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**Ph.D. Thesis
in Geology**

Evolution of the Late Miocene Torfufell Central Volcano, North Iceland

Geology, magnetostratigraphy, geochemistry, age and
geochronology

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

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Abstract

Iceland features numerous Miocene and Pliocene central volcanoes that have been excavated by rivers and glaciers, thereby providing excellent windows into their volcanic interiors and opportunities to explore the construction and histories of volcanic edifices. At the same time, addressing the timing of silicic volcanism and magmatism of ancient volcanic centres provides spatio-temporal constraints that can significantly improve our understanding of the geodynamic evolution of Iceland. This thesis aims at detailing the evolution of the Late Miocene Torfufell central volcano and the surrounding area in central North Iceland through detailed geological mapping, paleomagnetic measurements, geochemistry, descriptions of key geological features, and integration with new and existing age data. These observations indicate that the edifice construction commenced at ~7.8-8.0 Ma, with the early stages featuring mafic effusive volcanism producing series of basaltic *ā'a* lavas and latter stages typified by a broader compositional range, including intermediate and silicic volcanic products. This volcanism was associated with intrusive activity on the form of mafic dykes and silicic plugs. The two volcanic sequences are separated by a peculiar tephra-, smectite- and fossil-bearing sediment horizon in several outcrops. Silicic activity, which commenced at approximately 7.12 Ma and lasted ~400.000 years, was characterized by both intrusions and effusive and explosive volcanism and formed a complex in the central zone of the volcano. The silicic magmatism at the Torfufell volcano took place at a crucial time in the region's geological history, in a period when a major reorganization of rift segments is inferred and may mark the onset of the presently active rift in North Iceland. The Torfufell central volcano was not among the large Miocene volcanos. However, the mapping indicates a mountain that may have risen some hundred meters above its surroundings. The volcanic activity continued in the vicinity and little by little it was covered by younger geological formations. Finally its traces disappeared from the surface. Much later, the forces of erosion, especially the Ice Age glaciers, uncovered it again and exposed its interiors.

Útdráttur

Jöklar ísaldar og vatnsföll hafa grafið sig inn í fjölda megineldstöðva sem mynduðust á Íslandi á Míósen og Plíósen og því má nú með góðu móti kanna innviði margra þeirra og rannsaka um leið gerð og þróun slíkra eldfjalla. Ritgerð þessi fjallar um megineldstöð innst í Eyjafirði sem myndaðist á Síð-Míósen og kennd er við Torfufell. Markmið verkefnisins er að lýsa þróun Torfufellseldstöðvarinnar og nánasta umhverfis hennar með nákvæmri jarðfræðikortlagningu, segulmælingum, jarðefnafræði, lýsingum á lykiljarðmyndunum og samþættingu við bæði gamlar og nýjar aldursákvarðanir. Þessar athuganir benda til að megineldstöðin hafi byrjað að hlaðast upp fyrir ~7,8-8,0 milljón árum og að fyrri stig upphleðslunnar hafi einkennst af basískum apalhraunum en seinni stig af fjölbreyttari bergtegundum, að meðtöldum ísúrum og súrum (þ.e. kísilríkum) myndunum. Í nokkrum opnum sést að þessar tvær lotur eru aðskildar af sérstæðu setlagi sem inniheldur gjósku, smektítleir og steingervinga, þ.e. viðarstein. Rýólítvirkni - sem hófst í eldstöðinni fyrir u.þ.b. 7,12 milljón árum og stóð yfir í um 400.000 ár - einkenndist bæði af innskotum og sprengi- og hraungosum og myndaði margbrotna heild á miðsvæði eldvirkinnar. Þessi virkni í Torfufellseldstöðinni hófst á þýðingarmikilli stund í jarðsögu landsins, þ.e.a.s. á sama tíma og rekbeltaflutningur var að eiga sér stað, og gæti markað upphaf rekbeltisins sem nú er virkt á Norðurlandi. Torfufellseldstöðin var ekki í hópi hinna stóru megineldstöðva míoSENTÍmans. Kortlagningin bendir þó til að hún hafi risið nokkur hundruð metra yfir umhverfi sitt. Eldvirknin hélt áfram þar í grennd og smátt og smátt grófst hún í yngri jarðmyndanir og ummerki hennar hurfu af yfirborði jarðar. Löngu síðar grófu veðrunaröflin, einkum jöklar ísaldar, hana upp á ný og afhjúpuðu innviði hennar.

Fyrir Afa

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List of Publications

This thesis aims at detailing the evolution of the Upper-Miocene Torfufell central volcano and the surrounding area in central North Iceland through detailed geological mapping, paleomagnetic measurements, whole-rock and mineral chemistry and descriptions of key geological features. The results are integrated with new and previous age data to address the chronology and life-span of the volcano and the volcano-tectonic evolution of central North Iceland. The results are presented in three papers, included in the Appendix of this thesis:

Paper I: Árnadóttir, S., Hjartarson, Á., Thordarson, Th., Gautason, B., In Prep. Evolution of the Late-Miocene Torfufell central volcano, N-Iceland.

Paper II: Árnadóttir, S., Thordarson, Th., Gautason, B., Hjartarson Á., Caggianelli, A., In Prep. Geochemistry and petrology of basaltic to rhyolitic products of the Late Miocene Torfufell Central Volcano, North Iceland.

Paper III: Árnadóttir, S., Thordarson, Th., Hjartarson, Á., Gautason, B., 2023. U-Pb zircon age and chronology of the Torfufell central volcano: implications for timing of rift relocation in North Iceland. *Bulletin of Volcanology* **85**, 52. <https://doi.org/10.1007/s00445-023-01667-8>.

The manuscripts described above are the result of combined efforts by all the authors. The author's contributions are as follows:

Paper 1: Sigurveig Árnadóttir, main author, procured funding, undertook fieldwork (geological mapping, palaeomagnetic measurements, sampling), GIS work, interpretation. Árni Hjartarson, second author, supervisor, undertook fieldwork, interpretation, scientific knowledge input. Thorvaldur Thordarson, third author, supervisor, participated in fieldwork, scientific knowledge input. Bjarni Gautason, fourth author, supervisor, scientific knowledge input.

Paper 2: Sigurveig Árnadóttir, main author, undertook fieldwork, sampling, sample preparation, lab work (ICP-OES and SEM/EDS analysis, petrography), interpretation. Thorvaldur Thordarson, second author, supervisor, undertook lab work (EPMA analysis), scientific knowledge input. Bjarni Gautason, third author, supervisor, scientific knowledge input. Árni Hjartarson, fourth author, supervisor, scientific knowledge input. Alfredo Caggianelli, fifth author, undertook lab work (SEM/EDS analysis, petrography), scientific knowledge input.

Paper 3: Sigurveig Árnadóttir, main author, undertook fieldwork and sampling, procured funding, sample preparation, SEM imaging and analysis, U-Pb age determinations at the NordSIM facility, interpretation. Thorvaldur Thordarson, second author, supervisor, procured funding, participated in SEM imaging and analysis, scientific knowledge input. Árni Hjartarson, third author, supervisor, undertook fieldwork and sampling, scientific knowledge input. Bjarni Gautason, fourth author, supervisor, scientific knowledge input.

Abbreviations

ToCV	Torfufell Central Volcano
TiCV	Tinná Central Volcano
NVZ	Northern Volcanic Zone
WVZ	Western Volcanic Zone
EVZ	Eastern Volcanic Zone
MIB	Mid Iceland Belt
SVB	Snæfellsnes Volcanic Belt
ÖVB	Öræfi Volcanic Belt
TFZ	Tjörnes Fracture Zone
SISZ	South Iceland Seismic Zone
SHRZ	Snæfellsnes-Húnaflói Rift Zone
MAR	Mid-Atlantic Ridge
XRD	X-ray diffraction
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
SEM	Scanning Electron Microscopy
EPMA	Electron Microprobe Analysis
SIMS	Secondary Ion Mass Spectrometry
CA-TIMS	Chemical Abrasion – Isotope Dilution Thermal Ionization Mass Spectrometry
MSWD	Mean Squared Weighted Deviation

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1 Introduction

1.1 Iceland: geodynamic setting

Iceland is situated on the slow-spreading Mid-Atlantic Ridge (MAR) – which embodies the tectonic boundary separating the North American and Eurasian plates – and constitutes anomalously thick crust (~20-40 km) compared to the submarine mid-ocean ridge system (e.g., Darbyshire et al., 1998; 2000; Brandsdóttir and Menke, 2008). The extension accompanying the divergent motion between the two tectonic plates results in passive decompression that facilitates partial melting in the sub-lithospheric mantle (e.g., Sengör and Burke, 1978) and thereby magma production, accompanied by volcanism through components of the opening developed at the plate boundary. The atypical thickness of Iceland's crust is generally explained by the MAR's superimposition over a source of anomalously hot mantle material (e.g., Schilling 1973; Vink, 1984), normally termed the Iceland mantle plume. Due to its anomalous heat and thereby low density compared to the surrounding mantle, the plume rises to regions of lower pressure where it undergoes adiabatic decompression, resulting in partial melting of its material. This results in a higher magma production rate than on the submarine MAR and is combined with a dynamic uplift, lifting Iceland above sea level. Although alternative explanations exist, assigning Iceland's thickened igneous crust and the melting anomaly to structures and processes related to plate tectonics that are unmarked by any plume weakening the lithosphere (e.g., Foulger and Anderson, 2005; Foulger et al., 2020), the present thesis pursues the prevailing perception.

While the Iceland mantle plume is generally suggested to be centred beneath NW Vatnajökull glacier (Fig.1), the two tectonic plates migrate independently in a WNW direction with respect to it (e.g., Müller et al., 1998; Torsvik et al., 2001). This relative movement is considered to have resulted in complex segmentation and repeated shifts of the plate boundary (generally termed rift relocations or rift jumps) towards east as it is periodically recaptured by the plume (e.g., Ward, 1971; Sæmundsson, 1974;1979; Jóhannesson, 1980; Harðarson et al., 1997; 2008; Vink 1984; Martin et al., 2011). By this, previous relocations have resulted in an eastward position of the plate boundary on land, relative to the submarine MAR, and this offset is accommodated by two major transform zones; the Tjörnes fracture zone (TFZ) in the North and the South Iceland Seismic Zone (SISZ) in the South (Fig.1).

The present arrangement of the plate boundary in Iceland (Fig.1) is represented by three principal rifting segments; the N-S trending Northern Volcanic Zone (NVZ) in the North and the sub-parallel NE-SW trending Western and Eastern Volcanic Zones (WVZ and EVZ) in the South. These three segments exemplify different stages in the evolution of a rift axis

across Iceland, where the NVZ may be referred to as an established rifting zone as it accommodates the full spreading rate in North Iceland; the WVZ is declining, and the southern part of the EVZ is propagating into the Eurasian plate toward SW, thus occurring in an intra-plate setting (e.g., Einarsson, 2008; Óskarsson et al., 1985). A presently ongoing rift relocation is assumed to be occurring between the propagating EVZ and the declining WVZ (Sæmundsson, 1979; Einarsson, 1991; 2008). The three rifting segments are joined across central Iceland by a transverse (E-W trending) volcanic zone termed the Mid Iceland Belt (MIB) which has been described as a “leaky” transform fault (e.g., Óskarsson et al., 1985), i.e., comprising a small component of extension, sufficient to induce local volcanism. The northern end of the NVZ is linked with the southern end of the submarine Kolbeinsey Ridge by the WNW-ESE trending TFZ, while the Reykjanes Peninsula (RP) joins with the WVZ and the SISZ as an oblique continuation of the submarine Reykjanes Ridge (Sæmundsson, 1974; 1979; Einarsson, 1991; 2008; Stefánsson et al., 2008). Two volcanic belts – the Örfajökull Volcanic Belt (ÖVB) and the transverse Snæfellsnes Volcanic Belt (SVB) – occur outside the immediate plate boundary, i.e., within plate interiors (e.g., Sæmundsson, 1978; Einarsson, 2008). These belts, referred to as intra-plate belts, and the propagating (southern) part of the EVZ, are collectively termed flank zones.

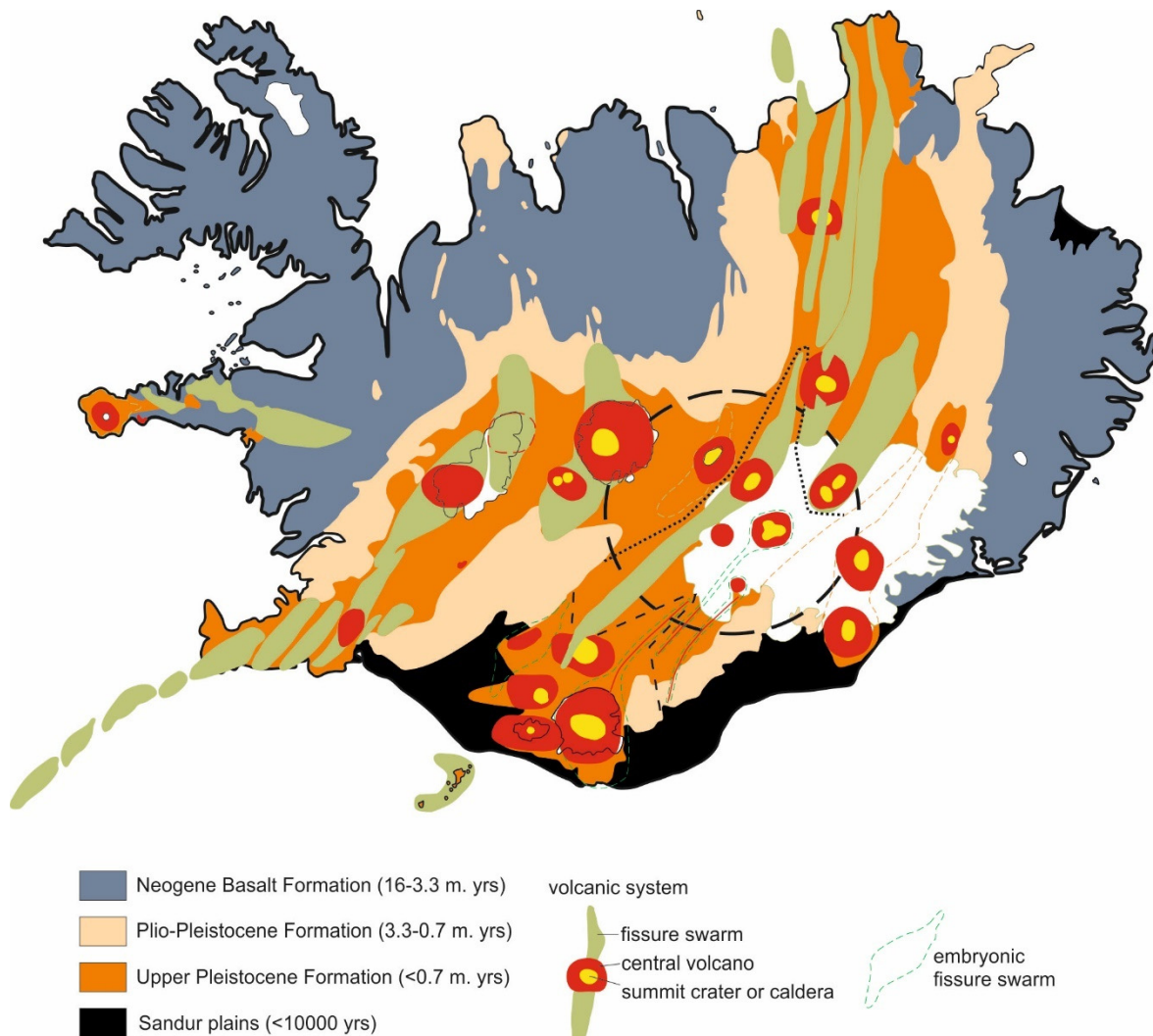


Figure 1. Volcanic zones and systems in Iceland. RR: Reykjanes Ridge; RVB: Reykjanes Volcanic Belt; SISZ: South Iceland Seismic Zone; SVZ: Western Volcanic Zone; SVB: Snæfellsnes Volcanic Belt; MIB: Mid Iceland Belt; EVZ: Eastern Volcanic Zone; NVZ: Northern Volcanic Zone; ÖVB: Öraefi Volcanic Belt; TFZ: Tjörnes Fracture Zone; KR: Kolbeinsey Ridge. The large dotted circle indicates the approximate centre of the Iceland mantle plume as depicted by Wolfe et al. (1997). The figure is from Askew et al. (2020); modified from Thordarson and Larsen (2007).

The main rock series that have been recognized within the active volcanic zones and belts of Iceland are tholeiitic, alkalic and transitional in nature. Jakobsson (1972) observed a remarkably regular pattern in the compositional variation of Icelandic postglacial basalts according to tectonic setting, where basalts of the tholeiitic series are only produced in the mature rift zones (i.e., the WVZ, the NVZ, and the northern part of the EVZ) while the flank zones are typified by mildly alkalic and/or transitional, and more incompatible element enriched magmatism compared to the tholeiitic magmas of the rifting zones, with basalts characterized by enrichment in iron and titanium occurring in the central volcanoes of the southern EVZ (e.g., Jakobsson et al., 2008; Sigmarsson et al., 2008). Compared to the diversity of recent magmatism in the neovolcanic zone, lava flows within the Tertiary sequences of Iceland have shown smaller compositional variations (Harðarson et al., 2008). The alkalic/transitional nature has been attributed to smaller degrees of and deeper decompression (partial) melting of mantle material (see e.g., Silva and Lindsay, 2015) beneath the flank zones than beneath the rifting zones of Iceland (e.g., Furman et al., 1991; Harðarson and Fitton, 1991), resulting from smaller lithospheric extension, thicker crust and lower geothermal gradients (see e.g., Pálmason, 1973). The low degree of partial melting produces lesser amounts of magma, facilitating elevated contents of Na and incompatible trace elements (K, Rb, Sr, Cs and Ba) in the resulting rock, i.e., elements that partition readily into the melt phase when the mantle undergoes melting (see e.g., White, 2005). Such elements remain concentrated in the extraction of partial melts if only small amounts of magmas are produced, while greater degrees of melting (as in the mature rift zones) will cause dilution of these elements.

Each of the volcanic zones and belts in Iceland is defined by several volcanic systems, and each system is characterized by either a fissure swarm, a central volcano, or both. The fissure swarms typically consist of monogenetic eruptive fissures that trend subparallel to the respective volcanic zone and erupt only basaltic magmas (e.g., Thordarson and Höskuldsson, 2008). The central volcano represents the centre of lava emission within the volcanic system and is thought to be underlain and maintained by a shallow and long-lived magma storage system (i.e., a magma chamber) that discharges basaltic to silicic magmas (e.g., Sæmundsson, 1978; 1979; Guðmundsson, 2000). As noted e.g., by Askew et al. (2020), volcanic systems that feature both a central volcano and a well-developed fissure swarm are situated along the axial rifts in the interior of Iceland, where the crust is thickest, while systems lacking central volcanoes tend to be situated at the coastal ends of the axial rifts, where the crust is thin. Systems featuring only central volcanoes and no fissure swarms are situated within the flank zones and on relatively thick crust.

Regional volcanic activity in Iceland is dominated volumetrically by basaltic lavas which are erupted from both fissure swarms and central volcanoes, while silicic products are particularly associated with the presence of the latter and generally considered as an

indication of an underlying shallow magma chamber (e.g., Walker, 1966; Guðmundsson, 1995). Silicic products have been estimated to constitute approximately 10-15% of the exposed bedrock volume (Walker, 1966; Thorarinsson, 1967; Jakobsson, 1972; Jóhannesson and Sæmundsson, 1998; Jónasson, 2007; Jakobsson et al., 2008). When eruptive magma volume of post-glacial age only is considered, 6% are intermediate and 3% silicic (Thordarson and Höskuldsson, 2008). The petrogenesis of Icelandic rhyolites is still a subject of debate with most current models invoking either or both processes of partial melting of hydrothermally altered basaltic crust and fractional crystallization of parental basaltic magmas (e.g., Carmichael, 1964; Óskarsson et al., 1982; Furman et al., 1992; Jónasson, 1994; Gunnarsson et al., 1998; Martin and Sigmarsson, 2007; 2010; Bindeman et al., 2012). The typical lifetime of a volcanic system has been assumed to be ~0.5-1.5 Myr (Jakobsson et al., 1978; Jakobsson, 1979; Sæmundsson, 1978; 1979). However, a lifespan of 2.3-2.4 Myr was estimated in a recent study for a fossilized volcanic system in East Iceland featuring both a fissure swarm and a central volcano, where the central volcano within the system was active for around 1 Myr (Askew et al., 2020). While recent studies on several fossil Icelandic central volcanoes have indicated that the lifetimes of silicic volcanism within these volcanoes were around 400 to 500 kyr (Askew et al., 2020; Banik et al., 2023), longevity of silicic magmatism within individual central volcanoes have been recorded to reach >1 Myr (Flude et al., 2008) and ≥ 1.5 Myr (Banik et al., 2018), with ≥ 2.8 Myr documented as the longest lifespan of silicic activity within an Icelandic central volcano (Carley et al., 2017), indicating that central volcanoes in Iceland appear to have potentials for longer lifetimes than previously documented.

Due to the divergence at the plate boundary, together with the associated crustal drift, lavas emplaced along the axial rift are predicted to drift laterally in both directions from the rift axis (Böðvarsson and Walker, 1964; Walker, 1963; Pálmason, 1973). By this, successions of Neogene basaltic lavas, with Neogene central volcanoes preserved as entities, occur adjacent to both sides of the present axial rift along with the sub-glacial eruption products of the Early Pleistocene. The Neogene successions have been influenced by the glaciations of the Pleistocene period, resulting in deep fjords and valleys that provide natural cross-sections through the lava pile and windows into the interiors of fossil volcanic systems and thereby excellent opportunities to recreate the histories of ancient systems. This can be achieved by examining the nature and duration of the magmatism and volcanism that built up these edifices. Commencing with Walker's (1963; 1964; 1966) pioneering work, mapping of Iceland's Neogene central volcanoes has resulted in valuable insights into the internal structure and plumbing systems of volcanoes along with improved understanding of silicic magma genesis, evolution of volcanic systems and crustal accretion processes in Iceland, in addition to contributing to enhanced control of geothermal fluid pathways in deep roots of geothermal systems (e.g., Gibson, 1963; Carmichael, 1964; 1967; Blake, 1964; 1966; 1970; Hald et al., 1971; Franzson, 1972; 1978; Jóhannesson, 1975; Sigurðsson, 1970; Friðleifsson, 1983; Gautneb et al., 1989; Gústafsson et al., 1989; Jónasson et al., 1992; Furman et al., 1992; Gústafsson, 1992; Geirsson, 1993; Hjartarson, 2003; 2005; Klausen, 2004; Martin et al., 2011; Burchardt et al., 2011; Vogler, 2014; Berg, 2016; Carley et al., 2017; Askew, 2020; Askew et al., 2020; Liotta et al., 2020).

Contrary to the low-aspect-ratio basaltic lavas that may extend tens of kilometres away from the eruptive vent(s), the high-aspect-ratio rhyolite lavas occur close to and over the eruptive site due to the high viscosity and inability to flow long distances (e.g., Walker, 1973; Pinkerton and Wilson, 1994). Thus, addressing the timing of rhyolitic volcanism of ancient

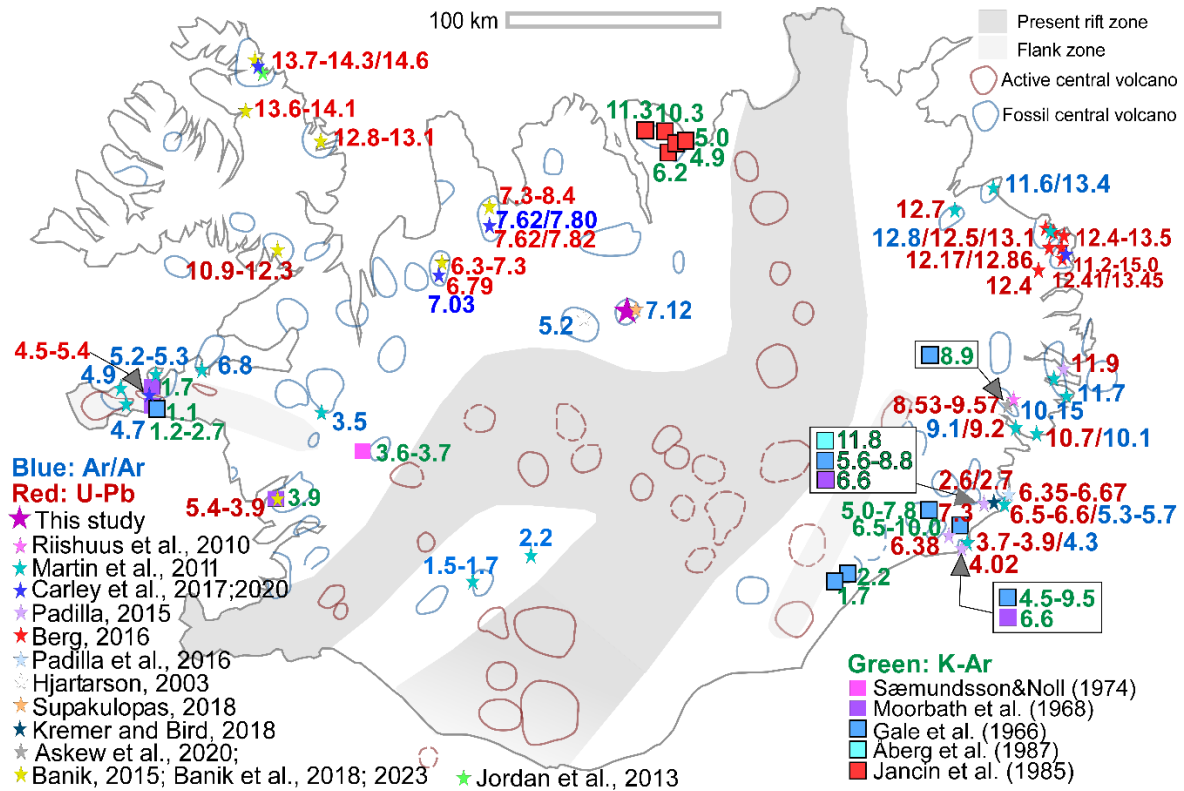


Figure 3. Published radiometric ages on extinct (Neogene and Early Pleistocene) silicic rocks in Iceland (compilation aided by Hopper et al., 2014).

Table 1. Compilation of research on extinct (Neogene and Early Pleistocene) central volcanoes in Iceland. Locations are presented in Fig.2; available rhyolite ages in Fig.3.

Region	Central volcano	Geological mapping	
		Non-peer-reviewed	Scientific papers
Central North	Tinná (5.2 Ma)	Hjartarson, 2003 (PhD thesis)	Republ./modified in Hjartarson, 2005
Central North/Tröllaskagi	Öxnadalur		
Central North/Tröllaskagi	Flókadalur		
Central North	Bleiksmýrardalur		
Central North	Torfufell (7.12 Ma)		
Central North	Miðfjörður		
Central North	Víðidalur (6.3-7.3 Ma)		
Central North	Vatnsdalur		
Central North/Flateyjarskagi	Flateyjardalur		
Central North/Flateyjarskagi	Náttfaravík		
Central North/Skagi Peninsula	Spákonufell		
Central North/Skagi Peninsula	Laxárdalur (7.3-8.4 Ma)		
East fjords	Geitafell	Friðleifsson, 1983 (PhD thesis)	Republished/modified in Burchardt et al., 2011
East fjords	Dyrfjöll (12.5-13.1 Ma)	Gústafsson, 1992a (PhD thesis)	Gústafsson et al., 1989; Gústafsson, 1992b; republished/modified in Burchardt et al., 2011
East fjords	Fagridalur (11.6-13.4 Ma)	Geirsson, 1993 (PhD thesis)	
East fjords	Refsstaðir (12.7 Ma)		
East fjords	Breiðavík-Kækjuskörð (10.6-14.8 Ma)	Southern part: Vogler et al., 2014 (MSc thesis)	
East fjords	Reyðarfjörður (11.3-11.9 Ma)	Gibson, 1963 (PhD thesis)	Walker, 1958
East fjords	Breiðdalur (8.5-9.6 Ma)	Askew, 2020 (PhD thesis)	Walker, 1963; Askew et al., 2020
East fjords	Þingmúli		Carmichael, 1964; Carreter et al., 2013
East fjords	Álftafjörður		Blake, 1970 (Sientia Islandica)
East fjords	Eystrahorn (Austurhorn) Pluton (5.3-6.7 Ma)		Blake, 1966; Cargill et al., 1928; republished/modified in Furman et al., 1992, Weidendorfer et al., 2014 and Padilla et al., 2016
East fjords	Vestrahorn (Vesturhorn) Pluton (3.7-6.6 Ma)	Roobol, 1969 (PdD thesis)	Cargill et al., 1928; Roobol, 1974
East fjords	Slaufrudalur Pluton	Beswick, 1965; Carmody, 1991 (PhD thesis)	Cargill et al., 1928
East fjords	Ketillaugarfjall Pluton		
East fjords	Þverártindur/Veðurárdalur/Staðarfjall Pluton	Annels, 1967 (PhD thesis)	Republished/modified in Klausen, 2004
East fjords	Lón		
East fjords	Hofsdalur		

Table 1. Continued.

Region	Central volcano	Geological mapping	
		Non-peer-reviewed	Scientific papers
East fjords	Skrúður/Seley		
East fjords	Álftavík		
East fjords	Barðsnes		
East fjords	Eyjabakkar		
East fjords/SE region	Kollumúli		
East fjords/SE region	Birnunestindur		
East fjords/SE region	Kjós		
Midwest region	Húsafell (3.6-3.7 Ma)	Sæmundsson&Noll (1974); republished/modified in McGovan, 2016	Sæmundsson and Noll, 1974; republished/modified in Unwin et al., 2021
Midwest region	Reykjadalur (3.5 Ma)	Jóhannesson, 1975 (PhD thesis)	
Midwest region	Laugardalur		
Midwest region	Hallarmúli	Khodayar, 2009 (Technical report)	
NW region/Central North	Prestbakki/Hrútafjörður		
NW region/Central North	Vatnsnes		
NW region/Hvammsfjörður	Svinadalur/Sælingsdalur		
NW region/NW Peninsula	Hergilsey		
NW region/NW Peninsula	Hrafnfjörður (13.7-14.6 Ma)	Jordan et al., 2013 (abstract); republished/modified in Banik, 2015 (PhD thesis)	
NW region/NW Peninsula	Árnes (12.8-13.1 Ma)	Jordan et al., 2013 (abstract); republished/modified in Banik, 2015 (PhD thesis)	
NW region/NW Peninsula	Kaldalón (13.6-14.1 Ma)		
NW region/NW Peninsula	Króksfjörður (10.9-12.3 Ma)		Hald et al., 1971; republished/modified in Pedersen&Hald, 1982 and Willbold et al., 2009.
NW region/NW Peninsula	Kálfadalur/Reiphólsfjöll		
NW region/NW Peninsula	Tjaldanes		
NW region/NW Peninsula	Álftafjörður		
NW region/NW Peninsula	Kollafjörður		
NW region/Snáefellsnes	Setberg/Kolgrafarfjörður (5.2-5.3 Ma)	Sigurðsson, 1970 (PhD th.)	
NW region/Snáefellsnes	Ellidži		
NW region/Snáefellsnes	Fróðá (4.9 Ma)		

Table 1. Continued.

Region	Central volcano	Geological mapping	
		Non-peer-reviewed	Scientific papers
NW region/Snæfellsnes	Álftafjörður/Hrappsey/Purkey (6.8 Ma)		(Kristmannsdóttir, 1971 (generalized map of Hrappsey-Purkey))
SW (Hreppar) region	Thjórsárdalur (1.5-1.7 Ma)		
SW (Hreppar) region	Laxá (Stóra-Laxá)	Friðleifsson et al., 1980 (technical report)	
SW region	Hvalfjörður	Kristinsson, 2009 (MSc th.)	
SW region	Hafnarfjall-Skarðsheiði (3.9-5.4 Ma)	Franzson, 1978 (PhD thesis); republished in Banik, 2015 (PhD thesis)	Republished/modified in Banik et al., 2018 and Browning&Guðmundsson, 2015
SW region (E. Pleistocene)	Stardalur/Esja	Friðleifsson, 1973 (PhD th.); republished/modified in Friðleifsson, 1976 (technical report)	Friðleifsson&Kristjánsson, 1972; republished/modified in Vahle et al., 2007 and Sæmundsson, 1979
SW region (E. Pleistocene)	Kollafjörður		

Table 1. Continued.

Central volcano	Petrological study	
	Non-peer-reviewed	Scientific papers
Tinná (5.2 Ma)	Hjartarson, 2003 (PhD th.)	Hjartarson, 2005
Öxnadalur	Kaiser, 2010 (MSc thesis)	
Flókadalur		
Bleiksmýrardalur		
Torfufell (this study) (7.12 Ma)		
Miðfjörður		
Víðidalur (6.3-7.3 Ma)		
Vatnsdalur		
Flateyjaralur		
Náttfaravík		
Spákonufell		
Laxárdalur (7.3-8.4 Ma)		
Geitafell	Friðleifsson, 1983 (PhD thesis)	
Dyrfjöll (12.5-13.1 Ma)	Gústafsson, 1992a (PhD th.)	Gústafsson et al., 1989; Gústafsson, 1992b; Berg et al., 2018
Fagridalur (11.6-13.4 Ma)		
Refsstaðir (12.7 Ma)		
Breiðavík-Kækjuskörð (10.6-14.8 Ma)	Vogler, 2014 (MSc thesis)	Berg et al., 2018
Reyðarfjörður (11.3-11.9 Ma)		
Breiðdalur (8.5-9.6 Ma)	Askew, 2020 (PhD thesis)	Askew et al., 2020; Charreteur&Tegner, 2013 (Rauðafell)
Þingmúli		Carmichael, 1964; 1967: Charreteur et al., 2013; Chiasera&Cortes, 2011
Álftafjörður		
Eystrahorn (Austurhorn) Pluton (5.3-6.7 Ma)	Doden, 1988	Cargill et al., 1928; Furman et al., 1992; Thorarinsson&Tegner, 2009; Mattson et al., 1986; Weidendorfer et al., 2014; Padilla et al., 2016
Vestrahorn (Vesturhorn) Pluton (3.7-6.6 Ma)	Doden, 1988	Cargill et al., 1928; Mattson et al., 1986
Slaufudalur Pluton		Cargill et al., 1928
Ketillaugarfjall Pluton		
Þverártindur/Veðurárdalur/Staðarfjall Pluton		Soesoo, 1998.
Lón		
Hofsdalur		
Skrúður/Seley		
Álftavík		
Barðsnes		
Eyjabakkar		
Kollumúli		
Birnunestindur		
Kjós		
Húsafell (3.6-3.7 Ma)		
Reykjadalur (3.5 Ma)	Jóhannesson, 1975 (PhD thesis)	

Table 1. Continued.

Central volcano	Petrological study	
	Non-peer-reviewed	Scientific papers
Laugardalur		
Hallarmúli		
Prestbakki/Hrútafjörður		
Svínadalur/Sælingsdalur		
Hergilsey		
Hrafnfjörður (13.7-14.6 Ma)	Jordan&Olin, 2008 (abstract); Banik, 2015 (PhD thesis)	Banik et al., 2023
Árnes (12.8-13.1 Ma)	Banik et al., 2014 (abstract); Banik, 2015 (PhD thesis)	Banik et al., 2023
Kaldalón (13.6-14.1 Ma)		
Króksfjörður (10.9-12.3 Ma)		Pedersen&Hald, 1982; Jónasson et al., 1992; Willbold et al., 2009
Kálfadalur/Reiphólsfjöll		
Tjaldanes		
Álftafjörður		
Kollafjörður		
Setberg/Kolgrafarfjörður (5.2-5.3 Ma)	Sigurðsson, 1970 (PhD thesis)	
Elliði		
Fróðá (4.9 Ma)	(Harðarson, 1993 (PhD thesis)	
Álftafjörður/Hrappsey/Purkey (6.8 Ma)		Kristmannsdóttir, 1971 (Hrappsey-Purkey)
Thjórsárdalur (1.5-1.7 Ma)		
Laxá (Stóra-Laxá)		
Hvalfjörður		
Hafnarfjall-Skarðsheiði (3.9-5.4 Ma)	Franzson, 1978 (PhD thesis); Banik et al., 2014 (abstract); Banik, 2015 (PhD thesis)	
Stardalur/Esja	Friðleifsson, 1973 (PhD thesis)	
Kollafjörður		

Table 1. Continued.

Central volcano	Structural analysis	
	Non-peer-reviewed	Scientific papers
Tinná (5.2 Ma)		
Öxnadalur		
Flókadalur		
Bleiksmýrardalur		
Torfufell (7.12 Ma)		
Miðfjörður		
Víðidalur (6.3-7.3 Ma)		
Vatnsdalur		
Flateyjardalur		
Náttfaravík		
Spákonufell		
Laxárdalur (7.3-8.4 Ma)		
Geitafell	Friðleifsson, 1983 (PhD thesis)	Burchardt et al., 2011; Liotta et al., 2020
Dyrfjöll (12.5-13.1 Ma)		Burchard et al., 2011
Fagridalur (11.6-13.4 Ma)		
Refsstaðir (12.7 Ma)		
Breiðavík-Kækjuskörð (10.6-14.8 Ma)		
Reyðarfjörður (11.3-11.9 Ma)		Mattson et al., 2018 (Sandfell)
Breiðdalur (8.5-9.6 Ma)		
Þingmúli		
Álftafjörður		Urbani et al., 2015; Paquet et al., 2007
Eystrahorn (Austurhorn) Pluton (5.3-6.7 Ma)		
Vestrahorn (Vesturhorn) Pluton (3.7-6.6 Ma)		
Slaufudalur Pluton		Burchardt et al., 2010
Ketillaugarfjall Pluton		
Þverártindur/Veðurárdalur/ Staðarfjall Pluton		Klausen, 2004
Lón		
Hofsdalur		
Skrúður/Seley		
Álftavík		
Barðsnes		
Eyjabakkar		
Kollumúli		
Birnunestindur		
Kjós		
Húsafell (3.6-3.7 Ma)	McGovan, 2016 (PhD thesis)	Unwin et al., 2021 (tuffisites)
Reykjadalur (3.5 Ma)	Jóhannesson, 1975 (PhD thesis)	Gautneb&Guðmundsson, 1992
Laugardalur		
Hallarmúli	Khodayar, 2009 (technical report)	
Prestbakki/Hrútafjörður		
Vatnsnes		
Svínadalur/Sælingsdalur		
Hergilsey		

Table 1. Continued.

Central volcano	Structural analysis	
	Non-peer-reviewed	Scientific papers
Hrafnfjörður (13.7-14.6 Ma)		
Árnes (12.8-13.1 Ma)		
Króksfjörður (10.9-12.3 Ma)		
Kálfadalur/Reiphólsfjöll		
Tjaldanes		Guðmundsson et al., 1996
Álftafjörður		
Kollafjörður		
Setberg/Kolgrafarfjörður (5.2-5.3 Ma)	Sigurðsson, 1970 (PhD thesis)	
Elliði		
Fróðá (4.9 Ma)		
Álftafjörður/Hrappsey/Purkey (6.8 Ma)		
Thjórsárdalur (1.5-1.7 Ma)		Khodayar&Franzson, 2007
Laxá (Stóra-Laxá)		
Hvalfjörður	Kristinsson, 2009 (MSc thesis)	
Hafnarfjall-Skarðsheiði (3.9-5.4 Ma)	Franzson, 1978 (PhD thesis)	Gautneb et al., 1989; Browning&Guðmundsson, 2015
Stardalur/Esja		Villemin et al., 1994; Pasquare&Tibaldi, 2007; Tibaldi&Pasquare, 2008
Kollafjörður		

1.2 Iceland's rift relocations

It is a general consensus that the WNW motion of the North American and the Eurasian tectonic plates relative to the Iceland mantle plume has resulted in repeated eastward relocations of the plate boundary in the past (e.g., Ward, 1971; Sæmundsson, 1974; 1979; Jóhannesson, 1980; Harðarson et al., 1997; 2008; Vink 1984; Martin et al., 2011). Hitherto, this has been taken to be a dominant process in the formation and tectonic evolution of Iceland (e.g., Harðarson et al., 1997; 2008). Classical ideas presume that as the plate boundary has migrated some distance away from the plume, magma production continues above its centre due to decompression melting, east of the boundary and inside the Eurasian plate. By this, magma penetrates the lithosphere with accompanying intra-plate volcanism, carrying heat that is partly transferred to the surroundings. The magmatic heating gradually weakens the lithosphere and the slow spreading rate of the MAR allows sufficient heating time, enabling the lithosphere to thin until new rifting commences above the plume centre (e.g., Middelstaedt et al., 2008). Finally – when two parallel rifting segments have been active simultaneously for a while – spreading ceases at the old axis and the younger rift segment seizes the full spreading rate (e.g., Harðarson et al., 1997). Some features within the Neogene lava successions of Iceland have been interpreted as records of past rift relocations, including asymmetric dips and discontinuities (unconformities) in the lava pile, typically accompanied by thick and fairly continuous sedimentary horizons supporting indications of volcanic quietness (Sæmundsson, 1974). The general assumption is that the lavas originating from (and dipping toward) the older rift zone are below the unconformity/hiatu while lavas originating from (and dipping toward) the younger zone are resting on its top.

