Xenoliths of exotic origin at Surtsey volcano, Iceland

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ABSTRACT

Numerous xenoliths of considerable diversity have been collected from the tephra pile of the Surtsey volcanic island. In total, 102 samples were classified as of foreign origin and studied further. Thin sections were available of 71 samples and they were analysed with the aid of the petrological microscope. The other 31 samples were studied by macroscopic observations. Many of the xenoliths display irregular shapes and have a combination of sharp edges, rough surfaces, and smoothly weathered faces as can be expected from ice-rafted debris (IRD). In addition, the samples are poorly sorted which further suggests IRD origin. Iceberg-producing outlet glaciers north of Iceland are primarily in East Greenland and to a lesser extent on Kvit Øya, Franz Joseph Land, and Novaya Zemlya. By comparing the rock type classification of the samples to bedrock maps of the main iceberg-producing areas, a further indication on origin was established. At least 90% of the samples could be originated from Daugaard-Jensen glacier which is the most fertile iceberg producer north of Iceland and therefore has to be considered the most likely origin of the exotic xenoliths.

INTRODUCTION

Numerous xenoliths have been collected from the volcanic island Surtsey, most of them by scientists at the Icelandic Institute of Natural History. The xenoliths are of considerable diversity, varying from angular basalt rock fragments to well rounded gneiss. More than 100 of the sampled xenoliths are of rock types that cannot be of Icelandic origin.

Rocks of foreign origin in Iceland have for long attracted the attention of nature observers. In the late 18th century, Sveinn Pálsson (1945) noted several rocks around the Iceland coast that he concluded were of foreign origin. Thorvaldur Thoroddsen (1958–1960) observed granite, quartzite and schist on his travel on the North coast of Iceland in 1895. Several other observations of foreign rock types have been documented (Noe-Nygaard 1950, Einarsson 1963, Líndal 1964, Thórarinsson 1966b, Einarsson 1969, Kjartansson 1970, Jóhannesson 2000) and many samples have been collected by scientists at the Icelandic Institute of Natural History (Jakobsson 1982). Clasts of petrological composition foreign to Iceland have been noted in Early Pleistocene rocks in Iceland (e.g. Eiríksson 1981) and in Holocene and Late glacial marine sediments (e.g. Knudsen & Eiríksson 2002, Haflidason *et al.* 2000). It is commonly believed that these rocks were brought to Iceland either as ballast in ships or with icebergs.

This report is based on a B.Sc. thesis submitted at the University of Iceland in the spring 2004 (Reynisson 2004). The aim of the research was to identify the rock types believed to be of foreign origin that were found on Surtsey. Petrological microscopy of thin sections and macroscopical examination of hand specimens were used to classify the rocks and observe morphological properties. The aim was also to propose a likely place of

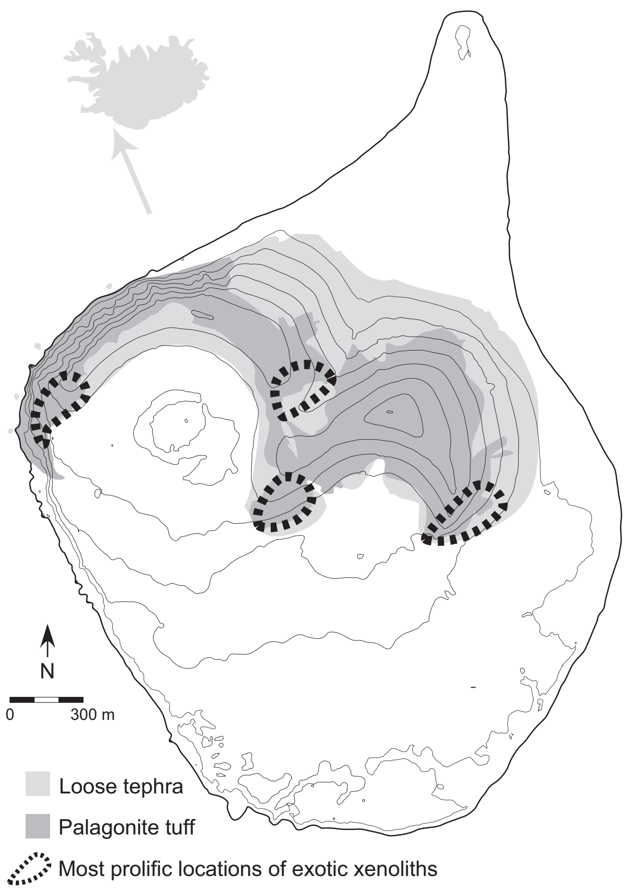

Figure 1. The four most prolific collection areas of exotic xenoliths on Surtsey. All four locations are in the proximity of the border of loose tephra and underlying palagonite tuff. Modified from Jakobsson (2000) and Jakobsson *et al.* (2000).

