discussion

This study demonstrates the potential of aeromagnetic surveying coupled with detailed bathymetry for the analysis of past eruptive activity in shallow submarine settings. This applies in particular where the volcanic structures are formed within and on top of thick sedimentary sections, that do not produce magnetic anomalies. In such settings, magnetized bodies detected would be pillows and other submarine lavas, buried bodies of subaerially erupted lava formed at times of lower sea level, and crystalline intrusions of significant thickness.

The main aim of our work is to use geophysical data to constrain interpretations of the structure of the 1963-67 formations and their association with possible intrusions into the sedimentary succession underlying Surtsey. A second aim is to use the results to assess the usefulness of aeromagnetic surveying in identifying volcanic formations on the sea floor.

A limitation that must be kept in mind is that only large scale/overall bulk properties of formations can be obtained through aeromagnetic surveying. The approximately minimum clearance between aircraft/magnetometer and sources is about 200 m. This implies that minor intrusions of spatially limited extent produce very subtle anomalies that are difficult to pick out. It is therefore to be expected, that in order for magnetized bodies to produce detectable, anomalies they need to have a large enough spatial extent.

The overall character of the Surtsey eruption formations is as follows: They are mostly non-magnetic below sea level. No significant anomalies seem to arise from the hyaloclastite tuff bodies that were produced in the explosive eruptive activity (tuff cores of Surtsey, Syrtlingur and Jólnir). An exception to this is principally the sea-bottom pillow lava flow to the SE of Surtsey. Above sea level, the lava flows are highly magnetic and the strongest source of magnetic anomalies.

There are differences between the magnetic anomalies for Surtla on one hand and Jólnir and Syrtlingur on the other. The ephemeral islands of Syrtlingur and Jólnir were produced in explosive subaerial eruptions that added clastic deposits to their apparently clastic, non-magnetic, submarine-grown bases. Styles of eruption from these islands were like those seen at Surtsey, but only Surtsey retains subaerial deposits that can be studied. Surtsey's deposits contain large numbers of blocks formed by disruption of crystalline, apparently syngenetic, dikes. They are tabular, with two characteristically rugged exterior surfaces enclosing crystalline, poorly vesicular cores. The width of these fragments is typically 10-20 cm,

representing the width of the disrupted dikes. Even thinner, glassier, dikes are seen in cores extracted from Surtsey, and the overall impression given is that Surtsey, and by extension Syrtlingur and Jólnir, host numerous dikes that are individually very thin. The feeder dykes for individual vents may be considerably wider. The drillhole SE03 intersected the feeder of the Surtur effusive eruption of 1966-67, revealing a composite dyke with a total thickness of about 5 meters (Jackson et al., 2019; Weisenberger et al., 2019; 2022). An important constraint on the volumetric contribution of the minor intrusions, feeders and other dykes, comes from the 1979 and 2017 drillcores. Overall, intrusive crystalline rocks (dykes) constitute 19 m out of 727 m total in holes SE01, SE02B and SE03 (Jakobsson and Moore, 1982; Jackson et al., 2019; Weisenberger et al., 2019), or 2.6%. Using magnetization of 10-15 A/m, this would result in a volumetric average of 0.3-0.4 A/m.

The small but significant magnetic anomaly over Surtla fits with the eruption of Surtla having been of lower explosive intensity. The edifice never grew above sea level to form an island; it also did not experience the powerful phreatomagmatic explosions observed subaerially during the explosive phases of Surtsey, Syrtlingur and Jólnir. The smaller volume of magma erupted at Surtla, along with its wholly submarine growth, is reflected in its different magnetic signature, which is dominated by an apparently vertical sheet of highly magnetic rock. One possibility is that the anomaly represents a single dike about 2 m thick. Another possibility is that the sheetlike magnetic body at Surtla represents a meters-wide fissure that was backfilled and mingled with enclosing pyroclastic debris during weakly explosive activity. We would expect such a feature to share some characteristics of fissure-filling deposits now visible where erosion has removed weak country rock enclosing the upper few hundred meters of fissures linked with subaerial eruptions (e.g. Lefebvre et al. 2012; Re et al. 2016). No submarine equivalent is known, though spatter deposits formed during a submarine fissure eruption at Miyakejima in 2000 (Kaneko et al. 2005).

This project can be regarded as one step towards developing methods for better hazard assessment and eruption frequency in the shallow ocean setting of the Vestmannaeyjar archipelago. Further analysis of aeromagnetic survey data obtained in this project, including comparison with the detailed bathymetric map offers potential to better assess the characteristics of volcanic formations buried by seafloor sediments or intruded into the sedimentary succession, as well as those of younger volcanics deposits.

Finally, compared to drone surveys, aircraft aeromagnetic surveys allow the coverage of larger regions in a shorter period of time, providing considerable amounts of magnetic data at modest cost. The high resolution of these surveys supports detailed analysis of the subsurface distribution and geometry of magnetized bodies in the volcanic area. Shallow depth anomalies correlate with high-frequency magnetic anomalies and are more detectable in low elevation and higher resolution surveys. (Caratori Tontini et al. 2016; Miller and Williams-jones 2016; Blanco-Montenegro et al. 2020).

8. Conclusions

- The depth estimates for the area obtained by 2D spectral analysis and Euler deconvolution indicate that all significant sources of magnetic anomalies, with the exception of the Surtsey subaerial lava field, are located on the sea floor or in the uppermost 200-300 meters of the seafloor sedimentary succession.
- By far the strongest anomaly is associated with the subaerial lava field on Surtsey. The ~700 nT anomaly is best explained by 14-19 A/m magnetization of the subaerial lava flow field formed on Surtsey in two episodes in 1964-1967. The magnetic data are not consistent with the presence of significant volumes of magnetic rocks at or above the seafloor underneath the vent areas of Surtsey, supporting previous results and inferences that no mounds of pillow lava were formed in the initial phases of the eruption.
- A subtle magnetic high is correlated with the pillow lava field observed to the south of Surtsey. Modelling in 2.5D indicates that this anomaly is best explained by ~10-m - thick layer of pillow lava at the sea bottom, with a magnetization of order 10-15 A/m. This pillow lava field likely formed in May-June 1964.
- A clear magnetic anomaly is located on the southern edge of the submarine mound that is the remnant of the temporary island of Jólnir formed in 1966. Data obtained in 1964 indicates that a 50-m-high submarine knob is the cause of this anomaly. This feature apparently pre-dates the formation of Surtsey because surveys of ocean surface temperature, done in the first days of the eruption, did not indicate any activity at this location in November 1963.
- No magnetic anomaly is associated with the mound that is the remnant of the temporary island Syrtlingur, formed in 1965. In contrast, a weak anomaly is

associated with mound of Surtla, formed in 1963/64. The Surtla anomaly can be modelled with a 2-meter-wide dyke along the ridge of Surtla, intruding a Surtla edifice with weak (<1 A/m) magnetization. An alternative explanation is that the anomaly arises from a broader fissure fill such as seen associated with some subaerial eruptions – this is more consistent with the observed narrowness of dikes in Surtsey, which are typically an order of magnitude thinner than 2 meters.

- The differences between the magnetic anomalies for Surtla on one hand and Jólnir and Syrtlingur on the other, may be that the eruption of Surtla was of lower explosive intensity, never experiencing the powerful phreatomagmatic explosions observed during the explosive phases of Surtsey, Syrtlingur and Jólnir. Surtla is likely to preserve a complex tabular fissure fill, whereas at Syrtlingur and Jólnir, explosive Surtseyan activity destroyed any early-formed fill of this sort or prevented one from forming.
- There are no sub-seafloor intrusions beneath Surtsey and its satellite islands at a scale sufficient to generate an anomaly detectable by the aeromagnetic survey. This does not rule out intrusions, but their volume and extent would have to be relatively minor compared to the main bodies causing anomalies in this area.

Acknowledgements

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Appendices

Appendix A: Analog seismic records seismogram records from October 31 until November 14, 1963, at Kirkjubæjarklaustur (SID).

Appendix B: A list of earthquakes detected by the seismic network in Iceland associated with the Surtsey eruption, during the period 14 November 1963 - 1 July 1967

Appendix C: earthquake magnitude distribution graph

Appendix D: Timing of tremor detections in seismic records during the Surtsey eruption

Appendix E: Remanence and susceptibility of lava samples from Surtsey

Appendix A:

Bulletin of Volcanology - Supplementary Material for:
Seismic activity associated with the 1963-1967 Surtsey eruption off the coast of South Iceland.