As a result of loading by voluminous lava flows at the active plate boundary, in combination with the spreading, Iceland's lava successions are characterized by a general tilt toward the active rift axis (Böðvarsson and Walker, 1964; Pálmason, 1973; Pálmason and Sæmundsson, 1974; Daignieres et al., 1975). Such major synform-like structures are also recognized in the Neogene strata pile where they are interpreted as extinct, abandoned rift zones (Fig.4) (Sæmundsson, 1967; Aronson and Sæmundsson, 1975; Jóhannesson, 1975). The axis of such synform runs from the Snæfellsnes peninsula to the Húnaflói bay and is classically considered to represent the centre-line of the paleo Snæfellsnes-Húnaflói Rift Zone (SHRZ; Fig.4), normally quoted to have been abandoned at 6-7 Ma (Sæmundsson, 1979; Jóhannesson, 1980). Another paleo-rift is indicated in the extreme NW Iceland (Fig.4) by a 14.9 Ma laterite-lignite horizon that is considered to mark the extinction of the NW Iceland Rift (Harðarson et al., 1997). Although the horizon only represents a 200 kyr volcanic hiatus, it has been interpreted to be a record of a rearrangement of the rift zones at ~15 Ma, when rifting relocated from the NW Iceland Rift to the SHRZ, with lavas originating from the former zone occurring below the hiatus and lavas originating from the latter zone resting on top of the hiatus (Harðarson et al., 1997). Similarly, major unconformities, mapped within the lava succession in western and eastern Iceland and along the Tjörnes and the Flateyjarskagi peninsulas (Fig.4), are interpreted to be records of the 6-7 Ma relocation, representing a hiatus between the accumulation of lavas originating from the paleo SHRZ and the presently active NVZ and WVZ (e.g., Jóhannesson, 1980; Cotman, 1979; Jancin et al., 1985; Aronson and Sæmundsson, 1975; Ragnarsdóttir, 1979; Franzson, 1978). Pleistocene lavas (≤ 1.7 Ma; Everts, 1975) in the valleys of Skagafjörður and on the Skagi peninsula, as well as in the islands of Skagafjörður, have been recorded to rest

unconformably on top of Neogene (≥ 5 Ma) lava successions and to be accompanied by thick sedimentary sequences indicating volcanic quiescence for millions of years (Hjartarson, 2003). The renewed volcanism has been suggested to have occurred along an ephemeral paleo-rift zone running from the Hofsjökull glacier to the northern tip of the Skagi peninsula (i.e., the “Skagafjörður” paleo-rift zone in Fig.4) as interpreted from the arrangement of eruptive vents of Pleistocene age in the region (Hjartarson, 2003).

While the indications described above have hitherto been considered as classical evidence for previous rift relocations, the history of these events is still not fully understood. For example, Garcia et al. (2008) suggest that the synform running from the Snæfellsnes peninsula to the Húnaflói bay is not necessarily the result of a paleo-rift axis and may be produced by the weight of Plio-Pleistocene lavas extending from the central part of Iceland; an extension that has now been reduced by glacial erosion. The same authors emphasize that the hiatus indicated by the laterite-lignite horizon in NW Iceland is brief, and that available ages on both of its sides do not provide a coherent frame for the rift relocation. Moreover, the timing of initiation at the NVZ is still not fully constrained, as although generally assumed to have initiated at 6-7 Ma, some authors have proposed that its propagation commenced earlier; e.g., around 8-8.5 Ma (Garcia et al., 2003) or more than 12 Ma, with spreading partitioned between two rifting zones in North Iceland for several million years (Martin et al., 2011). While additional efforts are clearly needed to better constrain the process and history of Iceland’s rift relocations, the key to a better understanding will particularly involve efforts devoted to date these events.

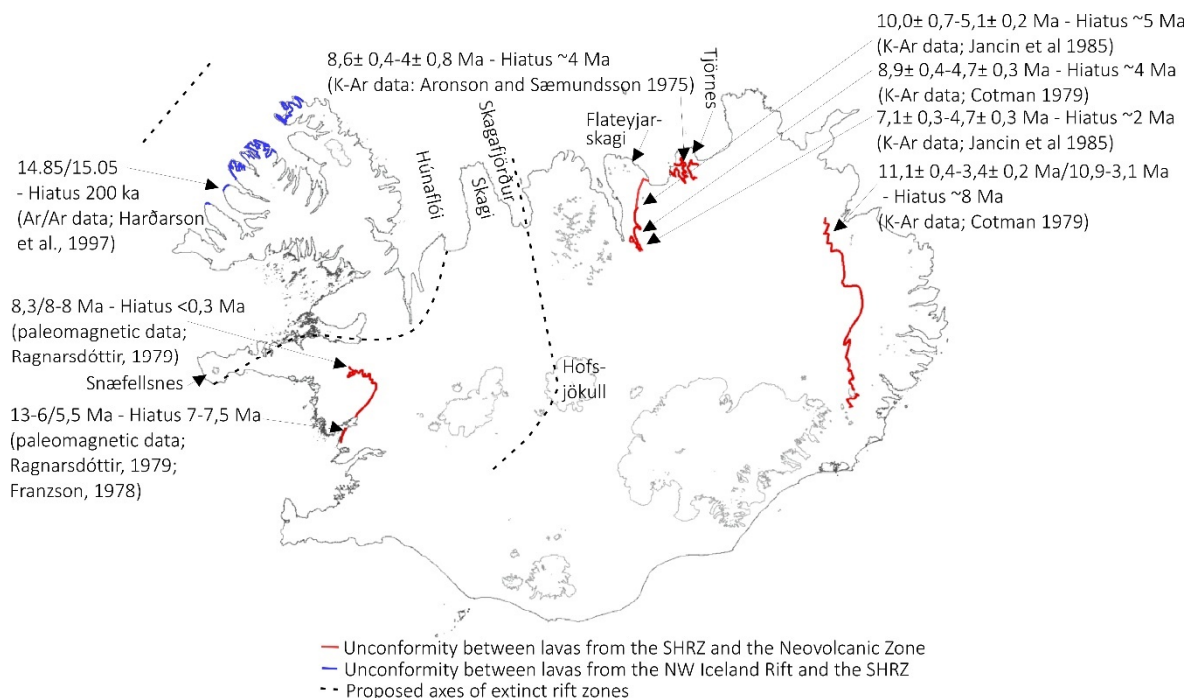


Figure 4. Unconformities interpreted as records of past rift relocations (from Hjartarson and Sæmundsson, 2014) and alignments of proposed extinct rift zones (from Harðarson et al., 2008; Sæmundsson, 1979; Jóhannesson, 1980; Hjartarson, 2003).

1.3 Central North Iceland: age data

This study focuses on central North Iceland (Fig.5); a region composed of a deeply dissected succession of subaerial basaltic lavas which are intercalated with minor clastic interbeds, with several fossil central volcanoes buried within. The lava succession is of Neogene and Early Pleistocene age, as evident from the numerous age determinations available from the region (Fig.5). These ages are mostly obtained from basaltic lavas by the K-Ar dating method in the 1970's and 1980's, with the majority from the Tröllaskagi and Flateyjarskagi peninsulas. Although certainly useful, the K-Ar method has proved to be problematic in Iceland due to low concentrations of K_2O in Icelandic basalts (often resulting in imprecise and inaccurate measurements of the K_2O concentrations) in combination with mobility of K, resulting in sensitivity to the thermal history of the rock (often leading to results reflecting the time of subsequent alteration rather than time of crystallization). Nonetheless, the numerous K-Ar ages available from central North Iceland have contributed significantly to the understanding of the volcano-tectonic evolution of the region, e.g., by providing constraints on a major hiatus along the Flateyjarskagi peninsula (Jancin et al., 1975; Cotman, 1979). This hiatus is considered to be related to the 6-7 Ma rift relocation in North Iceland. While the $^{40}Ar/^{39}Ar$ method has now superseded the K-Ar method (e.g., Lee., 2015) and is considered an optimal method for dating Icelandic rocks (e.g., Sigmarsson et al., 2012), only several $^{40}Ar/^{39}Ar$ ages of lavas in the central North region have been obtained. The vast majority comes from the Garcia et al.'s (2003) study, which focused on dating regional basaltic dykes with the aim of providing age data on the rifting process and thereby spatio-temporal constraints on the 6-7 Ma rift relocation. That being said, the compilation presented in Fig.5b and c shows that the majority of dated igneous formations in central North Iceland are of basaltic composition and meanwhile, some of the buried silicic centers remain undated.

A closer look at Fig.5b and c shows that the age distribution does not follow a straightforward progression away from the NVZ as typical for mid ocean ridges. The ages of igneous formations stratigraphically below the Flateyjarskagi unconformity show a general younging to the west, from 12 Ma to 7/7.5 Ma towards the Húnaflói synform. The igneous formations above the unconformity are mostly in the 4-5 Ma range and younging eastward towards the current axial rift (i.e. the NVZ). Very young ages are recorded in the Skagafjörður region which have been interpreted as renewed volcanism, long after extinction of the SHRZ (a westward rift relocation). However, lavas of Quaternary age in the Eyjafjörður region have been assumed to have run out of the Fnjóskadalur valley (Guillou et al., 2010), i.e., a long distance from an origin within the NVZ. A general younging is observed from the coastline and into the land in the eastern part of the region which appears to be non-existent in the western part. This younging in the east may possibly, at least to some extent, be explained by the generally southerly dipping of the strata pile below the Flateyjarskagi unconformity. The apparently non-existent younging from the coastline into the land in the western part of the region is unexplained, although it should be noted that in the west, the age data is scarcer than in the east, and furthermore, that a large part of the dated formations are from dykes instead of lavas. A relatively wide range of ages are recorded in some locations; especially in Flateyjarskagi which may largely be explained by sampling at different stratigraphic levels, while some may possibly be explained by the uncertainties associated with the K-Ar method.

1.4 Geology of the Eyjafjörður region

The Torfufell central volcano (ToCV) is situated in the southern part of the Eyjafjarðardalur valley, in the region of the Eyjafjörður fjord (Figs.5 and 7). This region is composed of sequences of flat-lying Neogene basaltic lavas (e.g., Sæmundsson, et al., 1980; Jancin et al., 1985; Jóhannesson and Sæmundsson, 1998; Kristjánsson et al., 2004), commonly separated by horizons of lithified sediments which are often distinctively red in color and consisting largely of wind-blown tephra mixed with ancient soils (Sæmundsson, 1979; Sæmundsson et al., 1980; Roaldset, 1983). The originally sub-horizontal lava succession now tilts regionally a few degrees in southerly directions, i.e., southwest in the northern part, turning to southeast in the southern part (Einarsson, 1960; 1965; Sæmundsson et al., 1980). The oldest lavas (11-12 Ma; Sæmundsson et al., 1980; Jancin et al., 1985) occur near the mouth of the fjord while strata from Early Pleistocene (2.6 Ma; Hjartarson and Sæmundsson, 2014; Supakulopas, 2018) are present at the head of the southernmost valley. The Eyjafjörður fjord is bordered to the east by the Flateyjarskagi peninsula, while the conspicuously high mountain range of the Tröllaskagi peninsula borders its western side. Several Miocene central volcanoes are identified in the region (e.g., Hjartarson and Sæmundsson, 2014), including the volcanoes of Flókadalur and Öxnadalur along the Tröllaskagi peninsula, Torfufell by the peninsula's southern end, and Flateyjardalur and Náttfararvík on the Flateyjarskagi peninsula (see also Table 1). Only ~15 km west of the ToCV is the 5-6 Ma Tinná central volcano (TiCV), described by some authors as potentially related to the rhyolite in Mt. Torfufell and thereby of similar age (Harðarson and Guðmundsson, 1986; Hjartarson et al., 1997; Hjartarson, 2003; 2005).

The northernmost part of the Eyjafjörður region is greatly affected by the TFZ, with WNW to ESE trending seismic lines occurring along the Flateyjarskagi peninsula and the northernmost part of the Tröllaskagi peninsula (e.g., Stefánsson et al., 2008). The TFZ is a broad zone of active seismicity, transform faulting and crustal extension (Einarsson, 2008), considered to have formed to accommodate the 6-7 Ma rift relocation from the SHRZ to the NVZ and WVZ (Sæmundsson, 1974). A gentle antiform, or half-dome, with lavas tilting toward south and southeast along its eastern flank and toward southwest on the western flank, runs along the Tröllaskagi peninsula (Einarsson, 1960; 1965; Sæmundsson, 1974; Aronson and Sæmundsson, 1975; Jóhannesson, 1991). This antiform has also been interpreted as evidence for the 6-7 Ma rift relocation, potentially during a transitional stage in which two subparallel rifting segments coexisted in northern Iceland (Sæmundsson, 1974; Aronson and Sæmundsson, 1975), with the lava succession progressively sagging due to the weight of voluminous lavas erupting at two different zones. The previously described Flateyjarskagi unconformity, running along the Flateyjarskagi peninsula, is defined by an angular unconformity and a hiatus in accumulation of the volcanic succession, spanning the time from ~10 Ma to ~6 Ma by the peninsula's SE end and from ~7 Ma to ~5 Ma in the southern part of the Fnjóskadalur valley (Figs.4 and 5; Jancin et al., 1985; Cotman, 1979). Generally, the lavas below the hiatus are considered to have originated within the SHRZ while lavas above the hiatus are assumed to be originated from the NVZ. Accordingly, it is readily apparent that the Eyjafjörður region, being located between the paleo SHRZ and the present NVZ, pertains to a key area in the evolving understanding of the 6-7 Ma axial rift relocation in North Iceland. Of particular interest are the silicic formations of the region's fossil central volcanoes that, due to their inability to spread or flow long distances, are sitting close to their original eruption sites. Thus, addressing the timing of these formations provides geometric relationships that can significantly improve our understanding of the geodynamic

evolution and crustal accretion of Iceland and may hold the key to a more refined comprehension of the 6-7 Ma rift relocation event.

While erosion is assumed to have been dominated by streams and rivers in the Eyjafjörður region during the Miocene and Pliocene, erosion was greatly intensified during the Pleistocene, when numerous ice sheet pathways dissected the Tröllaskagi peninsula and the main glacier finalized carving of the fjord of Eyjafjörður and the Eyjafjarðardalur valley. Erosion of both glaciers and rivers has excavated the Neogene lava succession and the central volcanoes in the region, thus providing access into fossil volcanic interiors that enables mapping, sampling and recreation of the histories of ancient volcanic systems and edifices. This study focuses in particular on the exposed interiors of the Torfufell central volcano, which prior to the present work was mostly uncharted and unmapped. The principal aims of the study are to map the volcano and establish the nature and architecture of this volcanic construct while addressing its timing, longevity, build-up rate, chronological evolution and absolute lifespan. An added task is to explore a potential continuation of the Flateyjarskagi unconformity to the south - i.e., to resolve if this unconformity/hiatus exists in the strata pile of the study area - and to examine the inferred relation of the Torfufell central volcano with the neighbouring Tinná central volcano in the valleys of the adjacent fjord, Skagafjörður, thereby addressing a hypothesis that the silicic rocks of the Torfufell and Tinná comprise a single large central volcano as suggested e.g., by Hjartarson (2005).

2 Study area

The study area (Figs.6 to 9) is in the southern part of the Tröllaskagi peninsula deep in the valley of Eyjafjörður (i. Eyjafjarðardalur), approximately 40 km south of the largest town in North Iceland, Akureyri. The area extends from Mt. Hleiðargarðsfjall and Núpá river in the north to the Hafrá canyon and Mt. Selfjall in the south and covers around 270 km² (Fig.7). The area is dissected from north to south by Eyjafjarðardalur, from which several tributary valleys run, including the NE-SW trending valley of Torfufellsdalur (Villingadalur) and the ~E-W trending remote Svarfdalur in the SW part of the study area. Mt. Torfufell (Figs.8 and 9) is the highest summit of the inner Tröllaskagi highlands, 1244 m above sea level, and forms a topographic high rising about 100 m above the surrounding mountain tops. Lower slopes of the valleys are generally vegetated and partly covered with scree. The valley floors are overlain by alluvial deposits and partly by landslide debris. The bedrock sequence is well exposed in the steep upper mountain cliffs as well as in ruts and gullies. While grey basaltic lavas dominate in these exposures, bright and colourful silicic and intermediate formations are exposed in the upper slopes of mountains in the area's southern half; most prominently in Mt. Torfufell itself, and also in the western slopes of Mt. Hólafjall and in the eastern slopes of Villingadalur and into Svarfdalur. North of the rhyolite in the NW slopes of Mt. Hólafjall is a prominent, ~700 m long NNW striking line of black cliffs named Vothamrar (meaning "wet cliffs"). This is a massive basaltic dyke, arranged into an echelon right-stepping segments in map view (Figure 10), which contains up to 40% plagioclase macrocrysts and taken to represent one of the feeder dykes for the basaltic lavas overlying the central volcano (Árnadóttir et al., in prep).

Large landslides characterize the environment of the study area, with the most recent occurring in the valleys of Sölvadalur and Torfufellsdalur in 1995 and 2011, and in Mt. Hleiðargarðsfjall in 2020 (Pétursson, 1997; Sæmundsson et al., 2014; Brynjólfsson, 2021). A large cluster of mounds, termed Leyningshólar, is present in front of the mouth of Villingadalur, in the center of the area. The mounds are considered by Jónsson (1976) as rockslides, mostly derived from the mountain south of the Tröllshöfði cape, and possibly partly glacial drift, while Guðmundsson (2010) identifies a part of the mounds as relict rock glaciers. We examined the soil overlying the Leyningshólar mounds in two locations (section 1 and 2 in Figure 11), recognizing several tephra layers in the field, i.e., Hekla 1104, the Landnám Tephra, Hekla-3 and Hekla-4 in section 1 and Hekla-3, Hekla-4 and Hekla-5 in section 2. By the bottom of section 2 is a dark tephra layer, identified in the field as a possible Grímsvötn 10ka (previously Saksunarvatn) tephra horizon (e.g., Harning et al., 2019), indicating that the Leyningshólar mounds were formed before ~10.300 yr BP and presumably after 11.7ka, when the Younger Dryas glacier retreated. At the bottom of section 1 is diatomaceous earth, indicating that Lake Hólavatn (Fig.11) was much larger during Early Holocene than today. As the surface of the Villingadalur valley is extremely flat where the farmlands are now (Figs.6 and 8), it may be speculated that the Leyningshólar mounds have dammed the valley in the past, resulting in the formation of a temporary lake,

accompanied by sediment deposition at the lake's bed and in between the westernmost mounds.

Prior to the study presented in this thesis, the main features of the bedrock geology of the study area had been illustrated in the small-scale geological maps of Iceland (Thoroddsen, 1901; Jóhannesson and Sæmundsson, 1998; 2009; Hjartarson and Sæmundsson, 2014) and of Central Iceland (Kjartansson, 1965). These maps delineate silicic volcanic formations, centred in Mt. Torfufell and enveloped by basaltic lavas, just beneath the boundary between the Miocene and the Pliocene periods. Stratigraphic mapping and paleomagnetic studies were carried out east of the Eyjafjarðará river by Kristjánsson et al. (2004), with three of the mapped stratigraphic profiles located within the research area and one just north of it, thus establishing an excellent base for the present study. Most of these profiles were remeasured by Supakulopas (2018), who also added two new profiles and $^{40}\text{Ar}/^{39}\text{Ar}$ age data (also presented in Muxworthy et al., 2024). These studies demonstrated the stratigraphy of Mt. Hólafljall in the eastern part of the study area in more details than shown by the small-scale maps, e.g., covering the eastern edge of the rhyolites of the Torfufell central volcano and depicting a thick series of plagioclase- and olivine phyric lavas in the mountain's uppermost section. Although only partly covering the central volcano, the study conducted by Supakulopas (2018) indicated a ~1.5 Ma hiatus between the rhyolite lavas of the volcano and the overlying basalts.



Figure 6. The Villingadalur valley and farmlands. Photo by Anett Blischke, 2021.

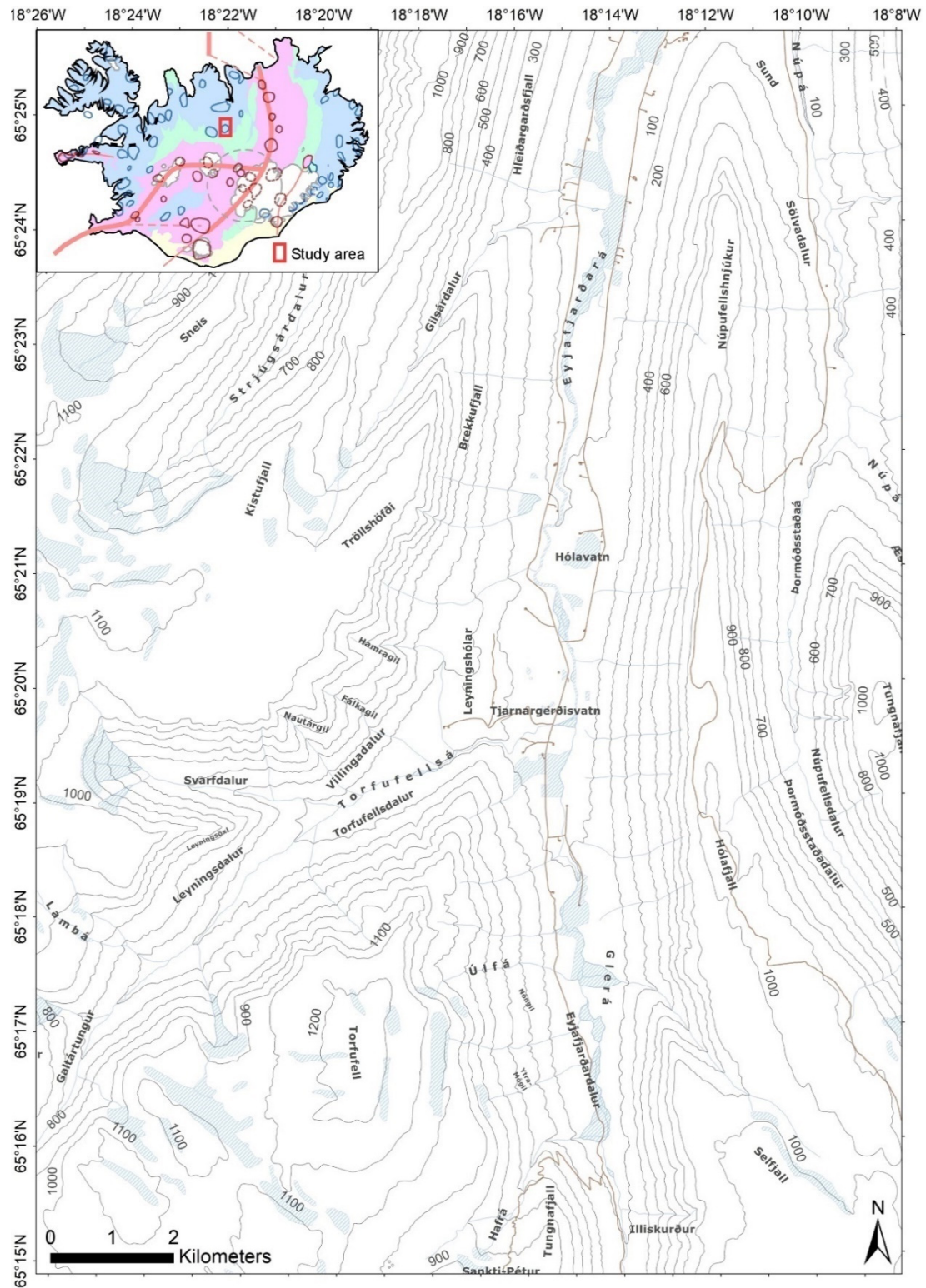


Figure 7. Geographical overview of the study area showing the locations mentioned in the text (basemap from Landmælingar Íslands, with additions).



Figure 8. 3D model of Mt. Torfufell, created from close-range airborne photogrammetry (photographed by Dr. Birgir Vilhelm Óskarsson, Icelandic Institute of Natural History). The boundary between the mafic and the intermediate/silicic succession is indicated with white triangles. The southern edge of the Leyningshólar mounds appears in the lower left corner of the image, and the Torfufellsá river runs through the even floor of the Villingadalur valley's farmlands in the lower part of the image. The Eyjafjarðardalur valley, observed behind Mt. Torfufell, in the upper left to upper middle part of the image, dissects the study area from north to south.

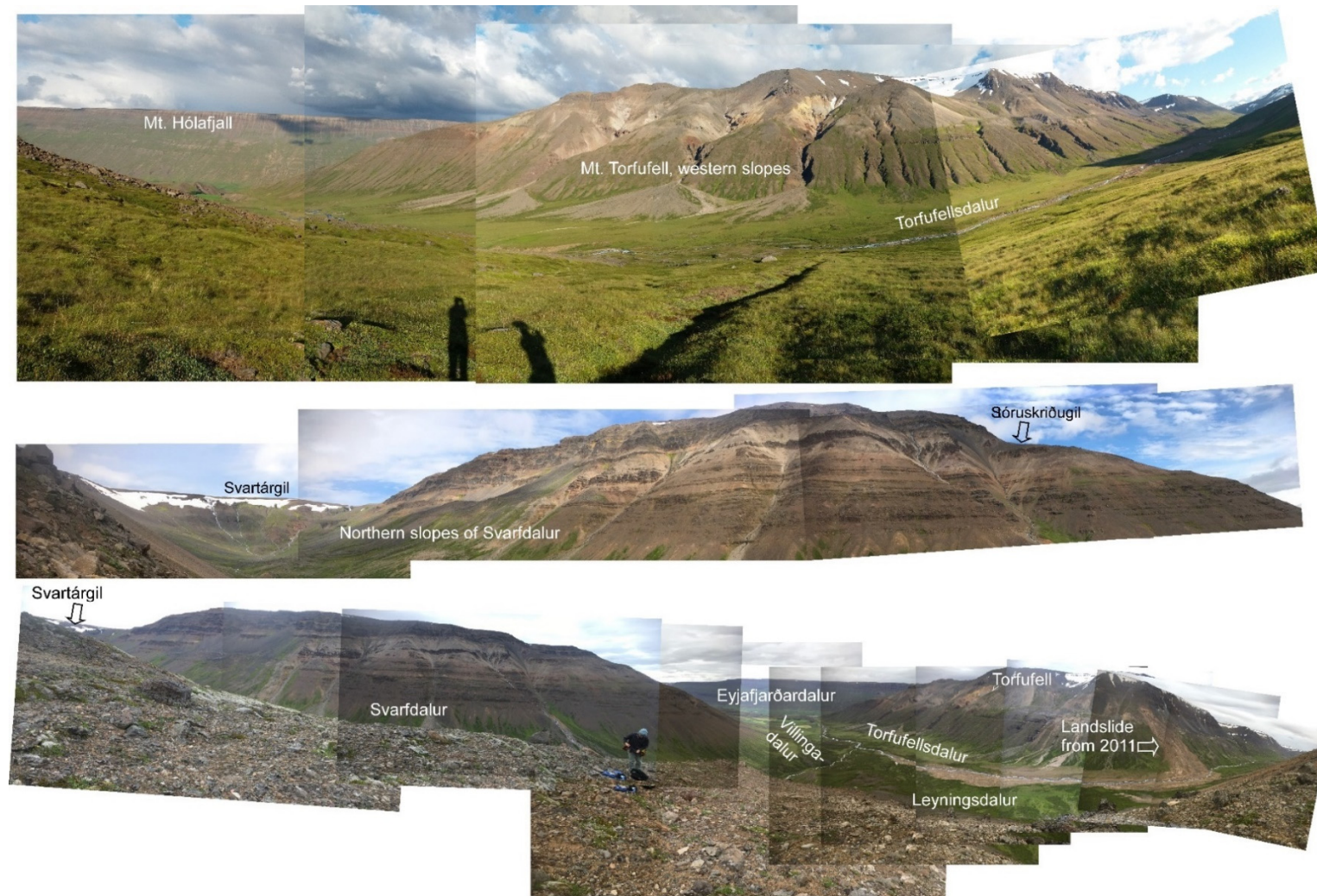


Figure 9. Overview of parts of the study area. Uppermost image: Western slopes of Mt. Torfufell, as seen from the mouth of the Svarfdalur valley. Middle image: Northern slopes of the Svarfdalur valley. Lowermost image: Overview from the top of Leyningsöxl.

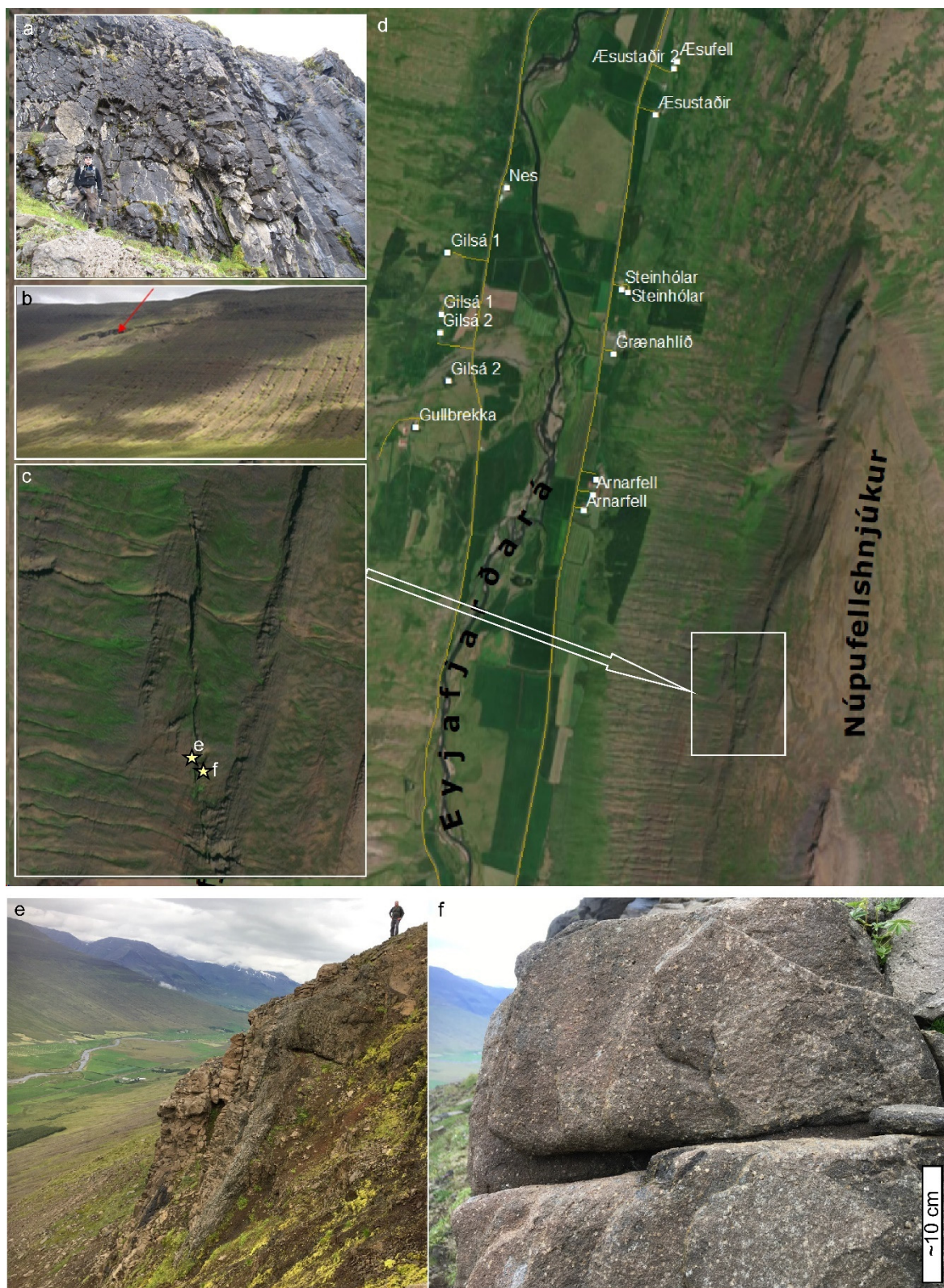


Figure 10. The Vothamrar dyke in Mt. Hólafljall. a) Close-up field photograph of the dyke, taken approximately where the red arrow is in b). c) Overview of the dyke (location in Mt. Hólafljall shown in d), showing its en echelon arrangement and cross-cutting relationship with an (apparently older) NE-SW trending dyke. The yellow stars show the locations of

figures e and f. e) The dyke's contact with the adjacent basaltic lavas. f) Close-up of the dyke, with macrocrysts visible.

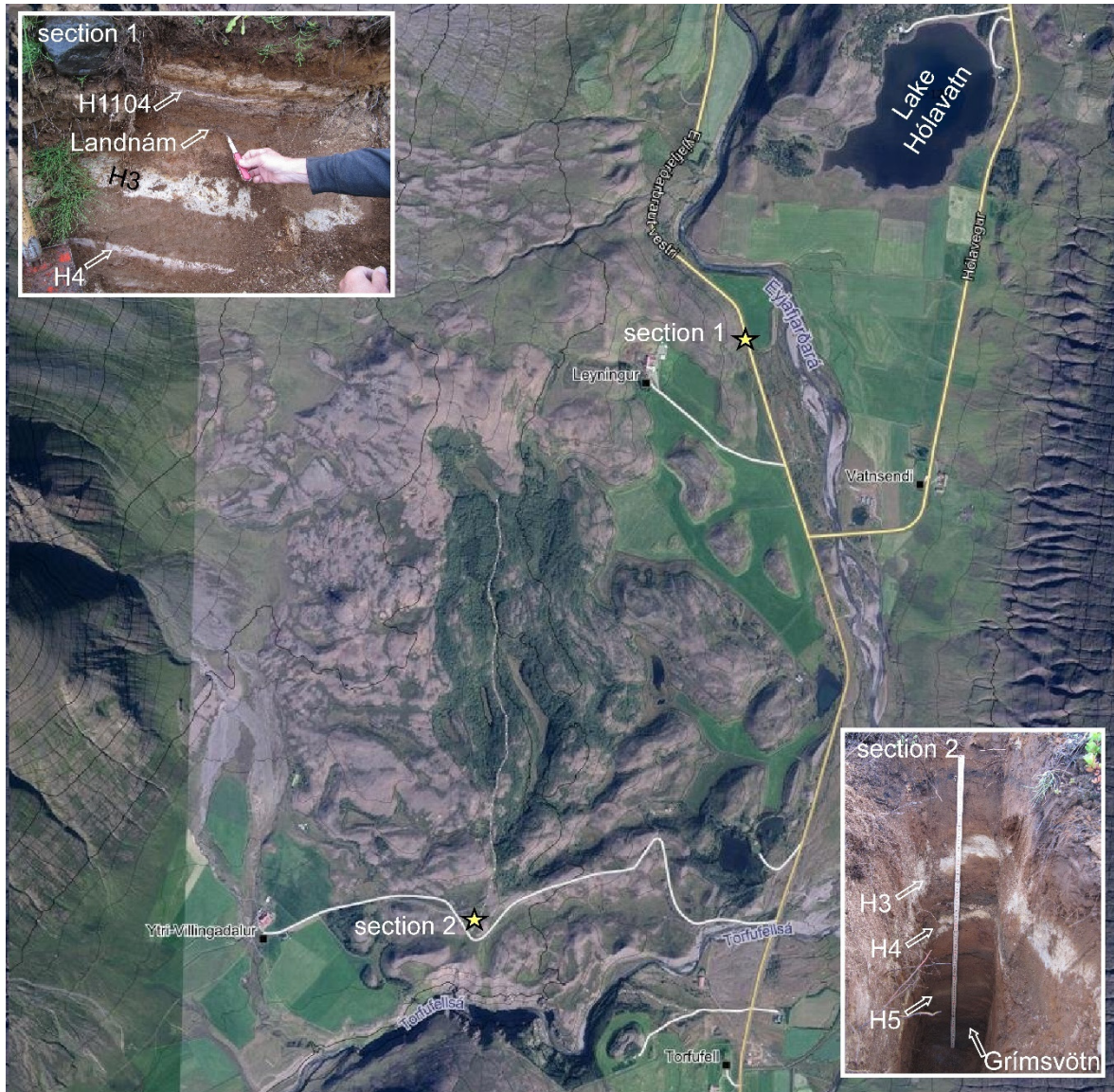


Figure 11. Overview of Leyningshólar mounds. Yellow stars show the locations of examined tephra sections (see insets for details).

3 Methods

3.1 Background

The present work uses several methods to investigate the Torfufell central volcano and to understand its chronology and evolution (see Chapters 3.2 to 3.5). A combination of these various tools enables identifying of the main elements of the nature, architecture and evolution of the ToCV volcanic construct, chronicling of its history and an improved understanding of its part in a larger perspective. Thereby, these surveys collectively provide a new insight into the geology of the area and represent a contribution to field observations, geological mapping, volcano geology, magnetostratigraphy, geochemistry and age dating of the Miocene bedrock and central volcanoes in central North Iceland.

3.1.1 Field observations and geological mapping

Geological fieldwork is the direct observation and recording of geological information from the bedrock where it crops out at the surface and involves description of surface features and their interrelationships. However, as emphasized by Lahee (1961), many conclusions drawn from field observations are deductions made from inferences and thus, in fact, are based on on-site interpretation by the observer. While geological fieldwork can be undertaken to address particular scientific problems, the main objectives of such undertaking for the present study is to (i) gain a more in depth insight into the geology of the study area, (ii) reconstruct the geological history of the area, (iii) determine the nature, stratigraphical order and time sequence of igneous events in the area, (iv) collect samples for geochemical analysis in order to get better grasp of the magmatism, and (v) enhance our understanding of the composition and structure of geological formations exposed at the surface in the study area. In other words to produce a detailed geological map for this part of Iceland.

The geological information, recorded from outcrops during the fieldwork, will establish a foundation for a geological map. The recorded information are electronically stored and displayed by software tools provided by the geographic information (GIS) technology, permitting queries and analysing of characteristics of rock bodies and other geologic features (Soller, 2004). However, it is good practice to be mindful of that the correlation between information recorded from outcrops (i.e., drawing of units and formations covered by scree and vegetation) is unavoidably an interpretation of the geologist, although aided by measurements of the strata dip (and in this case palaeomagnetic measurements), in combination with observations on aerial images. Thereby, even with a detailed map, there is always room for further investigation and data collection in the given area, as for improvements and reconstructions on the geological map.

3.1.2 Magnetostratigraphy

During the fieldwork phase of the present work, individual lava flows were measured with a portable fluxgate (vector) magnetometer in order to obtain information on their remanent magnetic direction (polarity). The method (e.g., Radhakrishna et al., 2021; Torsvik, 2005; Lucas, 2005; Kono, 2007) uses the north- or south- seeking property of a magnet and is based on the fact that most rocks, including volcanic rocks, contain minerals that are naturally magnetic (most importantly magnetite, hematite and titanomagnetite), and minute grains within these crystals act like tiny bar magnets. The magnetic minerals align themselves parallel with the Earth's magnetic field while the lava is fluid, and when it cools below its Curie point, they "freeze" in this position. By this, the lava flow will contain evidence of the direction of Earth's magnetic field, as it was at the time of cooling. The Earth's magnetic field is not steady and its polarity has been reversed frequently in the past, and the record of its ancient state is generally termed remanent magnetism. The declination, inclination and intensity of the magnetization are preserved within the lava and can be measured with adequate precision in the laboratory. A very simplified, much less expensive and more effortless method was however used in the present project which can easily be applied in parallel with stratigraphic mapping during fieldwork. With this method, only the direction of the magnetization is measured (in the field, by a portable fluxgate magnetometer), where a direction approximately parallel to today's field is considered as "normal" and a direction about 180° from today's field is considered as "reverse". Sometimes no magnetization is detected, then the rock is considered as "anomal", indicating a geomagnetic reversal or an "excursion" when the geomagnetic poles weaken and drift toward the equator without completing the reversal. This method is however much less precise than the laboratory-based method; not only as it only measures the magnetic direction but also as various factors such as subsequent dipping of the strata (which alters the orientation of the lavas and thereby the samples; only slightly however in this case) and rock composition can affect the magnetization of the rock (for example, the magnetic susceptibilities of silicic rocks are frequently small compared to those of basaltic rocks, as silicic rocks are characterized as having a lower iron content). Even so, measurements of ancient magnetic directions can in suitable outcrops (i.e., in outcrops enabling dense sampling from stratigraphic sections) provide patterns of normal and reverse polarity zones, the so-called chrons, that facilitate stratigraphic correlations between outcrops and may be anchored into the global magnetic polarity timescale by calibrating it with radiometric ages. When successfully calibrated, the magnetic polarity reversals represent time planes that augment the radiometric age data.

3.1.3 Geochemistry

Geochemical analysis is a quantitative examination of the composition of natural Earth materials, typically employed by use of analytical geochemical device using a detector output in the form of an electrical signal that is converted into a meaningful parameter such as a unit of concentration (Worden, 2005). The conversion must be achieved by applying previously characterized standards that are analyzed in exactly the same way as the unknown sample and provide a calibration curve whose quality determines the quality of the analytical output (Worden, 2005). While a variety of geochemical techniques exists, this study employs in particular techniques using X-rays, spectroscopy and the optical effects of samples.