origin and way of transport for the foreign rock types.

The xenoliths were all found in the tephra (Fig. 1) which formed during the submarine explosive phase of the Surtsey eruption, from November 1963 to April 1964 (Thórarinsson 1966a). The tephra formed two merged crescent-shaped cones. It has been subject to hydrothermal alteration and in 1998 some 80–85% of the remaining tephra pile above sea level had been altered to palagonite tuff (Jakobsson *et al.* 2000).

EXOTIC XENOLITHS ON SURTSEY

All xenoliths from Surtsey which are registered in the rock collection of the Icelandic Institute of Natural History, Reykjavík, were examined and the samples likely to be of foreign origin were analysed further. Coarse-grained rocks apart from gabbro were considered to be of foreign origin, as well as all medium and high grade metamorphic rocks and all sedimentary rocks containing high amounts of quartz or carbonate. A total of 102 samples were classified as of foreign origin. Figure 2 shows some typical samples and variation in kind, shape, and size.

The morphological properties of the chosen samples were examined and classified according to the classification schemes of the British Geological Society (Gillespie *et al.* 1999, Hallsworth & Knox 1999, Robertson 1999). The classification scheme is based as far as possible on actual, descriptive attributes and is essentially non-genetic. The hierarchical approach of the scheme allows a name to be assigned to a rock at the level of the hierarchy most appropriate to the rock type and level of information available. Thin sections were available of 71 samples and they were analysed with the aid of the petrological microscope. The remaining 31 samples were studied by macroscopic observation. Table 1 lists the classification of all the studied samples.

The first sample was found on Surtsey as early as in the summer of 1967 and samples are still being collected. The locations of the findings are very disperse but four areas have been the most prolific (Fig. 1). Most of the xenoliths have been collected immediately under or on the slopes of the two prominent tuff cones. Eolian erosion of both tephra and tuff has been heavy in these areas, leaving xenoliths on the surface.

Sedimentary xenoliths that are believed to be from the ocean floor prior to the eruption have also been found on Surtsey. Observations on fossils from these xenoliths and two carbon age determinations indicate that the xenoliths are Holocene in age (Alexanderson 1972, Símonarson 1974). In addition, about one third of the exotic xenoliths have remnants of a sedimentary coat to some extent. The coat appears to be of the same composition as the sedimentary xenoliths, i.e. volcanic clast. Therefore it is feasible to assume that the exotic xenoliths studied in this report were part of young sediment having accumulated on the sea floor prior to the eruption.

ORIGIN OF THE EXOTIC XENOLITHS

Most of the exotic xenolith samples were classified as pebbles and a few as cobbles (Fig. 3). One sample stands out in terms of size (23x23x17 cm) and is the only exotic xenolith that is big enough to be assumed to be from ballast. All the other samples are too small to be potential ballast. Furthermore it is highly unlikely that a high concentration of ballast is to be found on the ocean bottom in the Surtsey area as it is not close to any harbor.

Icebergs are the main mechanism by which coarse-grained terrestrial debris can be transported to the ocean bottom (Dowdeswell *et al.* 1998, Cofaigh *et al.* 2001). The morphological aspects displayed by the majority of the samples suggest that after they were detached from abraded exposures they were not modified by subsequent abrasion, as can be expected from ice-rafted debris (IRD)

Figure 2. Typical samples of the exotic xenoliths from Surtsey showing the variety in size, shape, and rock type. The top row is a selection of sedimentary rocks, the middle row contains metamorphic rocks and the bottom row represents igneous rocks. Note the irregular shapes and the combination of rough, broken faces and smoothly worn faces. It should be noted that some of the samples have been cut. Numbers are sample numbers of the Icelandic Institute of Natural History, see Table 1.