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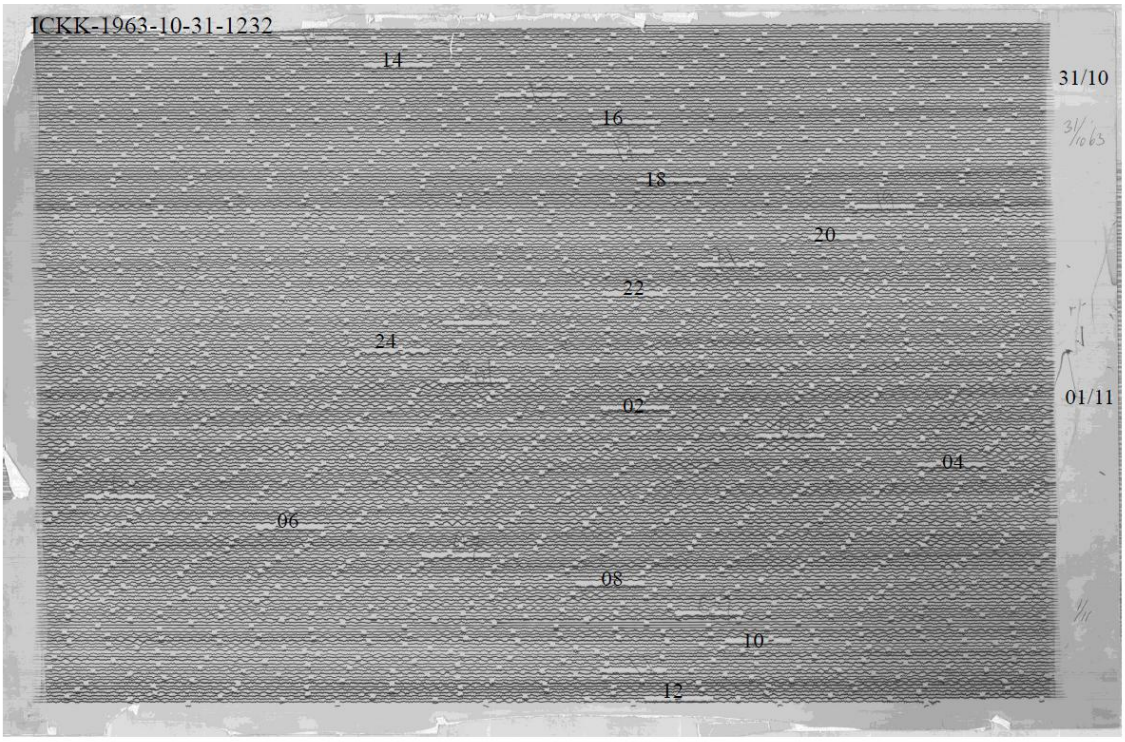
This PDF file includes:

Recording of analog seismic records from October 31 until November 14, 1963, at Kirkjubæjarklaustur (SID). All figures are accessible online at following address:
http://seismis.hi.is/.

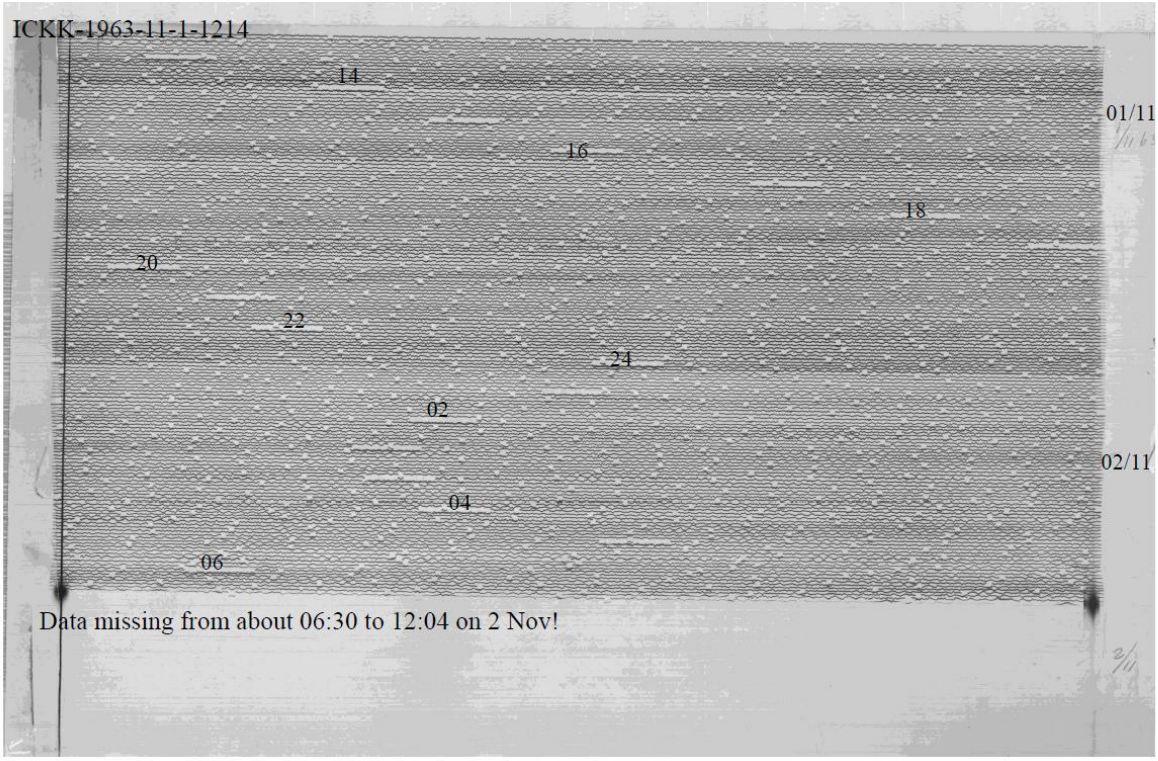
Description of figures:

Each page shows approximately 24 hours, numbered as S1 to S15.
Each seismogram has a header stating year-month-day and hour for the start of the recording. ICKK stands for records at SID station.

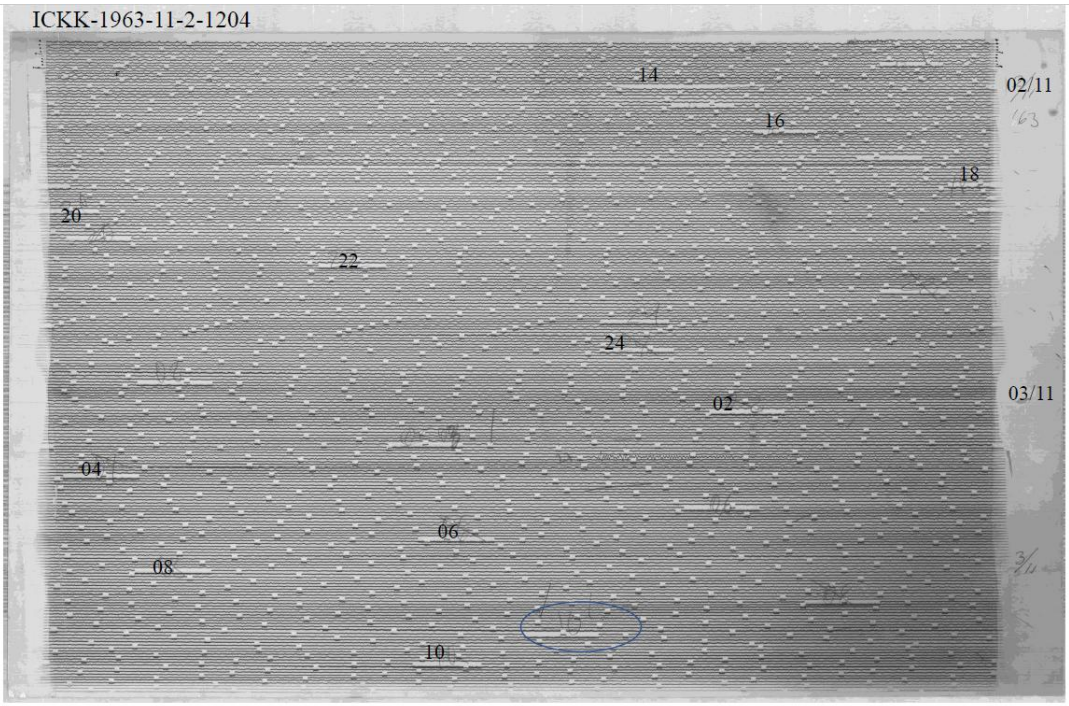
In each figure the earthquakes/events suspected to be associated with Surtsey are shown with blue ellipses. Suspected bursts of tremor on November 12 and 13 are shown in the same way.


ICKK-1963-10-31-1232
14
16
18
20
22
24
02
04
06
08
10
12
31/10
01/11

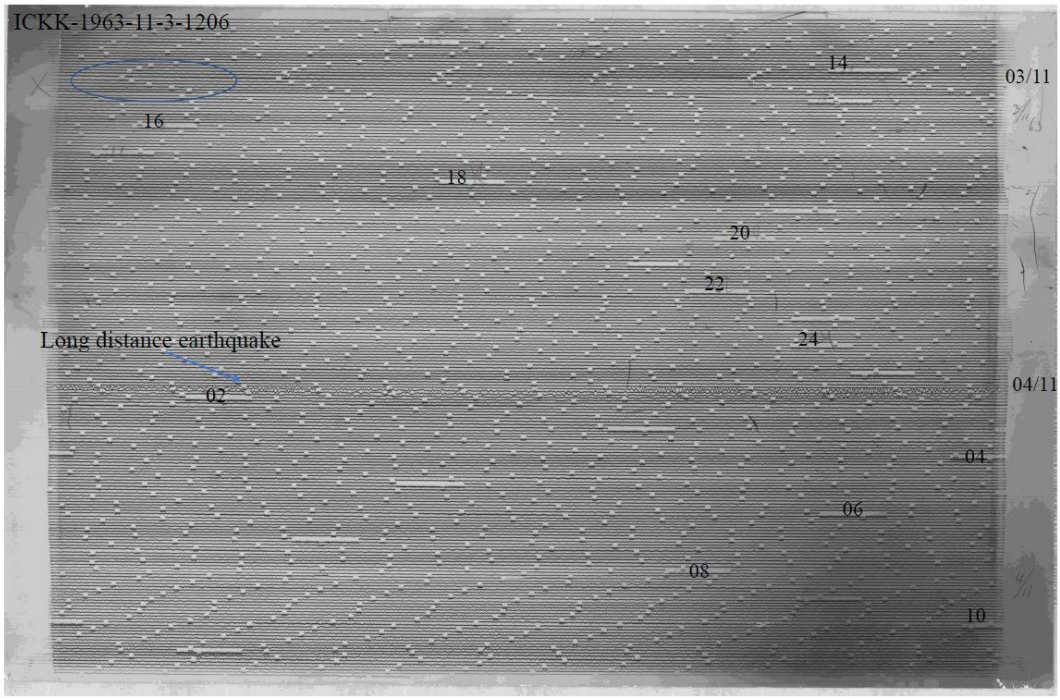
S1


ICKK-1963-11-1-1214
14
16
18
20
22
24
02
04
06
01/11
02/11
Data missing from about 06:30 to 12:04 on 2 Nov!