Electron microprobe analysis (EPMA)

X-rays are a part of the electromagnetic spectrum and have no mass and no electrical charge, and travel in straight lines as they are not affected by electrical or magnetic fields (e.g., Worden, 2005). A technique known as electron microprobe analysis (EPMA) uses X-rays (generated by an electron gun) to provide spatially resolved major- and trace-element geochemical data from solid samples (e.g., Worden, 2005). The technique employs an electron microscope which is fitted with a secondary X-ray detector and uses electromagnetic lenses to focus and direct a stream of electrons into a highly polished (flat) sample. When the impinging electron stream interacts with the sample, some electrons are knocked out of their quantum shells, and this is accompanied by outer-shell electrons falling in to fill the vacancy. When free electrons move from one shell to another and interact with the orbital electrons or the nucleus of an atom, they give up some of their energy and by that they generate characteristic X-rays (e.g., Worden, 2005). The energy and wavelength of the X-rays are controlled by the present element and the specific nature of the electron orbital transition (e.g., Worden, 2005). Secondary X-rays are detected and quantified by either energy dispersive or wavelength dispersive analysis (the present study uses the latter).

X-ray diffraction (XRD)

The X-ray diffraction (XRD) analytical technique (see e.g., Worden, 2005) is used to analyze the crystal structure of minerals. The technique uses Bragg's law ($n\lambda = 2d\sin\theta$) which describes the diffraction of X-rays in crystals (i.e., the relationship between the X-ray and its reflection of from a crystal surface). An XRD analyzer essentially includes an X-ray source, an X-ray detector and a sample holder. Typically, the sample is powdered and placed onto the sample holder. The X-ray source and the X-ray detector are rotated about the sample and define the same angle relative to the sample. X-rays are produced by the source and diffraction occurs when an X-ray passes into, but is then bounced back out of the sample. In Bragg's law, d is the distance (i.e., the path) between regular layers (lattice planes) in the crystal, λ is the wavelength of the beam and θ is its angle. The X-ray beam is recast from the regular planes in the crystal, and when the path difference of the beam is equal to a whole number (n) of the wavelength, Bragg's law is satisfied and a constructive interference will occur between the X-ray and the crystal (i.e., the crystal will appear to have reflected the X-radiation). This can only occur under one angle of incidence (θ). The regular layers constitute the lattice of the crystal and as no two minerals have exactly the same crystal structure, the X-ray diffraction patterns can be used to identify minerals by comparison with patterns in reference databases.

Inductively coupled plasma optical emission spectrometry (ICP-OES)

Spectroscopy takes advantage of absorption, emission or scattering of electromagnetic radiation by atoms or molecules (e.g., Worden, 2005). The present study uses optical emission spectrometry with inductively coupled plasma (ICP-OES), where the sample is solid rock, quantitatively dissolved in acid. The plasma in this technique is a luminous volume of atoms and gas at extremely high temperatures (up to $\sim 10000^\circ\text{C}$), formed by argon flowing through a radio frequency field where it is kept in a state of partial ionization (e.g., Worden, 2005). When an aerosolized sample is introduced into the plasma, its molecules are atomized and ionized and eventually excited (e.g., Soltanpour et al., 1996) as electrons move from ground state to higher energy levels. As electrons return to the ground state, they emit

light with characteristic wavelength for each individual element (e.g., Khan et al., 2022). Measurements of these wavelengths are used to determine the concentration of the elements in the solution (e.g., Worden, 2005). By this, many elements can be analyzed simultaneously and relatively fast.

Scanning electron microscopy (SEM)

Scanning electron microscopy uses the optical effects of samples, taking advantage of electromagnetic radiation emitted by the material, and can provide fabric, mineralogy, mineral chemistry and high-resolution crystallographic information (e.g., Worden, 2005). The scanning electron microscope uses a beam of high-energy electrons (carrying significant amounts of kinetic energy), emitted from a filament and focused by magnetic lenses on the sample surface in a fine, precise spot (ThermoFisher Scientific, 2019). As the beam reaches the sample, electrons get reflected on the surface or even ionize atoms within the sample by liberating electrons (ThermoFisher Scientific, 2019). By this interaction between the electrons and the sample, the kinetic energy of the electrons is dissipated as a variety of signals, including backscattered electrons and secondary electrons, which are used to build up an image. As the size of the signal of backscattering depends on the size of the atom (i.e., the number of backscattered electrons is proportional to their atomic number), the backscattering signal provides information on the distribution of different chemical elements within the sample while obtaining a high-resolution picture of the sample surface (ThermoFisher Scientific, 2019).

When a beam of high-energy electrons, bombarded from a cathode gun, impinges on a sample (i.e., crystal), the sample emits photons (particles of light), a phenomenon called cathodoluminescence (e.g., Boggs and Krinsley, 2006). The energy levels in a crystal are so closely spaced that they form energy bands, and bombardment with high-energy electrons can cause electrons in lower-energy bands to be transferred to higher-energy bands, i.e., promoted (e.g., Boggs and Krinsley, 2006). Some crystals contain band gaps between the low- and high- energy bands, where electrons do not reside permanently but can travel back and forth through it (e.g., Broggs and Krinsley, 2006). The promoted electrons undergo de-excitation after a short time and move randomly through the crystal structure on their way back to the lower-energy bands, until they encounter electron traps (luminescence centers, most importantly impurity centers and defect centers) within the band gaps (e.g., Boggs and Krinsley, 2006). The presence of such traps/centers is a precondition for cathodoluminescence in the visible light range because some of the energy lost when electrons vacate electron traps (and continue their fall to the lower-energy band) is converted into photons (e.g., Boggs and Krinsley, 2006). A scanning electron microscope equipped with a cathodoluminescence detector provides high-resolution cathodoluminescent images of luminescent materials. The cathodoluminescence signal may be used as a signature of the genetic conditions of the mineral and a tool for studying and interpreting the characteristics of the crystal.

3.1.4 Age dating

Geochronology is the study of time, as recorded by geological materials, and is defined as the science of determining and dating the sequence of events in the history of the Earth (Harmon, 2019). Various age dating methods exist which are broadly divided into relative and absolute dating methods. Relative age dating delineates geological materials in

sequential order without measuring their absolute age while absolute dating measures the actual amount of time that has passed since the material was formed. In the present study, the absolute age of the Torfufell central volcano was determined through the U-Pb zircon geochronological technique by measuring the content of Uranium (U) and lead (Pb) in zircon crystals found in silicic samples. The presence of zircon crystals in igneous rocks depends on the Zr^{4+} ion – a small cation with a high ionic charge that generally behaves as an incompatible trace element in most rock-forming minerals. Therefore, a small amount of silicic magma that evolves from a larger amount of basaltic magma tends to become enriched in this incompatible element, where sufficient enrichment will enable precipitation of zircon (ZrSiO_4), meaning that zircon is more likely to crystallize from silicic magma than from basaltic magma (e.g., Shao et al., 2019). During crystallization, the zircon mineral conveniently incorporates small but measurable amounts of U which substitute for Zr^{4+} in the crystal lattice. At the same time, the mineral strongly rejects Pb. The nucleus of U is unstable and with time, it undergoes a radioactive decay by emitting alpha and beta radiation via a sequence of alpha and beta decays (i.e., ejection of alpha and beta particles) before reaching a stable state by producing Pb by the end of the decay process. As no (or virtually no) Pb is present in a newly formed zircon crystal, any Pb that is measured in the mineral must have been created through the decay of U. As the rate of U decay is known, the current ratio of Pb to U in a zircon crystal will record the time of crystallization (i.e., if not compromised by metamictization and subsequent Pb-loss (e.g., Keller et al., 2018)). Zircons are very hard and extremely resistant to subsequent disturbance such as weathering and alteration/metamorphism (see e.g., White, 2005), thereby representing an unaltered primary mineral in igneous rocks which are ideal for age dating. U decays to Pb via three different routes, i.e., from ^{238}U to ^{206}Pb , from ^{235}U to ^{207}Pb and from ^{232}Th to ^{208}Pb , and using these routes in combination – particularly the two former – allows a cross-correlation by the use of the Concordia diagram (which is a plot of $^{206}\text{Pb}/^{238}\text{U}$ vs. $^{207}\text{Pb}/^{235}\text{U}$) and a check of the fidelity of the calculated age (see e.g., White, 2005).

However, U-Pb zircon ages only record the time of zircon crystallization, which is not an instantaneous process and may span 200-700 kyr for magmatic zircons (Lissenberg et al., 2009; Wotzlav et al., 2013; Samperton et al., 2017). Therefore, the obtained zircon age only provides information about the intrusive part of a system's life and may not yield a robust estimate of the eruption age. Various age interpretations have been developed that can be broadly categorized into 1) a weighted-mean interpretation, calculated for the entire dataset and resulting in a precise, averaged age of emplacement; 2) a youngest zircon interpretation, where the youngest analysis is considered as an estimation of the eruption age; and 3) low mean squared weighted deviation (MSWD) weighted mean interpretation, where a weighted mean is calculated from only the youngest analyses (see e.g., Keller et al., 2018; Samperton et al., 2015). The weighted-mean interpretation is often used when the variance of the dataset is plausibly consistent with analytical uncertainty alone and is fully justified for instantaneous crystallization (Keller et al., 2018), but when the ratio of the true crystallization timescale to analytical uncertainty is high, a youngest zircon estimate is considered likely to outperform the weighted-mean interpretation but may pre- or post-date the true eruption age (Keller et al., 2018). The present study uses the weighted-mean interpretation although it is likely to slightly pre-date the true eruption age. Additionally, an alternative method was applied to produce reliable ages from two complex zircon aliquots by identifying the mean age of the youngest coherent age component, using the TuffZirc algorithm from Berkley Geochronology Center's ISOPLOT program (Ludwig and Mundill, 2002; Ludwig, 2003).

3.2 Techniques

This study uses several methods of analysis: 1) Field mapping and field observations, 2) Paleomagnetic measurements, 3) GIS map production, 4) Hand specimen and thin-section description, 5) X-ray powder diffraction analysis (XRD) of secondary minerals and clay, 6) Imaging, identification and Energy-Dispersive X-ray Spectroscopy (EDS) analysis of zircons using Scanning Electron Microscope (SEM), 7) Analysing of mineral geochemistry via Scanning Electron Microscope equipped with an ED detector (SEM/ED), 8) Analyses of glass chemistry via Electron Probe Microanalyses (EPMA), 9) Age dating via Secondary Ion Mass Spectrometry (SIMS) and 10) Chemical Abrasion – Isotope Dilution Thermal Ionization Mass Spectrometry (CA-TIMS), and 11) Analysis of whole-rock geochemistry (major and selected trace elements) via Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES).

3.3 Field mapping and map production

The main fieldwork phase (2015-2018) consisted in measurements of 28 new stratigraphic and paleomagnetic profiles, mainly in accessible outcrops in ruts and gullies. These localities (Fig. S1.18 and S1.19 of the supporting information of Paper I) represent the field data from which the map was manually drawn (in ArcMap), using aerial images when possible. The fieldwork included conventional methods necessary for geological mapping by use of appropriate equipment such as handheld GPS, compass, clinometer, geological hammer and magnifying glass, in addition to a tablet computer with the Collector software for ArcGIS. To enable mapping of basaltic lavas, we slightly modified the terminology of Walker's (1958) traditional classification system, as we demarcated basaltic lavas as aphyric basalt (including sparsely phyric basalts), olivine basalt, plagioclase phyric and plagioclase- and olivine phyric basalt. The intermediate and silicic rocks are divided into basaltic andesite, andesite, dacite and rhyolite. To facilitate stratigraphic correlations, we measured the remanent magnetic direction (polarity) of each lava flow in the field with a portable fluxgate magnetometer. Such field measurements can be inaccurate, so to reduce the imprecision as much as possible, at least three samples from each lava flow were measured. In case of inconsistency and/or uncertainty, the lava was assigned an anomalous/uncertain polarity. The fieldwork additionally involved identification of amygdalites, measurements of lava flow thicknesses, measurements of strike and dip of strata, mapping of faults, fractures and dikes, hot and cold springs and fossil finding sites, and mapping of outlines of large landslides and landslide scarps. Fieldwork also involved systematic collection of rock samples for geochemical and petrographical analysis and radiometric age determinations. Descriptions of hand specimens and thin sections are presented in Appendix B1 (six of these are described in more details in Paper 2) and field descriptions in Appendix B2.

The geological map is based on original fieldwork and integrated with data from previous authors (above-mentioned stratigraphic and polarity profiles from Kristjánsson et al., 2004 and Supakulopas, 2018; faults/dykes from magnetic surveys by Flóvenz and Tómasson, 1992 and landslide outlines partly taken from Pétursson, 1997).

3.4 Geochemistry

The fieldwork involved systematic collection of rock samples, and 32 of these samples were selected for whole-rock geochemical investigation, performed in particular to 1) provide insight into the rock (and magma) compositions, 2) identify and/or confirm rock types identified in the field, 3) explore the evolution of the volcano, 4) investigate the extent of the central volcano, and 5) collect background data that can be compared with the geochemistry of presently active volcanic systems in Iceland and may help with constraining the area's geodynamic conditions. Six of the geochemically analysed samples were selected for petrographical studies to provide precise microscopic descriptions, including an investigation of the chemical composition of its minerals, of the ToCV's basaltic to silicic volcanic formations. XRD analyses were performed to 1) identify amygdales and vein fillings that were indiscernible in the field and to 2) identify clay types within a peculiar sedimentary horizon separating the basaltic and silicic/intermediate sequences of the volcano.

3.4.1 Whole-rock geochemistry

Whole-rock major (SiO_2 , Al_2O_3 , FeO , MnO , MgO , CaO , Na_2O , K_2O , TiO_2 and P_2O_5) and selected trace element (Ba, Co, Cr, Cu, Ni, Sc, Sr, V, Y, Zn and Zr) compositions were measured for 32 samples by means of a ThermoFisher iCAP 7400 ICP-OES instrument hosted at the Institute of Earth sciences at the University of Iceland in 2019. The analytical procedure is based on a method developed by Govindaraju and Mevelle (1987) and follows a scheme previously published by Halldórsson et al. (2008). Preparation, also performed at the University of Iceland, included cleaning of organic and weathered material and secondary fillings from the samples, followed by crushing using a steel jaw crusher and fine-grinding (powdering) in an agate mill. 100 mg of the rock powder were then weighed in carbon crucibles along with 200 mg of flux (LiBO_2) and the mixture was kept at 1000°C for 30 minutes to fuse the mixture. The mixture then solidified into homogeneous glass beads upon cooling. The beads were dissolved in acid made of 5% HNO_3 , 1.33% HCl and 1.33% oxalic acid. Calibration was based on analyses of in-house reference samples (A-THO-, B-THO and B-ALK) and international rock standards (RGM-1 and K1919). The analytical scheme is considered to yield precision better than $\pm 2\%$ (RSD) relative for major and minor elements (% range) and better than $\pm 5\%$ (RSD) relative for trace elements (ppm range) (Halldórsson et al., 2008; Halldórsson et al., 2022). No volatile and redox titration analyses were performed, and therefore the chemical composition is reported on dry basis, calculated to 100% expressing total iron as FeO (Halldórsson et al., 2008). The ICP-OES chemical analysis was managed and performed by Sæmundur Ari Halldórsson and Jóhann Gunnarsson-Robin at the Institute of Earth Sciences of the University of Iceland.

3.4.2 Glass geochemistry

Geochemistry of silicic glass was obtained by use of JEOL JXA-8230 SuperProbe Electron Probe Microanalyser (EPMA) hosted at the Institute of Earth sciences at the University of Iceland - equipped with five wavelength-dispersive spectrometers and a LaB6 electron emitter (see Halldórsson et al., 2018). The glass was analyzed with an accelerating voltage of 15 keV, a 10 nA probe current and a beam of $10\text{ }\mu\text{m}$ in diameter. Calibration was based

on analyses of the A-THO reference sample. Altogether 10 spots were analysed within the obsidian sample.

3.4.3 Mineral geochemistry

Thin sections of six samples, which had been examined in a petrographic microscope, were further examined via analyses of major element composition of minerals in a Cambridge S360 SEM equipped with a LINK AN 10 000 ED detector (SEM/ED), hosted at Dipartimento di Scienze della Terra e Geoambientali of the University of Bari, Italy. Number of cations in formula were calculated from the weight percents, provided by the SEM, by the method of Deer, Howie and Zussman (1992). End members of plagioclases were calculated by:

$$X_{An} = (Fe + Mg + Ca) / x * 100$$

$$X_{Ab} = Na / x * 100$$

$$X_{Or} = K / x * 100$$

Where $x = Fe + Mg + Ca + Na + K$

End members of K-feldspars were calculated by:

$$X_{Or} = K / x * 100$$

$$X_{Ab} = Na / x * 100$$

$$X_{An} = (Ca + Fe + Mn + Mg) / x * 100$$

Where $x = K + Na + Ca + Fe + Mn + Mg$

These are based on atomic units. Mineral composition is in molecular per cent.

Nomenclature of pyroxenes were derived from the PX-NOM Microsoft Excel spreadsheet program by Sturm (2002), enabling calculations of structural formulae of pyroxene analyses obtained from the electron microprobe and determination of respective pyroxene names according to the classification scheme of the International Mineral Association (Sturm, 2002). The program includes the allocation of iron to Fe^{2+} and Fe^{3+} .

3.4.4 XRD analyses of secondary minerals and clay

Six samples of amygdales/vein fillings were analysed via X-ray powder diffraction analysis (XRD) at ÍSOR's XRD-laboratory by Sigurður Sveinn Jónsson. Prior to analysis, the samples were dried, powdered in a mortar, moistened in acetone and placed onto a quartz sample holder. The samples were then analysed in a Bruker AXS D8 Focus instrument, equipped with a Bragg-Brentano goniometer and a Cu anode lamp with a NaI crystal type scintillation counter.

Four samples of clay were analysed via XRD measurements at the Geosciences Department at Ecole Normale Supérieure (Paris, France) by Léa Lévy and Damien Deldicque. Clay

mineralogy was specifically investigated on oriented preparations of clay separates (granulometric fraction less than 2 μm) to enhance the basal 00l reflections and to ease the determination of the layer-to-layer distance. The fine-grained (infra 2 μm) clay mineral suspension was obtained by sedimentation during 8 hours. The clay suspensions were then deposited on a glass slide and slowly dried. Acquisitions were performed under air-dried conditions using a Rigaku Ultima diffractometer equipped with Cu K α radiation. The analytical conditions of the XRD acquisition on the oriented preparations were: 2–30 $^{\circ}2\theta$, step size of 0.01 $^{\circ}2\theta$ and acquisition time per step of 0.5 s.

3.5 Age Dating

Age data was obtained by the U-Pb zircon geochronological technique for six different units within the Torfufell central volcano to provide a chronological sequence of magmatic events. This study uses two U-Pb zircon dating methods; the SIMS and the CA-TIMS method. The SIMS method dates domains within single crystals that have been separated from the host, mounted into an epoxy mount and polished to expose their interiors. The method ablates small-diameter (10–40 μm) spots by hitting the surface of the exposed crystal interiors with a high-energy ion beam under vacuum. By this, a small portion of the released material forms either atomic ions or ionic compounds and is accelerated into a mass spectrometer (see e.g., Schoene, 2014). Mineral standards with known Pb/U are analysed regularly in between the unknown samples and corrections applied accordingly (e.g., Schoene, 2014). In the CA-TIMS method, the mineral separates are chemically abraded prior to analysis (Mattinson, 2005) to dissolve radiation-damaged or altered domains of the zircons, and then spiked with a tracer solution, dissolved in hydrofluoric acid, and U and Pb separated from other elements using ion exchange chemistry (Schoene, 2014). Samples from six silicic (≥ 65 wt% SiO_2) formations of the ToCV were selected, on grounds of the geological mapping and in terms of stratigraphic relations, for U-Pb zircon dating by the SIMS and CA-TIMS methods. Zircons from five samples were dated by the SIMS method while zircons from one sample were dated by the CA-TIMS method.

3.5.1 SIMS (secondary ion mass spectrometry)

Zircon crystals were separated from five whole-rock samples by Geotrack in Australia by conventional density and magnetic methods. The zircon grains (commonly ~ 50 –200 μm) were mounted by hand onto a two-sided tape along with reference materials, Geostandards zircon 91500 and Penglai, and then epoxy-casted and polished. The polished mounts were mapped by backscattered electron images (BSE) using scanning electron microscope (Hitachi TM3000 SEM) at the University of Iceland. U-Pb zircon dating of the five samples was carried out using the CAMECA ims 1280 in the NordSIMS facility, Swedish Museum of Natural History, Stockholm. The analytical and calibration procedures generally followed those described in Whitehouse and Kamber (2005) and Jeon and Whitehouse (2015), with a few differences noted here. A defocused O_2 -primary beam generated by a Hyperion H201 RF Plasma source was used to project the image of a 200 μm aperture onto the sample, generating elliptical, flat-bottomed craters of nominal ca. 20 μm . Complete U–Th–Pb analyses at a mass resolution ($M/\Delta M$) of ca. 5400 were performed using a peak switching routine, with a single ion-counting electron multiplier (EM) as the detection device. An energy window of 45 eV was used throughout, with energy adjustments made using the

$^{238}\text{U}^{16}\text{O}$ peak. Pb/U ratios, elemental concentrations and Th/U ratios were calibrated relative to the Geostandards zircon 91500 reference, which has an age of 1065 Ma (Wiedenbeck et al., 1995). The 4.4 Ma (Li et al., 2010) Penglai zircon was also analysed as unknowns to monitor the accuracy of the Pb/U calibration. Individual ages in the data table (Table S3) were calculated using simple basic decay equations. Isoplot (vers. 4.15, Ludwig, 2012) was used to make the plots and regressions.

3.5.2 CA-TIMS (chemical abrasion – isotope dilution thermal ionization mass spectrometry)

Zircons from one sample were dated by Dr. Corey Wall at PCIGR, UBC by chemical abrasion - isotope dilution thermal ionization mass spectrometry (CA-TIMS) method. The sample was prepared at PCIGR, including zircon separation and catholuminescence (CL) scanning electron microscope (SEM) imaging. An abundant population of relatively large zircon crystals was separated from the hand sample by conventional density and magnetic methods. Zircon crystals were subjected to a pre-treatment combining annealing and a modified version of Mattinson's (2005) chemical abrasion method for removing zircon domains that have lost lead from the interior of grains (detailed below). By this, the CA-TIMS method can isolate and analyze closed-system, high-quality domains within the zircon grains and exclude discordance due to loss of lead. The method furthermore samples larger volumes of material than the SIMS method, resulting in higher attainable precision. Prior to the chemical abrasion, 33 zircon grains from sample 20190823-3 were selected for in situ determination of trace element concentrations by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS), presented in Tables S7 and S8, in order to identify the best grains for the TIMS analysis. Following is Dr. Wall's Report of Investigation, detailing the pre-treatment and analytical method:

An abundant population of relatively large, (approximately 100-150 micron in long dimension), elongate, prismatic zircon crystals was separated from a hand sample of each sample by conventional density and magnetic methods. The entire zircon separate was placed in a muffle furnace at 900°C for 60 hours in quartz beakers to anneal minor radiation damage; annealing enhances cathodoluminescence (CL) emission (Nasdala et al., 2002), promotes more reproducible interelement fractionation during laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) (Allen and Campbell, 2012), and prepares the crystals for subsequent chemical abrasion (Mattinson, 2005). Following annealing, individual grains from all samples were hand-picked based on morphology, clarity, and the absence of inclusions.

U-Pb geochronology methods for isotope dilution thermal ionization mass spectrometry follow those previously published by Wall et al. (2018). Zircon crystals were subjected to a modified version of the chemical abrasion method of Mattinson (2005), whereby single crystal fragments plucked from grain mounts were individually abraded in a single step with concentrated HF at 190°C for 12 hours. All analyses were undertaken on crystals previously mounted, polished and imaged by cathodoluminescence (CL), and selected on the basis of zoning patterns. Zircon was put into 3 mL Teflon PFA beakers and loaded into 300 μL Teflon PFA microcapsules. Fifteen microcapsules were placed in a large-capacity Parr vessel and the zircon partially dissolved in 120 μL of 29 M HF for 12 hours at 190°C. Zircon was returned to 3 mL Teflon PFA beakers, the HF was removed, and the zircon was immersed in 3.5 M HNO_3 , ultrasonically cleaned for an hour, and fluxed on a hotplate at

80°C for an hour. The HNO₃ was removed, and zircon was rinsed twice in ultrapure H₂O before being reloaded into the 300 µL Teflon PFA microcapsules and spiked with the EARTHTIME mixed ²³³U-²³⁵U-²⁰⁵Pb tracer solution (ET535). Zircon was dissolved in Parr vessels in 120 µL of 29 M HF with a trace of 3.5 M HNO₃ at 220°C for 48 hours, dried to fluorides, and re-dissolved in 6 M HCl at 180°C overnight. U and Pb were separated from the zircon matrix using HCl-based anion-exchange chromatographic procedure (Krogh, 1973), eluted together and dried with 2 µL of 0.05 N H₃PO₄.

The U-Pb aliquots were loaded in a silica gel emitter (Gerstenberger and Haase, 1997) to outgassed, zone-refined Re filaments. Isotopic determinations were performed using a Nu Instruments TIMS. A correction for mass-dependent Pb fractionation was applied based on repeated measurements of NBS 982 (Catanzaro et al., 1968) Pb on both the Daly ion counter [0.16 (± 0.03%) amu⁻¹; 1 s] and the Faraday cups [0.10 × (1 ± 0.02%) amu⁻¹; 1 s]. Uranium was run as an oxide (UO₂) and measured in static mode on Faraday detectors equipped with 1012 Ω resistors. The U mass fractionation for the same analyses was calculated using the ²³³U/²³⁵U ratio of the double spike solution (0.99506% ± 0.01%, 1 s).

U-Pb dates and uncertainties for each analysis were calculated using the algorithms of Schmitz and Schoene (2007) and the U decay constants of Jaffey et al. (1971). Uncertainties are based upon non-systematic analytical errors, including counting statistics, instrumental fractionation, tracer subtraction, and blank subtraction. These error estimates should be considered when comparing our ²⁰⁷Pb/²⁰⁶U dates with those from other laboratories that used tracer solutions calibrated against the EARTHTIME gravimetric standards. When comparing our dates with those derived from other decay schemes (e.g., ⁴⁰Ar/³⁹Ar, ¹⁸⁷Re-¹⁸⁷Os), the uncertainties in tracer calibration (0.03%; Condon et al., 2015; McLean et al., 2015) and U decay constants (0.108%; Jaffey et al., 1971) should be added to the internal error in quadrature. Quoted errors for calculated weighted means are thus of the form ±X [Z], where X is solely analytical uncertainty and Z is the combined analytical and ²³⁸U and ²³⁵U decay constant uncertainties.

Six zircon grains were selected for CA-TIMS analysis on the basis of LA-ICPMS results in combination with the prismatic morphology and the absence of inclusions, avoiding those crystals with rounded edges. Chemical abrasion in concentrated HF at 190° for 12 hours resulted in only minor dissolution of the zircon crystals. All six analyses are concordant and equivalent, with a weighted mean ²⁰⁶Pb/²³⁸U date of 6.757 ± 0.015(0.02)[0.02] Ma (MSWD = 0.98), which is interpreted as dating the eruption and depositional age of this rhyolite.

4 Summary of papers

This chapter provides a summary of the following papers:

Paper 1:

Evolution of the Late-Miocene Torfufell central volcano, N-Iceland (In Prep) Sigurveig Árnadóttir, Árni Hjartarson, Thorvaldur Thordarson, Bjarni Gautason

Paper 2:

Geochemistry and petrography of basaltic to rhyolitic products of the Late Miocene Torfufell Central Volcano, North Iceland (In prep) Sigurveig Árnadóttir, Thorvaldur Thordarson, Bjarni Gautason, Árni Hjartarson, Alfredo Caggianelli

Paper 3:

U-Pb zircon age and chronology of the Torfufell central volcano: implication for timing of rift relocation in North Iceland (2023) Sigurveig Árnadóttir, Thor Thordarson, Árni Hjartarson and Bjarni Gautason

4.1 Paper 1: Evolution of the Late-Miocene Torfufell central volcano, N-Iceland

4.1.1 Overview

The aim of the present work is to investigate the previously uncharted Late-Miocene Torfufell central volcano in central North Iceland by field observations and mapping. The main purpose of the study is to identify the key elements of the structure and architecture of the volcano and thus contributing to a better understanding of the framework and inner workings of central volcanoes. We provide a detailed geological map of the volcano and its surroundings (at a 1:25.000 scale) and descriptions of lithostratigraphic units, structures, key geological features and lithofacies associations. This is integrated with geochemical assessment of its products and new and previous age data to address the age, chronology and evolution of the volcano. The map (Fig. 12) is based on original fieldwork and integrated with data from previous authors. The main fieldwork phase involved measurements of 28 new stratigraphic and palaeomagnetic profiles, identification of amygdalites, measurements of lava flow thicknesses, measurements of strike and dip of strata, mapping of faults, fractures and dykes, hot and cold springs, fossil finding sites and outlines of large landslides and landslide scarps, as well a systematic collection of rock samples.

4.1.2 Summary of results

Our observations demonstrate that the early phases of the Torfufell central volcano were characterized by eruptions producing series of thin (<5 m) mafic *ā*'a lavas. Our geochemical data manifest that the composition of these lavas is rather evolved and more evolved than the underlying plateau basalt, indicating longer residence of the magma in the upper crust and/or extended interaction between the rising magma and the crust. Latter phases of the volcano involved intermediate and silicic volcanism, both effusive and explosive, with the activity ceasing with a Plinian eruption. A peculiar tephra-rich and smectite- and (plant) fossil-bearing sediment horizon separates this sequence from the underlying *ā*'a lavas in several locations. Basaltic volcanism continued throughout the lifespan of the central volcano, indicating that its products are largely basaltic. Outcropping silicic and intermediate lavas and intrusions of the central volcano are limited to an area that lies from Mt. Hólafjall above Lake Hólavatn south to the Hafrá canyon and west to Svarfdalur valley. These formations are thickest in the northern part of Mt. Torfufell, where they form a ~350 m thick pile. The lowermost ~30-60 m of this pile are composed of andesite and dacite lavas which are overlain by thicker rhyolite lavas. Different palaeomagnetic polarities and sediments and individual basaltic to andesitic lavas separating the rhyolite lavas manifest that these are several discrete formations. The rhyolite lavas produced domes during the volcano's active period, forming topographic highs that became buried by basaltic lavas after the silicic phase ceased activity. The outcropping silicic formations seem to terminate in the Svarfdalur valley, indicating that the rhyolite is not connected geographically to the rhyolite of the neighbouring Tinná central volcano. Our geological observations demonstrate that tectonic uplift and glacial erosion have exposed extrusive rocks and shallow intrusions, providing a window into the uppermost part of the magma feeding system of the volcano. Silicic dykes are concentrated in the northern part of Mt. Torfufell, where they principally trend from ENE-WSW to ESE-WNW. This zone of maximum dyke intensity is interpreted to indicate

a central feeding zone for silicic products. Field examples provide evidence of silicic magma ascending through transgressive sills and erupting through sub-vertical dykes as well as sub-cylindrical conduits. Three such silicic conduits are indicated on the map; in Svarfdalur, in Nautárgil and in Hamragil (Fig. 12). They are aligned in a NE-SW strike with ca. 1600-1700 m intervals. In Svarfdalur valley is a magnificent section through the uppermost part of a feeder conduit and the adjacent basaltic lava pile. A cross-section like this is rarely seen. The volcanic plug is ca. 90 m in diameter and is exposed vertically over 300 m. In the upper part it is connected to an extrusive acidic dome. A NNE-SSW trending swarm of basaltic dykes with unclear affinity is observed in the northern part of the study area, intersecting the lowermost part of the mapped strata pile.

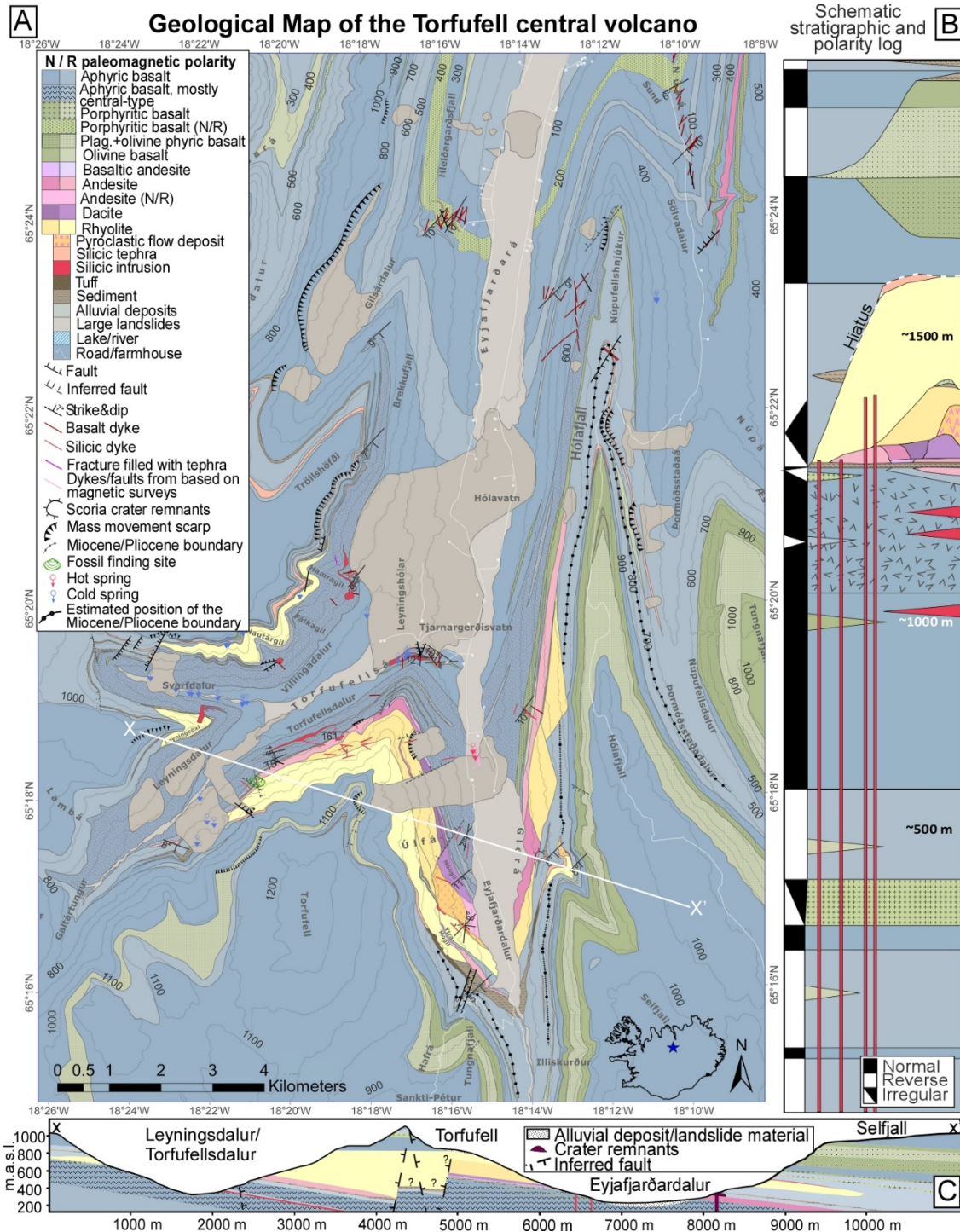


Figure 12. A) Geological map of the study area (see key for details). B) Simplified and schematic composite stratigraphic profile of the mapped strata, with measured magnetic polarities. C) Cross-section of the strata pile from Leyningsdalur (X) to Selfjall above the Glerá gully (X'). The map is provided in higher resolution in Fig.S1.17 of the supporting information.

4.2 Paper 2: Geochemistry and petrography of basaltic to rhyolitic products of the Late Miocene Torfufell Central Volcano, North Iceland

4.2.1 Overview

In this study, we explore the geochemical evolution of the Torfufell central volcano by focusing on petrological, mineralogical and geochemical characterization of eruptive and intrusive units belonging to the volcano. We provide new data on the whole-rock and mineral compositions of basaltic to rhyolitic products of the volcano. The results are integrated with a mapping campaign and new and previous age data to provide a stratigraphic framework and allowing evaluation of temporal changes in chemistry and mineralogy throughout the volcano's 1-1.2 Myr life span during the Late Miocene. 32 samples from the mapped strata pile were carefully selected for the study. The samples are collected from extrusive (n=25) and intrusive (n=2) rocks belonging to the central volcano, as well as from the enveloping plateau lavas, both overlying (n=2) and underlying (n=2) in addition to an overlying feeder dyke (n=1). All 32 samples were subjected to whole-rock geochemical investigation via ICP-OES analyses. One of the 32 samples, consisting of pure and unaltered obsidian, was selected to represent glass geochemistry of silicic products at the volcano via analyses by Electron Probe Microanalyser (EPMA). Six of the 32 samples, representing the spectrum of basaltic to rhyolitic volcanic products of the ToCV, were selected for petrographic studies and mineral geochemistry via Scanning Electron Microscope equipped with a LINK AN 10 000 ED detector (SEM/EDS). These six samples were collected from (1) a thin basaltic lava flow of *ā'a* type, considered to represent the base of the volcanic edifice; (2) basaltic andesite, marking the base of the intermediate/silicic extrusive portion of the central volcano, (3) andesite, (4) dacite, representing the initiation of silicic volcanism, and (5,6) rhyolites representing the later phases of activity at the volcano.

4.2.2 Summary of results

The whole-rock geochemical data presented in the study, ranging in SiO₂ from 46 to 76 wt%, enable us to discriminate between basaltic lavas sourced from the Torfufell central volcano and enveloping basaltic plateau lavas. The data document that basaltic lavas sourced from the central volcano are higher in TiO₂, FeO_t, MnO, K₂O and P₂O₅, and lower in Ca and Al than the enveloping plateau lavas and strongly indicate that the transition (shift) from predominantly fissure-fed eruptions toward central volcanism can be recognized in the field by a transition from thick (>5 m) to unusually thin (<5 m) lavas of *ā'a* type. Geochemistry of minerals documents that basaltic to dacite lavas of the central volcano contain pyroxenes (i.e., augite). Two pyroxenes are only observed in basaltic andesite, with pigeonite coexisting with augite, and in a basaltic xenolith. Plagioclase compositions range from An₁₆₋₂₁ in rhyolites to An₅₆₋₇₉ in the basalt, with reverse zoning in macrocrysts documented in a dacite sample. Integration with previous and new age data document that these geochemical and mineralogical variations span approximately 1-1.2 Myr during the Late-Miocene. The new geochemical data show that the Torfufell central volcano features basalts that are high in Ti and Fe compared to typical products from the presently active axial rift in Iceland and

rhyolites that are similar to rhyolites produced in the Mid Iceland Belt and by the east end of the South Iceland Seismic Zone (Fig.13).

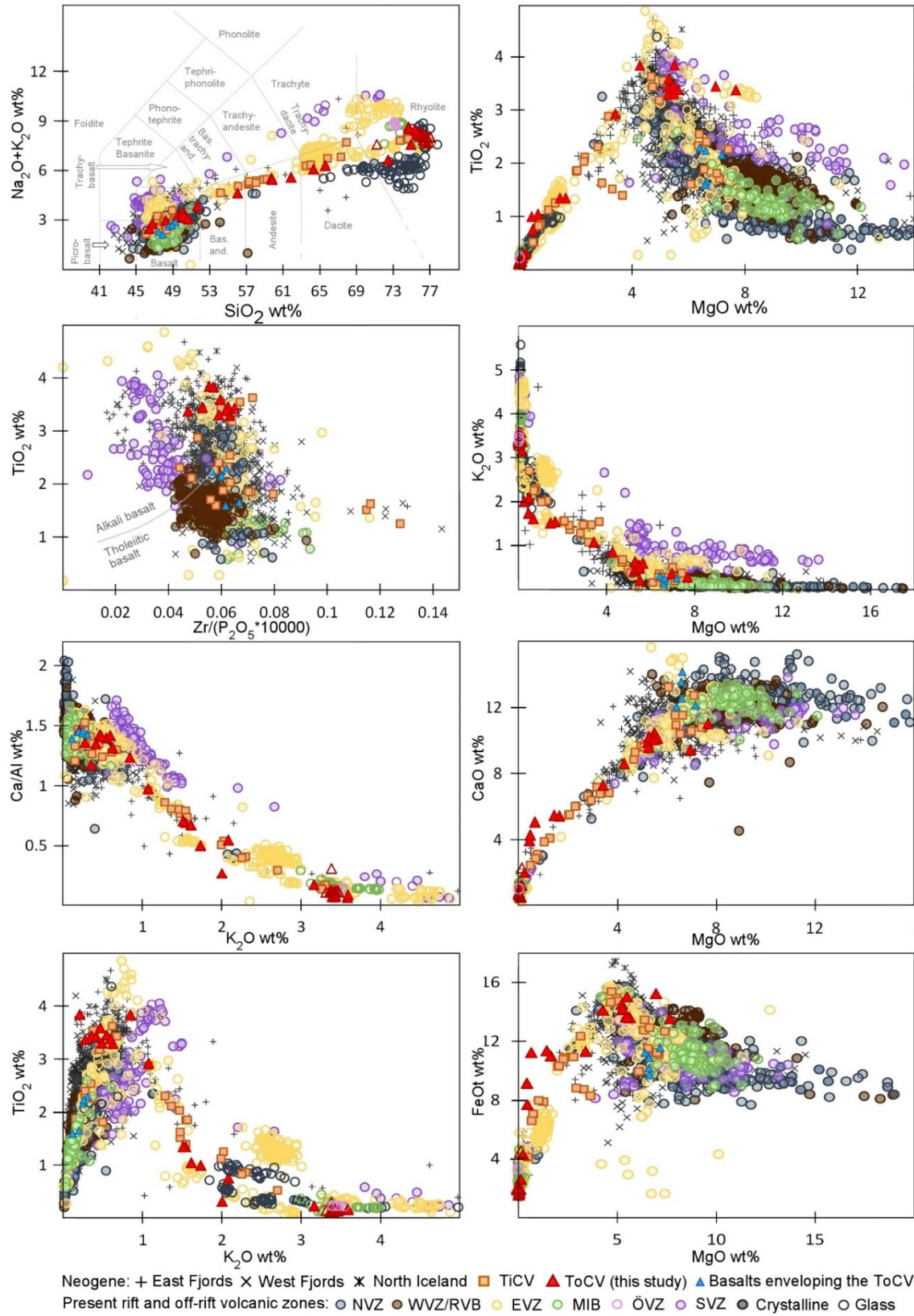


Figure 13. Geochemistry of the ToCV in comparison with samples from the neovolcanic zones in Iceland, the adjacent Tinná central volcano and data from the Neogene East and West fjords. Comparison data is from Clay et al. (2015), Debaille et al. (2009), Fitton et al. (1997), Flude et al. (2010), Fowler et al. (2016), Guðmundsdóttir et al. (2011), Gunnarsson et al. (1998), Harðarson (1993), Harðarson and Fitton (1997), Harðarson et al. (1997), Hjartarson (2003), Kuritani et al. (2011), Lacasse et al. (2007), Larsen et al. (1999; 2001; 2002), MacLennan et al. (2001), Martin and Sigmarsson (2007), Mattsson and Óskarsson (2005), McGarvie et al. (1990; 2007), Meara et al. (2020), Nicholson et al. (1991), Óladóttir et al. (2011), Pollock et al. (2014), Selbekk and Trønnes (2007), Sigvaldason (1979), Sinton et al. (2005), Slater (1996), Slater et al. (2001), Viccaro et al. (2015), and Zierenberg et al. (2013). The total alkali-silica diagram (TAS; uppermost left) shows root names from Le Bas et al. (1986). The TiO_2 vs $\text{Zr}/(\text{P}_2\text{O}_5 \cdot 10000)$ plot shows the discrimination between alkali basalts and tholeiite basalts after Winchester and Floyd (1976).