(Linthout *et al.* 2000). Many samples are of irregular shapes and have a combination of sharp edges, rough surfaces, and smoothly weathered faces. In addition, range of observed sizes is consistent with IRD origin (Dowdeswell *et al.* 1998).

Ocean currents generally control the route icebergs are transported and the drift speed is influenced by winds (Bigg *et al.* 1997). Because ocean currents have not changed much during the Holocene (Bond *et al.* 2001) today's currents are indicative of the routes icebergs have travelled during the Holocene (Fig. 4). Therefore it can be assumed that the origin of the icebergs that deposited the exotic xenoliths is somewhere up-current of the deposition site.

Iceberg-producing outlet glaciers north of Iceland are primarily in East Greenland and to a lesser extent on Kvit Øya, Franz Joseph Land, and Novaya Zemlya (Wadhams 1986). The main contributors to iceberg production in East Greenland are the fast-flowing Daugaard-Jensen and Vestfjord glaciers which calve into Scoresby Sund (Cofaigh *et al.* 2001). Storstrømmen glacier and De Geer glacier are also significant producers of icebergs

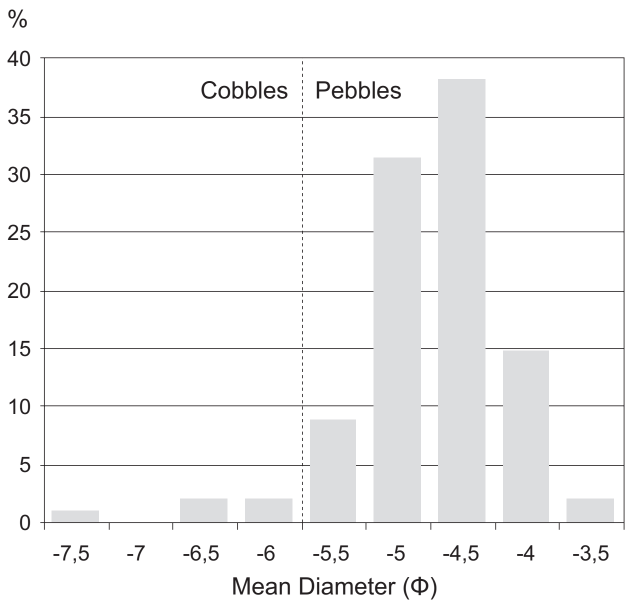

Figure 3. Size distribution of the exotic xenoliths from Surtsey. Most of the samples are pebbles and only a few are cobbles. Vertical axis is percentage of total number of samples. Horizontal axis is the mean diameter of the samples on Phi scale.

Table 1. Principal type classification and assigned rock names of the studied samples. Samples that were studied microscopically have thin section numbers.