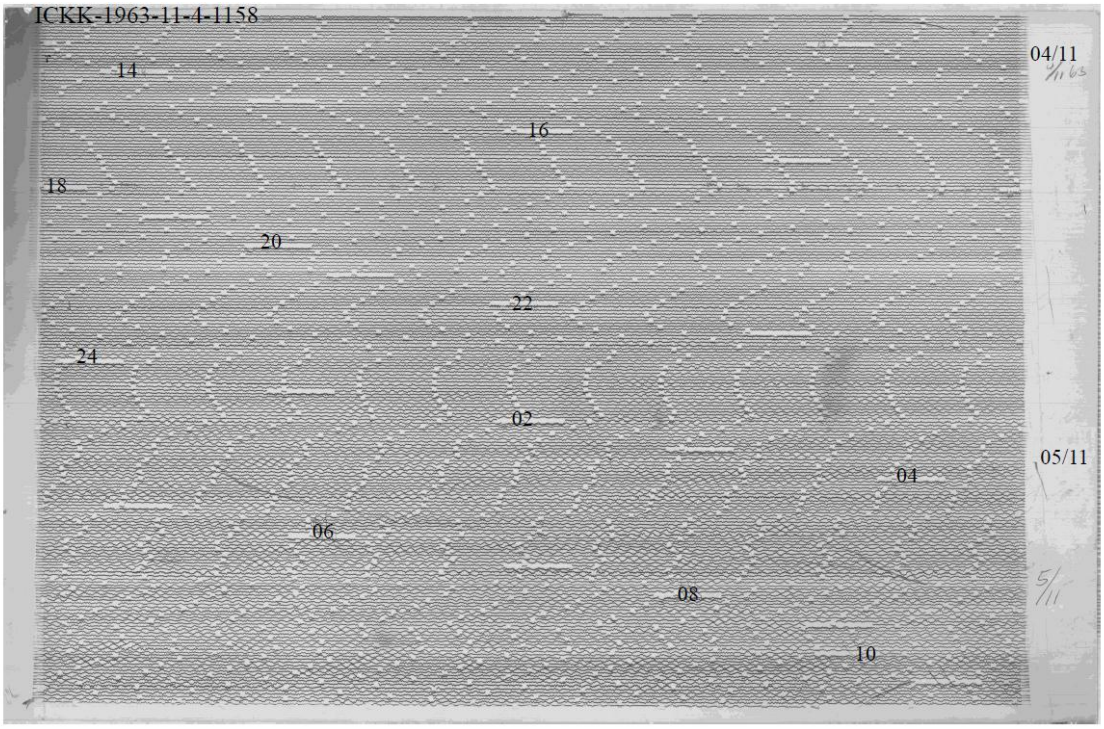
S2


ICKK-1963-11-2-1204
14
16
18
20
22
24
02
04
06
08
10
02/11
03/11

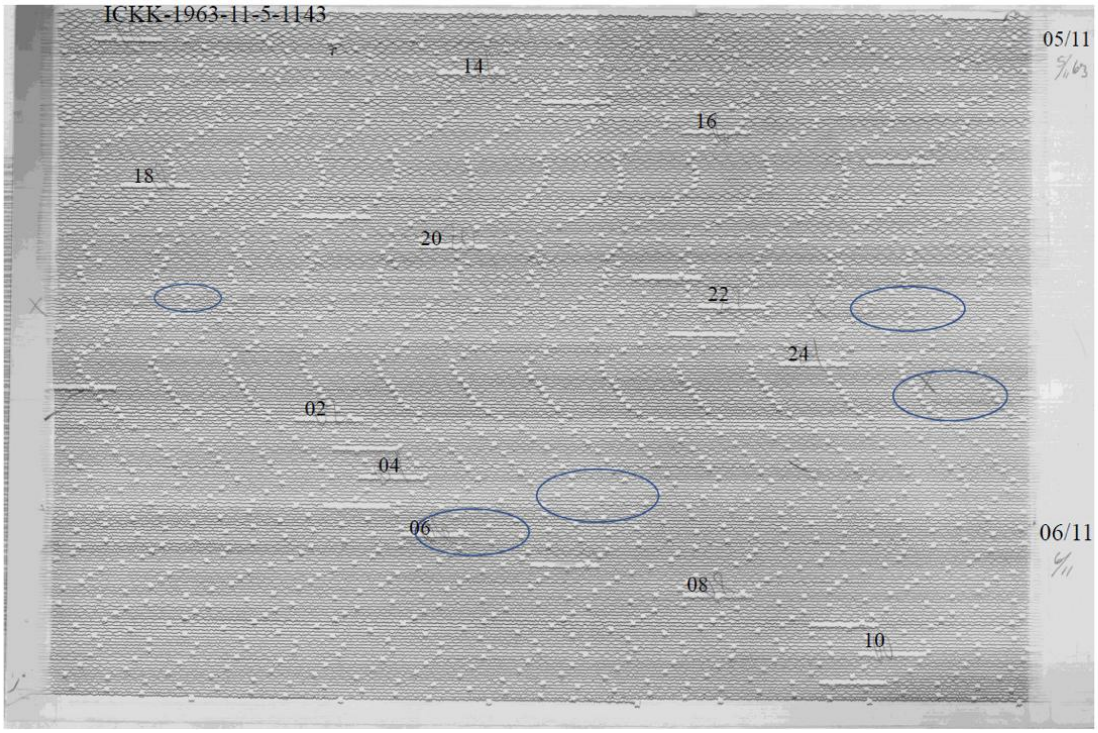
S3


ICKK-1963-11-3-1206
14
16
18
20
22
24
Long distance earthquake
02
04
06
08
10
03/11
04/11