4.3 Paper 3: U-Pb zircon age and chronology of the Torfufell central volcano: implication for timing of rift relocation in North Iceland

4.3.1 Overview

In this paper, we define ages of different components of the Torfufell central volcano in central North Iceland via the U-Pb zircon geochronological technique. We present new age data from six silicic units belonging to the volcano, acquired by the SIMS (five units) and CA-TIMS (one unit) methods. The six units were selected for dating on grounds of geological mapping and in terms of stratigraphic relations. Four of the selected samples are from volcanic formations located at different stratigraphic levels, including samples marking both the base and top of the silicic volcanic products as observed in outcrops. Three of the volcanic formations are lavas while one is an ignimbrite. The remaining two samples are from intrusive units. The primary objective is to address the timing and longevity of silicic magmatism and volcanism at the Torfufell central volcano. The volcano is situated by the Tröllaskagi peninsula's southern end, between the presently active rift zone in North Iceland and the northern segment of the palaeo Snæfellsnes-Húnaflói rift zone. This is a key area in the evolving understanding of rift transfer in North Iceland, allowing us to explore a potential continuation of the Flateyjarskagi unconformity to the south and to examine an inferred relation of the Torfufell central volcano with the neighboring Tinná central volcano, previously considered to be of similar age and potentially the same volcano (e.g., Hjartarson, 2003). The study was conducted synchronously with field mapping and palaeomagnetic measurements in the study area, accompanied by sampling and whole-rock geochemical analyses. In this study, we couple the six new U-Pb zircon ages with these observations to reconstruct the volcanic history of the Torfufell central volcano and to propose a new model for the geotectonic evolution of Iceland during Miocene time.

4.3.2 Summary of results

The results range from 7.15 ± 0.12 to 6.76 ± 0.02 Ma, interpreted to represent the age range of silicic magmatism and volcanism at the volcano. Before that, the central volcano had produced basaltic lavas for 600-800 kyr, implying that it was active for ~ 1 -1.2 Myr. The timing of the transition from predominantly fissure-fed basaltic lavas towards central volcanism is based on Supakulopas's (2018) $^{40}\text{Ar}/^{39}\text{Ar}$ 7.77 ± 0.15 and 7.98 ± 0.15 Ma ages, obtained from samples collected above and below the stratigraphic level of the base of basaltic $\bar{a}$ 'a lavas that are assumed to define the onset of eruptions at the central volcano. However, as these two ages are inconsistent to the stratigraphic order (as the higher age was obtained for the lava that is located higher in the strata pile while the lower lava gave a younger age), the estimated timing of the establishment of the edifice base is quite imprecise. Our two lowermost silicic samples indicate an emplacement age of ~ 7 Ma, while one of these samples introduces a complexity and possible recycling/mixing of older zircons (possibly from zircon inclusions in plagioclase phenocrysts and/or from silicic lithics) into younger melt, implying silicic magmatism as early as 7.4 Ma at the Torfufell central volcano. Our youngest average age is obtained from a sample collected at the highest rhyolite peak and shows decidedly that rhyolitic activity at the volcano continued until 6.76 ± 0.02 Ma.

The new U-Pb ages show that silicic volcanism at the Torfufell central volcano took place 1-2 Myr earlier than assumed previously and nearly synchronously with a major rift relocation in North Iceland. As the age progression of the volcano and the neighboring Tinná central volcano conflicts with the generally established geotectonic framework of central North Iceland, we propose that these two volcanoes were formed at a leaky transform zone that developed to accommodate the rift relocation, with Torfufell formed at its junction with the embryonic rift zone, thus marking the initiation of the presently active rift in North Iceland. Since then, the two volcanoes have drifted away from the rift system due to plate spreading and migration of the plate boundary relative to the Iceland mantle plume (Fig.14).

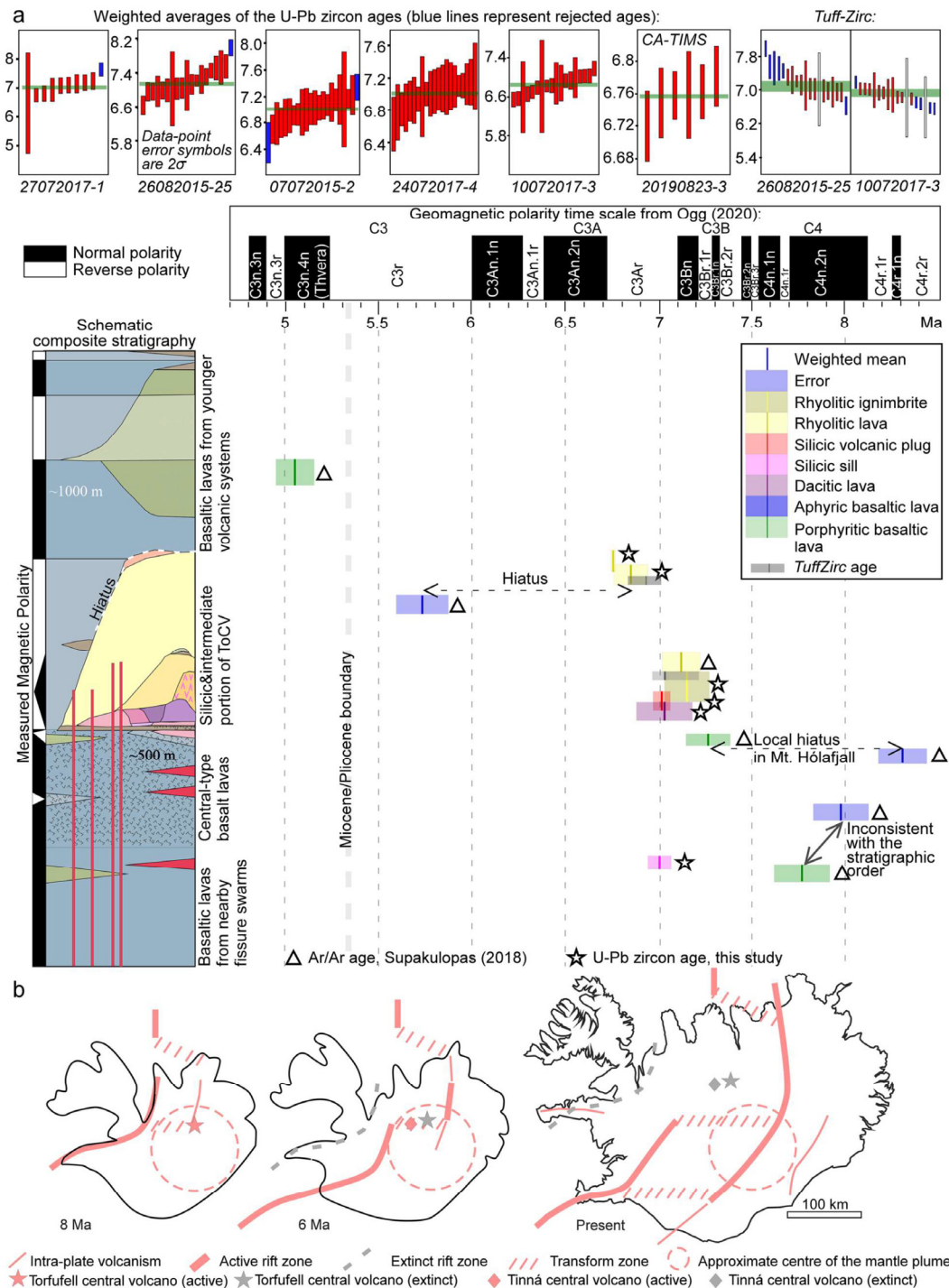


Figure 14. a) New U-Pb zircon ages, combined with Supakulopas' (2018) $^{40}\text{Ar}/^{39}\text{Ar}$ ages and coupling of the schematic, composite stratigraphic column with the geomagnetic polarity time scale. The schematic stratigraphic column (same color legend as in Fig.2) is based on original fieldwork, integrated with data by Kristjánsson et al. (2004) and Supakulopas (2018) from Mt. Hólafljall. The weighted average plots were made with Isoplot (Ludwig, 2012). TuffZirc age plots for the two high-MSWD samples are presented in the upper right corner (generated using the TuffZirc algorithm of Isoplot by Ludwig and Mundil, 2002; detailed in Fig.S3 of the Supplementary material). b) Schematic illustration of our new hypothesis; proposed to explain a discrepancy (younging towards west) in the ages of TiCV and ToCV.

4.4 Non-first author papers

1. Brogi, A., Israde, I., Árnadóttir, S., Capezzuoli, E. (2023). Tectonic control on travertine and silica sinter deposition in oceanic transform-fault setting: the case of the Lýsuskarð volcano-geothermal area, Snæfellsnes Peninsula, Iceland. *International Geology Review*. <https://doi.org/10.1080/00206814.2023.2180779>.

Role: Contribute to the manuscript, scientific input.

2. Hoffmann, H., Zimmermann, G., Huenges, E., Regenspurg, S., Aldaz, S., Milkereit, C., Heimann, S., Dahm, T., Zang, Grigoli, F., Karvounis, D., Broccardo, M., Wiemer, S., Hjörleifsdóttir, V., Kristjánsson, B.R., Hersir, G.P., Ásgeirsdóttir, R.S., Magnússon, R., Árnadóttir, Á. (2021). Soft stimulation treatment of geothermal well RV-43 to meet the growing heat demand of Reykjavík. *Geothermics*, 96, 102146.

Role: Process and analyze Acoustic Borehole Image (Televiewer) data.

3. Liotta, D., Brogi, A., Árnadóttir, Á., Ágústsson, K., Þorsteinsdóttir, U. (2021). Field evidence of the interplay between rift and transform structures in the Krafla geothermal area, N-Iceland. *Geothermics*, 91, 102039.

Role: Participate in fieldwork, contribute to the manuscript, scientific input.

4. Millet, J., Planke, S., Kästner, F. Blischke, A., Hersir, G.P., Halldórsdóttir, S., Flóvenz, Ó.G., Árnadóttir, Á., Helgadóttir, H.M., Vakulenko, S., Buryak, S., Erlendsson, Ö., Giese, R., Cavailhes, J.P., Jerram, D.A., Guðmundsson, Á., Júlíusson, E. (2020). Sub-surface geology and velocity structure of the Krafla high temperature geothermal field, Iceland: Integrated ditch cuttings, wireline and zero offset vertical seismic profile analysis. *Journal of Volcanology and Geothermal Research*, 391, 106342.

Role: Compile borehole data, scientific input.

5. Ziegler, M., Heidbach, O., Rajabi, M., Hersir, G.P., Ágústsson, K., Árnadóttir, S., Zang, A. (2016). The stress pattern of Iceland. *Tectonophysics*, 674, 101-113.

Role: Compile all available Televiewer data from Iceland, contribute to the manuscript, scientific input.

5 Conclusions

The present work involves a reconnaissance of the Late Miocene Torfufell central volcano and surroundings in Eyjafjarðardalur in central North Iceland, with field observations, geological mapping, paleomagnetic profiling, whole-rock and mineral chemistry and absolute age dating. A detailed geological map of the area is presented along with detailed descriptions of the strata pile and key geological formations in the study area. These observations are coupled with both previous age data and new high-quality U-Pb zircon age data to address the timing, longevity and geochronology of the volcano. Our results pertain to a key area in the evolving understanding of the development of crustal accretion in Iceland and underline the extensive room for additional high-quality radiometric dating on silicic activity in the central north region.

A semi-continuous series of basaltic to rhyolitic magmas was erupted from the Torfufell central volcano that deviates from lavas enveloping the volcano by higher TiO_2 , FeO_t , MnO , K_2O and P_2O_5 , lower Al and Ca, and higher Y, Co and Zr. A comparison with field observations concludes that a transition (shift) from thick (>5 m) grey lavas to unusually thin (<5 m) black $\bar{a}$ lavas defines the transition from predominantly fissure-fed basalts towards basalts sourced from the Torfufell magma system and thereby the base of the central volcano. Thus, eruptions producing series of thin basaltic $\bar{a}$ lavas characterized early phases of the volcanic construct while latter phases involved intermediate and silicic effusive and explosive volcanism, ceasing with a Plinian eruption. Subsequent erosion has provided a window into the shallow plumbing system of the volcano, enabling recognition of a central feeding zone for silicic products in northern Mt. Torfufell and fossil manifestations of silicic magma ascension through transgressive sills, sub-vertical dykes and sub-cylindrical conduits. Although a swarm of basaltic dykes intersects the lowermost part of the mapped strata pile, its affinity with the central volcano is unclear. The new set of geochemical data shows that the Torfufell central volcano features basalts that are high in Ti and Fe compared to typical products of the presently active mature rift zones of Iceland and rhyolites similar to rhyolites produced in the Mid Iceland Belt and by the east end of the South Iceland Seismic Zone.

Available age data indicate that the Torfufell central volcano was active from ~ 7.8 - 8.0 Ma to 6.76 ± 0.02 Ma, or for ~ 1 - 1.2 Myr, and that silicic magmatism and volcanism occurred during the last ~ 0.4 Myr of the volcano's life-span. The longest hiatus in the research area appears to be between the volcano's uppermost rhyolites and the younger, succeeding basalts, and although broadly contemporaneous with (but shorter than) the Flateyjarskagi unconformity, we propose that this hiatus represents a local break at the end of the volcano's active period. The new U-Pb age data demonstrate that the silicic portion of the Torfufell central volcano was formed nearly synchronously with a major rift relocation in North Iceland. After its extinction, the Torfufell central volcano was buried beneath younger formations making up the lava succession above the hiatus. We propose that these younger lavas originated from the large, neighbouring 5-6 Ma Tinná central volcano in the west as

well as from the newly formed NVZ in the east. The new age data demonstrate that while the Torfufell central volcano shows strong geochemical similarities with the Tinná central volcano, their rhyolites do not appear to be geographically connected. Moreover, the new age data have refuted a previous hypothesis of a relation between these two volcanoes. The project's results do not comply with the general geo-tectonic framework of Iceland that has been presented hitherto (e.g., Sæmundsson, 1979; Einarsson, 2008), as the two neighbouring Torfufell and Tinná central volcanoes show an enigmatic age difference and age progression that conflicts with concepts of straightforward spreading. Therefore, we propose a new hypothesis, awaiting critical testing, that these two volcanoes were formed at a leaky transform zone that developed to accommodate the rift relocation, with the Torfufell central volcano formed at its junction with the embryonic rift zone, thus marking the initiation of the presently active rift in North Iceland. Since then, the two volcanoes have drifted away from the rift system due to plate spreading and migration of the plate boundary relative to the Iceland mantle plume.

5.1 Future work

As previously cited, many conclusions made from geological fieldwork are predicated on inferences and moreover, it would be impossible to produce a geological map that is on no account an interpretation of the geologist. This is absolutely applicable to the present case, not least because even with several fieldwork seasons (mainly during the summers of 2015-2018, with some additional work in 2019-2021) and application of various analytical methods, this study represents only the very beginning of investigations in the Torfufell central volcano's area. Therefore, we emphasize the remaining extensive room for further investigations and data collection in the area, as for improvements and reconstructions on the geological map. Moreover, we highlight that with its numerous spectacular phenomena, including excellent cross-sections of exposed silicic intrusions and conduit systems, the Torfufell central volcano awaits more detailed research, alternative viewpoints and future discoveries.

The new hypothesis presented in this thesis, that the Torfufell and Tinná central volcanoes were formed at a leaky transform zone (a proto-MIB) that developed to accommodate the 6-7 Ma rift relocation in N-Iceland, awaits critical testing. This will optimally involve extensive structural mapping along the hypothesized proto-MIB, to seek evidence of potential transform-related structures, that may be compared with future collection of isotopic data from zircon crystals and whole rocks of the Torfufell and Tinná central volcanoes and may be indicators of petrogenetic environments for silicic magmas at these volcanoes (see Carley et al., 2020). We emphasize the necessity of additional precise age determinations of the remaining undated silicic centers in the central north region of Iceland to enhance the constraints of the timing and nature of shifting of volcanic activity and rifting from the SHRZ to the NVZ and provide a better understanding of the history of Iceland's rift relocations. So, to obtain more robust geometric relationships in the region, we consider age dating of the rhyolites of Flókadalur, Öxnadalur and Bleiksmýrardalur central volcanoes to be essential. Dating of additional samples from the Tinná central volcano and the two adjacent volcanoes in the Flateyjarskagi peninsula that can confidently confirm their ages would furthermore strengthen the dataset, and a closer look at the Víðidalur central volcano would be of particular interest as recent U-Pb zircon ages (6.3-7.3 Ma; Carley et al., 2020) document silicic magmatism at the SHRZ concurrently with silicic activity at the ToCV.

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Appendix A: Manuscripts

A1 Paper I: Evolution of the Late-Miocene Torfufell central volcano, N-Iceland

Evolution of the Late-Miocene Torfufell central volcano, N-Iceland

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Key Points:

- The first detailed geological research on the Torfufell central volcano in Eyjafjarðardalur, N-Iceland, is presented.
- Volcanism at the volcano commenced with basaltic eruptions while latter stages were typified with a broader compositional range.
- Silicic volcanism spanned approximately 400.000 years and was characterized by effusive lava dome-forming eruptions, accompanied by explosive activity.

Abstract

Excavated Miocene central volcanoes in Iceland often provide excellent windows into fossilized volcanic interiors and thereby opportunities to recreate the histories of ancient systems. Several of these volcanoes, particularly in central North Iceland, have not received proper attention, thus lacking detailed mapping and radiometric dating. Here, we provide the first detailed geological map of the Late Miocene Torfufell central volcano and the surrounding area in central North Iceland and descriptions of key geological features, integrated with new and previous age data. Our observations indicate that the edifice construction commenced at ~7.8-8.0 Ma, with the early stages featuring series of basaltic *ā* lavas, while latter stages were typified by a broader compositional range, including intermediate and silicic products. These two sequences are separated in several outcrops by a peculiar tephra-rich fossil- and smectite-bearing sediment horizon. Silicic volcanism, commencing at approximately 7.12 Ma and spanning ~400.000-years, was both effusive and explosive and formed a complex in the central zone of the volcanic area. Shallow silicic intrusions are abundantly exposed, with a cluster of anisotropically striking dykes interpreted as an indication of a central feeding zone. Basaltic lavas were formed concurrently with the rhyolites and continued to flow alongside the volcanic edifice after the end of silicic activity, eventually burying the highest rhyolitic peaks.

Plain Language Summary

Rivers and glaciers have dissected the ancient Torfufell central volcano in North Iceland and exposed internal structures of the volcano. The paper presents the first detailed geological map of the volcano and descriptions of key geological features. The results demonstrate that the base of the volcano is characterized by thin basaltic *ā* lavas while the upper part is typified by rhyolitic products. A peculiar sediment horizon separates these two sequences in several locations.

1 Introduction

Iceland is situated where the Mid-Atlantic Ridge and the Iceland mantle plume coincide and is constructed by the interaction of these two systems (e.g., Schilling, 1973; Vink, 1984; Lawver and Müller, 1994; Wolfe et al., 1997; Allen et al., 2002; Bjarnason, 2008; Guðmundsson 2000; Jacoby and Guðmundsson 2007; Brandsdóttir and Menke, 2008). Volcanism in Iceland occurs along both rift and off-rift (intra-plate) segments, typically referred to as volcanic zones. Each volcanic zone is defined by several volcanic systems (e.g., Walker, 1958; 1963; 1975; Sæmundsson, 1978; 1979; Tryggvason, 1973; Pálmason and Sæmundsson, 1974; Jakobsson et al., 1978; 2008; Jakobsson, 1979), characterized by a fissure swarm that trends subparallel to the respective volcanic zone and/or a central (composite) volcano. 30 active volcanic systems are identified onshore by Jóhannesson and Sæmundsson (1998; see also Thordarson and Höskuldsson, 2008), nine of which lack a distinct fissure swarm, while six are lacking a central volcano. While basaltic lavas erupt along the whole volcanic system, evolved magmatism is particularly associated with the presence of central volcanoes and considered as a strong indicator of a shallow crustal magma chamber. This is reflected by a low ratio of exposed silicic and intermediate products in Iceland in comparison with the volumetrically dominating basaltic lavas (exposed silicic and intermediate products have been estimated from around 15% to less than 10% (Walker, 1966; Thorarinnsson, 1967; Jakobsson, 1972; Sæmundsson, 1979; Jóhannesson and Sæmundsson, 1998; Jónasson, 2007; Jakobsson et al., 2008) while Thordarson and Höskuldsson (2008) showed that 3% of the total post-glacial eruptive magma volume are silicic and 6% are intermediate).

Adjacent to the active rift systems, including their sub-glacial eruption products of the Pleistocene, are successions of Neogene basalt lavas, generally emplaced onto low angle terrains. More than 50 Neogene central volcanoes are preserved as entities within these successions (Hjartarson and Sæmundsson, 2014), contrasting the uniformity of the basaltic lava piles with diverse rock types, paleotopographies and complexities. These ancient volcanoes are often associated with dyke swarms which are considered as subsurface indications of fossil fissure swarms. The Neogene successions were heavily eroded by the Pleistocene glaciations and the resulting deep fjords and valleys provide natural cross-sections through the lava piles and windows into the interiors of ancient volcanic systems. Commencing with Walker's (1963; 1964; 1966) pioneering work, mapping of Iceland's Neogene central volcanoes has resulted in valuable insights into the internal structure and plumbing systems of volcanoes along with improved understanding of silicic magma genesis, evolution of volcanic systems and crustal accretion processes in Iceland, and has in addition contributed to enhanced control of geothermal fluid pathways in deep roots of geothermal systems (e.g., Gibson, 1963; Carmichael, 1964; 1967; Blake, 1964; 1966; 1970; Hald et al., 1971; Franzson, 1972; 1978; Jóhannesson, 1975; Sigurðsson, 1970; Friðleifsson, 1983; Gautneb et al., 1989; Gústafsson et al., 1989; Jónasson et al., 1992; Furman et al., 1992; Gústafsson, 1992; Geirsson, 1993; Hjartarson, 2003; 2005; Klausen, 2004; Martin et al., 2011; Burchardt et al., 2011; Vogler, 2014; Berg, 2016; Carley et al., 2017; Askew, 2020; Askew et al., 2020; Liotta et al., 2020). Still, several of Iceland's fossilized volcanoes remain unexplored and undated, leaving extensive room for future discoveries.

The aim of the present work is to investigate the previously uncharted Torfufell central volcano as a contribution to field observations, volcano geology and geological mapping of the Miocene bedrock and central volcanoes in central North Iceland. With the purpose of characterizing the main structure, architecture and evolution of this volcanic construct, we provide a detailed geological map of the volcano and its surroundings (at a 1:25.000 scale) and descriptions of the lithostratigraphic units and tectonics in the study area. This is coupled with age data and geochemical campaigns (detailed separately) to understand the volcano's chronology and evolution.

2 Geological background

2.1 Regional setting

The region surrounding the Eyjafjörður fjord and valley is composed of sequences of Neogene semi-horizontal subaerially erupted basalt lavas (e.g., Sæmundsson et al., 1980; Jancin et al., 1985; Jóhannesson and Sæmundsson, 1998; Kristjánsson et al., 2004) which are commonly interbedded with layers of lithified sediments, typically distinctively red and consisting largely of weathered, wind-blown tephra mixed with ancient soils (Sæmundsson, 1979; Sæmundsson et al., 1980; Roaldset, 1983). As the originally sub-horizontal lava pile now tilts regionally a few degrees toward southerly directions (e.g., Sæmundsson et al., 1980; Hjartarson and Jónsdóttir, 1999; Axelsson et al., 2006), the oldest lavas (11-12 Ma; Sæmundsson et al., 1980; Jancin et al., 1985) occur near the fjord's mouth while strata from Early Pleistocene is observed by the southernmost valley head (2.6 Ma; Jóhannesson and Sæmundsson, 1998; Hjartarson and Sæmundsson, 2014; Supakulopas, 2018). The fjord is bordered to the east by the mountainous Flateyjarskagi peninsula and the conspicuously high mountain range of the Tröllaskagi peninsula to the west (Fig.A1.1). Several ancient central volcanoes are recognized in the region, including the volcanoes of Flókadalur and Öxnadalur along the Tröllaskagi peninsula, Torfufell by the peninsula's southern end – in the southernmost part of the Eyjafjarðardalur valley – and Flateyjardalur and Náttfararvík on the Flateyjarskagi peninsula. Only ~15 km west of the Torfufell volcano is the 5-6 Ma (Hjartarson, 2003; 2005) Tinná central volcano, described by some authors as potentially related to the rhyolite in Mt. Torfufell and thereby of similar age (Harðarson and Guðmundsson, 1986; Hjartarson et al., 1997; Hjartarson, 2003; 2005).

A ~N-S trending flexure in lava dips, observed along the southern part of the Flateyjarskagi peninsula, defines an angular unconformity and a ~4 m.y. hiatus (Fig. A1.1), interpreted to reflect an eastward shift of the spreading centre from the northern segment of the now extinct Snæfellsnes-Húnaflói volcanic zone to its current position in north Iceland, classically quoted to have occurred at ~6-7 Ma (Aronson and Sæmundsson, 1975; Sæmundsson, 1979; Sæmundsson et al., 1980). A gentle anticline (or half-dome), with lavas dipping towards south and southeast along its eastern flank and towards southwesterly directions on the western flank, plunges along the Tröllaskagi peninsula, trending SSW from Dalvík (Einarsson, 1960; 1965; Sæmundsson, 1974; Aronson and Sæmundsson, 1975; Jóhannesson, 1991). This arrangement is also interpreted as evidence for a rift relocation, potentially during a transitional stage in which the two subparallel axes coexisted in northern Iceland (Sæmundsson, 1974; Aronson and Sæmundsson, 1975), with the lava pile progressively sagging due to the weight of voluminous lavas erupting at two different central zones. The transcurrent Tjörnes fracture zone north of Iceland results from the eastward shift of the spreading axis and affects the northernmost parts of the Flateyjarskagi and Tröllaskagi peninsulas (Fig. A1.1).

During the Neogene, erosion was dominated by streams and rivers that cut ravines and valleys into the lava succession. Carving of large valleys and fjords was finalized by the greatly intensified erosion of the Pleistocene, during which numerous ice sheet pathways dissected the Tröllaskagi peninsula, with large valleys often trending NE-SW and WNW-ESE and the bordering major fjords trending NNW-SSE. Mountain tops in the southern Tröllaskagi peninsula are fairly flat and at similar altitude and therefore considered to represent remnants of an ancient plateau. It has been estimated that no more than 100-200 m have been eroded from these mountain tops (e.g., Jóhannesson, 1991; Hjartarson, 2003).

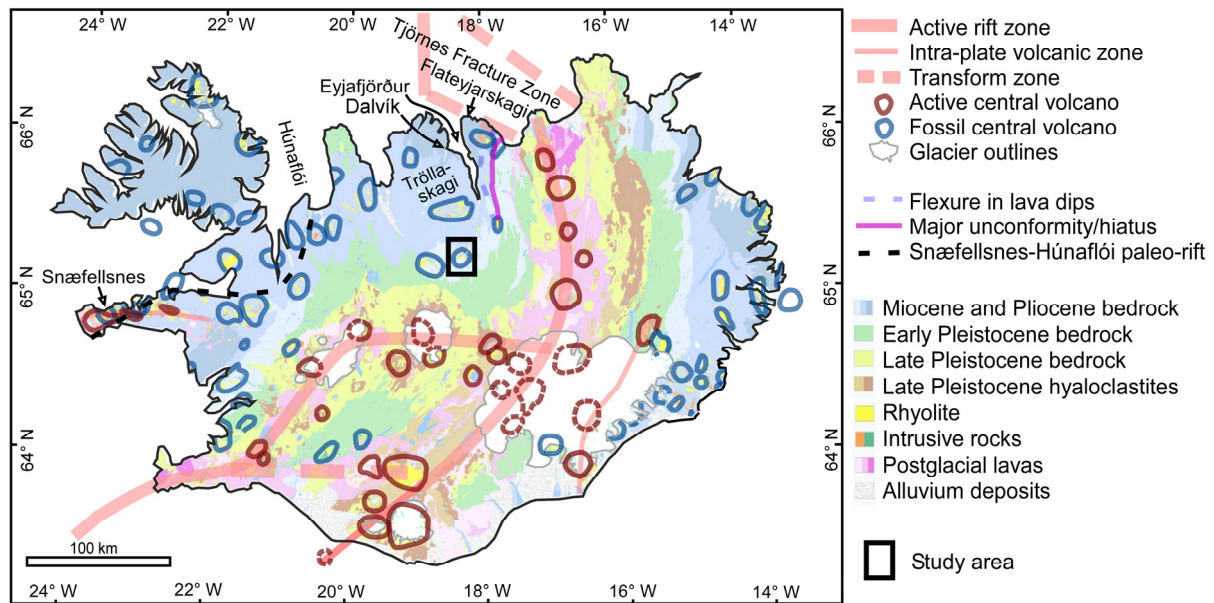


Figure A1.1. Generalized geology map of Iceland (modified from Hjartarson & Sæmundsson, 2014; Franzson et al., 2016), highlighting active and fossil central volcanoes and the presently active volcanic zones, with the study area indicated. Locations of the Snæfellsnes-Húnaflói paleorift, flexure and unconformity are from Sæmundsson (1979), Jóhannesson (1980) and Jancin et al. (1985).

2.2. Study area

The study area (Fig.A1.1) is approximately 40 km south of the largest town in North Iceland, Akureyri, extending from Mt. Hleiðargarðsfjall and Núpá river in the north to Hafrá canyon and Mt. Selfjall in the south and covering around 270 km². The area is dissected from north to south by the main glacial valley, Eyjafjarðardalur, from which several tributary valleys run, including the NE-SW trending Torfufellsdalur (Villingadalur) valley and the ~E-W trending remote Svarfdalur valley. As lower valley-side slopes are generally vegetated and partly covered with scree, the best outcrops are usually found in ruts and gullies. Valley floors are overlain by alluvial deposits and partly by landslide material while upper mountain cliffs are more or less steep with exposed lavas often visible in aerial images. Large clusters of mounds in the centre of the area, termed as Leyningshólar, have been considered to be a massive rockslide, possibly partly glacial drift (Jónsson, 1976) and partly relict rock glaciers (Guðmundsson, 2010). Another massive landslide, that never has been mapped or described before, has collapsed from Mt. Torfufell's east side some thousand years ago. It has no name but here we suggest the name Hólsgerðishólar as the farm Hólsgerði is situated on the landslide material. It dammed the Eyjafjarðará river and formed a large lagoon. Later the river has eroded the landslide dam and drained the lagoon. Now the river is cascading in a gorge across the landslide. The most recent landslides in the area occurred in the Sölvadalur and Torfufellsdalur valleys in 1995 (Pétursson, 1997) and 2011 (Sæmundsson et al., 2014), and in Mt. Hleiðargarðsfjall in 2020 (Brynjólfsson, 2021).

Two hot springs, Torfufellslaug and Hólsgerðislaug, are known in the vicinity of the central volcano; just north of the southernmost farm in the Eyjafjarðardalur valley, east of Mt. Torfufell. The temperature of these springs is approximately 40°C, with indications from chemical analysis of higher temperatures (>70°C) at deeper levels (Kristmannsdóttir and Johnsen, 1981; Flóvenz and Tómasson, 1992).

Mt. Torfufell is the highest summit of the inner Tröllaskagi highlands, 1244 m above sea level. It forms a topographic high rising about 100 m above the surrounding mountain tops. The Torfufell rhyolite was first delineated in Thoroddsen's geological map of Iceland (1901). Since then, the main features of the

bedrock geology of the study area have been illustrated in the small-scale geological maps of Iceland (Jóhannesson and Sæmundsson, 1998; 2009; Hjartarson and Sæmundsson, 2014) and of central Iceland (Kjartansson, 1965). Prior to the present project, Kristjánsson et al. (2004) carried out stratigraphic mapping and paleomagnetic studies in the Eyjafjörður region, with three of the measured stratigraphic and polarity profiles located within the research area (in Mt. Hólafjall) and one just north of it (in Kötlugjá), thus establishing an excellent base for the present study. The profiles in Mt. Hólafjall were remeasured by Supakulopas (2018), who also added two new profiles and age data.

3 Field data

We have produced a geological map of the Torfufell central volcano and surroundings at 1:25.000 scale. The map is based on original fieldwork and integrated with data from previous authors (above-mentioned stratigraphic and polarity profiles from Kristjánsson et al., 2004 and Supakulopas, 2018, faults/dykes from magnetic surveys by Flóvenz and Tómasson, 1992, and landslide outlines partly taken from Pétursson, 1997). The main fieldwork phase (2015-2018) consisted in measurements of 28 new stratigraphic and paleomagnetic profiles; mainly in accessible outcrops in ruts and gullies. These localities (Fig. S1.19 of the supporting information) represent the field data from which the map was manually drawn (in ArcMap), using aerial images when possible. The fieldwork included conventional methods necessary for geological mapping by use of appropriate equipment such as handheld GPS, compass, clinometer for the dip, geological hammer and magnifying glass, in addition to a tablet computer with the Collector software for ArcGIS. To enable mapping of basaltic lavas, we slightly modified the terminology of Walker's (1958) traditional classification system, as we demarcated basaltic lavas as aphyric basalt (including sparsely phyric basalts), olivine basalt, plagioclase phyric and plagioclase- and olivine phyric basalt. The intermediate and silicic rocks are divided into basaltic andesite, andesite, dacite and rhyolite. To facilitate stratigraphic correlations, we measured the remanent polarity direction of each lava flow in the field with a portable fluxgate magnetometer. Such field measurements can be inaccurate, but to reduce the imprecision as much as possible, at least three samples from each lava flow were measured. In case of inconsistency and/or uncertainty, the lava was assigned an anomalous/uncertain polarity. Additionally, the fieldwork involved identification of amygdalites; measurements of lava flow thicknesses; measurements of strike and dip of strata; mapping of faults, fractures and dikes, hot and cold springs and fossil finding sites; and mapping of outlines of large landslides and landslide scarps. Fieldwork also involved systematic collection of rock samples for geochemical and petrographical analysis and radiometric age determinations, which are detailed separately and only presented briefly in the present paper to complement the field observations by certifying rock types, defining key map units and addressing the chronostratigraphy.

3.1. Lithostratigraphy

The geological map, with a cross section and a simplified composite stratigraphic profile reflecting the main findings of our mapping, is presented in Fig.A1.2 and in the Supplementary material (Figure S1.17). The composite profile is approximately 2000 m thick. As the strata dips towards SE, the lowermost and oldest lavas in the study area are observed in the northern part of the map (e.g., in Gilsárdalur valley and Núpá river). (1) These are basaltic lava flows, mostly aphyric to sparsely phyric but with series of porphyritic and olivine basalts sandwiched in. Typical thickness of these lavas is around 5-10 m and thin (<1 m) red sediments are commonly interbedded. (2) This lava stack is overlain by a 200-300 m thick pile of thin (individual layers typically <5 m) basaltic lavas, featuring a lavas of rather evolved composition (up to almost basaltic andesite composition) and pahoehoe lavas of more primitive composition (section 3.1.2.), with a few porphyritic lavas sandwiched in. The thin-layered basalt pile is intruded by silicic intrusions (dykes, sills and volcanic plugs). (3) On top of this pile in several locations is a notable sediment horizon, characterized by light-colored tephra, swelling clay and

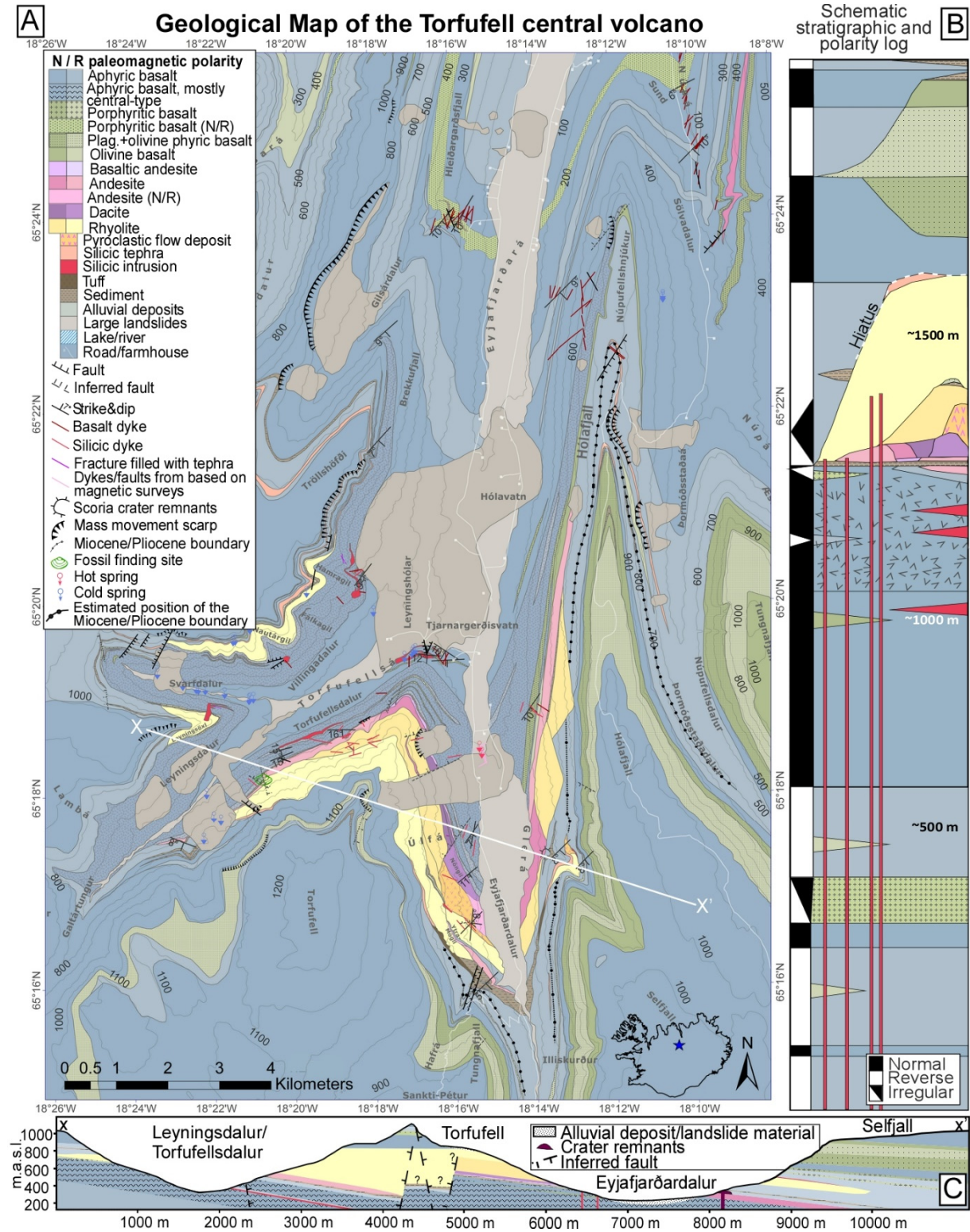


Figure A1.2. a) Geological map of the study area (see key for details). b) Simplified and schematic composite stratigraphic profile of the mapped strata, with measured magnetic polarities. c) Cross-section of the strata pile from Leyningsdalur (X) to Selfjall above the Glerá gully (X'). The map is provided in higher resolution in Fig.S1.17 of the supporting information.

fossilized wood (i.e., petrified wood where silica has replaced the original organic compounds). (4) Above the sediment horizon are intermediate to silicic lavas (basaltic andesite, andesite and dacite) which are overlain by rhyolite lavas. Different paleomagnetic polarities and sediments and basaltic to andesitic lavas separating the rhyolite lavas manifest that these are several formations, formed at different times. Evidence of at least three sub-cylindrical silicic eruptive vents is recorded and numerous silicic dykes are found intruding the rhyolite lavas. (5) Reverse polarity aphyric to sparsely phyrlic basaltic lavas adjoin the silicic complex. A localized thick (~60 m) stack of lake sediments, with interfingering reverse polarity basaltic lavas, borders upon the rhyolite complex in the southernmost part of the study area (observed in the Hafrá canyon). Rhyolitic formations recorded at stratigraphically higher levels than this sediment pile (i.e., a thin layer in the Hafrá canyon and a small patch in the Glerá gully) indicate that both the lake sediments and the lowermost part of the reverse polarity basaltic lavas were formed concurrently with the rhyolitic activity. (6) Two thick and widespread layers of silicic tephra are related to the uppermost part of the silicic formations. North of Hamragil some 150-200 m of basaltic lavas are between them. There the lower tephra layer is 10 m thick but becomes thinner and disappears 2-3 km farther north. The upper tephra layer is sandwiched between reverse polarity basalts and partly on top of the rhyolite in the western part of the study area. The maximum thickness of this layer is 23 m in the profile between Hamragil and Fálkagil. This layer can be traced from the Svarfdalur valley through the Villingadalur valley and Tröllshöfði cape, to the Strjúgsárdalur valley and perhaps even further and may be considered to represent the end of rhyolitic activity at the volcano. A distinct tephra layer observed at similar position in the strata pile in NW Mt. Hólafjall may correspond to the same eruption. (7) Reverse polarity aphyric basaltic lavas continued to flow alongside the complex after the end of silicic activity until the highest rhyolite peaks were eventually buried by normal polarity aphyric basaltic lavas. (8) These lavas are then overlain by up to ~300 m thick series of plagioclase- and olivine phyrlic basaltic lavas.