Sample No.	Thin Section No.	Principal Type	Rock Name
7971	N-3826	Igneous	Alkali-feldspar-granite
9745	N-1979	Igneous	Alkali-feldspar-granite
9748	N-1981	Igneous	Alkali-feldspar-granite
22960	N-3831	Igneous	Alkali-feldspar-granite
12352		Igneous	Granitic-rock
12356		Igneous	Granitic-rock
9744	N-1978	Igneous	Granodiorite
9753	N-1985	Igneous	Granodiorite
9997		Igneous	Micro-dioritic-rock
10724		Igneous	Micro-dioritic-rock
22877		Igneous	Micro-dioritic-rock
22958		Igneous	Micro-dioritic-rock
9751		Igneous	Micro-granitic-rock
10718	N-3847	Igneous	Micromonzogranite
9756	N-1990	Igneous	Micro-quartz-rich-granitic-rock
9750	N-1986	Igneous	Microsyenogranite
9764	N-1997	Igneous	Microsyenogranite
12375	N-3828	Igneous	Microsyenogranite
13306	N-3861	Igneous	Microsyenogranite
9746	N-3827	Igneous	Monzogranite
11587	N-3851	Igneous	Monzogranite
15381	N-3862	Igneous	Monzogranite
22976	N-3836	Igneous	Monzogranite
9747	N-1980	Igneous	Quartz-alkali-feldspar-syenite
15379		Igneous	Quartz-rich-coarse-grained-crystalline-rock
879	N-1984	Igneous	Syenogranite
7970	N-3845	Igneous	Syenogranite
9743	N-106	Igneous	Syenogranite
9752	N-1983	Igneous	Syenogranite
9763	N-1996	Igneous	Syenogranite
12226	N-2668	Igneous	Syenogranite
13304	N-3859	Igneous	Syenogranite
15387	N-3864	Igneous	Syenogranite
22883	N-3868	Igneous	Syenogranite
22961	N-3835	Igneous	Syenogranite
22968	N-3834	Igneous	Syenogranite
9758	N-1992	Igneous	Tonalite
10723	N-3850	Metamorphic	Biotite-chlorite-garnet-bearing schist
9765	N-1998	Metamorphic	Biotite-muscovite gneiss
15385	N-3863	Metamorphic	Feldspar-amphibole-plagioclase-chlorite-bearing gneiss
20616	N-3865	Metamorphic	Feldspar-plagioclace-epidote-chlorite gneiss
9762	N-1995	Metamorphic	Feldspar-plagioclase-biotite gneiss
9760		Metamorphic	Gneiss
10725		Metamorphic	Gneiss
13308		Metamorphic	Gneiss
12353		Metamorphic	Gneissose granite
10716	N-3828	Metamorphic	Gneissose-biotite-amphibole syenogranite
9766	N-3846	Metamorphic	Gneissose-biotite-myrmekite syenogranite
10717	N-3829	Metamorphic	Gneissose-chlorite-clinopyroxen-muscovite metagranite
9759	N-1993	Metamorphic	Granofelsic-chlorite-bearing metafelsic-rock
9735	N-2007	Metamorphic	Layered-biotite semipelite
13305	N-3860	Metamorphic	Layered-muscovite quartzite
12388		Metamorphic	Lineated semipelite

22957	N-3869	Metamorphic	Lineated-muscovite semipelite
9720	N-2001	Metamorphic	Lineated-muscovite-biotite semipelite
9761	N-1994	Metamorphic	Metacarbonate-rock
10720	N-3849	Metamorphic	Muscovite-biotite-bearing quartzite
22880	N-3867	Metamorphic	Mylonitic-porphyroclastic-muscovite-chlorite-garnet phyllonite
9719	N-1999	Metamorphic	Phyllitic-garnet-bearing semipelite
22966	N-3833	Metamorphic	Phyllitic-muscovite-chlorite semipelite
9757	N-1991	Metamorphic	Porphyroblastic-garnet amphibolite
9721	N-2000	Metamorphic	Pyllitic-muscovite-rich pelite
12355	N-3854	Metamorphic	Quartz-feldspar-muskovite orthogneiss
10726		Metamorphic	Quartzite
12350		Metamorphic	Quartzite
12354		Metamorphic	Quartzite
15384		Metamorphic	Quartzite
15389		Metamorphic	Quartzite
22058	N-3866	Metamorphic	Quartzite
22962		Metamorphic	Quartzite
9755	N-1989	Metamorphic	Quartz-plagioclace-biotite gneiss
21533		Metamorphic	Quartz-rich-medium-grained-crystalline-rock
10719	N-3848	Metamorphic	Slaty-muscovite-epidote semipelite
12368		Sedimentary	Dolomite-sparstone
7973	N-2320	Sedimentary	Dolostone
9723	N-2003	Sedimentary	Dolostone
9727		Sedimentary	Dolostone
11585		Sedimentary	Dolostone
15156		Sedimentary	Dolostone
22977	N-3837	Sedimentary	Feldspathic-wacke
22978	N-3870	Sedimentary	Feldspathic-wacke
11037		Sedimentary	Feldspathic-wacke
12367	N-3856	Sedimentary	Limestone
15157		Sedimentary	Limestone
9732	N-2045	Sedimentary	Lithoclastic feldspathic-arenite
9754	N-1987	Sedimentary	Lithoclastic silicate-mudstone
9733	N-2048	Sedimentary	Organic limestone
9722	N-2002	Sedimentary	Quartz-arenite
9731	N-2006	Sedimentary	Quartz-wacke
12348	N-3852	Sedimentary	Quartz-wacke
12369	N-3857	Sedimentary	Quartz-wacke
9730	N-2005	Sedimentary	Siliciclastic dolostone
11586		Sedimentary	Siliciclastic dolomite-sparstone
9726		Sedimentary	Siliciclastic dolostone
9749	N-1982	Sedimentary	Subfeldspathic-arenite
9734	N-2043	Sedimentary	Subfeldspathic-wacke
15155		Sedimentary	Thin-laminated dolostone
9724	N-2044	Sedimentary	Thin-laminated siliciclastic dolostone
12357		Sedimentary	Very-thin-laminated dolomite-sparstone
12374		Sedimentary	Very-thin-laminated dolostone
22967		Sedimentary	Very-thin-laminated dolostone
9725	N-2004	Sedimentary	Very-thin-laminated siliciclastic dolostone