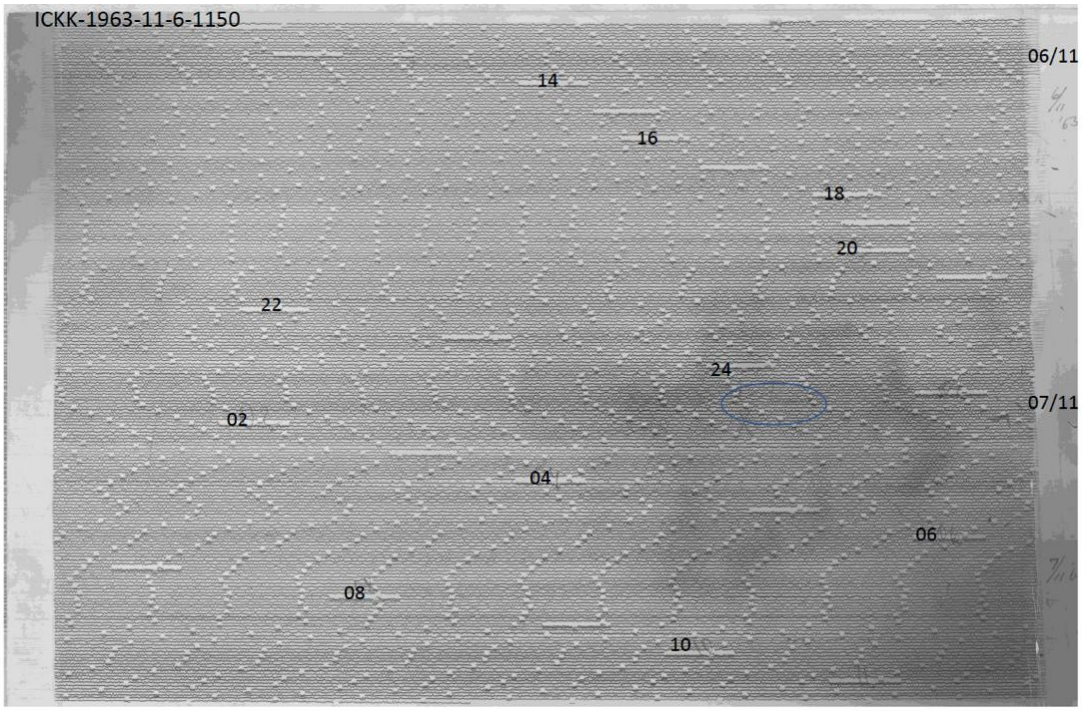
S4


ICKK-1963-11-4-1158
04/11
14
16
18
20
22
24
02
05/11
04
06
08
10

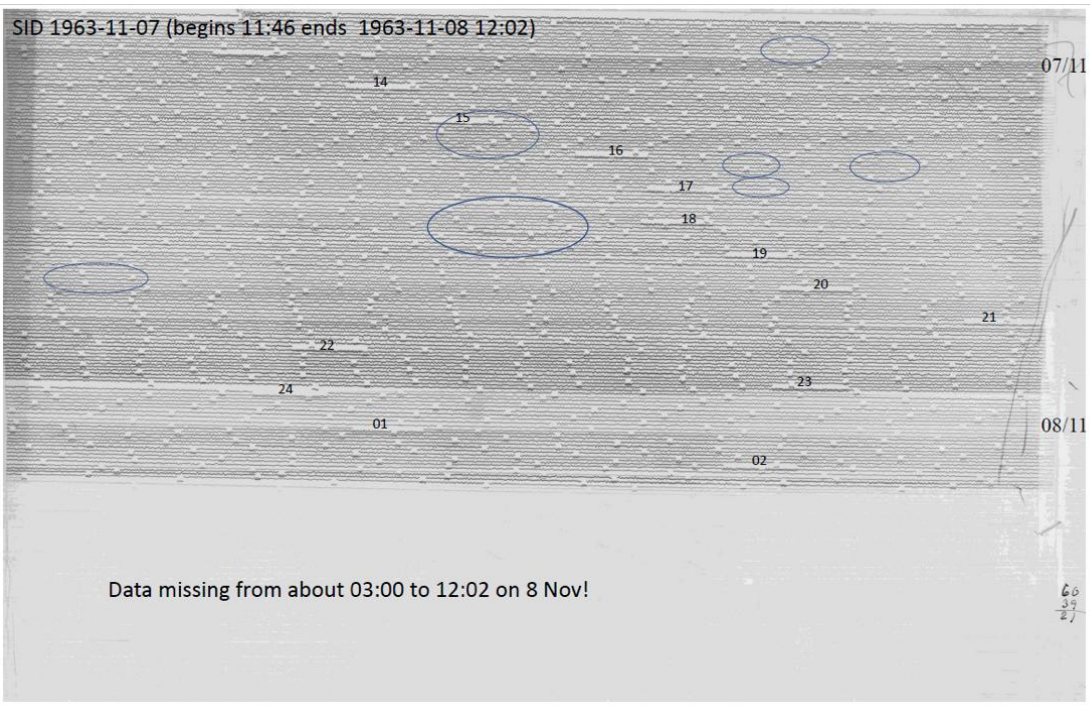
S5


ICKK-1963-11-5-1143
05/11
14
16
18
20
22
24
02
04
06
06/11
08
10

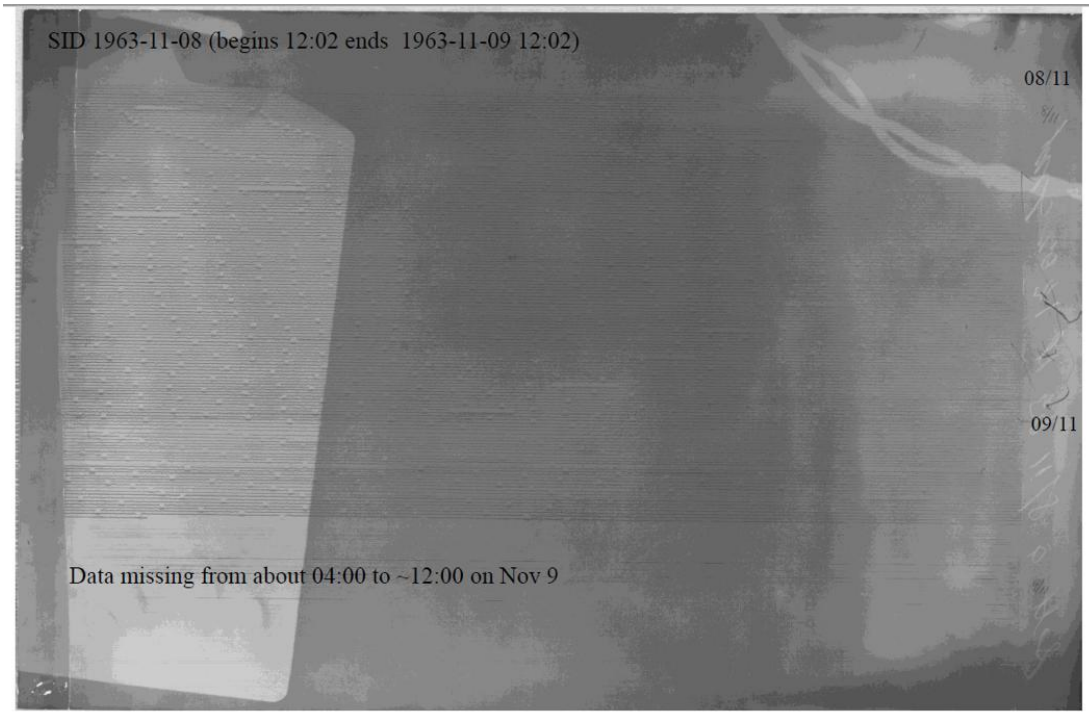
S6


ICKK-1963-11-6-1150
06/11
14
16
18
20
22
24
07/11
02
04
06
08
10

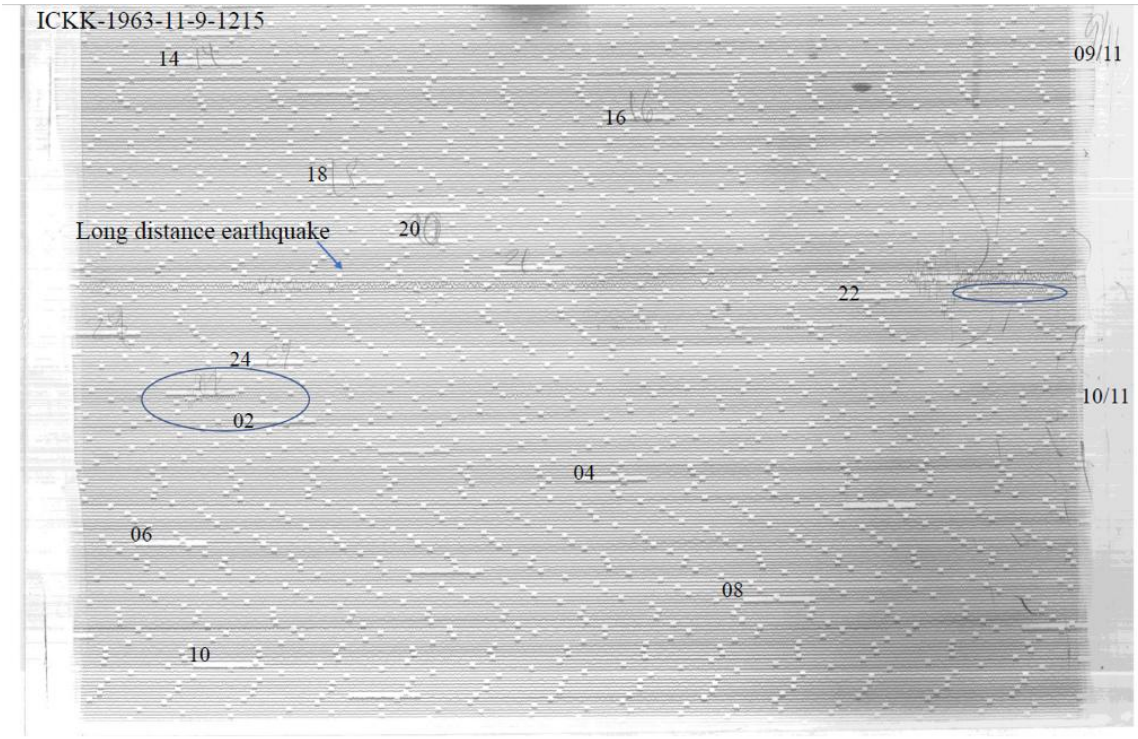
S7


SID 1963-11-07 (begins 11:46 ends 1963-11-08 12:02)
07/11
14
15
16
17
18
19
20
21
22
23
24
01
08/11
02
Data missing from about 03:00 to 12:02 on 8 Nov!