3.1.1 Early basaltic lavas

A series of dark-coloured (almost black) and thin-layered (individual layers typically <5 m as opposed to typical thickness of >5 m of underlying lavas), aphyric basaltic lavas of *ā'a* type is observed around 200-300 m below the base of the silicic/intermediate lava pile. Such unusually thin, phenocryst-free lava flows have been observed to be abundantly erupted from Icelandic central volcanoes (Sæmundsson, 1979), and a transition from thick (>5 m) grey lavas to thin (<5 m) black lavas, recognized in the Neogene Breiðdalur central volcano in Eastern Iceland, has been suggested to represent the transition from predominantly fissure-fed lavas towards central volcanism and thus the base of the volcano (Walker, 1963; Askew, 2020). Helgason (1983) similarly recognized by observations in Eastern Iceland that thin and scoraceous central facies lavas occur close to eruptive sites while thick distal facies lavas occur at distances exceeding ~10 km from volcanic centres. As slope is one of the factors that control lava thicknesses, such thinness of lavas belonging to central volcanoes may result from a rise in the paleotopography, suggesting that the lavas erupted onto sloping landscape (Walker, 1963; Askew, 2020). As such, we have a reason to speculate if these thin *ā'a* lavas in the Torfufell area are sourced from the central volcano, erupted during its early phases. This hypothesis is strongly supported by results from chemical analyses of five selected *ā'a* lavas (lavas no. 2-5 and 11 in Figures S1.1-S1.2 and Table S1.1 of the Supplementary material; samples 24072017-0 to -3 and 201809030-1) which manifest that the composition of these lavas is rather evolved and more evolved than underlying plateau basalts (~50-52 compared to ~48-49 wt% SiO₂; see Table S1.2 of the Supplementary material), indicating longer residence time of the magma in the shallow crust (and/or extended interaction between the rising magma in the crust), which may suggest the presence of an incipient magma storage system.

An excellent outcrop, exposing an ~80 m thick stack of well-preserved thin-layered basaltic lavas underlying rhyolite lava, is observed in the Nautárgil gully. The lower half of this stack comprises *ā* *ā* lavas, while the upper part is composed of lavas of pahoehoe type which are generally slightly thicker than the *ā* *ā* lavas. Our observations of this lava stack are described in Text S1.1, Fig.S1.1 and Table S1.1 of the Supplementary material. Examples of both lava types from this stack are presented in Fig.S1.2. A conspicuously thick (~40 m) pahoehoe lava lobe, observed in the Glerá gully, is also briefly described in Text S1.1 and Figs.S1.3-S1.4.

3.1.2. Sediments

Red sediment beds (Fig.A1.3a), representative of classic interbasaltic sediments within Iceland's Neogene pile, are recorded widely within the basaltic lava pile in the study area; typically siltstone beds from <1 m up to a few m in thickness. Occasional layers of sandstone, agglomerate and conglomerate are also found within the basaltic lava pile, often a few m thick. While thin siltstone beds are usually not confidently correlated between outcrops, the thickest sandstone layers may be traced up to ~5 km. Inside the rhyolite, we found red siltstone beds in several locations as evidence of separation between individual lavas, and a localized, ~15 m thick stack of sand- and siltstone beds in the Nóngil profile (Fig.A1.3b).

A peculiar sediment horizon (Fig.A1.3c and d) outcrops below the pile of silicic and intermediate lavas in several locations in Mt. Torfufell and is considered to extend to the Villingadalur valley. The horizon is thickest in the western side of Mt. Torfufell (~6-8 m) where it consists of at least 37 layers (detailed in Table S1.3 of the Supplementary material) which range in thickness from 1 cm to 46 cm and are mainly composed of variously coloured siltstone, often sandy, and variously coloured clay, often smeary and soggy and sometimes mixed with sand. Additionally, but less prominent, are light coloured tephra and shards of black volcanic glass. Fossils have been observed in one location in the western slopes of Mt. Torfufell, within scree originated from this sediment horizon. This location is in fact indicated in Kjartansson's (1965) geological map of central Iceland as a lignite locality. While his map indicates a second lignite locality in the Svarfdalur valley, our quest there for fossils was without success. Indeed, as recognized as early as 1839 (Hallgrímsson, 1989), the fossils observed in the western slopes of Mt. Torfufell should be classified as petrified wood rather than lignite as the organic materials making up cell walls have been replicated with minerals. Considering the position in the pile, this sediment horizon appears to represent a weak plane that may have contributed to some landslides in the area, including the occurrence of a large landslide in Torfufellsdalur in October 2011. Four key samples (Table S1.4 of the Supplementary material) from the sediment where it is thickest (i.e., in the western side of Mt. Torfufell) were analyzed in the present study via X-ray diffraction (XRD). The results indicated very consistently that only one type of clay exists in these samples, i.e., dioctahedral (Al-rich) smectite (Fig.S1.5 of the Supplementary material). As smectites are known to experience recurrent swelling and shrinking movements, depending on wet and dry seasons, this outcome supports the idea of the horizon forming instability in the stratigraphic pile.

A ~60 m thick stack of lake sediments is observed in the Hafrá canyon (Fig.A1.3a), characterized by black siltstone in the lower part and yellow-brownish laminated sandstone in the middle to upper part, while the uppermost ~10 m are more heterogeneous, consisting e.g., of volcanic breccia or conglomerate, red and yellowish siltstone and greenish sandstone (Fig.S1.6 of the Supplementary material). Thin layers of silicic tephra are found near the bottom and a thin layer of silicic tephra and rhyolite lava can be seen at the top of the sediment stack. Two thin reverse polarity basalt lavas are sandwiched within the lower half of the sediment pile. A large tillite formation, presumably formed during the Late Pleistocene, is observed unconformably filling up an abandoned gulch in the Hafrá canyon, later dissected by the present river.

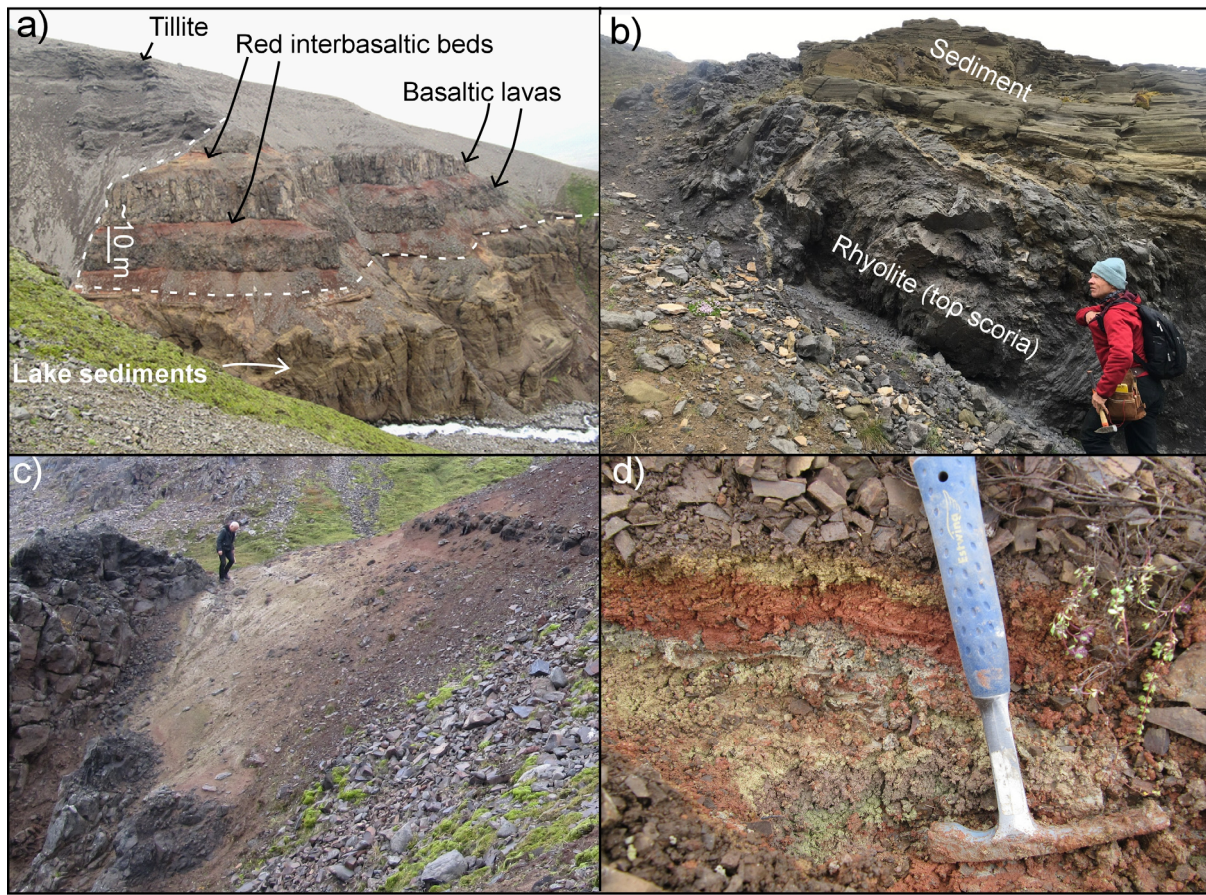


Figure A1.3. Sediments. a) The Hafrá lake sediments, overlain by basaltic lavas and typical red interbasaltic sediments. Pleistocene tillite unconformably fills up an abandoned river gully. b) Sand- and siltstone beds on top of a rhyolite lava in the Nóngil profile. c) Overview of the fossil-bearing sediment horizon (outcrop in the western slopes of Mt. Torfufell). d) Detail of the horizon (outcrop in northeast Mt. Torfufell). Locations of photographs presented in this paper are given in Figure S1.19 of the Supplementary materials.

3.2.3. Silicic and intermediate lavas

Above the thin basaltic lavas and the tephra-, smectite- and fossil-bearing sediment horizon in Mt. Torfufell are intermediate to silicic lavas, mainly andesites and dacites, with minor basaltic andesite. The andesites and dacites are typically around 30-60 m thick, very fine grained, dark grey and flow-banded (Fig.A1.4a and b). These lavas commonly comprise a glassy base (from a few cm up to ~2,5 m thick; Fig. A1.4b) and a reddish weathering coat, and the andesites typically feature a thick top scoria.

On top of the andesite and dacite lavas are extrusive rhyolites which are greatly intruded by silicic dykes and apophysis. As noted earlier, it is indicated by differences in magnetic polarities and by intercalation of sediments and basaltic to andesitic lavas, that several rhyolitic formations existed within the central volcano, formed at different times. Most of these formations are recognized as lava domes, typically constructed of a brecciated base (e.g., ~6-8 m thick; Fig. A1.4d), pitchstone or obsidian (e.g., ~3 m thick), and vesiculated and flow-banded stony (crystalline) rhyolite (Fig.A1.4c), sometimes with spherulitic arrangements. The effusive dome-forming eruptions were evidently accompanied by explosive volcanism, with rhyolitic ignimbrites in SE Mt. Torfufell representing good examples (section 3.2.4).



Figure A1.4. Examples of intermediate and silicic lavas. a) Andesite lava on the NW side of Mt. Torfufell (photographed ~300 m SW of the Torfufellsá profile). b) Dacite lava on the eastern side of Mt. Torfufell (photographed at the Úlfá profile). c) Rhyolite lava in the slopes of the Villingadalur valley (photographed at the Fálkagil profile). d) Breccia at the base of a rhyolite lava at Leyningsöxl (photographed at the Leyningsdalur profile).

3.2.4. *Pyroclastic flows*

While ignimbrites are recorded in several outcrops in SE Mt. Torfufell, the best outcrop was observed in the Ytra-Mógil gully, with ~15 m of good continuity, although the base of the ignimbrite was not observed to crop out and the upper part of the formation is rather poorly exposed. Text S1.2 and Fig.S1.7a of the supplementary material, which are based on our observations in this location, describe the ignimbrite in general as a densely welded flow-banded rhyolitic ignimbrite, composed of aphanitic groundmass tephra with lithics, phenocrysts and pumice lapilli, compacted in the lower part while vesicles become larger and less flattened in the uppermost layers.

Exposed in the middle of the gully of the Glerá river is a ~6.5 m thick formation, assumed as a block-and-ash flow deposition (BAF) resulted from collapse of a growing rhyolitic lava dome, either by

gravitational failure or an explosive disruption (described in Text S1.2 and Fig.S1.7b). The deposition is observed adjacent to a small patch of stony rhyolite, assumed as an edge of a larger lava dome which, according to its position in the strata pile, formed during later stages of silicic volcanism and overlies some of the reverse polarity basaltic lavas that adjoin older rhyolite domes. On top of the BAF deposition, with around 3 m scree between, lies a lahar deposit (also described in Text S1.2 and Fig. S1.7b) which indicates remobilization of the BAF material by water (possibly rainwater).

3.2. Intrusions

3.2.1. Basaltic dykes

We have measured approximately 50 basaltic dykes within the study area. Although recorded throughout the area, the vast majority of these dykes is located in the northern part, ca. 5-10 km north of the silicic complex, where they are observed cutting through the lower part of the mapped strata pile. It is not clear if these dykes belong to the fissure swarm of the Torfufell volcanic system or not. The basaltic dykes generally trend in the range from ~N-S to NE-SW, with NNE-SSW as the most common strike. Many of the recorded basaltic dykes are irregularly shaped or winding, as they change their dip and dip direction repeatedly in a single outcrop, while dykes that have a clear dip most commonly dip ~10° from vertical towards westerly directions. Thickness of the basaltic dykes is typically around 1-5 m although the thicknesses range from around 0.5 m up to 15-20 m. Several basaltic dykes show strikes that vary from the regional trend, e.g., NW-SE/WNW-ESE to approximately E-W. The majority of these anomalously striking dykes are situated within the silicic complex, where they are observed cutting through basaltic lavas just below the rhyolite, sometimes adjacent to silicic sills and volcanic plugs. A clear cross-cutting relationship by the Einbúi silicic plug (see section 3.2.3) shows that a sub-cylindrical feeder conduit cuts through an older, WNW-ESE striking basaltic dyke, suggesting that such abnormal trends of magma pathways may have existed prior to eruption of silicic products.

A cross-cutting relationship between two basaltic dykes is observed in the NW slopes of Mt. Hólafjall, ca. 5 km north of the rhyolite lavas, where a massive (at least 10 m thick), NNW-SSE striking dyke (named the Vothamrar dyke) cuts through a seemingly older NE-SW striking dyke. The younger, NNW-SSE striking dyke is porphyritic with macrocrysts (up to 40%) concentrated at the centre while diluting near the margin. Macrocrysts consist of both plagioclase and olivine. As such, the dyke could be considered likely to be the feeder to some of the plagioclase- and olivine phyric lavas by the top of the mapped strata pile and thereby younger than the Torfufell central volcano. However, comparison of the geochemistry of the dyke (sample 25072018-1 in Table S1.2 of the Supplementary material) with a sample from this series (sample 18072017-1) does not support this hypothesis. The composition correlates on the other hand nicely with a porphyritic lava flow lying below the olivine basalt group (sample 10072017-4). Although only plagioclase macrocrysts and no olivine macrocrysts were observed in the sample collected from this flow, it is considered quite likely that the NNW-SSE striking dyke is a feeder for this lava flow. In map view, the NNW-SSE striking (feeder) dyke appears to be arranged into en échelon right-stepping segments.

3.2.2. Silicic dykes

Approximately 30 silicic dykes (examples in Fig.A1.5) are recorded in the study area, exclusively in the southern part, within the central volcano itself, where they are observed cutting the rhyolite lavas as well as the underlying basaltic lavas. The silicic dykes range in thickness from a few cm to ~6 m and the margins are typically chilled and glassy. Strikes are quite various, although ~E-W strikes are most common (ranging from ENE-WSW to ESE-WNW). Fig.A1.5a and c show a glassy margin of a ~6 m thick silicic dyke, intruded into a rhyolite lava in NW Mt. Torfufell. The thickness of the glassy margin ranges

from 60 to 180 cm and it is separated from the hosting rhyolite by a ~1-2 cm thick zone of fine contact breccia containing some mm to cm sized clasts from the glassy margin. The dip of this dyke changes from ~30° from vertical to approximately vertical in a single outcrop, over only a 10 m interval. Indeed, the mapped silicic dykes in the study area are often winding (Fig.A1.5c) but apparently vertical overall or dipping in the range ~10-20° from vertical. Only one dyke (situated in NW Mt. Torfufell) was observed as decisively inclined (i.e., ~65° from vertical towards north; Fig.A1.5b). Where dyke dips are clear and measurable, dip directions are various and apparently without a decisive order. Thin, (e.g., ca. 1-2 m) winding apophyses are common in NW Mt. Torfufell (Fig.A1.5d and e). Maximum intensity of silicic dykes is recorded in the northern part of Mt. Torfufell which we interpret as an indication of a central feeding zone. Although not observed continuously or decisively, orientations of the observed silicic dyke segments, especially in NW Mt. Torfufell and the nearest surroundings, may potentially belong to arcuate alignments implying a centre NW of Mt. Torfufell. Several fractures filled with light-colored tephra have been recorded. These fractures primarily strike ESE-WNW and dip towards north. Some of the tephra-filled fractures are situated adjacent to and radiating from a volcanic conduit (discussed below).



Figure A1.5. Examples taken in the zone of maximum intensity of silicic dykes. a) Fine-grained contact breccia (pinkish) at the contact between a glassy (black) margin of a silicic dyke and the adjacent rhyolite. b) Inclined sheet (silver grey), assumed as dacitic. c) 60-180 cm thick glassy margin (black; same as in a) of a silicic dyke, winding from 0° to 30° from vertical in a ca. 10 m outcrop. d) and e) Winding, glassy apophyses (bluish grey, ca. 1-2 m thick; upper boundaries traced with dotted line); the apophyses in e) has caused oxidation in the immediate adjacent rock.

3.2.3. Silicic sills

While dykes appear to be the main magma pathways, it is also evident that silicic magma travelled along weak interfaces such as sedimentary beds between pre-existing basaltic lavas to form subhorizontal sills. Sills are recorded in several locations at ~100-300 m below the base of the silicic and intermediate lava pile, while one sill is observed above a small patch of rhyolite lava (in the Glerá gully). The sills range in thickness from 1 to 36 m and feature glassy margins. A magnificent sill outcrop is observed at the southern bank of the Torfufellsá river's canyon which allows examination of magma pathways through a stack of basaltic lavas (Figs.A1.6-A1.7), with outcropping silicic sills visible on three concurrent levels. The sills feature narrowly (approximately 10-15 cm) spaced columnar jointing (Fig.A1.6c) and glassy margins (ca. 0.5-2 m thick) that gradually turn into finely crystalline interior. The crystalline interior (Fig.A1.6e) is light-grey and aphanitic with sparse feldspar and plagioclase phenocrysts (with zircon inclusions). Some of these features (e.g., the narrowly spaced columnar jointing, glassy margins, aphanitic interiors) are indicators of rather fast cooling, which again suggests emplacement at shallow level. Flow texture is visible at the transition between the glassy margin and the crystalline rock (Fig.A1.6d), while no flow textures are observed in the crystalline core.

We have recorded three NNW and NNE striking mineralized faults within a 90 m interval at the northern bank of the Torfufellsá river. Although the intersection of these faults on the southern riverbank (fault intersection in Fig.A1.6b) is covered with scree, it appears that the adjacent lowermost sill bottom dips towards it, which may indicate that the intruding silicic magma did ascend from this intersection into a lithological boundary, i.e. between two pre-existing basaltic lavas, along a red sedimentary bed towards east. After having propagated horizontally along this boundary for approximately 40 m, the sill climbs discordantly through the stratigraphy as a gently inclined section (Fig.A1.7) for another ~40 m. To the west, the silicic magma passes sub-vertically from one level to another as a dyke-like segment, apparently using secondary fractures related to the intersection of the faults (Fig.A1.7b). The lower part of this subvertical dyke forms a branch that appears as an abandoned lateral propagation towards west (Fig.A1.7b). From the dyke itself, the silicic magma intruded between two basaltic lavas towards west, again using the weakness of a red sedimentary bed, at a slightly higher level than east of the dyke. After having propagated along this sedimentary bed approximately 150 meters towards west, this sill transgresses through at least one lava before disappearing into scree (A1.7c). An upper silicic sill is then observed approximately 10 m (one lava) higher west of the dyke and ca. 30 m (four lavas) higher east of the dyke. The western part of this upper sill dips towards the fault intersection and appears to transgress through the upper part of the underlying lava. Although the upper and the lower sills appear to be connected through the dyke, a more detailed study would be required to conclude whether they were formed in the same or separate emplacement events.

Subhorizontal slicken-sides are observed on fault surfaces related to the abovementioned NNW-SSE and NNE-SSW striking faults (Fig.A1.8), which may suggest minor lateral movement of crustal blocks. While the significance of these traces remains to be explored in detail, preferably coupled with additional and more extensive indications, it may be casually speculated if they were formed due to minor lateral movements induced to accommodate the intruding magma, or, alternatively, if they may potentially suggest an embryonic strike-slip system. By the westernmost fault (NNW-SSE striking), a chilled margin of a silicic intrusion is observed against a fault surface in porphyritic basalt (Fig.A1.7d and e), testifying that at least one of these faults was a pathway for the intruding magma. The intrusion contact at this location features a ~20-30 cm thick pitchstone which is altered and crumbled next to the immediate contact with the adjacent rock (Fig.A1.7d and e). Against the pitchstone, the porphyritic basalt is brown in colour and decayed by heat generated from the intrusion, thus presenting a ~5-10 cm thick contact aureole.

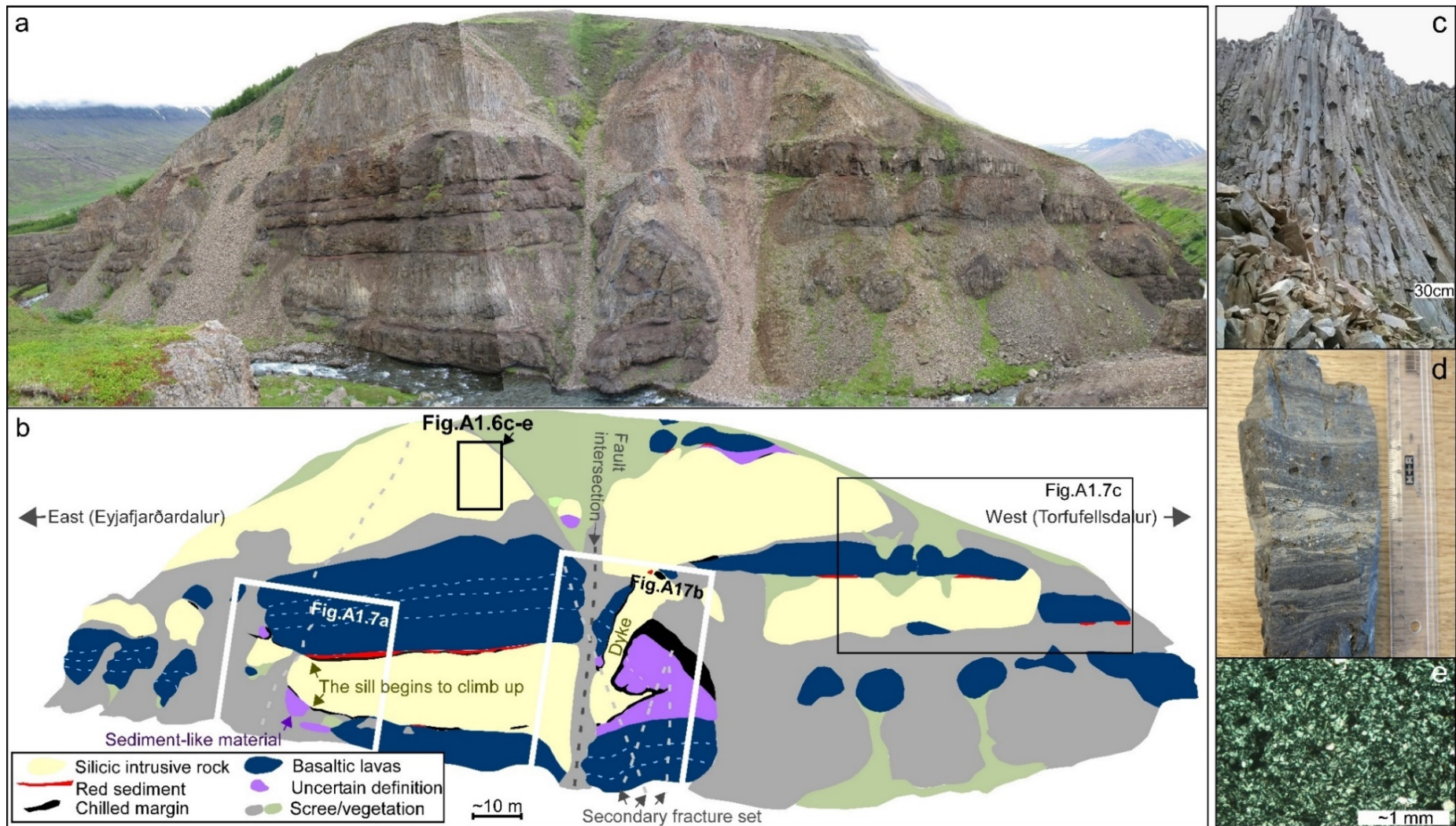


Figure A1.6. Silicic sill intrusions in the Torfufellsá river canyon. a) View of the outcrop at the southern riverbank (composite photos). b) Illustration of the outcrop. c) Columnar jointing. d) A sample showing the transition from the glassy margin towards the crystalline interior. d) A micrograph showing the finely crystalline interior of the sill.

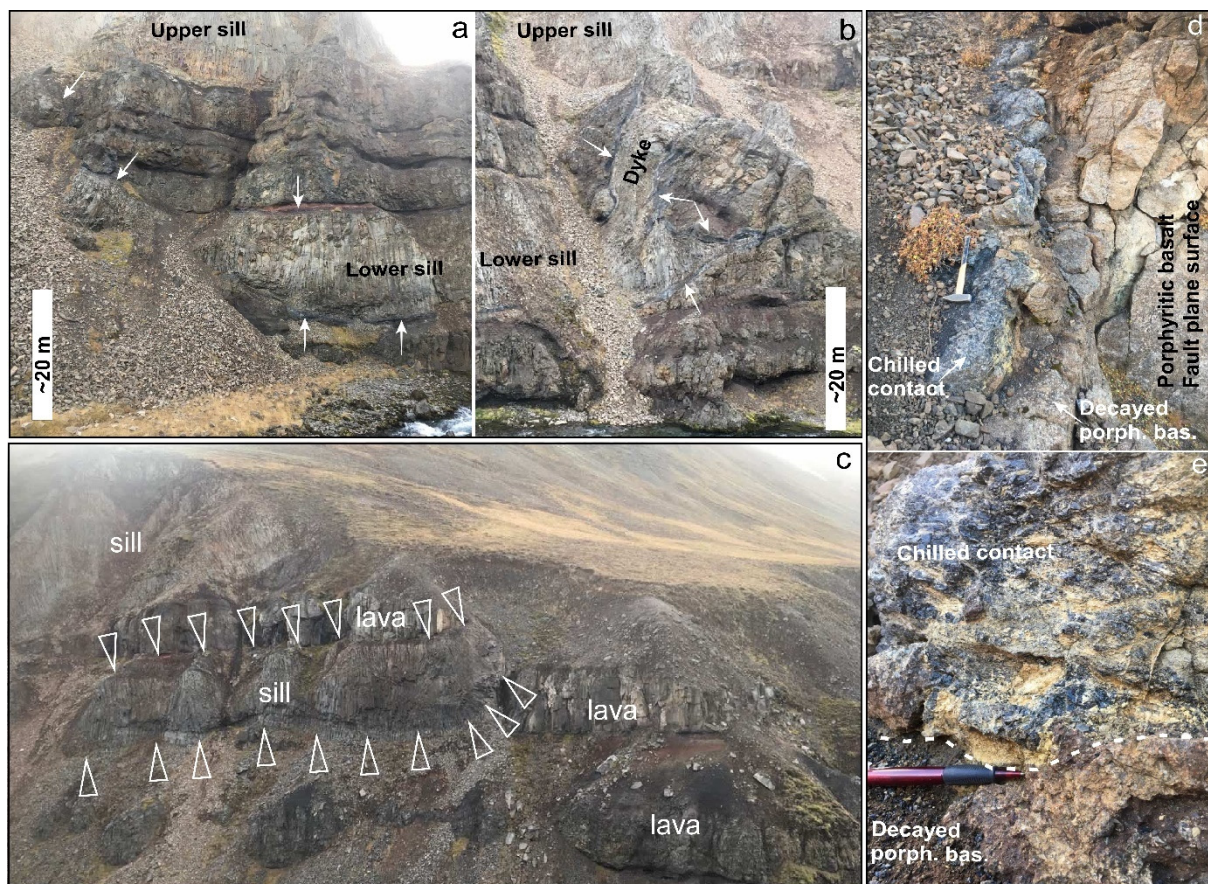


Figure A1.7. Silicic intrusions in the canyon of the Torfufellsá river. a) and b) Details of the intrusion on the southern riverbank (chilled contact indicated with arrows). a) Lower sill starts to climb up, apparently crossing the basaltic lavas, with gentle inclination. b) Close-up of the dyke part of the intrusion and the abandoned branch. c) Magma intrudes from the dyke part of the intrusion towards west, propagates along a red sedimentary bed and then disappears into scree. d) and e) Intrusion contact on the northern riverbank, against a fault surface. d) The immediate contact (indicated by dotted line) of the chilled intrusion and the brown-colored and decayed porphyritic basalt.



Figure A1.8. Subhorizontal inferred slicken-sides and striations on fault planes related to the three faults observed on the northern bank of the Torfufellsá river. a) Inferred slicken-sides with constant orientation on a fault surface (westernmost fault) adjacent to the chilled intrusion contact shown in Fig.A1.7c and d. b) Subhorizontal inferred slicken-sides on a fault plane of a NNW striking fault (middle fault). c) Striations on a fault plane related to the easternmost fault (NNE striking).

3.2.4. Conduits and craters

Three silicic sub-cylindrical intrusions, interpreted as solidified plugs of feeder conduits, are recorded in the basalt lava pile just below the rhyolite lavas. The three plugs are aligned in a NE-SW strike with ca. 1600-1700 m intervals between each conduit. They are rather similarly constructed, with breccia composed of white fine-grained groundmass with fragments from the adjacent basaltic rock at the outermost contact and an intermediate layer of pitchstone that turns into crystalline rock towards the centre. Next to two of the conduits are silicic sills and multiple pockets and veins filled with light-coloured breccia and/or tephra. A fourth eruptive site is confirmed by the remnants of a scoria crater in Glerá, at the bottom of the pile of reverse polarity basalt lavas that abut against the rhyolitic domes. Potential crater remnants are furthermore observed in the Hamragil profile (ca. 450 m.y.s.), approximately colinear to the NE-SW trend of the three conduits.

3.2.4.1. Volcanic plug in Svarfdalur

The glacier that carved out the remote Svarfdalur valley has exposed a magnificent section through the uppermost part of a feeder conduit and a volcanic plug or neck, via the adjacent pile of basaltic lavas and up to the rhyolitic lava dome it fed (Fig.A1.9). A cross-section like this is very notable and rarely seen in Iceland. The volcanic neck is ca. 90 m in diameter and is exposed vertically over approximately 300 m. Within ~150 meters, the adjacent basaltic lavas dip towards the plug. Our field observations conclude that the conduit is constructed in the following way. Next to the country rock is ca. 10 m thick breccia (Fig.A1.9b-c) which is composed of white fine-grained groundmass with large angular fragments from the adjacent basaltic rock (up to 1.4 m in diameter over the major axis). Inside the breccia is ca. 4 m thick wall of black rather intact pitchstone (Fig. A1.9b and d) containing light-coloured phenocrysts that strikes ~N-S (and tilts ca. 20° from vertical towards west) at the observed location but bends towards southeast slightly higher up. The pitchstone has gradational contact (Fig.A1.9e) with crystalline silicic rock which forms the centre of the plug (Fig.A1.9b and d). A sample from the crystalline rock features feldspar and quartz in the groundmass and interstitial glass (Fig.S1.8 of the Supplementary material). Both the pitchstone and the crystalline rock feature ~5% white phenocrysts (generally <1 mm). While the pitchstone sample is vesicle free, the crystalline sample contains few (~2-3%) and small (typically <0.5 mm) vesicles that have a slight tendency to form ca. 1 cm thick bands although the rock is essentially not flow-banded. These vesicles are not elongated (i.e., undeformed) and feature groundmass crystals extending into the vesicle walls. Adjacent to and radiating from the plug are pockets and fractures or veins filled with breccia and fine-grained tephra-like material (Fig.A1.10). The pockets are filled with breccia composed of light-coloured to white groundmass with fragments from the adjacent basaltic rock as well as fragments of pitchstone. Yellow-brownish to dark brown very fine-grained contact breccia is sometimes observed at the outermost margins of these pockets (Fig.A1.10b). A thin section of material sampled from a few cm wide fracture observed in the country rock (WNW-ESE striking and dipping 54° from horizontal towards north; Fig.A1.10a) features considerable amount of pumice and apparently a mixture of tachylite and silicic glass, mixed with lithics (Fig.S1.9 of the Supplementary material). The upper part of the plug is surrounded by rhyolitic lava (Fig. 1.9a), assumedly formed in the same event as the plug.

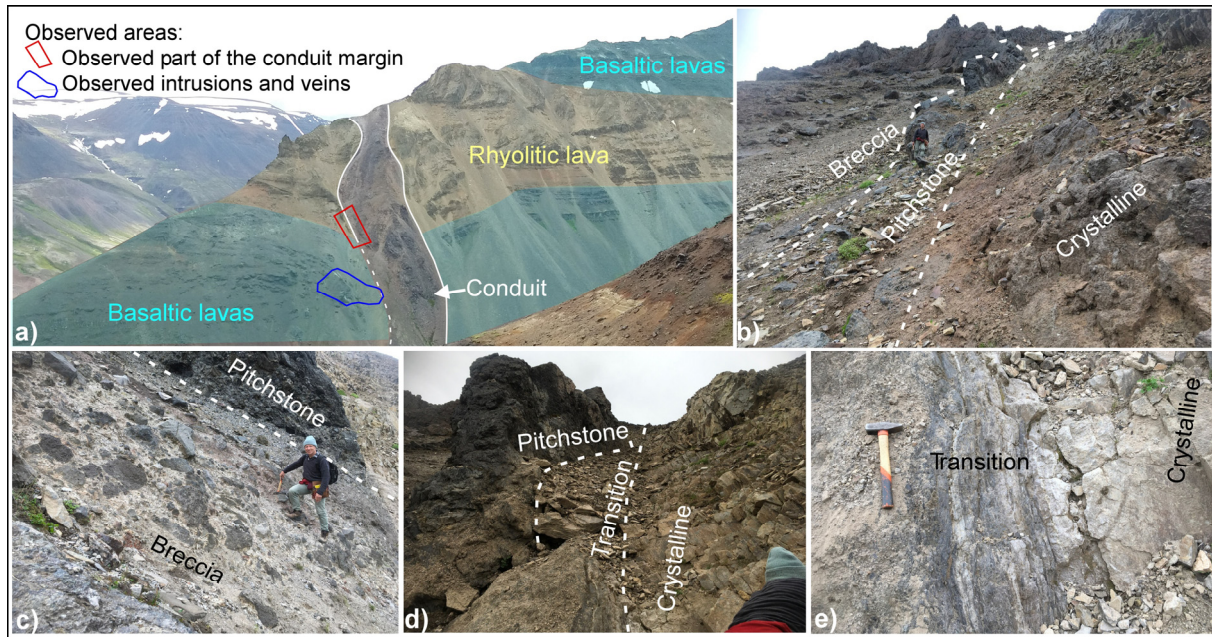


Figure A1.9. Interiors of a volcanic plug in Svarfdalur. a) Overview of the plug and the adjacent rocks, with locations of the observed areas. b) Overview of the plug's contact (person for scale). c) Breccia next to the country rock, composed of brecciated pitchstone and fragments from the adjacent basaltic rock. d) Pitchstone sheet inside the breccia (left) that turns into crystalline rhyolite that forms the plug's center (right) (person for scale in the bottom right corner). e) Transition from pitchstone to crystalline silicic rock.



Figure A1.10. Intrusions and veins adjacent to the silicic plug in Svarfdalur. a) Thin fracture filled with pumice and lithics mixed with finer tephra grains. b) Yellow-brownish to dark-brown very fine-grained sediment-like material at the margin of a breccia-filled pocket (book for scale). c) Tephra-filled veins (indicated with arrows) radiating from the plug.

3.2.4.2. Einbúi intrusion by Hamragil

A roundish cliff named Einbúi is observed south of the Hamragil gully around 400 m a.s.l., near the center of the study area (Fig.A1.11). This is a silicic intrusion, approximately 130 m in diameter. We assume that this outcrop provides a window into the interiors of a volcanic conduit. Our observations of the lower part of the intrusion concluded that the contact with the ambient basaltic rock is rather similar to the contact of the volcanic plug in the Svarfdalur valley. Next to the adjacent basaltic rock is ~1-1.5 m thick breccia, composed of white fine-grained material in the groundmass with abundant, variously sized angular fragments from the adjacent basaltic lavas (Fig.A1.11a). The white groundmass occasionally turns into very fine-grained, brown, clay-like material at the immediate contact with the ambient basaltic rock (Fig.A1.11b). Inside the breccia is a ca. 80 cm thick coat of pitchstone featuring fractures filled with the same white fine material as observed next to the adjacent basaltic rock

(Fig.A1.11d). The pitchstone turns into light-grey flow-banded crystalline silicic rock that forms the centre of the intrusion (Fig.A1.11a). Both the pitchstone and the crystalline rock are vesicle free and feature sparse (<1%) white phenocrysts. In the uppermost part of the outcrop, flow-banding is very prominent in the crystalline part, and the flow-bands strike approximately parallel to the margin of the intrusion where observed. In thin-section, the white fine-grained material observed by the conduit margin appears to be composed of consolidated ash (tuff; Fig.S1.10 of the Supplementary material), thus interpreted as finely crushed pitchstone. Pockets filled with breccia (composed of the same white consolidated ash in groundmass and abundant fragments from the country rock) are observed close to the conduit and magma has also radiated from the intrusion between basaltic lavas towards north as indicated by a thin pitchstone sill (Fig.A1.11c). Fractures (ca. 0.5 m wide) filled with light-colored tephra are found approximately 650 m NNW of the plug, striking ~N-S and NNW. Below these fractures, ca. 550-650 m north of the plug, are additional silicic intrusion outcrops, considered as sills radiating from the volcanic neck. The largest of these outcrops has a reddish hue and is named Rauðiklettur (Red cliff).