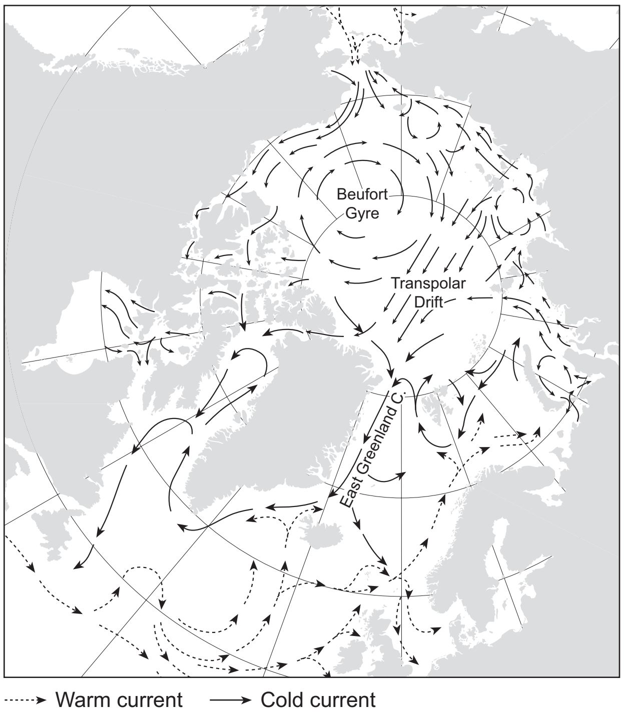

Figure 4. Surface currents in the Arctic region. Modified from AMAP 1998.

in East Greenland (Reeh 2004, Koch 1945). Most icebergs remain at or near their glaciers of origin, because of grounding or because of adverse winds and currents. Fjords which are wide enough to have a gyral circulation can discharge icebergs more easily. Thus the most fertile iceberg-producing fjord in East Greenland is Scoresby Sund. Most icebergs produced on Kvit Øya, Franz Joseph Land, and Novaya Zemlya appear to go aground in the Barents or Kara Seas, and a true iceberg in the ice drift emerging from the Trans-Polar Drift Stream into the East Greenland Current is rare (Wadhams 1986).

By comparing the rock-type classification of the exotic xenoliths from Surtsey to bedrock maps of areas surrounding the aforementioned glaciers, a further indication on origin was established (Escher & Pulvertaft 1995, Dallmann *et al.* 2002, Hjelle 1993, Ministry of Geology of the USSR 1980). The proportion of the exotic xenoliths that can be accounted for in areas surrounding the glaciers of interest, is assumed to be indicative of probable origin of the samples. Figure 5 summarises the results of the comparison. East Greenland offers a wide variety of rock types and the full variation of the samples collected on Surtsey can be traced to rock units exposed in East Greeland. At least 90% of the samples could have originated from Daugaard-Jensen glacier which is the most fertile iceberg producer north of Iceland and therefore that glacier has to be considered the most likely origin of the exotic xenoliths.