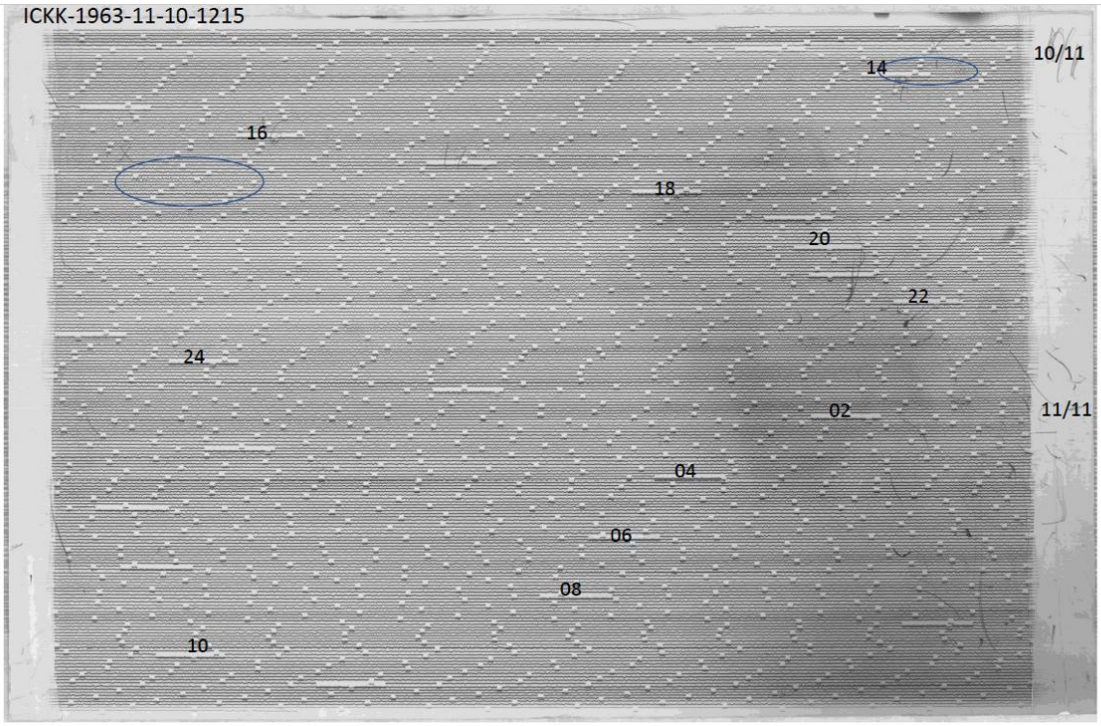
S8


SID 1963-11-08 (begins 12:02 ends 1963-11-09 12:02)
08/11
09/11
Data missing from about 04:00 to ~12:00 on Nov 9

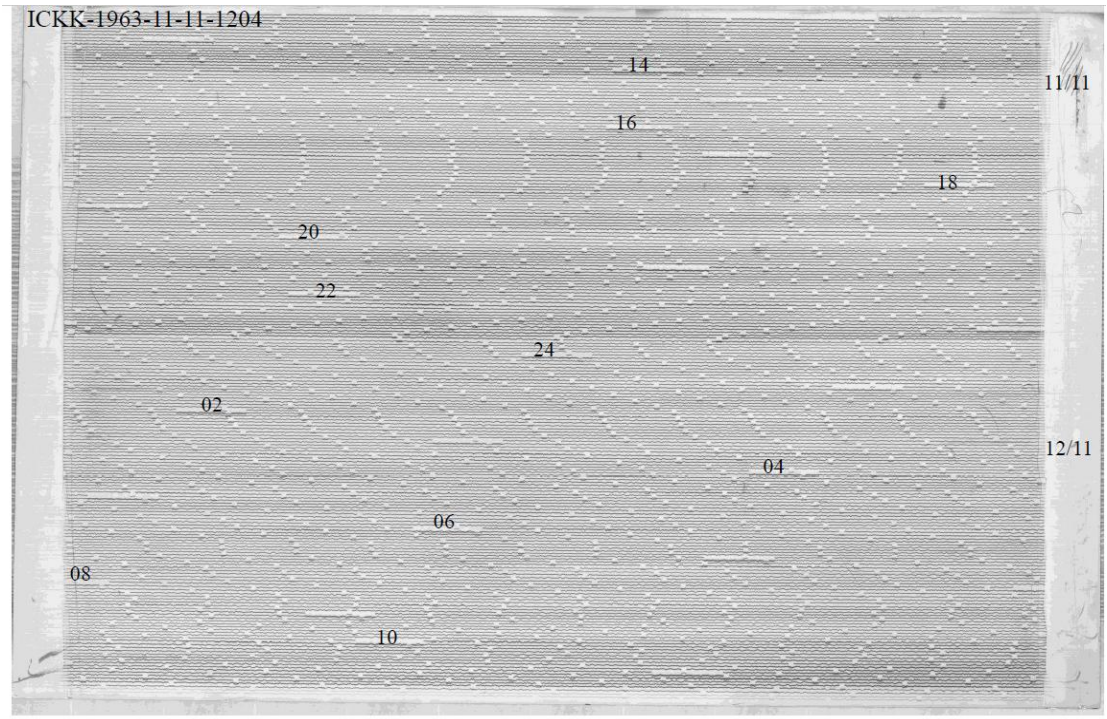
S9

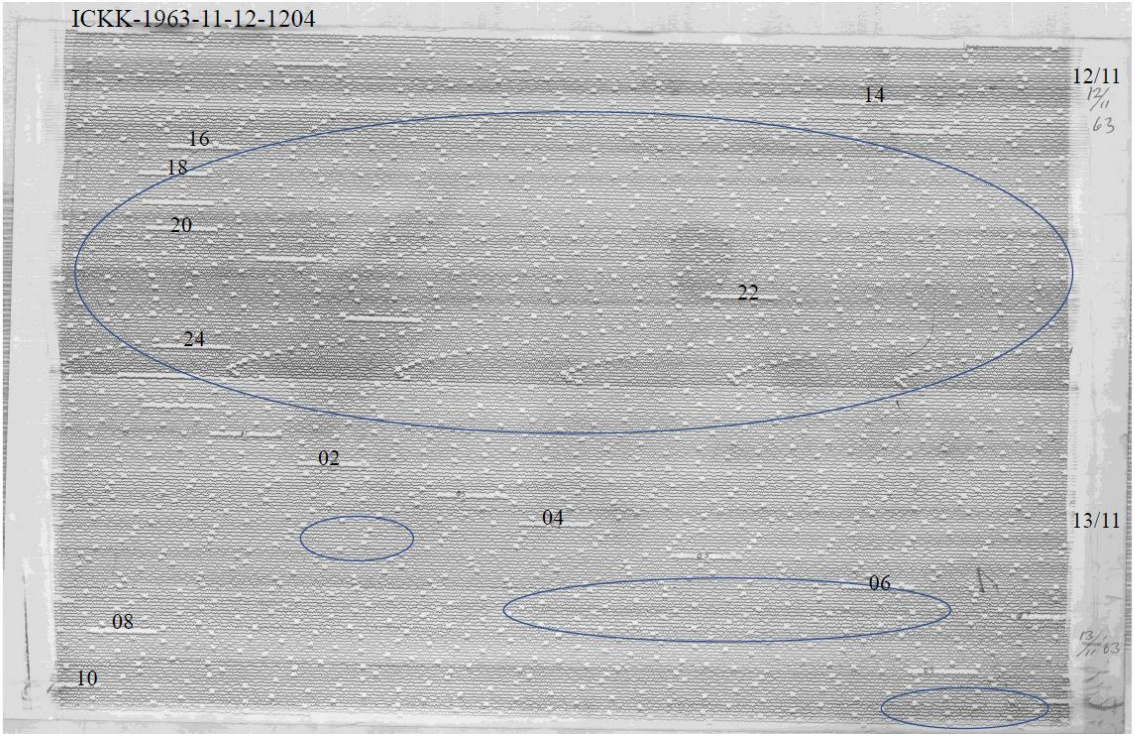

ICKK-1963-11-9-1215
14
09/11
16
18
Long distance earthquake
20
22
24
10/11
02
04
06
08
10