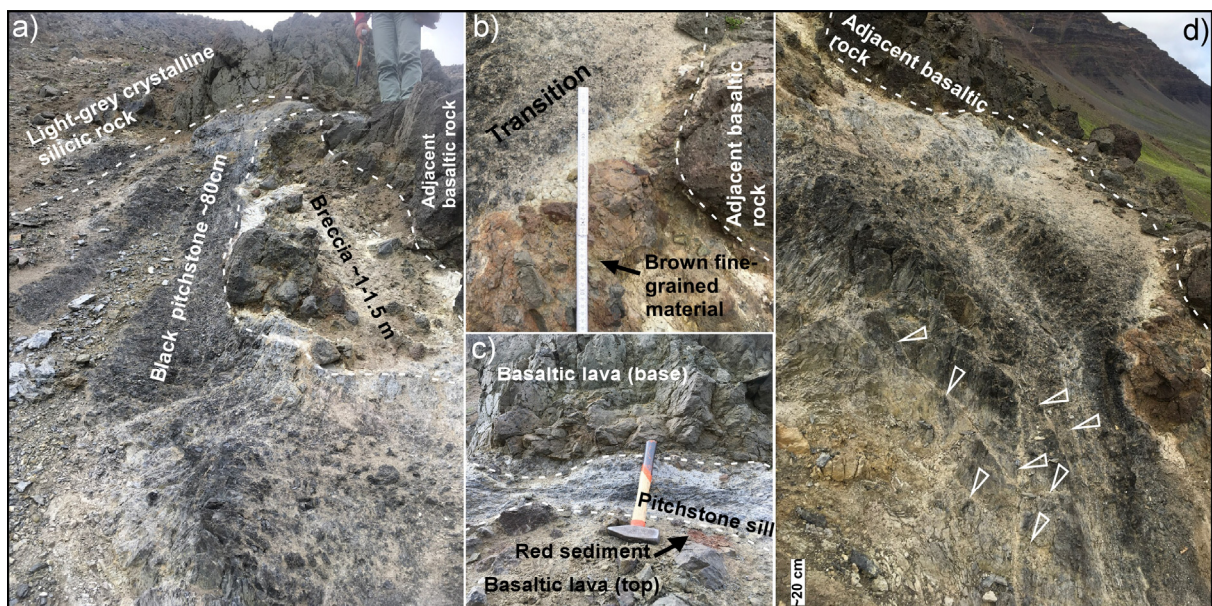


Figure A1.11. The Einbúi volcanic plug by Hamragil. a) Contact with the adjacent rock in the lower part of the intrusion. At the immediate contact with the adjacent rock is breccia which consists of white finely crushed pitchstone in the groundmass and fragments from the adjacent rock (basaltic lava). Inside the breccia is a ca. 80 cm thick coat of more intact (but still fractured) black pitchstone which turns into light-grey crystalline silicic rock with small-scale columnar jointing. b) Brown very fine-grained (even clay-like) breccia is occasionally observed at the immediate contact. c) Magma from the intrusion has squeezed between two basaltic lavas, apparently along a thin sediment layer. d) Examples of fractures in the black pitchstone (indicated with white triangles).

3.2.4.3. Svartiklettur intrusion in Nautárgil

A large silicic intrusion in Nautárgil, called Svartiklettur (Black cliff; 400-500 m a.s.l.), is also an assumed volcanic plug. The intrusion is in the middle between the two conduits in Hamragil and Svarfdalur, in ca. 1600-1700 m distance from each. The plug is ca. 115 m in diameter. At the contact with the adjacent basaltic lavas is breccia; up to 2 m thick where it was observed and mostly composed of variously sized fragments from the adjacent basalts and finer pitchstone pieces. Inside the breccia is a thin (a few cm) pitchstone sheet and inside that is crystalline flow-banded silicic rock with flow-band strikes approximately parallel to the contact where observed. Two faults are observed west of the intrusion, on

the west side of the gully, which appear to form a small horst that may be related to uplift from the intrusion.

3.2.4.4. Scoria crater in Glerá

Another location of an eruption site is recorded in the lower part of the Glerá gully in the southern part of the study area, just above an andesitic lava and at the bottom of a pile of reverse polarity basaltic lavas that underlie a small patch of stony rhyolite. An eruption vent is manifested by well-preserved remnants of a (basaltic) scoria crater, or tephra pile very close to a crater. The tephra formation features xenoliths from the underlying andesitic lava (Fig.A1.12b), lapilli pieces (Fig. A1.12c), up to 1 m long volcanic bombs (white arrows in Fig.A1.12e and f) and holes by volcanic bombs (Fig.A1.12d). The occurrence of a basaltic scoria crater at this position in the stratigraphic pile implicates Hawaiian or Strombolian eruptive activity concurrent to buildup of the silicic edifice.



Figure A1.12. Scoria crater in Glerá. a) Overview. b) Xenolith from the andesite lava below. c). Lapilli piece. d). Holes by volcanic bombs. e) and f) Volcanic bombs.

3.3. Alteration

The main amygdaloids identified in the field include chabazite, thomsonite, calcite, opal and clay. Chabazite is generally recorded from ~200 to ~800 m a.s.l., indicating paleotemperatures less than 80°C (Sæmundsson and Gunnlaugsson, 1999), while the uppermost strata generally contain no amygdaloids apart from opal in some locations. XRD analyses (Table S1.5 and Fig.S1.11 to S1.16 of the Supplementary material) indicate that in addition to these minerals, heulandite, mordenite and stilbite are present in the lowermost part of the mapped lava pile, generally at ~100-200 m a.s.l., suggesting higher paleotemperatures at deeper levels (~70-155°C, ~90-230°C, ~80-145°C, respectively; Sæmundsson and Gunnlaugsson, 1999). In addition to the abovementioned amygdaloids, which are common alteration minerals in Icelandic basalts (Walker, 1960; Sæmundsson and Gunnlaugsson, 1999), stellerite is

indicated by XRD in one sample. Although not widely recorded in Iceland, stellerite has been identified in Hvalfjörður in SW Iceland (Selbekk and Weisenberger, 2005; Weisenberger and Selbekk, 2009) and by the Miocene Geitafell central volcano, SE Iceland (Pilicita, B., 2020). Our secondary mineral recordings generally suggest that the upper part of the mapped strata pile is mostly situated within the chabazite-thomsonite alteration zone and does not indicate deep burial of the volcano. Thus, it is evident that erosion has not exposed deep levels of the lava pile, and comparison with Walker's (1960) diagram from eastern Iceland suggests that rather little has been eroded from the mountain tops.

Localized increase in alteration of the bedrock is observed in the NW slopes of Mt. Torfufell, where the basaltic lavas just below the tephra-, smectite- and fossil-bearing sediment horizon is quite altered, and the overlying andesite is often rather greenish and decayed, particularly adjacent to and within an ENE striking fault zone, at 420 m a.s.l. XRD analyses of a vein filling and amygdales sampled from this fault zone indicated cristobalite and tridymite in both cases, which are high-temperature polymorphs of silica. In addition to these minerals, the XRD analyses recorded heulandite in the amygdales and a hint of albite in the vein filling. While heulandite might be an overprint by later or shallower processes, hydrothermal albite may provide implications for higher paleotemperatures as it has been identified in active geothermal systems in Iceland at rock temperatures ~220-300°C (Kristmannsdóttir, 1979). Furthermore, as the volcano is not deeply exhumed, higher paleotemperatures may have occurred at deeper levels at this location.

3.4. *Erosion*

When volcanic activity ceased in the Torfufell area as it had drifted out of the active volcanic zone, it became a part of the plateau of the Tröllaskagi peninsula. Quite soon, the numerous ice sheet pathways of the Pleistocene commenced with incising the lava succession, leading up to large valleys and fjords and re-emergence of engulfed strata. Later on, some uplift presumably took place due to the effects of isostasy. As the volcano was completely buried by younger basaltic lavas prior to the glaciation, it can be assumed that next to nothing was eroded from its top. The resulting present scenario provides a cross-section through the Torfufell central volcano and a window into the volcano's extrusive formations through its whole lifespan, as well as the shallowest part of its root system, consisting of supplying veins and intrusions. A potential crustal magma chamber still remains uneroded and hidden below the surface.

3.5. *Structure*

3.5.1 *Dip and strike*

Twenty-four strike and dip values are presented on the geological map (Fig.A1.2, Table A1.1 and Fig.S1.17 of the Supplementary material). These values are calculated from our field measurements, where apparent dip angles were measured with a Suunto clinometer and/or a compass clinometer in two different directions at each locality, preferably over long distances (at least 50-100 m) when possible, but shorter in some cases. In general, these measurements indicate that the entire rock succession is regionally dipping gently towards southeast, and more easterly than indicated in Jóhannesson and Sæmundsson's (2009a) tectonic map of Iceland. Seven of the measurements, located by the northern and western sides of Mt. Torfufell, indicate southerly dip directions (SSE to SSW) and most often steeper dips than elsewhere (up to ~16°). These values are considered to refer to local situations related to the central volcano and possibly induced by faulting and/or irregular subsidence of the volcano's floor. If these 7 measurements are excluded, dip values range from 5 to 11°, with a mean dip direction of N123°E. The dip measurements were performed at 90 to 800 m a.s.l. Although a slight decrease with increasing

elevation may be interpreted from the dip values at this interval, they do not indicate a distinct decrease as recorded farther north in the Tröllaskagi peninsula (Sæmundsson et al., 1980).

The position of the tephra-, smectite- and fossil-bearing sediment horizon in several visited outcrops, as well as the position of the base of the silicic/intermediate lavas in several encountered localities in Mt. Torfufell, does not indicate an even plane. From south to north in Mt. Torfufell, the silicic/intermediate base appears lower than expected in most of the visited outcrops considering the measured dip of the underlying basaltic lavas. This may either indicate that the silicic/intermediate base is actually dipping differently from the underlying basalt lavas and is thereby lying unconformably on top of them, or that major faults exist between these profiles that we did not recognize in the field (and may at least in some cases be covered with landslide material). Considering the setting (inside a volcanic complex), we find it rather likely that some faulting has taken place which may have caused tilting of the strata and thereby abnormal strikes and dips. Two minor volcanic hiatuses recorded at and near the silicic/intermediate base may also contribute to these discrepancies in addition to faulting.

Table A1.1. *Results of strata dip measurements in the study area:*

Location (profile)	Lat	Long	m.a.s.l.	Strike	Dip value	Dip direction
Gilsá	65.400593	-18.261059	160	31	10	121
Gilsá	65.399549	-18.269282	240	41	10	133
Uppermost Gilsárdalur	65.3804278	-18.293486	720	50	9	140
Núpá in Sölvadalur	65.422845	-18.168396	90	63	6	153
Núpá in Sölvadalur	65.411463	-18.16428	140	46	10	135
Nýibær	65.38685	-18.220286	230	45	9	135
Halldórsstaðir	65.314952	-18.234977	315	35	10	125
Glerá	65.288191	-18.213523	590	45	8	135
Glerá	65.289604	-18.224085	420	43	8	133
Úlfá	65.292839	-18.259064	275	11	6	101
Úlfá	65.292991	-18.259918	290	34	7	124
Nóngil	65.286157	-18.261196	330	56	11	146
Ytra-Mógil	65.277606	-18.260274	350	7	8	97
Ytra-Mógil	65.27761	-18.260551	355	43	9	133
Hafrá	65.267072	-18.254664	360	47	5	137
Hamragil	65.33828	-18.303877	400	37	9	127
Tröllshöfði	65.361508	-18.296777	800	30	7	120
Torfufellsdalur	65.306855	-18.338379	440	70	15	160
Torfufellsdalur	65.308038	-18.338514	370	76	15	166
Torfufellsdalur	65.311398	-18.313148	410	89	16	179
Torfufellsdalur	65.291937	-18.378913	500	118	8	202
Torfufellsá	65.323916	-18.269518	210	90	10	180
Torfufellsá	65.324895	-18.269759	160	124	10	214
Torfufellsá	65.324207	-18.277519	210	93	12	183

3.5.2. Faults

Recorded faults in the study area predominantly strike NNE-SSW to NE-SW. These faults typically indicate clear vertical movements from ~1.5 m to tens of meters (see examples in Fig.A1.13). Two small NE-SW striking grabens are recorded; in the Hafrá canyon and in the Svarfdalur valley; and a small NE/ENE trending horst is observed in the Nautárgil gully, considered to result from uplift by a nearby silicic intrusion. Several faults are presented in the geological map that are inferred from the stratigraphy but were not recognized in the field. Orientations of these faults are thus arbitrarily traced parallel to the most evident lineaments in the vicinity, observed in the field and/or in aerial images. As discussed above, inferred faults in Mt. Torfufell indicate stepwise downthrow towards north.

A noteworthy ENE striking fault contact between basaltic lavas and andesitic rock is observed in the northwest side of Mt. Torfufell (Fig.A1.13b and c). This fault appears to be approximately vertical, with at least 40 m vertical downthrow of the southeastern block. The fault zone is least 30 m wide and features chaotic breccia (Fig.A1.13c) with white fine-grained groundmass and subangular fragments of various origin, including basalt, volcanic glass and greenish decayed rock with abundant amygdales. Mineral veins are observed in several places cutting through the breccia. Alteration minerals sampled from the breccia (tridymite, cristobalite, heulandite and albite) imply that this fault acted as a pathway for hydrothermal fluids (see section 3.3). Fragments of volcanic glass are abundant at the immediate northern margin of the breccia, suggesting that this fault was also a pathway for magma. These glass fragments feature pronounced greenish alteration next to the adjacent basaltic lavas.



Figure A1.13. Fault examples. a) Fault by the Núpá river, cutting through the oldest basaltic lavas in the map. b) ENE-WSW trending fault in NW Mt. Torfufell; breccia from this fault zone is shown in c).

3.6. Age

The silicic rocks of the Torfufell central volcano commonly feature abundant zircon crystals of relatively large sizes (often around 100-150 μm), allowing us to provide 6 new U-Pb zircon ages (Table A1.2 and S1.19 of the Supplementary material). The age data is detailed in Árnadóttir et al. (2023) and only briefly introduced in the present paper. The new zircon ages, in combination with Supakulopas's (2018) $^{40}\text{Ar}/^{39}\text{Ar}$ ages from Mt. Hólafjall, were coupled with the stratigraphy and paleomagnetism to address the chronology of the central volcano (Fig.A1.14). These correlations indicate that the construction of the volcanic edifice commenced at approximately 7.8-8 Ma, during geomagnetic subchron C4n.2n (via correlation with Supakulopas, 2018) with eruptions producing thin basaltic lava flows, including series of a lavas of rather evolved composition. However, two of Supakulopas's (2018) dates (7.77 ± 0.15 and 7.98 ± 0.15 Ma), obtained from samples below and above our correlation with the intended edifice base, are inconsistent with the stratigraphic order (as the higher age was obtained for the lava that is located higher in the strata pile while the lower lava gave the younger age). Hence, the estimated timing for the onset of the edifice base is quite imprecise. Closely spaced lavas with ages of 8.31 ± 0.13 Ma and $7.27 \text{ Ma} \pm 0.12$ in Supakulopas's (2018) work (in the Halldórsstaðir profile) add to the complexity, indicating paleolandscape in the basaltic lava pile below the silicic and intermediate lavas and a local hiatus between these two samples.

Supakulopas (2018) couples his lava no. HS22 in Mt. Hólafjall with geomagnetic subchron C3Br2r. While he categorizes this lava as basalt, his XRF-obtained major element concentrations indicate 58.5 wt% SiO_2 . Therefore, and as we identified this lava as possible andesite in the field, we have classified it as andesite on the geological map. Based on this, intermediate volcanism is considered to have commenced at around 7.3-7.46 Ma. On top of this andesite lava are two sedimentary layers containing silicic tuffs that, according to Supakulopas's (2018) findings, indicate two minor volcanic hiatuses during subchron C3Br.1n on the one hand and at the boundary between C3Br.1r and C3Bn on the other hand (indicated in Fig.A1.14). We believe that one of these sedimentary beds may correspond to the tephra-, smectite-

and fossil-bearing sediment horizon observed in several outcrops in Mt. Torfufell and in the Villingadalur valley. Our recordings of an abrupt and decayed olivine basalt lava inside the sediment horizon in the western slopes of Mt. Torfufell (recorded in the Torfufellsdalur profile), in comparison with Supakulopas's (2018) recordings of brecciated olivine basalt inside the lower sediment in Mt. Hólafjall, may imply that the horizon correlates with the lower hiatus in Mt. Hólafjall. Above the two minor hiatuses in Mt. Hólafjall is a normal polarity rhyolite which Supakulopas (2018) dated as 7.12 ± 0.10 Ma and correlated with geomagnetic subchron C3Bn. As this is the only normal polarity subchron occurring within the lifespan of silicic activity at the volcano, it seems reasonable to also assign it to the 7.03 Ma U-Pb age of the normal polarity dacite (sample 27072017-1; Árnadóttir et al., 2023). Our highest U-Pb mean, 7.15 ± 0.12 Ma, was obtained in a reverse polarity ignimbrite. Data from this sample is however quite dispersed (MSWD = 4.3), and since the zircons are young and fairly low in U, it would not be reasonable to assign this to Pb-loss, as might be the case for older and/or U-rich zircons. Instead, we rather assume that the dispersion is related to recycling of ca. 7.4 Ma zircons (possibly partly derived from lithics in this whole-rock sample) into a ~7 Ma melt, which would assign this sample to geomagnetic subchron C3Ar. Therefore, Supakulopas's 7.12 m.y. age is considered here as the approximate initiation of silicic volcanism.

Table A1.2. U-Pb Zircon Ages from the Torfufell Central Volcano (detailed in Árnadóttir et al., 2023).

Sample Id.	Lat	Long	Sample details	U-Pb age	Error	Comments
27072017-1	65.292893	-18.268749	Dacite lava; normal middle silicic volcanism. East Mt. Torfufell	7.03	± 0.15	Normal polarity
26082015-25	65.277547	-18.259066	Ignimbrite; lower reverse silicic volcanism. East Mt. Torfufell	7.15	± 0.12	Possibly a ca. 7.4 Ma component in a 7 Ma melt. Reverse Polarity
07072015-2	65.324207	-18.277519	Silicic sill. Torfufellsá	7.002	± 0.064	Anomal/uncertain polarity
24072017-4	65.321931	-18.335686	Silicic intrusion (volcanic plug). Villingadalur	7.015	± 0.048	Reverse polarity
10072017-3	65.288856	-18.218619	Upper reverse silicic volcanism; small patch of rhyolite in Glerá	6.85	± 0.091	Disperses to slightly younger ages. Reverse polarity
20190823-3	65.305372	-18.294526	Upper reverse silicic volcanism; uppermost rhyolite in Mt. Torfufell	6.757	± 0.015	Reverse polarity

A puzzling complexity is indicated by our field measurements of remanent magnetism, implying disagreement between the paleomagnetic mapping and the age data within the Úlfá and the Nóngil profiles. As we measured lavas that are situated above reverse polarity ignimbrites in the Nóngil profile as normal polarity, these lavas should belong to subchron C3Bn, and the underlying reverse silicic formations may then be assumed to be formed during subchron C3Br.1r, i.e. prior to sample 27072017-1 and slightly before 7.2 Ma. If this is the case, an erosional or tectonic discontinuity must exist in SE Mt. Torfufell, between the Úlfá and Nóngil profiles. We highlight however that these measurements, carried out only in the field, should be applied with caution and can be refuted by more detailed paleomagnetic research.

As our youngest rhyolite age is 7.76 ± 0.015 Ma, we can conclude that the lifespan of the Torfufell central volcano ranges from subchron C4n2n (early basalts) to C3Ar (youngest rhyolites). Above the rhyolite, Supakulopas (2018) noted a volcanic hiatus covering almost the entire chron C3A. Our U-Pb zircon ages however abridge this hiatus by almost 400,000 yrs as silicic volcanism continued at least until 6.757 Ma. Basaltic lavas abutting against the silicic complex are dated at 5.73 Ma (Supakulopas, 2018), suggesting

a ~1 m.y. hiatus between the rhyolites and the younger basalts. A few basaltic lavas that exist below this dated flow – and probably abridge this hiatus slightly – are assigned to the Gilbert subchron (C3r; Supakulopas, 2018) and thus younger than 6.023 Ma (Ogg, 2020).

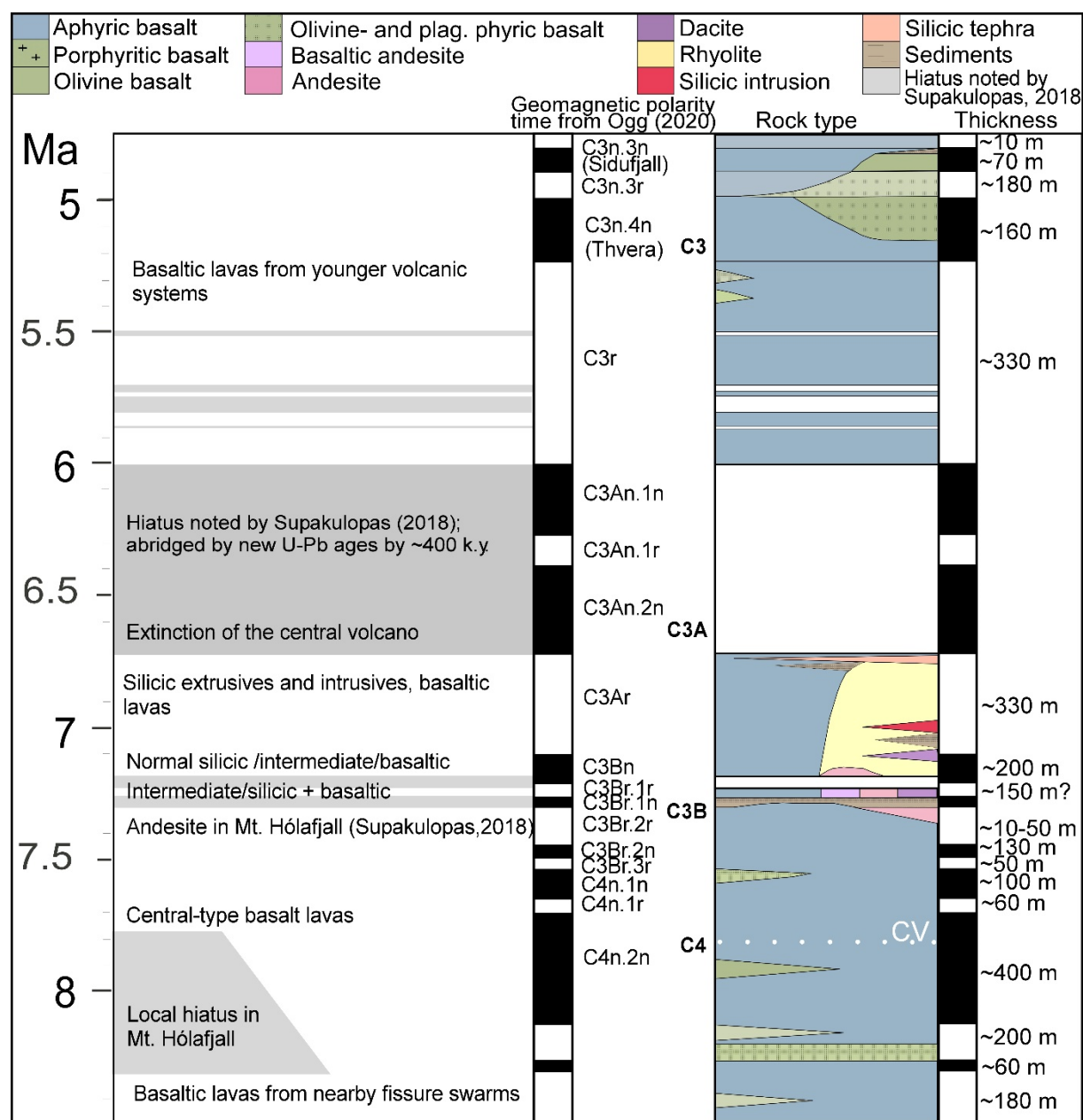


Figure A1.14. Stratigraphy of the study area, coupled with the new U-Pb zircon ages and Supakulopas's (2018) results. Estimated base of the central volcano is indicated with dotted lines (CV). Approximate thickness of volcanics produced during each geomagnetic subchron is estimated (far right).

4 Discussion

The geological mapping shows that outcropping silicic and intermediate lavas and intrusions of the Torfufell central volcano are limited to an area that lies from Mt. Hólafjall above Lake Hólavatn south to the Hafrá canyon and west to the Svarfdalur valley. Our mapping indicates that the erosion has exposed extrusive rocks and shallow intrusions and provided a window into the uppermost part of the magma feeding system associated with the Torfufell central volcano. This is indicated e.g., by low-temperature secondary minerals and slender columns of silicic intrusions, and furthermore we consider that the winding of basaltic and silicic dykes may also be an implication of emplacement rather close to the surface, reflecting the decrease in confining pressure at shallow levels. Deeper intrusions, including a potential shallow magma chamber, still remain unseen at the surface. We have recorded that outcropping silicic and intermediate extrusive formations belonging to the volcano are thickest in the northern part of Mt. Torfufell where they form a ca. 350 m thick pile. Our mapping shows that the outcropping silicic formations terminate in the Svarfdalur valley, indicating that the rhyolite is not connected geographically to the rhyolite of the Tinná central volcano which is situated only ~15 km farther west. The inferred relation of these two volcanic centers is furthermore refuted by new age data.

Our observations indicate that the composition of magmas utilizing the feeding system of the Torfufell central volcano ranged from basaltic to rhyolitic. The transition from thick grey lavas towards thin, black *ā'a* lavas of more evolved compositions is interpreted to represent the transition from predominantly fissure-fed lavas towards central volcanism. This sequence is found in several locations to be separated from overlying intermediate and silicic lavas by a tephra-, smectite- and fossil-bearing sediment horizon. The summit area of the volcanic edifice consisted of overlapping rhyolitic lava domes formed by effusive activity, with explosive activity evidently accompanying the dome growth. Basaltic volcanism continued throughout the lifespan of the central volcano, suggesting that the products of the central volcano were largely basaltic. A thick layer of silicic tephra (up to 23 m), recorded from the Svarfdalur valley through the Villingadalur valley and Tröllshöfði, to the Strjúgsárdalur valley and perhaps even further, appears to represent the uppermost silicic formation in the area and may indicate that silicic activity at the central volcano ceased with Plinian eruption, potentially forming a large tephra sector extending towards north. The rhyolite lava domes formed topographic highs during the volcano's active period, which became buried after its extinction by basaltic lavas.

4.1. Volcanic plugs

Exposed outcrops show at least three volcanic plugs, indicating that flow paths of silicic magmas became focused into several discrete conduits that were approximately cylindrical at shallow depths. These outcrops provide excellent cross-sections of the conduit interiors, exposing e.g., marginal breccias featuring fragments from the adjacent basaltic rock indicating that magma, gas and pyroclasts produced erosion or abrasion of the conduit wall during magma ascent. Pitchstone by the margin of the Einbúi conduit in Hamragil features a fracture network. As demonstrated e.g., by Goto (1999), high viscosity can cause brittle failure under high strain rates, it may be speculated if this fracture network was generated by brittle behaviour of the magma, resulting from high viscosity of the rising silicic magma and high shear rate next to the country rock. Thereby, the white, fine, consolidated tuff observed inside the fractures and next to the country rock, is considered as crumbled pitchstone, derived from fracture walls by abrasion during fracturing and frictional sliding. The crystalline interior of the plug is on the other hand more intact than the pitchstone part, which may suggest ductile behavior in the conduit center where temperature was higher than at the margins, and where the magma viscosity and the shear rate were lower during ascent.

We have observed fractures radiating from the Svarfdalur conduit that are filled with tephra particles, juvenile pumice and lithics. We consider these to represent tuffsite veins, i.e., ash-filled fractures formed either via opening of new or pre-existing fractures that may have provided permeable pathways permitting flow of gas-particle mixtures, thereby enabling exsolved gases to escape from the magma (see e.g., Stasiuk et al., 1996; Tuffen et al., 2003; Saubin et al., 2016). As such, the tephra in these fractures are assumed to be fragments of highly viscous magma while the lithics may be fragments from the country rock, generated by abrasion of the fracture walls. It may then be further speculated if outgassing via these pathways may have influenced the eruption style and favoured effusive behaviour of the volcanism, resulting in formation of the overlying lava dome.

The dissected volcanic plugs are exposed at different levels, with the Einbúi plug being exposed ~300 m below the base of the rhyolite lava while the observed part of the Svarfdalur plug is approximately at the same level as the bottom of the rhyolite. This may potentially explain some differences, e.g., in thicknesses of the breccias and glassy parts by the margins of these two outcrops and at the same time this may potentially provide indications of differences in plug construction with depth, suggesting that the zone of abrasion/erosion of the conduit wall is wider in the uppermost part than at ~300 m depth. Although these and other differences are not necessarily explained simply by exposures at different levels, variations in the cross-sectional areas of the conduits with depth are not implausible, e.g., as vent erosion is generally considered to occur most efficiently near the surface (e.g., Wilson et al., 1980). While samples obtained from the Einbúi plug are vesicle free, samples from the Svarfdalur plug are both vesicle free (i.e., a sample from the marginal pitchstone) and with vesicles (i.e., a sample from the crystalline core). Although more systematic sampling throughout the cross-sectional areas of these plugs would be necessary to reasonably evaluate vesicle distribution or to interpret strain rates using the geometry of deformed vesicles (as described e.g., by Rust et al., 2003), the presence of undeformed vesicles in the crystalline core of the Svarfdalur plug may be taken to indicate that no differential shear was acting on this part of the magma at the time of vesiculation. This may suggest either that the magma was not moving when these vesicles formed, or that this part of the magma was in an elastic/visco-elastic state at the time of vesiculation, and may have been moving as a plug. No flow-banding was observed in this part of the crystalline core, which may be considered to support this idea.

An approximate NE-SW trend of the three observed conduits has been noted, and possible scoria crater remnants (or proximity to a crater) are furthermore recorded in Hamragil as a continuation of the trend towards NE. While this alignment may simply be a perfect coincidence, it may also be casually speculated if these eruptive sites are situated on the same fracture or closely spaced NE-SW trending fractures.

4.2. Sills

Silicic sill intrusions are exposed at several levels below the central volcano, between 100 and 300 m below the base of the silicic/intermediate lavas, thereby providing evidence that shallow sill intrusions contributed to magma transport and storage. As the silicic sills are clearly partly conformable along discontinuities such as sedimentary beds, it is evident that weak interfaces between basaltic lavas greatly influenced the magma emplacement. Exposed outcrops also include evidence of how the sills changed stratigraphic levels within the intruded sequence, both discordantly at gentle inclination and at steep angles through dyke-like segments. Our field observations record sub-cylindrical conduits as well as fault zones contributing to sill emplacement. The exposed outcrops provide indications of what can be expected below the uneroded surface and reasons to speculate if an extensive sill system contributed significantly to upper crustal magma transport and storage within the volcanic centre.

4.3. Structures

The principal and regional tectonic trends, observed outside the silicic complex, are NNE-SSW to NE-SW trends of basaltic dykes and faults. These trends are observed cutting through basaltic lavas above the central volcano as well as below the volcano. Locally anisotropic strikes are recorded within the rhyolite complex, where NNE-SSW trends are mostly absent and ~E-W (most often in the range ENE-WSW to WNW-ESE) is the principal trend, commonly observed in silicic dykes. As this local anomaly is clearly concentrated within the silicic complex, it may be interpreted to be influenced by the interaction of a local magma induced stress field and a regional tectonic stress, as the stress field changed around the shallow magma chamber of the volcano. On the other hand, even though a slight indication of an arcuate alignment is noted, evidence of radial geometry is not very strong. Thus, it is possible that the trends of silicic dykes are actually linear, representing part of a regional ~E-W tectonic overprint. The frequency of silicic dykes increases towards the centre of the outcropping rhyolite, and this zone of maximum intensity is interpreted here as an implication of a central feeding zone. Implications of geothermal activity and abnormal strata dips are also recorded within this zone.

Some of the recorded fault and dyke orientations are indicated by the most prominent morphologic lineaments in the area. As an example, NNW-SSE and NNE-SSW striking faults recorded in the canyon of the Torfufellsá river, just north of Mt. Torfufell, and a NE striking fault in the NW slopes of Mt. Torfufell, fit almost perfectly with the form of the mountain. This may suggest that larger faults with similar strikes exist below surface along the adjacent valleys and controlled the glacial erosion. A NNW-SSE strike, subparallel with the trend of the Eyjafjarðardalur valley, is even recorded below surface east of Mt. Torfufell by Flóvenz and Tómasson (1992), indicated by magnetic and resistivity surveys.

Although a basaltic dyke swarm is recorded north of the volcano, we did not observe any clear evidence of whether this dyke swarm belongs to the Torfufell volcanic system or not. While Icelandic volcanic systems commonly comprise both a central volcano and a dyke swarm, such arrangements are not absolute, as is e.g., manifested by the active systems with a central volcano and no fissure swarm that tend to occur at the propagating part of the EVZ as well as in the intraplate zones where the crust is relatively thick (e.g., Thordarson and Larsen 2007). The lack of a visible dyke swarm that is clearly related to the central volcano might on the other hand be related to the shallow erosion levels, e.g., similar to Gústafsson's (1992) suggestions in the Neogene Dyrfjöll central volcano in East Iceland.

4.3.1. Calderas

Geometry of strata in Mt. Torfufell indicates several faults with stepwise downthrow towards the mountain's northern part. These faults are sometimes only inferred by the stratigraphy and thus arbitrarily traced on the geological map. Although no evidence of a pronounced collapse caldera has been observed, nor outcrops of typical massive caldera-fill ignimbrites and breccias, we do not preclude the existence of a caldera or calderas. While indications of the alignment of potential caldera structure boundaries are quite obscure, some of the observed and inferred faults in Mt. Torfufell may be interpreted as likely to have resulted from subsidence caused by decreased support from the magma reservoir, and at the same time, abnormal tilts of basaltic lavas in NW Mt. Torfufell may be considered to result from downsagging of the caldera floor. These remarks could potentially support the existence of a downsagging and internally fractured caldera with a central zone close to the northern part of Mt. Torfufell. Although the ignimbrites observed in SE Mt. Torfufell do not appear to be very widespread, such formations are indeed typical products of caldera-forming events. If our implications (discussed in section 3.6.), that the reverse polarity ignimbrites in the Nóngil profile were formed during paleomagnetic subchron C3Br1r, prove to be correct, these ignimbrites are situated adjacent to younger formations. Thus, it may be speculated if these ignimbrites were situated by the edge of a caldera,

possibly with some of the caldera-forming products being eroded away, and with the younger, normal polarity, dacite and rhyolite lavas emplaced inside the caldera. Then, thick lake sediments and tuffs in the southern part of the map may indicate the presence of a caldera lake south of the mapped silicic complex which, compared to the position in the strata pile, would be formed later in the volcano's lifespan. Although the outcropping rhyolites indicate abrupt termination in the Svarfdalur valley and Torfufellsdalur/Leyningsdalur, a possible extension of the silicic complex - and a potential paleo-caldera lake - towards south would be buried below the surface due to the SE tilt of the strata. On the other hand, the absence of a caldera is also quite possible, as the abnormal tilts of basalt lavas near the central feeding zone could be explained simply by subsidence due to the weight of the overlying rhyolite. As such, the existence, alignment and collapse style of a caldera - or calderas - within the Torfufell central volcano remain speculative.

5 Conclusions

We have presented the first detailed geological map of the Torfufell central volcano in central North Iceland, based on original fieldwork, and detailed descriptions of the strata pile and key geological formations in the study area. This is coupled with both previous age data and new high-quality U-Pb zircon age data and ICP-OES whole-rock geochemistry. Our observations indicate that early phases of the volcanic construct were characterized by eruptions producing series of thin basaltic *ā* lavas of rather evolved compositions, while latter phases involved intermediate and silicic effusive and explosive volcanism, ceasing with a Plinian eruption. Silicic dykes are concentrated in northern Mt. Torfufell, where they principally trend from ENE-WSW to ESE-WNW, and this zone of maximum dyke intensity is interpreted to indicate a central feeding zone for silicic products. While these orientations deviate significantly from the regional dyke trend outside the limit of the central volcano, it is unclear if they represent local sets with radial geometry, controlled by a stress anomaly generated by a shallow magma chamber, or if the magma did follow a part of a regional (linear) ~E-W tectonic overprint. Field examples provide evidence of silicic magma ascending through transgressive sills and erupting through sub-vertical dykes as well as sub-cylindrical conduits. The spectacular outcrops of dissected silicic dykes, volcanic plugs and transgressive sills provide a window into the shallow plumbing system of the central volcano. A swarm of basaltic dykes with unclear affinity is observed, with the vast majority recorded in the northern part of the study area, cutting through the lowermost part of the mapped strata pile. The predominant trend of these dykes is NNE-SSW to NE-SW.

Correlations with new and previous age data indicate that the construction of the central volcano edifice commenced at approximately 7.8-8 Ma with basaltic volcanism. The first intermediate products erupted at around 7.3-7.5 Ma (during geomagnetic subchron C3Br2r) and were followed by a minor hiatus, during which a notable tephra-, smectite- and fossil-bearing sediment horizon is considered to have formed. Silicic volcanism commenced with production of dacitic to rhyolitic formations at approximately 7.12 Ma. Silicic volcanism continued until 6.757 Ma, indicating that silicic volcanism was limited to approximately 400 k.y., while the life-span of the central volcano is ca. 1 m.y. A ~1 m.y. hiatus is recorded between the silicic complex and the adjoining basaltic lava flows. Our results highlight the extensive room for future discoveries in central North Iceland and likewise, the Torfufell central volcano, with its numerous spectacular phenomena, including excellent cross-sections of fossil silicic intrusions and conduit systems, awaits more detailed research and alternative viewpoints.

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**A2 Paper II: Geochemistry and petrography of
basaltic to rhyolitic products of the Late
Miocene Torfufell Central Volcano, North
Iceland**

Geochemistry and petrography of basaltic to rhyolitic products of the Late Miocene Torfufell Central Volcano, North Iceland

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Abstract

Present volcanism in Iceland occurs in both rifting and intra-plate context, where the axial rifts produce basalts of the tholeiitic series while mildly alkalic and transitional alkalic magmas are confined to intra-plate and flank zones. These volcanic zones are delineated by volcanic systems featuring either a basaltic fissure swarm, a composite central volcano, or both. In this study, we explore the geochemical evolution of the ancient and excavated Torfufell central volcano in the Eyjafjörður region of central North Iceland. We provide new data on the whole-rock and mineral compositions of basaltic to rhyolitic products of the volcano, integrated with mapping and age dating campaigns to provide a stratigraphic framework and allowing evaluation of temporal changes in chemistry and mineralogy throughout the volcano's 1-1.2 Myr life span during the Late Miocene. The geochemical data document that basaltic lavas sourced from the central volcano differ from enveloping plateau lavas in that they are mildly alkalic in nature (e.g., more enriched in Ti and Zr) and strongly indicate that the shift from predominantly fissure-fed eruptions toward central volcanism can be recognized in the field by a transition from thick (>5 m) to unusually thin (<5 m) lavas of *ā*'a type. The data furthermore indicate that the Torfufell central volcano features basalts that are high in Ti and Fe compared to typical products of the presently active rift zones of Iceland and rhyolites that have a transitional character towards alkaline rocks.

Introduction

Iceland extends above sea level where the Mid-Atlantic ridge crosses a mantle plume and is constructed by the ridge-plume interaction (e.g., Schilling, 1973; Vink, 1984). The island is composed almost entirely of volcanic rocks and depicts anomalies in both geochemistry and tectonic features compared to the submarine environment (e.g., Imsland, 1983; Óskarsson et al., 1985; Einarsson, 2008). Volcanism is presently confined to axial rifts, flank zones and intra-plate belts, generally termed volcanic zones and belts. The position and migration of the axial rifts is explained by the WNW movement of the Mid-Atlantic rift system relative to the mantle plume, which has resulted in complex segmentation and repeated eastward relocations of the plate boundary. The last major relocation is generally quoted to have occurred at ~6-7 Ma when activity ceased at the Snæfellsnes-Húnaflói rift zone (SHRZ) and rifting initiated at the presently active Northern and Western volcanic zones (NVZ and WVZ; Fig. A2.1) (e.g.,

Sæmundsson, 1974; 1979; Jóhannesson, 1980). The Eastern volcanic zone (EVZ) is <3 Ma (e.g., Einarsson, 2008) and is propagating into older lithosphere towards SW (e.g., Schilling et al., 1982; Óskarsson et al., 1985). Due to past relocations, the present position of the three rifting segments is east of the submarine Mid-Atlantic rift system, and this offset is accommodated by two transform zones; the Tjörnes Fracture Zone (TFZ) in the North and the South Iceland Seismic Zone (SISZ) in the South. The three rifting segments are linked by the transverse, E-W trending, Mid-Iceland Belt (MIB) which comprises several active central volcanoes and has been described as a “leaky” transform fault (e.g., Óskarsson et al., 1985), i.e. comprising a small component of extension, sufficient to induce local volcanism. Intra-plate volcanism occurs in the Snæfellsnes and Öraefi volcanic belts (SVB and ÖVB) with the former representing renewed volcanism through crust formed in the palaeo SHRZ (Hardarson et al., 1997; Sæmundsson, 1979) and the latter considered as an embryonic rift (e.g., Thordarson and Höskuldsson, 2002).