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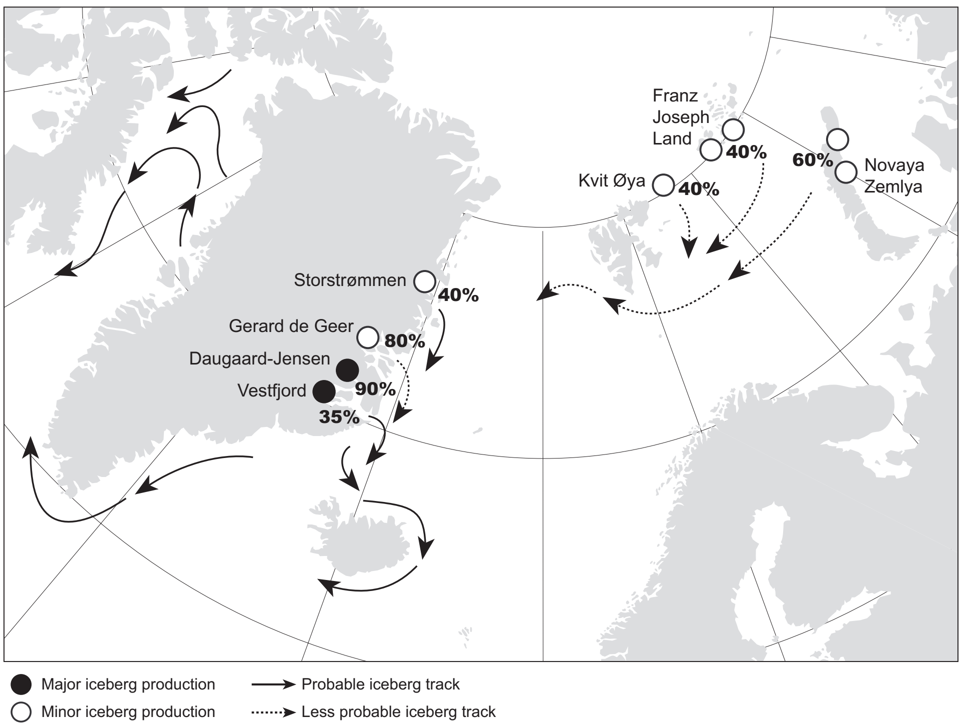

Figure 5. Possible origin of the exotic xenoliths from Surtsey. Numbers refer to the proportion of the exotic xenoliths that match formations shown on bedrock maps of each area. Three distinct factors combine to make Daugaard-Jensen glacier in Greenland the most probable origin of the exotic xenoliths. It is the most productive iceberg producer up-current from Iceland, it calves into Scoresby Sund which is known to release an abundance of icebergs to the East Greenland current and most of the samples from Surtsey can be traced to its surrounding area.

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References

Alexandersson, T. 1972. The sedimentary xenoliths from Surtsey turbidites indicating shelf growth. Surtsey Res. Progr. Rep. 6: 101–116.

AMAP 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xii+859 pp.

Bigg, G.R., M.R. Wadley, D.P. Stevens, & J.A. Johnson 1997. Modeling the dynamics and thermodynamics of icebergs. Cold Regions Sci. and Technol. 26: 113–135.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M.N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, & G. Bonani 2001. Persistent solar influence on north Atlantic climate during the Holocene. Science 294: 2130–2136.

Cofaigh, C.O, J.A. Dowdeswell & H. Grobe 2001. Holocene glacimarine sedimentation, inner Scoresby Sund, East Greenland: the influence of fast-flowing ice-sheet outlet glaciers. Mar. Geol. 174: 103–129.

Dallmann, W.K., Y. Ohta, S. Elvevold, & D. Blomeier (eds) 2002. Bedrock map of Svalbard and Jan Mayen. Temakart No. 33. Norsk Polarinstitutt, scale 1:750.000.

Dowdeswell, J.A., A. Elverhøi, & R. Spielhagen 1998. Glacimarine sedimentary processes and facies on the polar North Atlantic margins. Quatern. Sci. Rev. 17: 243–272.

Einarsson, T. 1963. Some new observations of the Breidavík deposits in Tjörnes. Jökull 13: 1–9.

Einarsson, Th. 1969. Loftslag, sjávarhiti og hafís á forsögulegum tíma. *In* M.Á. Einarsson (ed), Hafís. Almenna Bókafélagid, Reykjavík, pp. 389–402.

Eiríksson, J. 1981. Lithostratigraphy of the upper Tjörnes sequence, North Iceland: The Breidavík Group. Acta Naturalia Islandica 29, 37 pp.

Escher, J.C. & T.C.R. Pulvertaft 1995. Geological map of Greenland, scale 1:2.500.000. Geological Survey of Greenland, Copenhagen.