S10

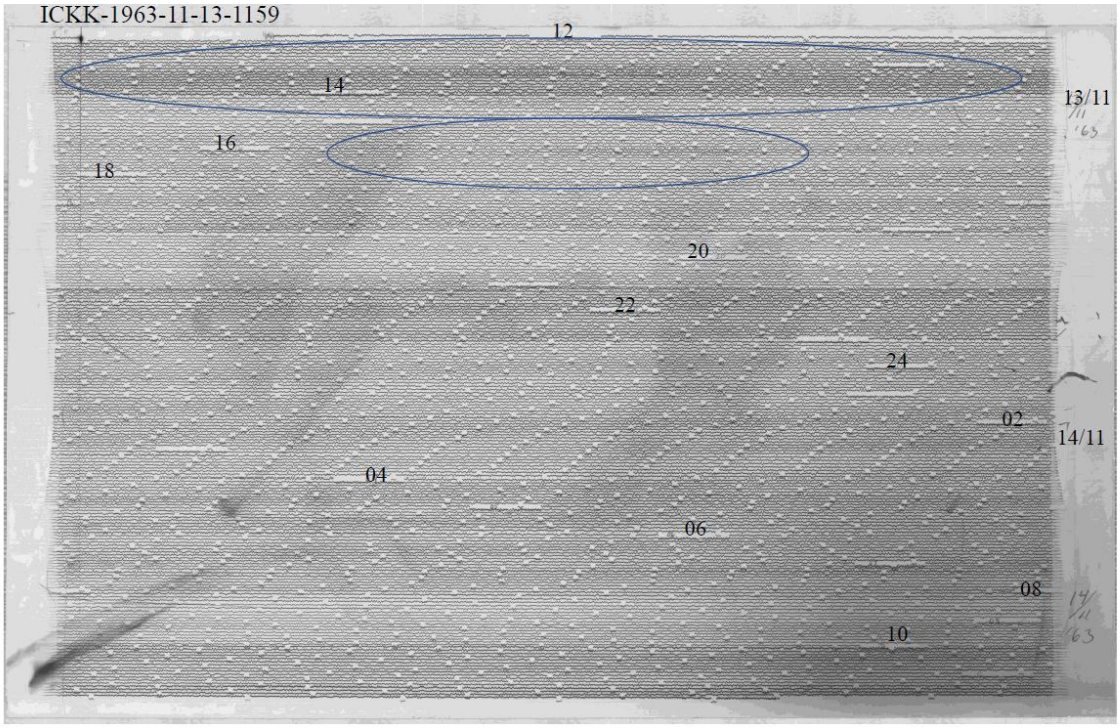

ICKK-1963-11-10-1215
10/11
14
16
18
20
22
24
02
11/11
04
06
08
10

S11

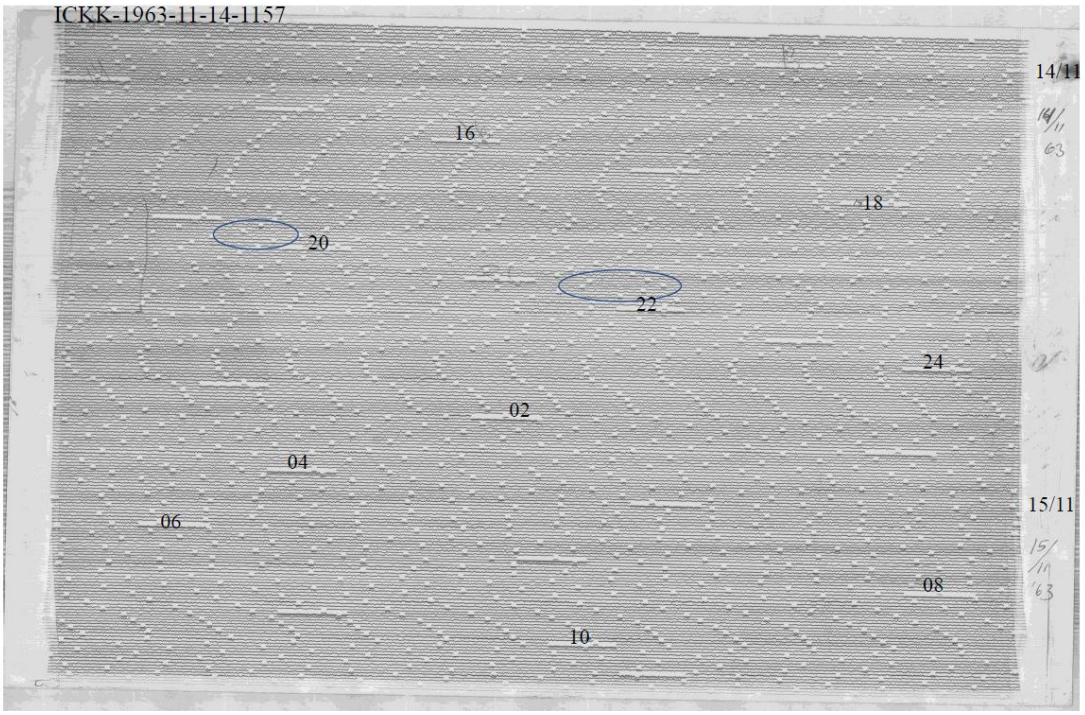

ICKK-1963-11-11-1204
14
11/11
16
18
20
22
24
02
12/11
04
06
08
10


ICKK-1963-11-12-1204
12/11
14
16
18
20
22
24
02
04
13/11
06
08
10

S13


ICKK-1963-11-13-1159
12
14
13/11
16
18
20
22
24
02
14/11
04
06
08
10

S14


ICKK-1963-11-14-1157
14/11
14/11 63
16
18
20
22
24
02
04
06
15/11
15/11 63
08
10

S15

Appendix B:

Bulletin of Volcanology - Supplementary Material 2 for:

Seismic activity associated with the 1963- 1967 Surtsey eruption off the coast of South Iceland

Sara Sayyadi[1], Páll Einarsson[1], Magnús T. Gudmundsson[1]

1.Nordvulk, Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

This PDF file includes:

A list of earthquakes detected by the seismic network in Iceland associated with the Surtsey eruption, during the period 14 November 1963 - 1 July 1967 (source of information are:

Iceland Meteorological Office (1964a, 1964b, 1970, 1978, 1979a, 1979b, 1980) and Sigtryggsson and Sigurdsson (1966).

Date	Magnitude	Days since November 14, 1963
December 9, 1963	2,1	25
December17, 1963	3,8	33
December 20, 1963	2,5	36
December 21, 1963	2,5	37
December 23, 1963	3,1	39
December 23, 1963	3,1	39
December 23, 1963	3,1	39
December 31, 1963	2,8	47
January 3, 1964	3	50
January 4, 1964	3,8	51
January 5, 1964	2,4	52
January 5, 1964	3,3	52
January 5, 1964	2,7	52
January 5, 1964	2,7	52
January 7, 1964	2,3	54
January 7, 1964	2,3	54
January 7, 1964	3,2	54
January 7, 1964	3,4	54
January 7, 1964	3,6	54
January 7, 1964	2,8	54
January 7, 1964	2,3	54
January 7, 1964	2,3	54
January 7, 1964	4	54
January 7, 1964	4	54
January 8, 1964	3,8	55
January 8, 1964	3,5	55
January 8, 1964	3,3	55
January 8, 1964	4,3	55
January 8, 1964	2,7	55
January 8, 1964	2,4	55
January 8, 1964	2,5	55

Date	Magnitude	Days since November 14, 1963
January 8, 1964	2,6	55
January 8, 1964	3,9	55
January 8, 1964	4,4	55
January 8, 1964	4,4	55
January 9, 1964	4	56
January 9, 1964	3,3	56
January 9, 1964	3,1	56
January 9, 1964	2,4	56
January 9, 1964	4,4	56
January 9, 1964	4	56
January 9, 1964	4,5	56
January 9, 1964	3,1	56
January 10, 1964	3,2	57
January 10, 1964	3,9	57
January 10, 1964	3,3	57
January 10, 1964	3	57
January 10, 1964	2,2	57
January 23, 1964	4	70
January 23, 1964	2,7	70
January 23, 1964	2,5	70
January 23, 1964	2,9	70
January 23, 1964	3,5	70
January 29, 1964	2,5	76
January 31, 1964	3	78
January 31, 1964	3,1	78
January 31, 1964	2,5	78
January 31, 1964	3,1	78
February 1, 1964	3,5	79
February 1, 1964	2,4	79
February 1, 1964	2,6	79
February 1, 1964	3,1	79
February 1, 1964	4,3	79

Date	Magnitude	Days since November 14, 1963
February 1, 1964	3,7	79
February 1, 1964	2,9	79
February 1, 1964	3,3	79
February 1, 1964	3,3	79
February 1, 1964	2,6	79
February 1, 1964	3,8	79
February 1, 1964	2,6	79
February 1, 1964	2,4	79
February 1, 1964	2,7	79
February 1, 1964	4,1	79
February 1, 1964	2,8	79
February 1, 1964	4,2	79
February 1, 1964	2,9	79
February 1, 1964	3,6	79
February 1, 1964	2,5	79
February 1, 1964	4,2	79
February 1, 1964	2,4	79
February 1, 1964	3	79
February 1, 1964	3,6	79
February 1, 1964	2,3	79
February 1, 1964	2,8	79
February 1, 1964	2,1	79
February 1, 1964	3,9	79
February 1, 1964	2,1	79
February 1, 1964	3,1	79
February 1, 1964	2,9	79
February 1, 1964	2,4	79
February 5, 1964	3	83
February 6, 1964	2,5	84
February 12, 1964	2,2	90
February 18, 1964	2,4	96
February 20, 1964	2,5	98
March 6, 1964	3,1	113