The volcanic zones and belts are composed of multiple volcanic systems, where each system consists of a fissure swarm and/or a polygenetic (composite) central volcano. While basaltic magmas are volumetrically dominating and erupted from the whole volcanic system, evolved products are concentrated in the central volcanoes and normally considered to indicate the presence of a shallow crustal magma chamber (e.g., Guðmundsson, 1995; 2000). Silicic intrusive and extrusive rocks have been estimated to comprise approximately 10% of the exposed Icelandic crust (e.g., Walker, 1966; Jónasson, 2007) while 3% of the extrusive Holocene sequence are silicic (e.g., Thordarson and Höskuldsson, 2008) – with higher proportions occurring in the intra-plate volcanic belts and the propagating part of the EVZ (collectively termed flank zones) than in the axial rift (e.g., Imsland, 1983). The flank zones also produce more diverse rock types, i.e. subalkalic, alkalic and mildly alkalic basaltic magmas – with transitional basalts characterized by enrichment in iron and titanium occurring in the central volcanoes of the coastal section of the EVZ – while only basalts of the tholeiitic series are produced in the axial rifts (e.g., Jakobsson, 1972; Imsland, 1983). The predominant petrogenesis of Icelandic rhyolites is still a subject of debate, where two end-member models invoke fractionation of parental basaltic magmas (e.g., Carmichael 1964; Furman et al 1992; Prestvik et al 2001) and partial melting of hydrated basaltic crustal rocks (e.g., Sigmarsson et al 1991; 1992; Gunnarsson et al., 1998). A link between the process of rhyolite production and the thermal state of the Icelandic crust has been noted, where silicic magmas at a distance from the rift zone and the plume centre are proposed to be generated by fractional crystallization of basaltic magmas in an intra-plate context, while partial melting of hydrothermally altered basaltic crust is likely to generate silicic magmas within or close to the rift zone (Martin and Sigmarsson, 2007; Sigmarsson et al., 2008). This hypothesis has been further tested via zircon oxygen isotope compositions, documenting that extensive assimilation of hydrothermally altered crust contributes significantly to silicic magma petrogenesis at on-rift and propagating-rift magma systems, but a lesser role off-rift (Carley et al., 2020).

Adjacent to both sides of Iceland’s present axial rift along with the sub-glacial eruption products of the Early Pleistocene are successions of Miocene basaltic lavas, generally emplaced onto low angle terrains. Hardarson et al. (2008) noted that the range of chemical composition of the Miocene basalts is much more limited than the basalts of the Pleistocene and Holocene, with only rift zone central volcanoes recognized. Grading into transitional alkaline trends has however been noticed in geochemical data from Miocene regions in several studies, as silicic lavas in the Reyðarfjörður central volcano have been documented to reach a trachytic composition (Gibson, 1967). Furthermore, higher alkali, titanium and iron contents compared to typical rocks of the tholeiitic series have been observed in the Dyrfjöll central volcano by Gústafsson (1992) who suggested that the volcano was formed in a flank zone rather than at a mature rift. Óskarsson (2015) also documented alkaline affinity of the lava groups of the Reyðarfjörður volcanic zone, which he interpreted to indicate that these volcanic systems were formed in flank zones.

Calc-alkaline dacites were furthermore observed in the Króksfjörður central volcano of NW Iceland by Jónasson et al. (1992), interpreted to be formed at a time when activity was waning at the volcano and as it was drifting away from the rift axis.

In the present study, we focus on petrological, mineralogical and geochemical characterization of eruptive and intrusive units belonging to the Late-Miocene Torfufell central volcano (ToCV), including whole-rock, mineral and glass data. The ToCV is located in the region of the Eyjafjörður fjord, by the Tröllaskagi peninsula's southern end (Fig.A2.1) and was active between $\sim 7.8/8.0$ and 6.8 Ma (Árnadóttir et al., 2023), nearly contemporaneously with the last major rift relocation in North Iceland. Being dissected by rivers and glaciers, the ToCV provides an excellent opportunity to recreate the construction history of a volcanic edifice. The samples analysed in this study were collected during mapping and age dating campaigns that provide a stratigraphic framework and enable examination of the volcano's history and evolution. Here we present new data on the whole-rock and mineral compositions of basaltic to rhyolitic products of the ToCV. The geochemical results are integrated with both previous and new age data, allowing us to evaluate temporal changes in chemistry and mineralogy throughout the volcano's 1-1.2 Myr life span during the Late-Miocene.

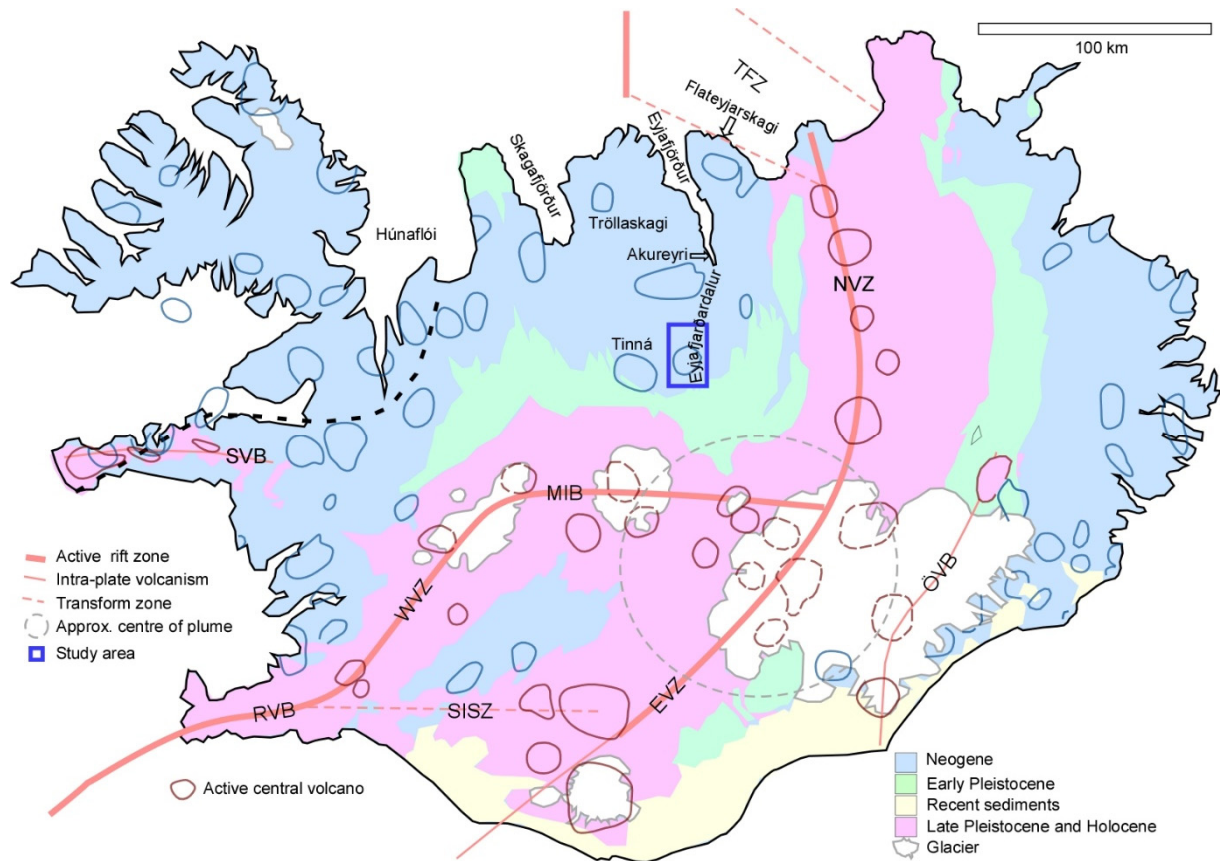


Figure A2.1. Generalized geological map of Iceland (modified from Hjartarson & Sæmundsson, 2014), highlighting active and fossil central volcanoes and active volcanic zones. The proposed axis of the palaeo SHRZ is from Sæmundsson (1979) and Jóhannesson (1980). The approximate centre of the Iceland mantle plume, as depicted by Wolfe et al. (1997), is indicated with a grey, dotted circle. RVB: Reykjanes Volcanic Belt; SVB: Snæfellsnes Volcanic Belt, WVZ: Western Volcanic Zone, MIB: Mid Iceland Belt; SISZ: South Iceland Seismic Zone; EVZ; Eastern Volcanic Zone; ÖVB: Öræfi Volcanic Belt; NVZ: Northern Volcanic Zone; TFZ: Tjörnes Fracture Zone.

Geological background

The study area is within and around the Torfufell central volcano (ToCV) in the southern part of the Eyjafjarðardalur valley, approximately 40 km south of the largest town in North Iceland, Akureyri (Fig. A2.1). The area is within the region of the glacially eroded fjord of Eyjafjörður in central North Iceland. The Eyjafjörður region is composed of sequences of flat-lying Miocene basaltic lavas, commonly interbedded with layers of lithified sediments consisting largely of weathered, wind-blown tephra mixed with ancient soils (Sæmundsson, 1979; Sæmundsson et al., 1980; Roaldset, 1983). The originally sub-horizontal lava pile now tilts regionally a few degrees to the south, i.e. towards SW in the northern part, turning to SE in the southern part (e.g., Sæmundsson et al., 1980). Several Miocene central volcanoes are identified in the region (e.g., Hjartarson and Sæmundsson, 2014), interrupting the monotony of the basaltic lava pile with complex structures and various rock types, including the Torfufell central volcano and the neighbouring Tinná central volcano, situated only ~15 km apart (Fig. A2.1). The main features of the bedrock in the present study area are illustrated in small-scale geological maps of Iceland (e.g., Hjartarson and Sæmundsson, 2014), delineating silicic volcanic formations – centered in Mt. Torfufell and enveloped by basaltic lavas – just beneath the boundary between the Miocene and Pliocene periods. Stratigraphic profiling and palaeomagnetic measurements have demonstrated the stratigraphy of Mt. Hólafjall in the eastern part of the area (Fig. A2.2) in more details, e.g., covering the eastern edge of the central volcano's rhyolite products and depicting a thick series of plagioclase- and olivine phyric lavas in the mountain's uppermost section (Kristjánsson et al., 2004; Supakulopas, 2018 (also described in Muxworthy, 2024)).

Geology, stratigraphy and lithostratigraphical relations of the ToCV are described in Árnadóttir et al. (in prep), while U-Pb zircon ages of six silicic samples from the volcano are presented in Árnadóttir et al. (2023). The field observations demonstrate that tectonic uplift and glacial erosion has exposed extrusive rocks and shallow intrusions of the ToCV. Below the central volcano are basaltic plateau lavas, both aphyric/sparsely phyric and porphyritic. A transition from thick (>5 m), grey lavas to unusually thin (<5 m), black lavas of *ā*'a type has been suggested to represent the transition from predominantly fissure-fed eruptions toward central volcanism and thus the base of the volcanic edifice (Árnadóttir et al., in prep). Such unusually thin, phenocryst-free lava flows have been observed to be abundantly erupted from Icelandic central volcanoes (Sæmundsson, 1979) and interpreted to be abnormally thin as they were erupted onto a sloping landscape resulting from the build-up of central volcanism (Walker, 1963). Therefore, we have a reason to assume that these thin *ā*'a lavas observed in the ToCV area are sourced from the central volcano and erupted during its early phases. About 200-300 m above the fissure-fed/central volcano transition is the base of intermediate and silicic lavas, underlain in several locations by a noteworthy smectite-, tephra-, and fossil-bearing sediment horizon that marks a minor hiatus in accumulation of the volcanic succession (via correlation with Supakulopas, 2018). Outcropping silicic and intermediate extrusive units belonging to the volcano are thickest in the northern part of Mt. Torfufell, where they form a ~350 m thick pile. The lowermost ~30-60 m of this pile are composed of andesite and dacite lavas, which are overlain by thicker rhyolite lavas. Different palaeomagnetic polarities and sediments and individual basaltic to andesitic lavas separating the rhyolite lavas manifest that these are several discrete formations. The silicic volcanism was accompanied by silicic intrusions that are exposed at shallow levels (up to ~300 m below the base of the silicic/intermediate lavas), with evidence of magma ascending through transgressive sills and erupting through sub-vertical dykes as well as sub-cylindrical conduits. The complex of silicic extrusive formations is abutted and overlain by basaltic lavas – including a thick series of olivine- and plagioclase phyric basalts – assumed to be originated from nearby fissure swarms. As a swarm of basaltic dykes, observed north of the silicic/intermediate complex, is of unclear affinity, it is not apparent if a regional fissure swarm was associated with the Torfufell volcanic system or not.

Sampling and analytical methods

32 samples from the mapped strata pile were carefully selected for this study. The sampling locations are presented in Fig.A2.2. The selected samples are collected from extrusive (n=25) and intrusive (n=2) rocks belonging to the ToCV, as well as from the enveloping plateau lavas, both overlying (n=2) and below the volcano (n=2) in addition to an overlying feeder dyke (n=1). Of the 25 extrusive samples collected from the central volcano, 10 samples are from basaltic lavas, 1 is from a basaltic andesite lava, 3 are from andesite lavas, 1 is from a dacite lava and 5 from rhyolite lavas, while 5 samples are from silicic pyroclastic flows. Of the pyroclastic samples, sample 10082018-1 is a pumice from the same formation as 26082015-25 (which is a whole-rock ignimbrite sample); samples 18072017-3a and 18072017-3b are also collected from the same ignimbrite formation, and sample 20180904-3 is obsidian obtained from a block-and-ash-flow deposit. One of the silicic intrusion samples is from the interiors of a volcanic conduit while the second sample is from a sill. All 32 samples were subjected to whole-rock geochemical investigation via ICP-OES analyses.

One of the 32 samples (20180904-3), consisting of pure and unaltered obsidian, was selected to represent glass geochemistry of silicic products at the volcano via analyses by Electron Probe Microanalyser (EPMA). Six of the 32 samples, representing the spectrum of basaltic to rhyolitic volcanic products of the ToCV, were selected for petrographic studies and mineral chemistry via Scanning Electron Microscope equipped with a LINK AN 10 000 ED detector (SEM/EDS). These six samples were collected from (1) a thin basaltic lava flow of *ā'a* type, considered to represent the base of the volcanic edifice (sample 24072017-0); (2) basaltic andesite, marking the base of the intermediate/silicic extrusive portion of the central volcano (sample 27072017-2), (3) andesite (sample 01092016-1), (4) dacite, representing the initiation of silicic volcanism (sample 27072017-1), and (5,6) rhyolites representing the later phases of activity at the volcano (samples 10072017-3 and 27072017-3).

Whole-rock geochemistry

Whole-rock major (SiO_2 , Al_2O_3 , FeO , MnO , MgO , CaO , Na_2O , K_2O , TiO_2 and P_2O_5) and selected trace element (Ba, Co, Cr, Cu, Ni, Sc, Sr, V, Y, Zn and Zr) compositions were measured for all 32 samples by means of a ThermoFisher iCAP 7400 ICP-OES instrument hosted at the Institute of Earth sciences at the University of Iceland. The analytical procedure is based on a method developed by Govindaraju and Mevelle (1987) and follows a scheme previously published by Halldórsson et al. (2008) and Halldórsson et al. (2022). Preparation, also performed at the University of Iceland, included cleaning of organic and weathered material and secondary fillings from the samples, followed by crushing, using a steel jaw crusher, and fine-grinding (powdering) in an agate mill. 100 mg of the powder were weighed in carbon crucibles along with 200 mg of flux (LiBO_2) and the mixture was kept at 1000°C for 30 minutes to fuse the mixture. The mixture then solidified into homogeneous glass beads upon cooling. The beads were dissolved in acid made of 5% HNO_3 , 1.33% HCl and 1.33% oxalic acid. Calibration was based on analyses of in-house reference samples (A-THO-, B-THO and B-ALK; defined by Óskarsson et al., 1979; 1982) and international rock standards (RGM-1 and K1919).

Glass geochemistry

Geochemistry of silicic glass was obtained by use of JEOL JXA-8230 SuperProbe Electron Probe Microanalyser (EPMA) hosted at the Institute of Earth sciences at the University of Iceland - equipped with five wavelength-dispersive spectrometers and a LaB6 electron emitter. The glass was analyzed with an accelerating voltage of 15 keV, a 10 nA probe current and a beam of 10 μm in diameter. Calibration was based on analyses of the A-THO reference sample. Altogether 10 spots were analysed within the obsidian sample.

Petrography and major element composition of minerals

A petrographic study was carried out by observations of thin sections of six samples in a petrographic microscope. The thin sections were further examined via analyses of major element composition of minerals in a Cambridge S360 SEM equipped with a LINK AN 10 000 ED detector, hosted at Dipartimento di Scienze della Terra e Geoambientali of the University of Bari, Italy. Operating conditions were 15 kV accelerating potential, 1 nA probe current and a 25 mm working distance. Standards manufactured by Micro-Analysis Consultants Ltd. were used for standardization.

Results

Petrography of basaltic to rhyolitic lavas of the ToCV

The six samples, selected as representatives of the petrography of basaltic to rhyolitic lavas of the ToCV, were collected from (1) a thin basaltic lava flow of *ā'a* type, considered to define the base of the volcanic edifice; (2) basaltic andesite and (3) andesite, representative of the volcano's intermediate products; (4) dacite, representing the initiation of silicic volcanism; and (5,6) rhyolites formed in the later phases of activity at the volcano. Textures of the six samples range from aphanitic to glassy, resulting from rapid solidification of extruded magma, generally with low porphyry index (<1%) and with phenocryst sizes ranging from ca. 0.1 to 2 mm. Petrography of the six samples is described hereunder and overview images of thin sections are given in Fig.A2.3.

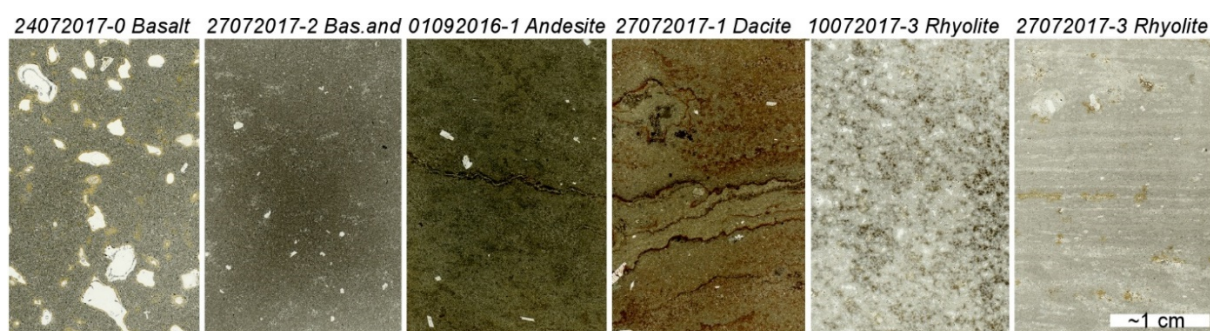


Figure A2.3. Thin section scans of the six samples selected for analysis of mineral chemistry. From left to right: sample 24072017-0 (basalt) containing augite, aluminian augite, labradorite and bytownite; sample 27072017-2 (basaltic andesite) containing pigeonite, augite, aluminian augite, labradorite and andesine; sample 01092016-1 (andesite) containing augite, sanidine, labradorite, and andesine; sample 27072017-1 (dacite) containing augite, aluminian augite, andesine and labradorite; sample 10072017-3 (rhyolite) containing anorthoclase and sanidine; sample 27072017-3 (rhyolite) containing anorthoclase and oligoclase.

The sample from the basaltic *ā'a* lava (24072017-0) is fresh and fine-grained with intergranular texture. The sample is vesicular, with vesicles 30-40% of the volume, up to 2 cm in diameter, and occasionally slightly elongated. Vesicles are coated or filled with light-brown clay (often ~0.2 mm thick), and a slight alteration aureole is observed in the groundmass next to vesicle walls. The groundmass is composed of pyroxene (~0.01-0.1 mm) and elongate plagioclase (~0.1-0.4 mm long) microlites with interstitial opaque minerals and altered glass, and with clay occurring as alteration spots. Macrocrysts are sparse and consist of plagioclase (up to ~1.5 mm long) and small pyroxene (~0.1-0.2 mm) crystals. No olivine is observed. The sample material is fractured; both in the vesicle walls and in the groundmass.

The basaltic andesite sample (27072017-2) is fine-grained, dark coloured and dense, with few and small vesicles. The sample is fine-grained and the groundmass consists of plagioclase and pyroxene microlites

(typically ~0.05-0.1 mm and 0.01-0.04 mm, respectively) and a large number of oxides. The texture is primarily intergranular, with plagioclases mostly randomly oriented, and with interstitial pyroxene. The porphyritic index is very low, with only a few plagioclase and pyroxene macrocrysts. The pyroxene phenocrysts are smaller (typically ~0.2 mm; up to ~0.5 mm long) than the plagioclase macrocrysts (up to ~1 mm) and with very slight green colour. Oscillatory zoning is observed in the plagioclase macrocrysts.

The andesite sample (01092016-1) is fine-grained and dense (i.e. massive), with no vesicles and with an orange-brown weathering coat. The rock is sparsely porphyritic and mostly composed of microlitic plagioclases which are elongated (typically 0.05-0.1 mm long) and arranged into localized flow textures, with a tendency to trachytic texture. Macrocrysts are plagioclase and pyroxene; up to ~1.2 and ~1 mm, respectively. The larger macrocrysts are often regular. No vesicles are observed in the sample. A thin vein, possibly composed of quartz, crosscuts the thin section.

The dacite sample (27072017-1) consists of aphanitic and dark grey groundmass that appears to be originally very rich in glass, composed of plagioclase (typically ~0.1 mm long), pyroxene (~0.01 mm) and opaque minerals, with sparse macrocrysts of plagioclase (~2 mm long), often with inclusions of opaque minerals, and elongated pyroxene (typically ~0.3 mm long). A vein with possible hydroxides is observed, and the rock is locally altered next to the vein. A basaltic xenolith, ~1 mm in diameter, is observed inside the thin section. The xenolith has ophitic texture, with random plagioclase laths (~0.05-0.2 mm long) enclosed by larger (~0.2-0.3 mm) pyroxene crystals.

Rhyolite sample 10072017-3 is from a flaky and flow-banded rhyolite lava. Texture is aphanitic to glassy, with sparse feldspar phenocrysts. Some spherulitic arrangements are present, which can be related to devitrification, indicating that the groundmass used to be very glassy. Each spherulite is typically ~0.2 mm in diameter. Late alkali feldspar (twinned) is observed inside vesicles. The groundmass is composed of quartz and alkali feldspar essentially, with some opaque minerals also observed. Some minerals are observed which are reddish in colour in plane polarized light, probably related to weathering and oxidation.

Rhyolite sample 27072017-3 is from dense, aphanitic to glassy flow-banded rhyolite with few vesicles and spots of orange alteration. Phenocrysts are few and mostly subhedral plagioclases, in addition to a few large titanomagnetite crystals. The groundmass is rich in glassy material but dominated by feldspar microlites, often preferentially oriented in a flow texture. In plane polarized light, white and grey bands are seen, as well as orange alteration. Flow bands consist of cryptocrystalline material and coarser grained material. Zeolites are observed in a fracture.

Whole-rock geochemistry: major and selected trace elements

In total 32 samples were analyzed by ICP-OES. The whole-rock major and selected trace element analyses are given in Tables A2.1 and A2.2, and in Supplementary Table S2.3. These samples range in SiO₂ content from 46 to 76 wt.%. Arrangement in order of stratigraphic position (Supplementary Table S2.3 and Fig.A2.4) documents that the lowermost 8 samples are basaltic in composition. Interestingly, it appears that the samples from the abovementioned unusually thin á lavas are rather evolved and more evolved than the underlying basalts (~50-52 wt% SiO₂ in samples 24072017-0 to -3 and 20180903-3 compared to ~49 wt% SiO₂ in samples 20072017-2 and 14072015-12). This may indicate longer residence for the magma in the upper crust or stronger interaction with the crust or both. This supports Árnadóttir et al.'s (in prep) hypothesis that these lavas are sourced from the central volcano during its early stages of activity. These lavas, in addition to those inside the rhyolitic lava pile, are considered in this study as lavas sourced from the central volcano, while lavas below the á lavas and above the

rhyolitic extrusive formations are considered as enveloping plateau basalts, except for those resting directly on top of the rhyolites (explained below). All intermediate and silicic samples are assumed to be sourced from the central volcano as such formations are normally unable to flow long distances due to high viscosity and are therefore found at or very close to the eruptive site, contrary to basaltic lavas that may flow tens of kilometres to be observed far away from the eruptive fissure.

Table A2.1 (continued in Table A2.2). ICP-OES determination of whole-rock major-element oxides of 32 samples representative of the Torfufell central volcano (CV) and enveloping basalts (EO = overlying, EU = underlying). Basaltic lavas from the ā'a and pahoehoe sequence below the intermediate/silicic portion of the volcano are indicated with a (ā'a) and p (pahoehoe); basaltic lavas in the middle of the rhyolite are indicated with m and basaltic lavas just above the rhyolite are signified with o. Feldspar phyric samples are indicated with fp and pyroxene phyric samples with pp. See detailed table in the Supplementary material.

Sample Id.	Group	SiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅
		Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
27072017-5	CV-m	46.42	14.72	13.54	0.22	7.67	11.03	2.20	0.27	3.38	0.38
20180904-2	CV-m, pp	46.78	14.58	15.25	0.24	6.96	9.44	2.43	0.35	3.45	0.36
25072018-1	EO(Dyke)-fp	47.46	17.68	9.73	0.16	6.63	14.14	2.09	0.19	1.66	0.12
10072017-4	EO-fp	47.88	17.67	10.17	0.17	6.59	13.55	2.01	0.11	1.60	0.13
20180903-3	CV-p	48.24	13.01	15.03	0.27	5.50	10.48	2.78	0.20	3.85	0.47
18072017-1	EO-fp	48.54	15.31	11.55	0.20	7.17	12.12	2.37	0.24	2.16	0.20
14072015-12	EU	48.92	15.57	10.88	0.20	6.61	12.54	2.42	0.25	2.24	0.23
20072017-2	EU	49.30	15.31	11.23	0.18	6.40	12.05	2.58	0.30	2.30	0.21
27072017-4	CVo	49.54	13.30	14.54	0.25	5.24	9.87	2.88	0.41	3.43	0.37
24072017-0	CV-a	49.75	13.02	14.16	0.23	5.29	10.22	2.69	0.46	3.60	0.42
24072017-3	CV-a	50.08	13.15	13.68	0.25	5.46	10.14	2.65	0.54	3.46	0.40
03072018-3	CV-o	50.12	13.24	14.20	0.25	5.28	9.59	2.88	0.62	3.30	0.38
24072017-1	CV-a	50.22	12.98	13.60	0.24	5.63	10.14	2.65	0.59	3.39	0.39
24072017-2	CV-a	50.69	12.95	13.65	0.23	5.49	10.07	2.58	0.48	3.31	0.39
20180903-1	CV-a	51.70	12.63	14.12	0.25	4.27	8.61	3.01	0.84	3.84	0.58
27072017-2	CV	56.04	13.59	11.33	0.20	3.41	7.31	3.58	1.07	2.93	0.40
20180904-1	CV	59.76	14.29	11.01	0.24	1.65	5.45	4.01	1.54	1.35	0.57
09072015-8	CV	59.83	14.11	11.36	0.27	1.44	5.48	3.95	1.51	1.35	0.56
01092016-1	CV	61.91	13.69	11.25	0.28	0.66	5.07	3.99	1.61	1.05	0.33
18072017-3b	CV	64.35	14.43	9.16	0.09	0.44	3.97	4.36	1.73	1.00	0.28
27072017-1	CV	65.63	14.24	7.70	0.21	0.47	4.29	4.23	2.08	0.76	0.21
10082018-1	CV	71.24	13.54	4.51	0.13	0.14	2.31	4.22	3.38	0.31	0.02
26082015-25	CV	72.46	13.70	4.31	0.11	0.24	2.01	4.65	2.00	0.32	0.03
10072017-3	CV	74.68	13.74	1.95	0.02	0.10	0.49	5.09	3.58	0.16	0.02
07072015-2	CV	74.71	13.66	2.01	0.06	0.01	0.64	4.98	3.59	0.17	0.00
18072017-3a	CV	74.95	12.95	2.63	0.14	0.12	1.21	4.43	3.16	0.23	0.02
24072017-4	CV	75.38	13.23	1.91	0.02	0.07	0.56	5.06	3.43	0.18	0.00
27072017-3	CV	75.60	13.16	2.01	0.02	0.08	0.52	4.86	3.39	0.16	0.02
14072017-2	CV	75.72	12.87	1.94	0.05	0.02	0.76	4.85	3.44	0.15	0.01
14072017-1	CV	75.80	13.39	1.54	0.04	0.03	0.77	4.74	3.37	0.16	0.00
20180904-3	CV	76.04	12.47	2.07	0.07	0.00	0.73	4.92	3.38	0.15	0.00
13072017-1	CV	76.29	12.83	1.71	0.02	0.06	0.48	4.88	3.42	0.16	0.01

Major and selected trace element variation diagrams for all samples are shown in Fig.A2.6. The diagrams clearly illustrate that the geochemistry of basalts from the central volcano deviates from the enveloping plateau basalts by higher TiO₂, FeO_t, MnO, K₂O and P₂O₅, lower Al₂O₃ and Ca, and higher Y, Co and Zr. Lavas classified in this image as "Basalts of the central volcano" are lavas occurring directly below, or in the center of, the silicic extrusive portion. The least evolved compositions in this group (and at the same time the least evolved compositions observed in all 32 samples) were observed in lavas sampled from the center of the rhyolite (samples 27072017-5 and 20180904-2), with 46-47 wt% SiO₂ and 5.5-7.7 wt% MgO. The most evolved lavas within this group are the thin ā'a lavas below the intermediate/silicic extrusive portion, comprising 50-52 wt% SiO₂ and 4.3-5.6 wt% MgO. Basaltic lavas resting directly on top of the rhyolite lavas (samples 03072018-3 and 27072017-4) are similarly rather

evolved, with 50 wt% SiO₂ and 5.2-5.3 wt% MgO. These lavas generally plot very close to the ā'a lavas and may therefore be considered to belong to the central volcano. With these two samples included, the central volcano samples plot in the variation diagrams within confined semi-continuous trends with regards to many major and trace elements, in particular TiO₂, FeO_t, MgO, CaO, Na₂O, K₂O, Ba and Co. It is however noted that Na, K and Ca are very mobile in incipiently to mildly altered volcanic rocks and hence for the types of rocks discussed in the present paper. Thus, any classification that involves these elements should be approached with caution.

When plotted on the K₂O vs. SiO₂ diagram (Fig.A2.5, bottom left), the majority of products belonging to the central volcano fall in Ewart's (1982) field of medium-K calc-alkaline series, while the rhyolites reach into the high-K calc-alkaline field. This diagram distinguishes between the central volcano products and the enveloping basalts by plotting the latter within the low-K field. The TiO₂ vs Zr(P₂O₅×10000) plot (bottom right in Fig.A2.5) shows the discrimination between alkali basalts and tholeiite basalts after Winchester and Floyd (1976) and plots the Torfufell basalts as mildly alkaline. The samples from the enveloping basalts are porphyritic, with the composition of olivine tholeiites. The composition of a porphyritic basalt dyke in Mt. Hólafljall (sample 250272018-1) matches a porphyritic lava (sample 18072017-1) located between the rhyolite complex and a massive olivine basalt group by the top of the composite stratigraphic profile. Although the dyke is plagioclase- and olivine phyric while the sample from the lava contains only plagioclase macrocrysts, it is still considered likely that this dyke was the feeder of the porphyritic lava flow.

Table A2.2. Continuation of Table A2.1. ICP-OES determination of selected trace elements of 32 samples representative of the Torfufell central volcano (CV) and enveloping basalts.

Sample Id.	Ba	Co	Cr	Cu	Ni	Sc	Sr	V	Y	Zn	Zr	Σ Norm %	Σ Run %
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm		
27072017-5	77.21	75.53	178.43	150.72	138.95	43.68	277.22	386.54	38.13	128.90	176.52	100.00	95.79
20180904-2	82.16	80.02	64.98	207.09	99.92	38.26	213.25	486.16	43.96	147.39	190.93	100.00	95.11
25072018-1	38.68	50.87	209.76	142.26	73.71	43.61	195.70	313.56	20.50	87.14	76.19	100.00	98.93
10072017-4	35.31	52.56	171.02	164.85	142.67	42.54	196.98	286.48	22.88	89.95	84.39	100.00	95.48
20180903-3	78.75	76.43	27.35	194.91	44.21	45.23	278.80	440.16	53.55	181.97	258.70	100.00	98.97
18072017-1	70.96	58.29	111.80	97.38	89.35	41.85	220.02	322.16	27.58	99.13	123.22	100.00	102.06
14072015-12	67.37	56.89	137.99	130.65	69.91	39.91	289.76	309.38	26.94	106.87	132.42	100.00	95.54
20072017-2	72.39	58.80	46.69	138.33	66.31	38.07	287.02	311.66	27.25	107.57	131.04	100.00	96.10
27072017-4	182.10	68.48	37.77	113.97	36.31	41.68	213.47	457.46	54.25	135.66	237.04	100.00	99.66
24072017-0	95.53	70.66	40.54	113.27	50.17	43.06	267.32	437.34	50.85	137.68	254.18	100.00	98.04
24072017-3	326.83	68.27	40.66	156.13	42.45	41.83	264.88	408.14	52.73	138.78	247.26	100.00	97.21
03072018-3	128.62	67.15	43.98	93.15	36.32	41.50	209.43	435.00	56.56	137.63	236.89	100.00	96.53
24072017-1	112.15	68.88	45.49	124.70	44.50	41.78	261.36	414.97	48.32	132.06	242.43	100.00	100.25
24072017-2	110.90	67.74	44.48	107.57	47.50	41.43	259.93	420.84	47.82	134.11	232.31	100.00	97.13
20180903-1	179.72	64.28	7.78	28.61	8.78	37.48	282.87	325.79	67.60	148.18	330.17	100.00	101.65
27072017-2	232.80	48.43	4.20	39.46	3.52	29.92	236.04	239.50	60.69	124.60	287.37	100.00	97.02
20180904-1	287.95	19.43	3.39	22.49	4.95	30.04	218.25	3.31	85.64	150.16	415.60	100.00	99.66
09072015-8	286.52	19.24	4.19	31.08	2.77	31.25	224.54	2.29	92.59	157.06	455.61	100.00	94.26
01092016-1	313.50	11.38	4.19	24.63	5.03	39.86	212.80	4.49	93.39	159.52	606.15	100.00	94.57
18072017-3b	341.61	10.34	5.24	21.74	4.62	33.49	214.67	7.87	93.54	180.30	713.30	100.00	94.94
27072017-1	351.15	7.39	4.49	22.66	5.06	29.20	191.41	5.15	83.76	133.51	713.73	100.00	98.38
10082018-1	498.08	1.13	3.97	16.35	4.71	7.69	144.37	6.23	127.52	139.71	640.67	100.00	93.58
26082015-25	476.12	1.30	4.05	16.16	3.55	7.44	144.60	8.78	115.31	132.47	594.91	100.00	97.26
10072017-3	638.86	0.72	6.60	21.06	6.54	1.38	68.45	18.42	112.21	136.41	367.47	100.00	93.07
07072015-2	633.07	0.42	5.54	17.28	6.43	1.19	80.00	7.21	124.83	142.42	387.38	100.00	92.05
18072017-3a	575.44	1.29	5.28	25.24	15.16	6.35	101.06	10.49	78.05	80.94	377.12	100.00	94.76
24072017-4	603.53	0.48	5.28	21.27	8.27	1.48	73.67	15.75	55.24	125.42	381.36	100.00	98.47
27072017-3	599.02	bdl	5.98	16.04	4.92	1.36	74.21	17.43	95.95	128.89	375.15	100.00	98.60
14072017-2	621.91	0.11	4.49	14.46	5.19	0.77	90.27	10.27	113.92	138.58	379.74	100.00	89.29
14072017-1	605.47	0.30	3.48	36.61	37.93	0.62	87.83	6.67	54.33	132.77	353.35	100.00	95.97
20180904-3	598.27	0.18	4.56	15.87	4.35	0.95	63.08	4.52	138.54	141.40	392.99	100.00	101.59
13072017-1	606.78	bdl	4.88	16.05	4.28	1.30	74.70	12.56	58.71	128.40	377.15	100.00	92.67

*bdl: below detection limit

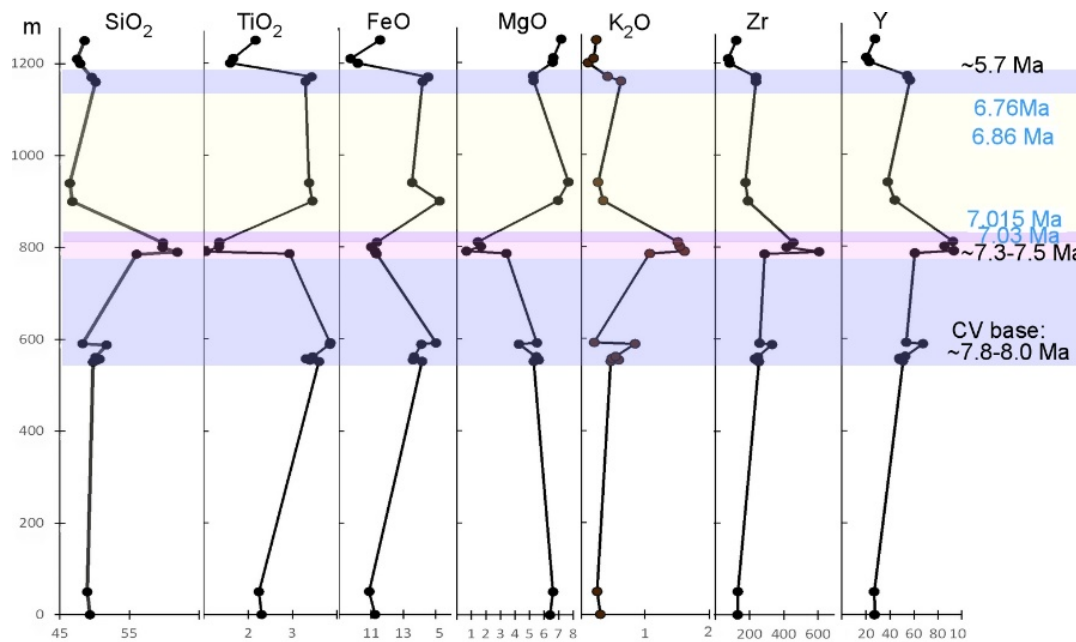


Figure A2.4. Major and selected trace element concentrations plotted against stratigraphic position (approximated thicknesses, not to scale). Samples over 64 wt% SiO_2 are not shown. Positions of basaltic, andesitic, dacitic and rhyolitic activity of the central volcano are indicated with blue, pink, purple and yellow, respectively. U-Pb zircon ages from Árnadóttir et al. (2023) are given in blue writing, and approximate age correlations (by same authors) with Supakulopas (2018) are indicated in black writing.

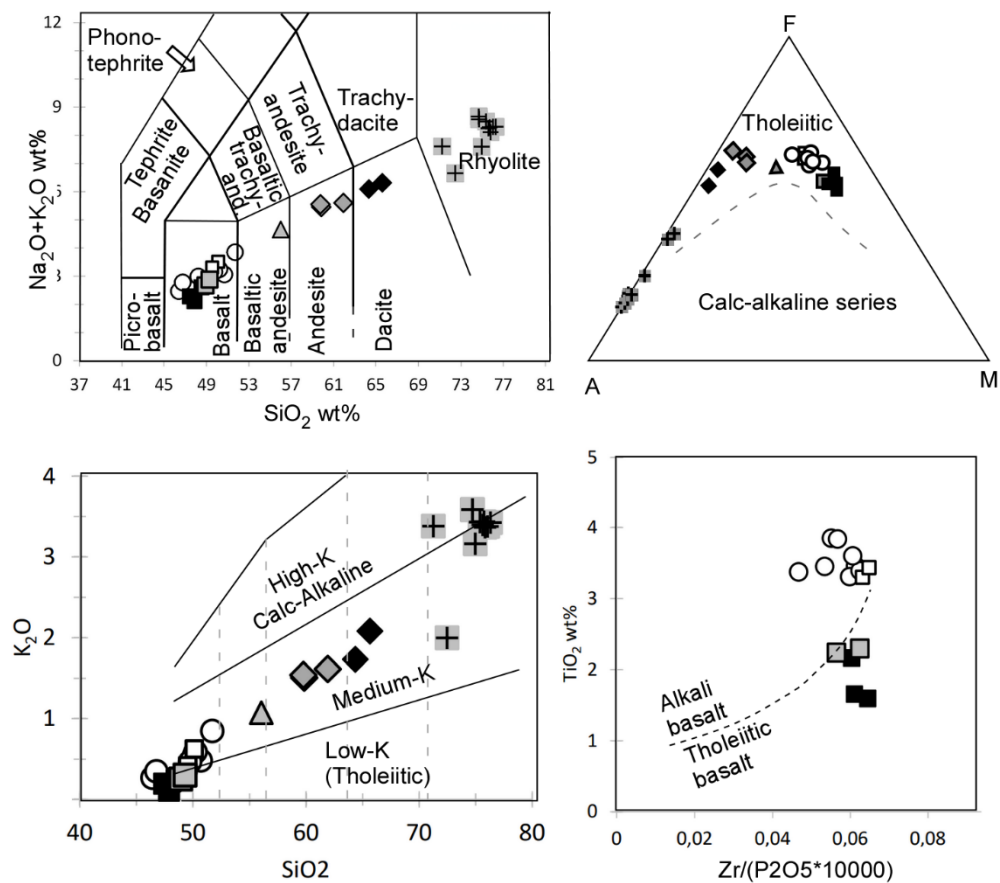


Figure A2.5. Top left: The Torfufell whole-rock geochemical data presented on a total alkalies-silica (TAS) diagram (Le Bas et al., 1986). Top right: Same data plotted on AFM Diagram showing Irvine & Baragar's (1971) discrimination between the tholeiitic and calc-alkaline series. Bottom left: K_2O - SiO_2 diagram (modified after Ewart, 1982; Best, 2003) showing the Torfufell samples. Bottom right: TiO_2 vs $Zr/(P_2O_5 \cdot 10000)$ plot showing the discrimination between alkali basalts and tholeiite basalts after Winchester and Floyd (1976). Same legend as in Fig.A2.6.