Gillespie, M.R. & M.T. Styles 1999. Classification of igneous rocks. BGS rock classification scheme, Vol. 1. British Geological Survey Research Report, RR 99–06.

Haflidason, H., J. Eiríksson & S. Van Kreveld 2000. The tephrochronology of Iceland and the North Atlantic region during the Middle and Late Quaternary: a review. Journ. Quatern. Sci. 15: 3–22.

Hallsworth, C.R. & R.W.O'B. Knox 1999. Classification of sediments and sedimentary rocks. BGS rock classification scheme, Vol. 3. British Geol. Surv. Res. Rep., RR 99–03.

Hjelle, A. 1993. Geology of Svalbard. Norsk Polarinstitutt, Oslo, 163 pp.

Jakobsson, S.P 1982. Dredge hauls from Vestmannaeyjagrunn, Iceland. Surtsey Res. Progr. Rep. 9: 142–148.

Jakobsson, S.P. 2000. Geological map of Surtsey, scale 1:5.000. Náttúrufraedistofnun Íslands and Surtseyjarfélagid, Reykjavík.

Jakobsson, S.P., G. Gudmundsson & J.G. Moore 2000. Geological monitoring of Surtsey, Iceland, 1967–1998. Surtsey Research 11: 99–108.

Jóhannesson, H. 2000. Lesid í landid í Árneshreppi á Ströndum. *In* H. Kristgeirsson, (ed) Í strandbyggdum nordan lands og vestan. Árbók 2000, Ferdafélag Íslands, pp. 45–118.

Kjartansson, G. 1970. Um stutt kynni af landslagi á Ströndum og um steininn í Stóru-Ávík. Strandapósturinn 4: 83–95.

Knudsen, K. L. & J. Eiríksson 2002 Application of tephrochronology to the timing and correlation of palaeoceanographic events recorded in Holocene and Late Glacial shelf sediments off North Iceland. Mar. Geol. 191: 165–188.

Koch, L. 1945. The East Greenland ice. Meddelelser om Grønland 130(3), 1373 pp.

Linthout, K., S.R. Troelstra, & A. Kuijpers 2000. Provenance of coarse ice-rafted detritus near the SE Greenland margin. Netherlands Journ. Geosci. 79: 109–121.

Líndal, J.H. 1964. Med huga og hamri. Jardfraedidagbaekur og ritgerdir. Bókaútgáfa Menningarsjóds, Reykjavík, 410 pp.

Ministry of Geology of the USSR 1980. Geologic map of the USSR, scale 1:10.000.000.

Noe-Nygaard, A. 1950. Erratic granite-pebbles from Morsárdalur in Öraefi, Iceland. Medd. Dan. Geol. Foren. 11: 584–587.

Pálsson, S. 1945. Ferdabók Sveins Pálssonar. Snaelandsútgáfan, Reykjavík, 813 pp.

Reeh, N. 2004. Holocene climate and fjord glaciation in Northeast Greenland: implications for IRD deposition in the North Atlantic. Sediment. Geol. 165: 333–342.

Reynisson, R.F. 2004. Uppruni erlendra framandsteina í Surtsey. B.S. Thesis, University of Iceland, Reykjavík, 54 pp.

Robertson, S. 1999. Classification of metamorphic rocks. BGS rock classification scheme, Vol. 2. British Geol. Surv. Res. Rep., RR 99–02.

Símonarson, L.A. 1974. Fossils from Surtsey – A preliminary report. Surtsey Res. Progr. Rep. 7: 80–82.

Thoroddsen, Th. 1958–1960. Ferdabók: skýrslur um rannsóknir á Íslandi 1882–1898, I.–IV. bindi. Second edition. Reykjavík.

Thórarinsson, S. 1966a. Sitt af hverju um Surtseyjargosid. (Engl. summ.: Some facts about the Surtsey eruption.) Náttúrufraedingurinn 35: 153–181.

Thórarinsson, S. 1966b. Sitt af hverju frá sídastlidnu sumri. Náttúrufraedingurinn 36: 35–47.

Wadhams, P. 1986. The ice cover. *In* B.G. Hurdle (ed.), The nordic seas. Springer-Verlag, New York, pp. 21–86.