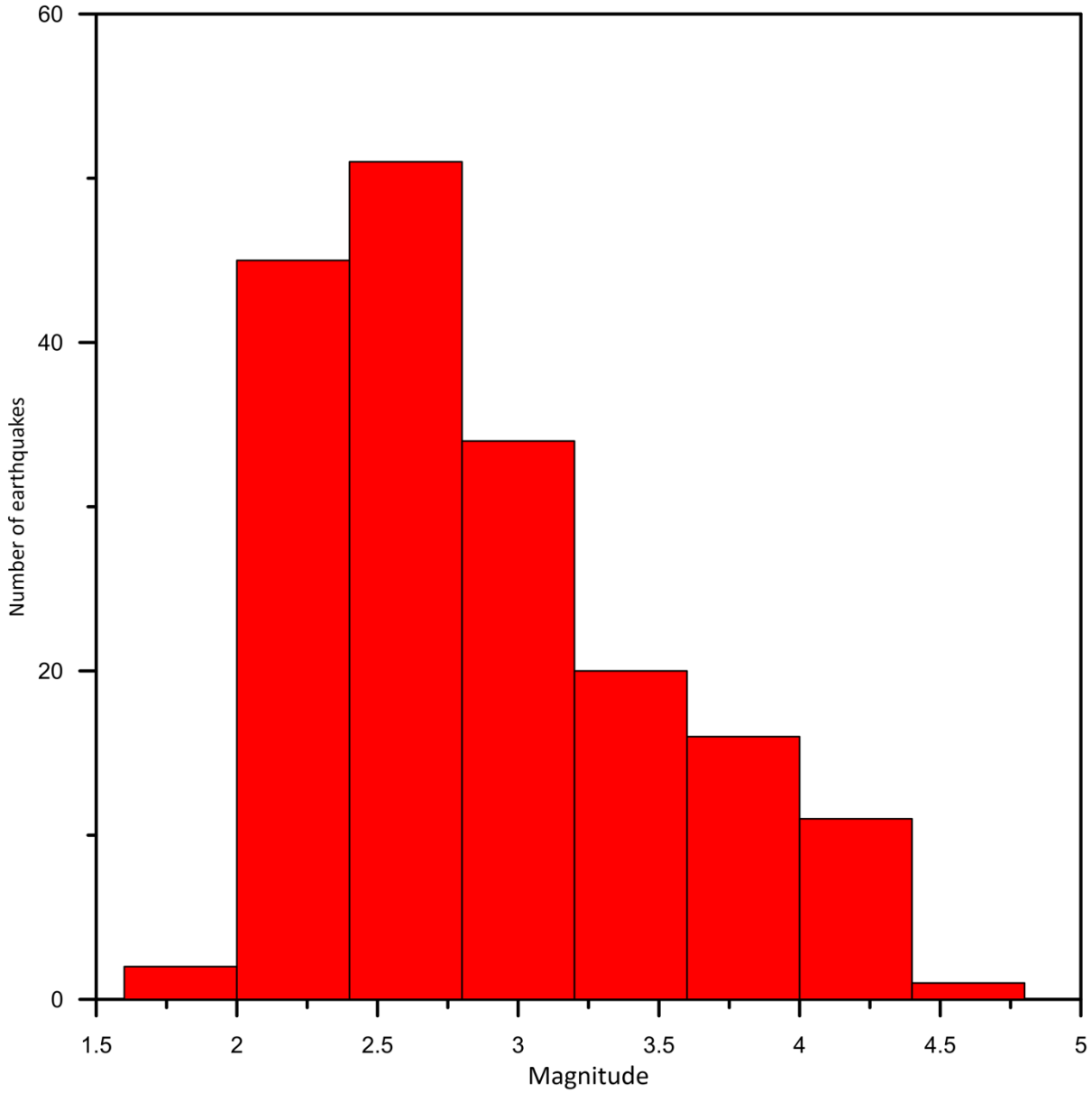
Date	Magnitude	Days since November 14, 1963
March 23, 1964	2,3	130
March 24, 1964	2,3	131
March 25, 1964	2,8	132
March 25, 1964	2,6	132
March 27, 1964	2,8	134
March 28, 1964	2,7	135
March 29, 1964	2,3	136
March 31, 1964	2,4	138
March 31, 1964	2,1	138
March 31, 1964	2,3	138
April 1, 1964	2,1	139
April 2, 1964	2,6	140
April 3, 1964	2,6	141
April 3, 1964	2,6	141
April 4, 1964	2,3	142
July 10, 1964	2,6	239
July 12, 1964	2,2	241
July 12, 1964	2,2	241
July 12, 1964	2,8	241
July 12, 1964	2,2	241
July 22, 1964	2,3	251
January 15, 1965	2,7	428
May 8, 1965	3,1	541
May 10, 1965	3,8	543
May 11, 1965	3,4	544
May 11, 1965	3,3	544
May 13, 1965	2,8	546
May 13, 1965	2,4	546
May 13, 1965	1,9	546
May 13, 1965	2,3	546
May 13, 1965	2,4	546

Date	Magnitude	Days since November 14, 1963
May 14, 1965	2,5	547
May 14, 1965	2,4	547
May 14, 1965	4,3	547
May 14, 1965	3,2	547
May 15, 1965	3,5	548
May 15, 1965	3,4	548
May 16, 1965	3,1	549
May 16, 1965	2,5	549
May 16, 1965	2,9	549
May 16, 1965	3,7	549
May 17, 1965	2,9	550
May 18, 1965	2,2	551
May 19, 1965	2,3	552
May 19, 1965	3,8	552
May 19, 1965	2,5	552
May 19, 1965	2,5	552
May 19, 1965	2,8	552
May 19, 1965	2,7	552
May 19, 1965	3,2	552
May 19, 1965	2,8	552
May 19, 1965	3,1	552
May 19, 1965	3,6	552
May 20, 1965	3,6	553
October 28, 1965	2,4	714
October 29, 1965	2,2	715
November 2, 1965	2,6	719
November 4, 1965	3,8	721
November 5, 1965	3,1	722
November 8, 1965	2,5	725
November 8, 1965	2,6	725
November 9, 1965	2,2	726

Date	Magnitude	Days since November 14, 1963
November 9, 1965	2,8	726
November 10, 1965	2,4	727
November 12, 1965	2,6	729
November 14, 1965	2,3	731
November 17, 1965	4,2	734
November 17, 1965	4,3	734
November 17, 1965	4,1	734
November 21, 1965	2,7	738
November 21, 1965	3,2	740
November 23, 1965	2,5	740
November 23, 1965	3,5	740
November 24, 1965	3,4	741
November 24, 1965	2,9	741
November 24, 1965	3,1	741
November 24, 1965	3	741
November 27, 1965	3,1	744
May 12, 1965	2,5	752
December 6, 1965	2,6	753
June 30, 1966	3,7	959
July 27, 1966	2,8	986
July 28, 1966	3,1	987
August 1, 1966	2,2	991
August 1, 1966	2,6	991
August 4, 1966	3,2	994
August 5, 1966	2,4	995
August 9, 1966	2,3	999

Appendix C:

Earthquakes distribution associated to Surtsey, during the period of 14 November 1963 - 1 July 1967



Appendix D:

Accumulative time of tremor records during Surtsey eruption

D.1: Tremor observation during first 150 days of eruption. This information is used for Fig.7 in paper 2.

D2: Tremor observation during eruption after April 12, 1964 until July 31, 1967. This information is used for Fig.5 in paper 2.

Here LF , HF and SP represent respectively, Low Frequency, High Frequency and Spasmodic Tremor. TII-1, TII-2 and TII-3 are tremor intensity index of 1, 2 and 3 respectively as it is categorized in Fig. 5 in paper 2.

Duration of periods wiht no detected tremor at any station are showned with red color.

D1: Tremor observation during first 150 days of the eruption

12 November 1963 - 12 April 1964 (First 150 days of Eruption)							
date	detected at SID	detected at REY	Type	TII-1 (hours)	TII-2 (hours)	TII-3 (hours)	No Tremor detected
11.11.1963							
12.11.1963			LF		6		
13.11.1963			LF	3			
14.11.1963							
15.11.1963							
16.11.1963							
17.11.1963							
18.11.1963							
19.11.1963							
20.11.1963							
21.11.1963							
22.11.1963							
23.11.1963			LF	4			
24.11.1963							
25.11.1963							
26.11.1963							
27.11.1963							
28.11.1963							
29.11.1963							
30.11.1963							
1.12.1963			HF		1		
2.12.1963			HF	4			
3.12.1963			LF	1			
4.12.1963			LF	1			
5.12.1963			LF&HF		6		
6.12.1963			LF		1,5		
7.12.1963			HF			13	
8.12.1963			HF			12	
9.12.1963			LF&HF		10		
10.12.1963							
11.12.1963							
12.12.1963							
13.12.1963							
14.12.1963							
15.12.1963							
16.12.1963							

date	detected at SID	detected at REY	Type	TII-1 (hours)	TII-2 (hours)	TII-3 (hours)	No Tremor detected
17.12.1963			LF	1			
18.12.1963							
19.12.1963							
20.12.1963			HF	2			
21.12.1963			HF			5	
22.12.1963			HF			4	
23.12.1963			HF	2			
24.12.1963							
25.12.1963							
26.12.1963							
27.12.1963							
28.12.1963							
29.12.1963							
30.12.1963			HF&LF			3	
31.12.1963			LF		3		
1.1.1964							
2.1.1964							
3.1.1964							
4.1.1964							
5.1.1964							
6.1.1964							
7.1.1964							
8.1.1964							
9.1.1964							
10.1.1964							
11.1.1964							
12.1.1964			HF&LF		6		
13.1.1964			LF&HF		5		
14.1.1964			LF&HF		3		
15.1.1964							
16.1.1964							
17.1.1964							
18.1.1964							
19.1.1964							
20.1.1964							
21.1.1964							
22.1.1964							
23.1.1964							
24.1.1964			LF			1	
25.1.1964			LF	2			
26.1.1964							

date	detected at SID	detected at REY	Type	TII-1 (hours)	TII-2 (hours)	TII-3 (hours)	No Tremor detected
27.1.1964			HF			3	
28.1.1964			LF	3			
29.1.1964							
30.1.1964			HF			12	
31.1.1964							
1.2.1964							
2.2.1964							
3.2.1964							
4.2.1964							
5.2.1964							
6.2.1964							
7.2.1964							
8.2.1964							
9.2.1964							
10.2.1964							
11.2.1964			HF	5			
12.2.1964							
13.2.1964			HF	6			
14.2.1964			HF	4			
15.2.1964			HF&SP		2		
16.2.1964			SP	9			
17.2.1964			SP		5		
18.2.1964			SP		4		
19.2.1964							
20.2.1964			SP	1			
21.2.1964			SP			6	
22.2.1964			HF&SP			3	
23.2.1964							
24.2.1964			SP			2	
25.2.1964							
26.2.1964							
27.2.1964							
28.2.1964			HF			8	
29.2.1964			SP			2	
1.3.1964			HF		2		
2.3.1964			HF		1.5		
3.3.1964			SP		3		
4.3.1964			SP	1			
5.3.1964							
6.3.1964							
7.3.1964			SP		1		
8.3.1964			SP	2			

date	detected at SID	detected at REY	Type	TII-1 (hours)	TII-2 (hours)	TII-3 (hours)	No Tremor detected
9.3.1964			SP		2		
10.3.1964			SP		2		
11.3.1964							
12.3.1964			SP	2			
13.3.1964							
14.3.1964							
15.3.1964							
16.3.1964							
17.3.1964							
18.3.1964			SP			2	
19.3.1964							
20.3.1964			SP	2			
21.3.1964			SP	1			
22.3.1964							
23.3.1964							
24.3.1964							
25.3.1964							
26.3.1964							
27.3.1964							
28.3.1964							
29.3.1964							
30.3.1964							
31.3.1964							
1.4.1964							
2.4.1964							
3.4.1964							
4.4.1964							
5.4.1964							
6.4.1964							
7.4.1964							
8.4.1964							
9.4.1964							
10.4.1964							
11.4.1964							
12.4.1964							

D.2: Tremor observation from 12 april until June 1967

date	detected at SID	detected at REY	Type
		1964	
Apr	19,26,27,29	21	
May	7,8,10,20,27,28	28,29	SP
June	6,10,25,26,27,28,30	15,17,20,24,29	SP
July	2,7,8,9		SP
Aug			
Sept			
Oct			
Nov			
Dec			
date	detected at SID	detected at REY	Type
		1965	
Jan			
Feb			
Mar			
April			
May	16,17,18,19,23,24,25,27,28		SP
June	2,3,4,5,6,7		SP
July		9,11,12,13,15,15,17,18,19,20,21,22,23, 24,25,26,27,28	HF
Aug	16,18,,20	3,5,8,9,10,14,15,1617,29,31	HF
Sept	1,2,11,12,16,18,24,29,30	2,3,4,7,8,9,10,16,21,23,29,30	HF
Oct	2,3,4,5,6,7,8,9,10,11	1,2,3,4,5,6,7,8,9,10,11	HF
Nov	31		LF
Dec	6,7,19,20,23,24	5,6,7,8,9,10,12,16,17,18,20,21,23,24	LF
date	detected at SID	detected at REY	Type
		1966	
Jan			
Feb			
Mar			
Apr			
May	5,7,17,29,30,31,	3,12,23,27,31	SP
June	4,22,25,27,30	15,16,	SP
July	1,5,9,13,23,25,	10,22,24,27,30	SP
Aug	1,2,3,4,5,7,8,10,23,24,25,28,31	1,2,3,4,7,8,10,11	SP
Sept			
Oct			
Nov			
Dec			

date	detected at SID	detected at REY	Type
1967			
Jan	1,3,4,7,8,9,10,11,12,13,14,15,16,17,19,27,31	3,10,12,14,19,27	SP
Feb	1,2,3,4.,5,6,7,8,9,10,11,12,13,14,15,16 ,18,24	2,4,5,6,9,18,24	SP
March	8,9,17,18,19,20,21,22,26,28,29,30,31	18,22,26	SP
Apr	1,3,4,5,6,7,8,11,12,13,22,25,26,27,28,29,30		SP
May	3,4,5,7,8,9,10,11,12,13,14,15,16,18,21,22,23,24		SP
June	1,7,8,9,10,11,16,17,22,23,28,30		SP
July			
Aug			
Sept			
Oct			
Nov			
Dec			

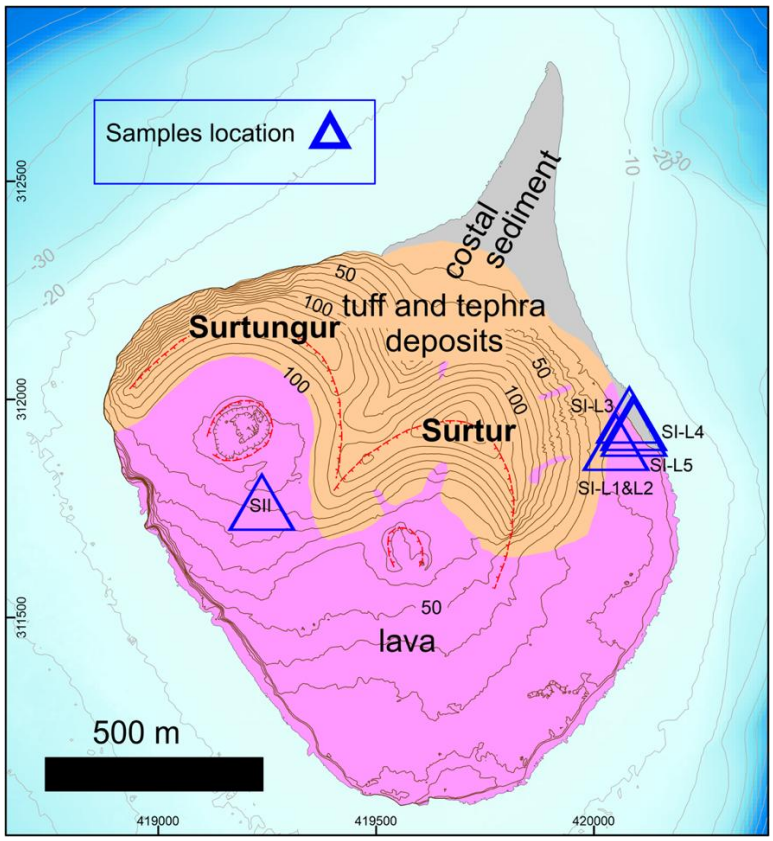
Appendix E**:**

Remanence and susceptibility of lava samples from Surtsey

Samples were taken at four locations (Fig. E1) on Surtsey during the 2018 field expedition; at one location in the Surtungur lava field, formed in 1964-65, and three in the Surtur lava field (1966-67). These samples were analyzed in the Paleomagnetic lab of the University of Iceland. In total 40 cores were extracted from the rocks sampled and used for the measurement. The results are given in Table E1.

Table E1: Results of remanence and susceptibility for Surtsey samples

Specimen	State	Latitude	Longitude	Magnetization [A/m]	Bulk susceptibility [SI]
SI-L1-1-1A	NRM	63° 18.23	20° 35.64	5.37	0.010
SI-L1-1-2A	NRM	63° 18.23	20° 35.64	4.67	0.009
SI-L1-1-3A	NRM	63° 18.23	20° 35.64	5.33	0.010
SI-L1-1-3B	NRM	63° 18.23	20° 35.64	7.04	0.014
SI-L1-1-4A	NRM	63° 18.23	20° 35.64	4.04	0.008
SI-L2-1-1A	NRM	63° 18.23	20° 35.64	15.9	0.030
SI-L2-1-1B	NRM	63° 18.23	20° 35.64	15.3	0.030
SI-L2-1-1C	NRM	63° 18.23	20° 35.64	15.78	0.030
SI-L2-1-2A	NRM	63° 18.23	20° 35.64	15.33	0.028
SI-L2-1-2B	NRM	63° 18.23	20° 35.64	15.04	0.027
SI-L2-1-3A	NRM	63° 18.23	20° 35.64	13.53	0.027
SI-L3-1-1A	NRM	63° 18.26	20° 35.6	2.33	0.023
SI-L3-1-2A	NRM	63° 18.26	20° 35.6	2.10	0.019
SI-L3-1-2B	NRM	63° 18.26	20° 35.6	2.19	0.021
SI-L3-1-3A	NRM	63° 18.26	20° 35.6	1.53	0.018
SI-L4-1-1A	NRM	63° 18.25	20° 35.6	25.61	0.037
SI-L4-1-3A	NRM	63° 18.25	20° 35.6	24.20	0.040
SI-L4-1-4A	NRM	63° 18.25	20° 35.6	22.88	0.032
SI-L4-1-4B	NRM	63° 18.25	20° 35.6	24.95	0.036
SI-L4-2-1A	NRM	63° 18.25	20° 35.6	15.70	0.017
SI-L4-2-1B	NRM	63° 18.25	20° 35.6	12.26	0.015
SI-L4-2-2A	NRM	63° 18.25	20° 35.6	12.53	0.015
SI-L4-2-2B	NRM	63° 18.25	20° 35.6	4.54	0.013
SI-L4-2-3A	NRM	63° 18.25	20° 35.6	18.62	0.019
SI-L4-2-4A	NRM	63° 18.25	20° 35.6	16.98	0.018
SI-L5-1-1A	NRM	63° 18.24	20° 35.6	8.47	0.016
SI-L5-1-2A	NRM	63° 18.24	20° 35.6	8.90	0.017
SI-L5-1-2B	NRM	63° 18.24	20° 35.6	6.72	0.013

Specimen	State	Latitude	Longitude	Magnetization [A/m]	Bulk susceptibility [SI]
SI-L5-1-3A	NRM	63° 18.24	20° 35.6	7.7	0.015
SI-L5-1-3B	NRM	63° 18.24	20° 35.6	5.40	0.011
SII-L1-1-1	NRM	63° 18.14	20° 36.6	4.4	0,009
SII-L1-1-1	NRM	63° 18.14	20° 36.6	9.218	0.005
SII-L1-1-2	NRM	63° 18.14	20° 36.6	6.52	0.008
SII-L1-3-1	NRM	63° 18.14	20° 36.6	8.358	0.006
SII-L1-3-1	NRM	63° 18.14	20° 36.6	6.78	0.013
SII-L1-3-2	NRM	63° 18.14	20° 36.6	10.69	0.017
SII-L1-3-2	NRM	63° 18.14	20° 36.6	6.55	0.014
SII-L1-3-2	NRM	63° 18.14	20° 36.6	6.69	0.021
SII-L1-3-3	NRM	63° 18.14	20° 36.6	11.63	0.019
SII-L1-3-3	NRM	63° 18.14	20° 36.6	9.85	0.016

Appendix E1: Figure E.1: Sampling sites