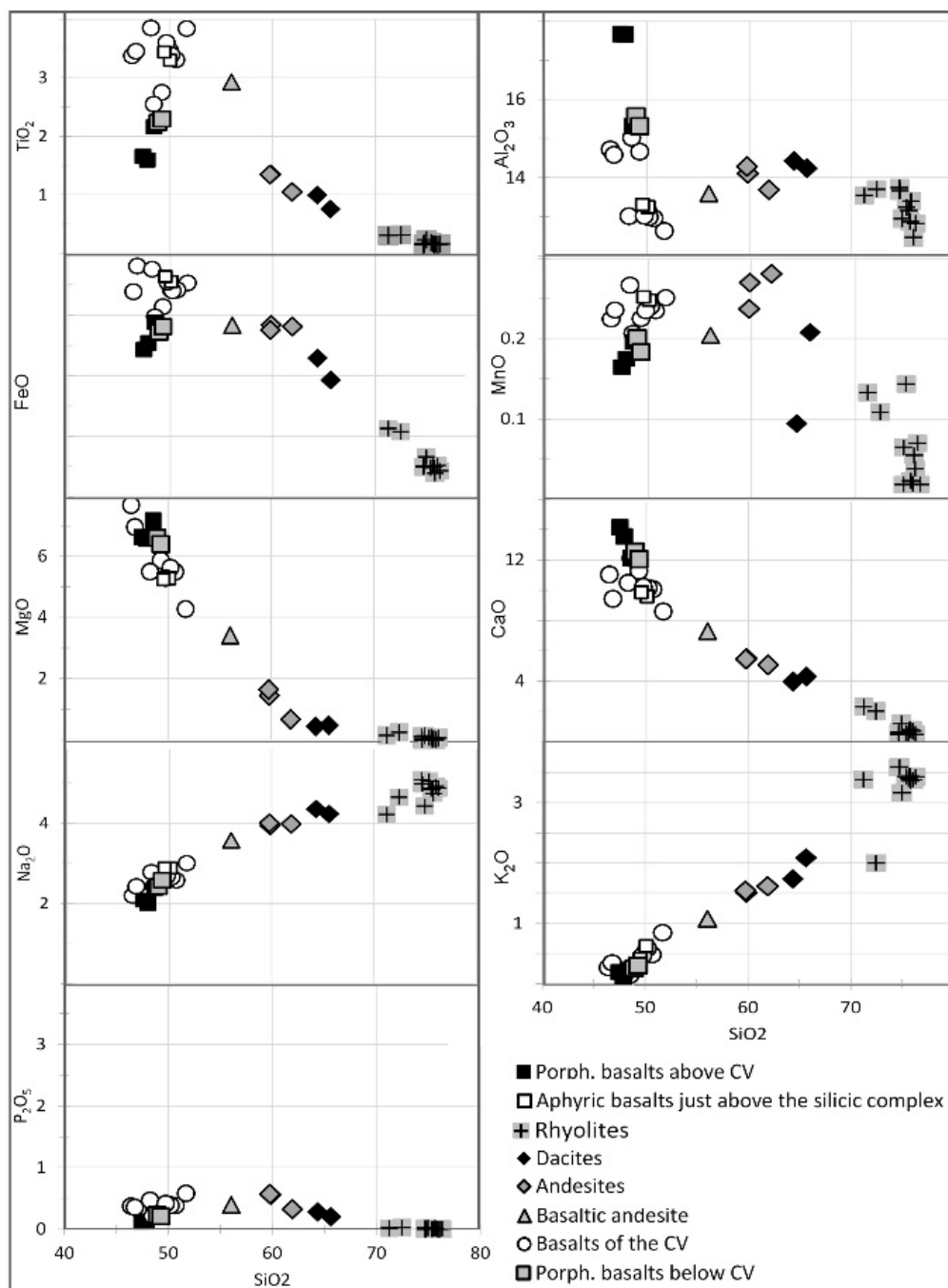


Figure A2.6 (continued on next page). Major elements (in wt%), plotted against SiO_2 .

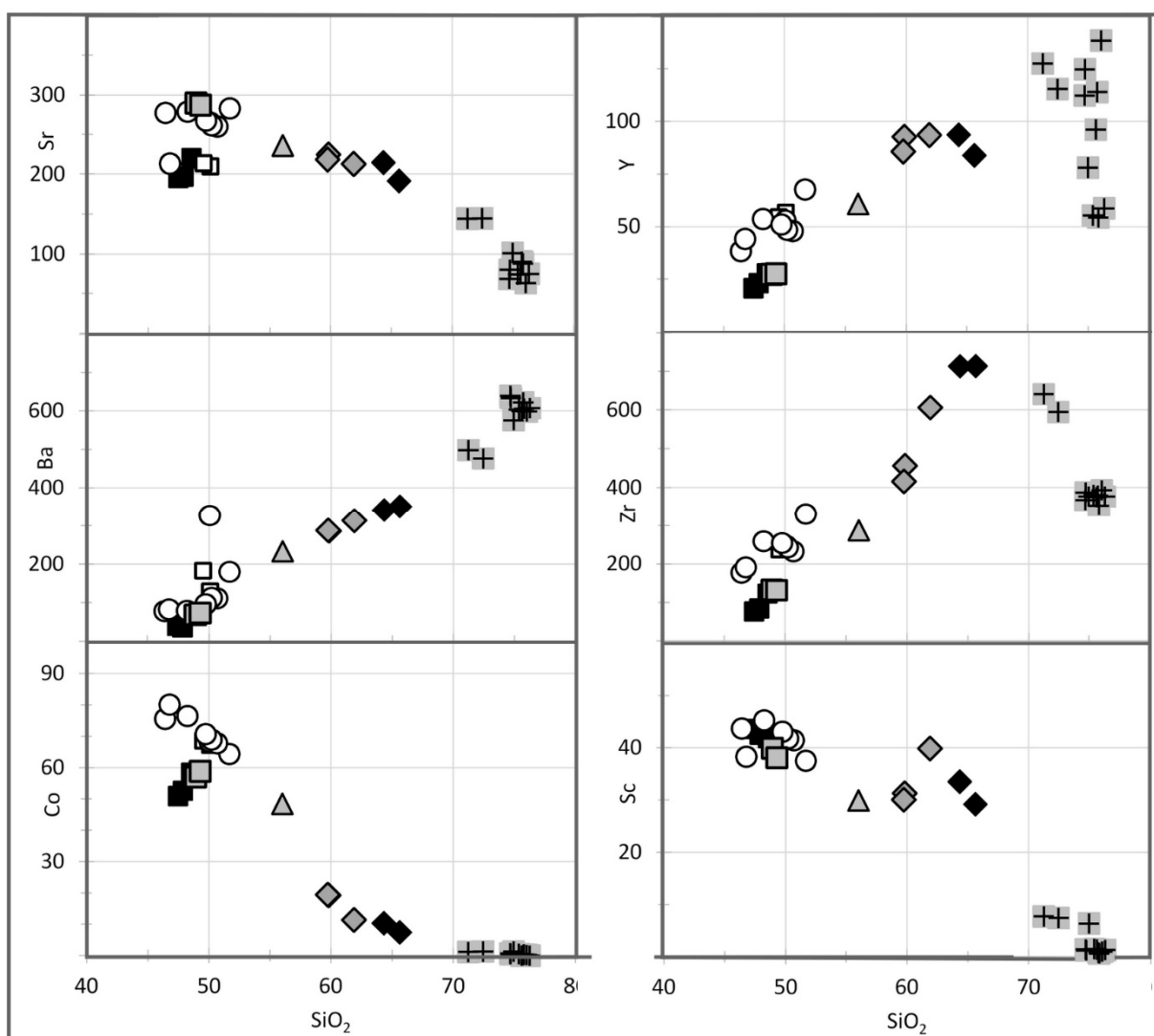


Figure A2.6. (continued). Selected trace elements (in ppm), plotted against SiO₂.

Glass geochemistry

A pure and unaltered obsidian is observed in a pyroclastic flow deposit, interpreted as a block-and-ash-flow, by the SE edge of the silicic complex of the ToCV. Sample 20180904-3, consisting of an obsidian collected from this formation, was selected to represent the glass geochemistry of the silicic portion of the ToCV. The geochemistry of the sample was analyzed via EPMA. The results (Table A2.3 and Fig. A2.7) document that the glass composition plots close to Kerlingarfjöll, Prestahnúkur and Hekla rhyolites on a TiO₂ vs FeO plot. It is noted in Table A2.3 that SiO₂ in the obsidian sample is unusually high for Icelandic rhyolite. This may be related to slight hydration in the glass; hence it may have lost some of its Na and Ca or gained some K.

Table A2.3. Results of microprobe analysis of obsidian (sample 20180904-3; in mass%).

Analysis id.	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Sum
Torfufell-1	76.26	0.14	12.27	2.02	0.08	0.01	0.79	4.47	3.38	bdl*	99.42
Torfufell-2	76.67	0.16	12.27	2.01	0.09	bdl	0.77	4.26	3.43	0.02	99.68
Torfufell-3	76.21	0.14	12.21	2.08	0.08	0.02	0.77	4.59	3.46	bdl	99.55
Torfufell-4	76.87	0.11	12.08	2.02	0.11	0.01	0.72	4.39	3.36	bdl	99.67
Torfufell-5	77.01	0.12	12.28	1.96	0.06	0.02	0.77	4.72	3.36	bdl	100.29
Torfufell-6	76.71	0.16	12.28	1.96	0.06	0.01	0.75	4.56	3.47	bdl	99.96
Torfufell-7	76.52	0.15	12.42	2.00	0.07	0.01	0.73	4.52	3.31	bdl	99.72
Torfufell-8	76.42	0.16	12.34	1.94	0.09	bdl	0.76	4.43	3.42	0.04	99.60
Torfufell-9	76.38	0.12	12.32	2.01	0.13	0.01	0.73	4.27	3.40	bdl	99.36
Torfufell-10	77.08	0.14	12.25	1.98	0.06	bdl	0.63	4.61	3.42	bdl	100.17

*bdl: below detection limit

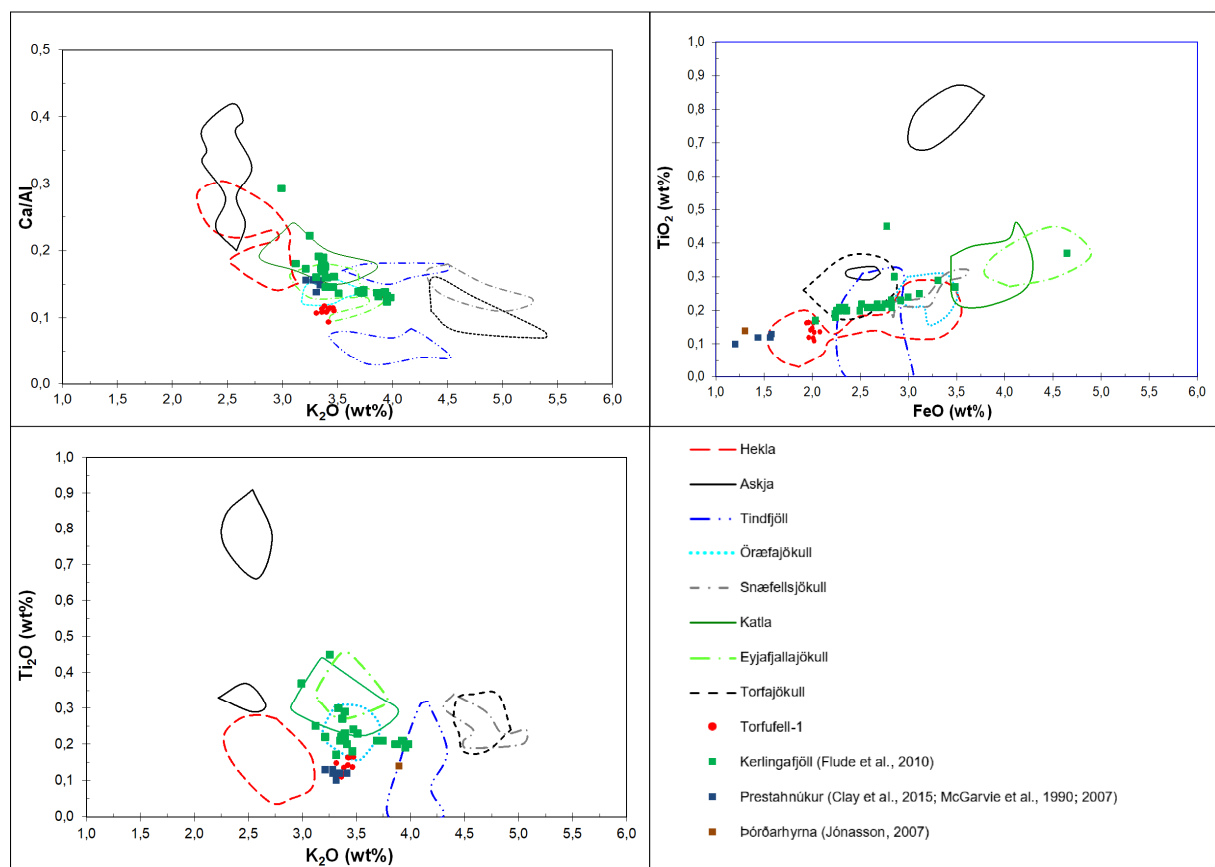


Figure A2.7. Comparison of sample 20180904-3 with tephra and obsidian samples from active central volcanoes in Iceland (Hekla, Katla, Eyjafjallajökull, Torfajökull, Tindfjöll and Hekla (including H3 and H4) in the EVZ; Öraefajökull in the ÖVB; Snæfellsjökull in the SVZ; Askja in the NVZ; Kerlingarfjöll in the MIB (data from Jennings et al., 2014; Harning et al., 2018; Flude et al., 2010); Prestahnúkur in the WVZ, close to its junction with the MIB (data from Clay et al., 2015; McGarvie et al., 1009; 2007); Þórðarhyrna in the northern part of the EVZ (data from Jónasson, 2007).

Major element composition of minerals

Major element composition of minerals in the six samples (samples 24072017-0, 27072017-2, 01092016-1, 27072017-1, 10072017-3 and 27072017-3) has been obtained through SEM/EDS. The samples represent the compositional range found at the ToCV. Since the minerals are mostly unaltered, the SEM analyses are considered representative of the primary phases, and suitable for classification purposes and calculation of crystal formulae. Selected results are given in Tables A2.4 to A2.6 and detailed results are presented in Table S2.1 of the Supplementary material.

Composition of the major constituent minerals, plagioclase and pyroxene, are summarized in Fig.A2.8, with micrographs and backscattered electron image examples presented in Fig.A2.9. All analyzed spots are given in Figures S2.1-S2.8 of the Supplementary material. The compositional variation of constituent minerals is discussed below.

Feldspar

Plagioclase compositions range from An_{16-21} in rhyolites to An_{56-79} in the basalt. The basalt sample contains plagioclase phenocrysts that are bytownitic in the core (An_{74-79}), increasing in Na towards a labradoritic rim (An_{58-70}) which is similar in composition to the microlites. Bytownitic plagioclases, similar to the cores in the basalt sample, are also documented in a basaltic xenolith observed in the dacite sample. Plagioclase compositions are very similar in the basaltic andesite and the andesite samples, ranging from andesine to labradorite (An_{33-55}), while the dacite crystals fall into a slightly narrower range (An_{40-54}). Microlites in the basaltic andesite are labradoritic (An_{51-55}), while phenocrysts are andesinic in the core (An_{41-45}), increasing in albite towards the internal rim (An_{32-40}), then increasing again in anorthite, resulting in either andesinic or labradoritic external rim (An_{42-54}). Microlites in the andesite occur as andesine to andesine/labradorite (An_{47-49}) while phenocrysts are either andesinic in both core and rim or labradoritic in both core and rim. The analyzed andesine phenocrysts are slightly richer in albite in the rim than in the core (An_{49} in the core, An_{41} in the rim), while the measured labradorite phenocryst is slightly richer in anorthite in the rim than in the core (An_{50} in the core, An_{54} in the rim). Patches of both andesine (An_{31}) and sanidine (Or_{59}) are observed inside plagioclase phenocrysts in this sample. Microlites in the dacite sample are andesinitic, close to labradoritic (An_{45-48}), and while some phenocrysts are rather homogeneous (either andesinic or labradoritic), others are clearly reversely zoned with andesinic core (An_{39}) and labradoritic rim (An_{53}). Phenocrysts occurring as oligoclase (An_{16-21}) from core to rim are observed in the 27072017-3 rhyolite sample, while their outermost rims are composed of K-feldspar with the composition of anorthoclase (close to sanidine; Or_{34}). K-feldspars are observed as microlites in both rhyolite samples, occurring as anorthoclase to sanidine (Or_{19-40}).

Pyroxene

If the analysed pyroxenes are plotted on a Al_2O_3/TiO_3 vs. Mg# diagram, it can be observed that in general, the andesite and dacite samples contain pyroxenes with lower Mg# than the basaltic and basaltic andesites, and that Mg# generally decreases towards the rim, with the rims typically similar to the microlites. The basalt and the basaltic andesite pyroxenes appear to be slightly more zoned than pyroxenes in the andesite and dacite, increasing in both Mg# and Al_2O_3/TiO_2 towards the rims. Microlites appear to exhibit less spread in Al_2O_3/TiO_2 than phenocrysts. The analysed phenocrysts in the basalt sample show increase in iron towards the rim; from aluminian-augitic cores (En_{39-41}) toward augitic rims (En_{31-40}), while microlites are even richer in iron than the phenocrysts (En_{38}). In the basaltic andesite both augite and pigeonite occur in the microlites, while macrocryst cores are either aluminian augite or pigeonite, in both cases with augitic rims. All pyroxenes analysed in the andesite sample are

augitic; both microlites and phenocrysts, with phenocryst cores slightly richer in MgO (En₁₉₋₂₂) than rims and microlites (En₁₃₋₁₇). The dacite sample also contains only pyroxenes of augitic composition. The augitic phenocrysts increase in iron from Fs₃₄₋₄₁ towards very iron-rich rims (Fs₄₂₋₄₈), with microlites even slightly richer in iron (Fs₅₀).

Titanium and zirconium minerals and spherulitic glass

Analyses of opaque minerals reveal that titanomagnetite occurs in all rock types, from basalt to rhyolite. While titanomagnetite is the only type of opaque mineral recorded in the dacite sample, ilmenite was documented in the basalt and basaltic andesite samples. Zircon was found in the groundmass of both rhyolite samples (Table A2.6). Analysis of spherulitic glass in rhyolite sample 10072017-3 indicate that the glass is rich in SiO₂ (74-78 wt%), with Al₂O₃ ranging from ~11 to 12.6 wt%.

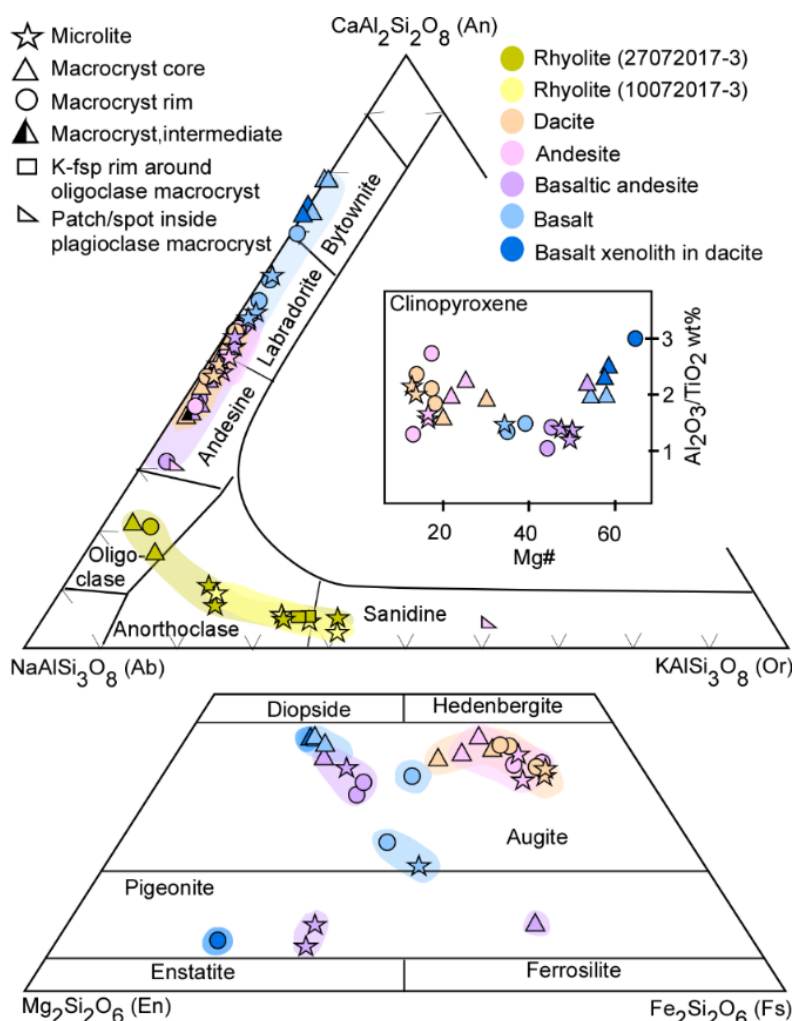


Figure A2.8. Summary of the ToCV mineral composition illustrating the compositional evolution of microlites and macrocrysts; pyroxene measurements plotted on an Al₂O₃/TiO₂ vs Mg#, and compositional variation of plagioclases and pyroxenes, presented on Ab-An-Or and En-Wo-Fs classification diagrams. Representative analytical data are presented in Tables A2.4 and A2.5, while detailed data are given in Table Table S2.1 of the Supplementary material.

Figure A2.9 (next page). Examples of spots analyzed by SEM/EDS in six samples representing the Torfufell central volcano. Petrographic microscope and SEM backscattered electron images. All analyzed spots are presented in Figures S2.1-S2.8 of the Supplementary material.

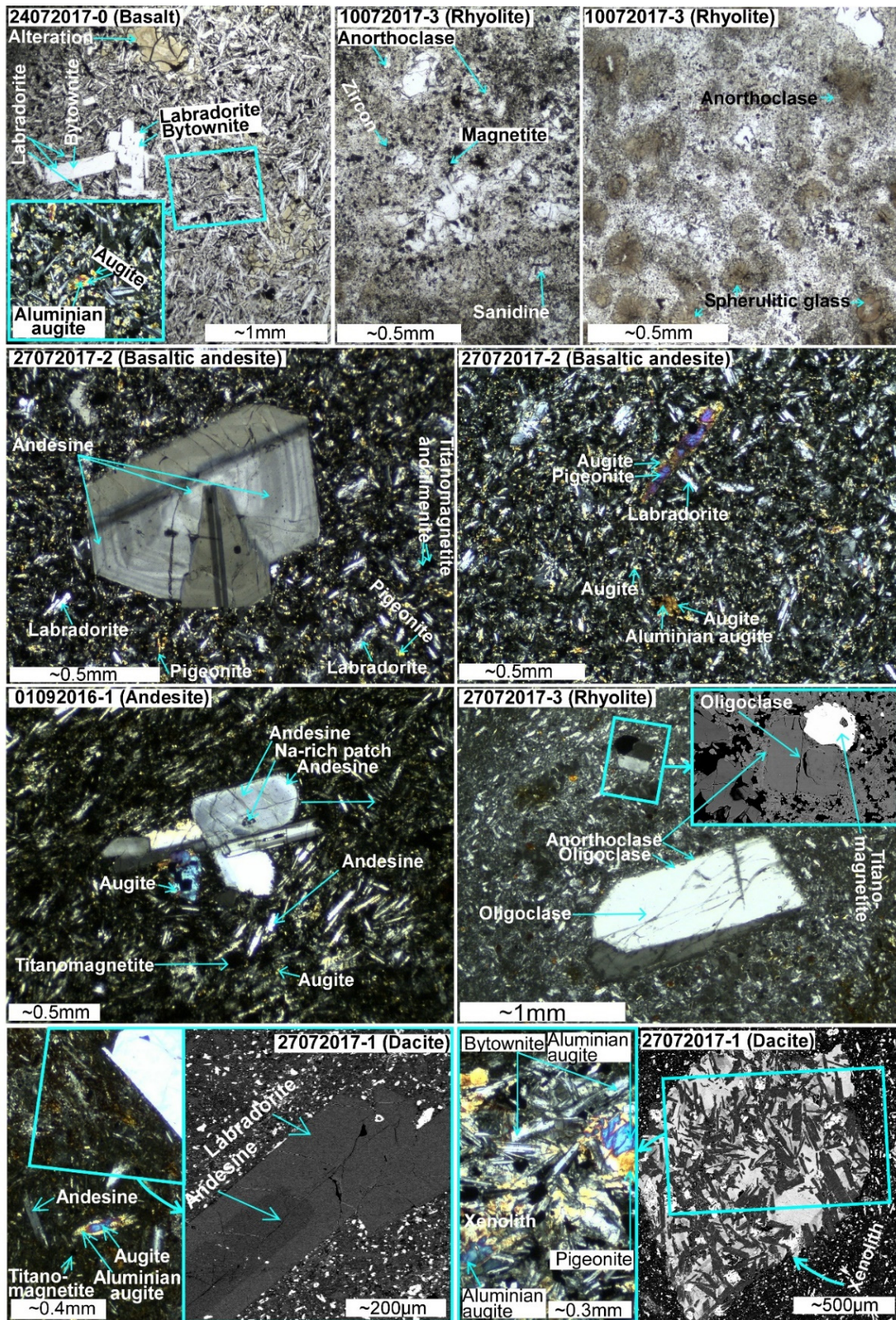


Table A2.4. Selected SEM/EDS analysis of feldspar minerals in basaltic to silicic lavas of the Torfufell central volcano. In wt. %.

Sample id	Rock type	Mineral	Analysis id.	SiO2	Al2O3	FeO	MgO	CaO	Na2O	K2O	Total	X Or	X Ab	X An	Classification
24072017-0	Basalt	Plag. Phenocryst (Rim)	2407 PI 03	53.49	27.93	0.85	0.2	12.39	4.36	0.17	99.39	0.94	36.83	62.23	Labradorite
24072017-0	Basalt	Plag. Phenocryst (Core)	2407 PI 04	48.87	31.25	0.68	0.16	16.05	2.49	0	99.51	0	21.14	78.86	Bytownite
24072017-0	Basalt	Plag. Microlite	2407 PI 06	55.48	26.95	0.94	0.13	11.19	5.1	0.29	100.09	1.59	42.57	55.84	Labradorite
27072017-2	Bas. And.	Plag. Microlite	2707_2 PI 06	55.69	27.21	1.02	0	11.05	5.2	0.31	100.48	1.71	43.51	54.78	Labradorite
27072017-2	Bas. And.	Plag. Phenocryst (Core)	2707 PI 16	59.05	24.96	0.33	0	8.25	6.47	0.4	99.47	2.3	56.58	41.12	Andesine
27072017-2	Bas. And.	Plag. Phen. (Internal Rim)	2707 PI 17	62.09	23.14	0.33	0	6.17	7.29	0.57	99.59	3.34	64.99	31.67	Andesine
27072017-2	Bas. And.	Plag. Phen. (External Rim)	2707 PI 18	55.54	26.94	0.93	0	11.03	5.27	0.26	99.98	1.43	44.15	54.42	Labradorite
01092016-1	Andesite	Phen.	0109 Kfs 34	67	18.23	0.58	0	0.39	4.26	10.07	100.52	58.59	37.37	4.04	Sanidine
01092016-1	Andesite	Plag. Phenocryst (Core)	0109 PI 27	56.4	26.66	0.48	0	10.21	5.63	0.25	99.64	1.41	48.35	50.24	And./Labr.
01092016-1	Andesite	Plag. Phenocryst (Rim)	0109 PI 28	55.57	27.44	0.47	0	11.14	5.26	0.22	100.09	1.23	44.71	54.06	Labradorite
01092016-1	Andesite	Plag. Microlite	0109 PI 32	56.55	25.63	1.74	0	9.36	5.84	0.42	99.55	2.3	48.51	49.2	Andesine
01092016-1	Andesite	Plag. Phenocryst (Core)	0109 PI 19	57.42	26.81	0.59	0.00	9.96	5.95	0.25	100.99	1.39	50.11	48.5	Andesine
01092016-1	Andesite	Plag. Phenocryst (Rim)	0109 PI 20	58.95	25.72	0.37	0	8.4	6.72	0.35	100.51	1.96	57.18	40.86	Andesine
01092016-1	Andesite	Ne-Rich Patch in Plag.													
01092016-1	Andesite	Phen.	0109 PI 26	62.64	22.39	1.12	0	5.75	7.66	0.75	100.31	4.18	64.94	30.99	And./Oligo.
27072017-1	Dacite	Large Plag. Phen. (Core)	2707_1 PI 21	60.31	25.59	0	0	8.15	6.79	0.29	101.12	39.22	59.12	1.66	Andesine
27072017-1	Dacite	Large Plag. Phen. (Rim)	2707_1 PI 22	56.07	27.58	0.43	0	10.95	5.31	0.18	100.52	53.46	45.52	1.02	Labradorite
27072017-1	Dacite	Large Plag. Phen. (Core)	2707_1 PI 36	58.69	25.87	0.39	0	8.94	6.37	0.26	100.52	43.85	54.68	1.47	Andesine
27072017-1	Dacite	Large Plag. Phen. (Rim)	2707_1 PI 37	58.18	26.09	0.41	0	9.27	6.23	0.25	100.43	45.32	53.27	1.41	Andesine
27072017-1	Dacite	Small Plag. Phen. (Core)	2707_1 PI 42	56.4	27.2	0.45	0	10.67	5.6	0.23	100.55	54.43	47.29	1.28	Labradorite
27072017-1	Dacite	Small Plag. Phen. (Rim)	2707_1 PI 43	55.43	27.69	0.55	0	10.8	5.37	0.23	100.07	1.29	45.79	52.92	Labradorite
27072017-1	Dacite	Plag. Microlite	2707_1 PI 40	56.75	26.12	0.73	0	9.45	6.19	0.29	99.53	45.46	51.94	1.6	Andesine
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 38	67.74	19.98	0.45	0	1.59	8.16	3.6	101.52	20.42	70.34	9.25	Anorthoclase
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 39	66.91	18.66	0.43	0	0.59	7.07	6.23	99.89	35.09	60.53	4.38	Anorthoclase
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 43	68.24	18.27	0.6	0	0.74	7.18	5.23	100.27	30.48	63.6	5.92	Anorthoclase
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 36	68.87	18.32	0.31	0	0.3	6.55	6.86	101.21	39.72	57.64	2.64	Sanidine
27072017-3	Rhyolite	K-feldspar in outer plag. rim	2707_3 Alk-Fs 50	66.91	18.76	0.48	0	0.67	7.06	5.85	99.74	33.51	61.46	5.03	Anorthoclase
27072017-3	Rhyolite	K-fsp spot in outer plag. Rim	2707_3 Alk-Fs 46	67.18	18.66	0.52	0	0.6	6.99	5.96	99.92	34.2	60.96	4.85	Anorthoclase
27072017-3	Rhyolite	Large Plag. Phen. (Core)	2707_3 PI 44	64.27	22.91	0	0	4.46	8.71	0.68	101.03	3.85	74.94	21.21	Oligoclase
27072017-3	Rhyolite	Large Plag. Phen. (Int. Rim)	2707_3 PI 45	64.1	22.67	0	0	4.25	8.39	1.13	100.54	6.48	73.07	20.45	Oligoclase
27072017-1	Xenolith	Plag. (Core)	2707_1 PI 32	50.91	30.58	0.61	0.24	15.15	3.25	0	100.74	0	26.93	73.07	Bytownite
27072017-1	Xenolith	Plag. (Core)	2707_1 PI 33	50.2	31.04	0.63	0.16	15.4	3.04	0	100.47	0	25.45	74.55	Bytownite

Table A2.5. Selected SEM/EDS analysis of pyroxenes in basaltic to dacitic lavas of the Torfufell central volcano.

Sample id	Rock type	Mineral	Analysis id.	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	Total	Mineral phase
24072017-0	Basalt	Small Pyroxene Phenocryst (Rim)	2407 Px 16	50.91	0.8	1.16	21.33	0.55	13.56	11.79	0	100.09	Augite
24072017-0	Basalt	Small Pyroxene Phenocryst (Core)	2407 Px 17	47.8	2.51	4.91	11.17	0.3	13.38	19.95	0.33	100.34	Aluminian augite
24072017-0	Basalt	Pyroxene Microlite	2407 Px 09	50.82	0.69	0.98	24.32	0.58	12.56	9.66	0.14	99.75	Augite
27072017-2	Bas. And.	Pyroxene Microlite	2707_2 Cpx 05	52.21	0.78	0.91	20.13	0.67	19.73	5.53	0	99.96	Pigeonite
27072017-2	Bas. And.	Pyroxene Microlite	2707_2 Px 13	51.41	1.14	1.55	14.78	0.4	13.34	18.24	0.23	101.09	Augite
27072017-2	Bas. And.	Pyroxene Phenocryst (Core)	2707_2 Px 10	49.67	0	0.34	35.46	1.65	8.75	4.97	0	100.83	Pigeonite
27072017-2	Bas. And.	Pyroxene Phenocryst (Rim)	2707_2 Px 11	52.21	0.9	1.25	17.05	0.54	14.1	16.38	0.15	102.57	Augite
27072017-2	Bas. And.	Small Pyroxene Phen. (Core)	2707_2 Px 14	48.84	1.83	4.03	12.02	0.36	13.92	18.59	0.29	99.87	Aluminian Augite
27072017-2	Bas. And.	Small Pyroxene Phenocryst (Rim)	2707_2 Px 15	51	1.16	1.15	16.38	0.4	13.01	16.95	0.22	100.28	Augite
01092016-1	Andesite	Pyroxene Phenocryst (Core)	0109 Px 29	48.61	0.56	1.1	22.25	0.8	6.21	19.64	0.21	99.37	Augite
01092016-1	Andesite	Pyroxene Phenocryst (Rim)	0109 Px 30	48.05	0.75	0.95	27.93	1.08	4.1	17.47	0.25	100.6	Augite
01092016-1	Andesite	Pyroxene Microlite	0109 Px 25	48.5	0.55	0.84	25.59	0.99	4.96	17.91	0.19	99.54	Augite
27072017-1	Dacite	Small Pyroxene Phenocryst (Core)	2707_1 Px 23	48.44	1.04	1.98	20.12	0.76	8.58	18	0.2	99.12	Augite
27072017-1	Dacite	Small Pyroxene Phenocryst (Rim)	2707_1 Px 24	46.97	1.08	2.25	24.04	0.96	5.02	18.38	0.26	98.96	Aluminian augite
27072017-1	Dacite	Large Clinopyroxene Phenocryst (Core)	2707_1 Px 28	49.11	0.65	1.02	24.01	0.9	5.97	18.61	0.19	100.46	Augite
27072017-1	Dacite	Large Clinopyroxene Phenocryst (Rim)	2707_1 Px 29	48.45	0.62	1.13	24.19	0.8	5.36	18.86	0.55	99.97	Augite
27072017-1	Dacite	Pyroxene Microlite	2707_1 Px 41	47.45	0.66	1.4	27.7	1.18	3.93	16.55	0.3	99.18	Augite
27072017-1	Xenolith	Large Pyroxene (Core)	2707_1 Px 30	49.88	1.34	3.11	10.27	0.28	14	20.25	0.3	99.44	Aluminian augite
27072017-1	Xenolith	Large Pyroxene (Rim)	2707_1 Px 31	54.94	0.28	0.84	13.77	0.51	25.49	4.34	0	100.16	Pigeonite

Table A2.6. Selected SEM/EDS analysis of titanium and zirconium minerals in basaltic to rhyolitic lavas of the Torfufell central volcano.

Sample id	Rock type	Mineral	Analysis id.	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	V2O5	Nb2O3	HfO2	ZrO2	Total
24072017-0	Basalt	Titanomagnetite	2407 Mt 19	0	25.63	1.85	66.18	0.43	0.65	0	0	0	1.32	-	-	-	96.06
24072017-0	Basalt	Ilmenite	2407 Ilm 10	0	51.33	0.2	47.35	0.66	0.61	0.16	0	0	-	-	-	-	100.31
27072017-2	Bas. And.	Titanomagnetite	2707_2 Mt 08	0.21	24.93	1.5	67.23	0.49	0.62	0.15	-	-	0.87	-	-	-	96
27072017-2	Bas. And.	Ilmenite	2707 Ilm 09	0.36	51.93	-	46.43	0.61	0.54	0.35	-	-	-	-	-	-	100.22
01092016-1	Andesite	Titanomagnetite	0109 Mt 23	0.21	24.17	1.09	69.32	0.72	0.3	0	0	0	-	-	-	-	95.81
27072017-1	Dacite	Titanomagnetite	2707_1 Mt 26	2.63	17.32	0.75	67.96	1.13	0	0	0	0.18	-	-	-	-	89.98
27072017-1	Xenolith	Titanomagnetite	2707_1 Mt 35	0.23	13.84	3.65	74.76	0.42	0.8	0	0	0	-	-	-	-	93.71
10072017-3	Rhyolite	Titanomagnetite	1007 Mt 35	0.36	13.93	0.4	71.02	1.02	0	0	0.28	0	-	0.39	-	-	87.4
27072017-3	Rhyolite	Zircon	2707_3 Zrc 53	31.88	0	0	0	0	0	0	0	0	-	-	1.64	64.87	98.39
10072017-3	Rhyolite	Zircon	1007 Zrc 37	32.33	-	-	-	-	-	-	-	-	-	-	0.99	68.91	102.24

Discussion

The 32 samples selected for this study are from basaltic to rhyolitic formations belonging to the ToCV and from basaltic plateau lavas above and below the volcano. By this, we were able to provide geochemical data that can be interpreted to represent the long-term geochemistry of the volcano throughout its 1-1.2 Myr life span during the Late Miocene. The new whole-rock data indicate that the most evolved basalts of the Torfufell area are sampled from a pile of thin $\bar{a}$ lavas resting underneath the silicic/intermediate extrusive portion of the volcano. The geochemistry of these evolved basalts deviates from the enveloping plateau basalts by higher FeO_t , TiO_2 , MnO , K_2O and P_2O_5 , lower Al_2O_3 and CaO , and higher Y, Co and Zr. Therefore, and as these lavas are unusually thin and therefore likely to be erupted onto a sloping landscape, they are considered to be sourced from the central volcano. Samples from basaltic lavas resting directly on top of the rhyolites are similarly evolved and therefore also considered to belong to the central volcano. Samples from basalts in the centre of the rhyolite, along with a thin (1-2 m) pahoehoe lava within the thin-layered lava stack (sample 20180903-3), are on the other hand less evolved. As it may be assumed that a topographic high is likely to have existed at the location of these lavas due to the build-up of central volcanism during the early phases of the edifice construct, these less evolved lavas are considered likely to be sourced from the central volcano. By classifying the abovementioned basaltic samples as central volcano rocks, along with intermediate and silicic samples, the whole-rock data documents that the rocks of the ToCV plot in variation diagrams within confined semi-continuous trends with respect to many major and trace elements (in particular TiO_2 , FeO_t , MgO , CaO , Na_2O , Ba and Co), indicating that a semi-continuous series of basaltic to rhyolitic magmas were erupted from the ToCV during a 1-1.2 Myr interval.

Six of the 32 samples were selected to represent the petrography and mineral chemistry of basaltic to rhyolitic formations of the ToCV. These studies document that composition of clino-pyroxene in the basalt sample show an increase in Fe content from core to rim. Only clinopyroxene (augite) is found in the basalt sample. The basaltic andesite sample contains two pyroxenes; a Ca-rich (augite) and a Ca-poor (pigeonite) phase. The pigeonite occurs both as Mg-rich microlites and as Fe-rich cores. Apart from this sample, two pyroxenes are only found in a xenolith which comprises pyroxenes with a core of augite enveloped by pigeonite. In both cases where two pyroxenes occur, a gap exists between the Ca-rich and the Ca-poor phases. The andesite and dacite samples contain only augites. These augites, which are Ca- and Fe-richer than the augites of the basalt and the basaltic andesite samples, increase in Fe towards the rim, in contact with Fe-rich microlites. While only normal zoning is observed in plagioclase phenocrysts in the basalt sample, the basaltic andesite, andesite and dacite samples show indications of reverse zoning. Plagioclases in the basaltic andesite sample show zoning towards decreased anorthite content from core (An_{41}) to internal rim (An_{32}), with the external rim consisting of higher anorthite content than the core (An_{54}). Slight reverse zoning is also observed in a plagioclase phenocryst in the andesite sample, increasing in anorthite from An_{50} in the core to An_{54} in the rim. In the dacite sample, we documented a clear reverse zoning in a plagioclase with increasing anorthite content from core to rim (from An_{39} in the core to An_{53} in the rim) indicating higher temperature composition towards the rim.

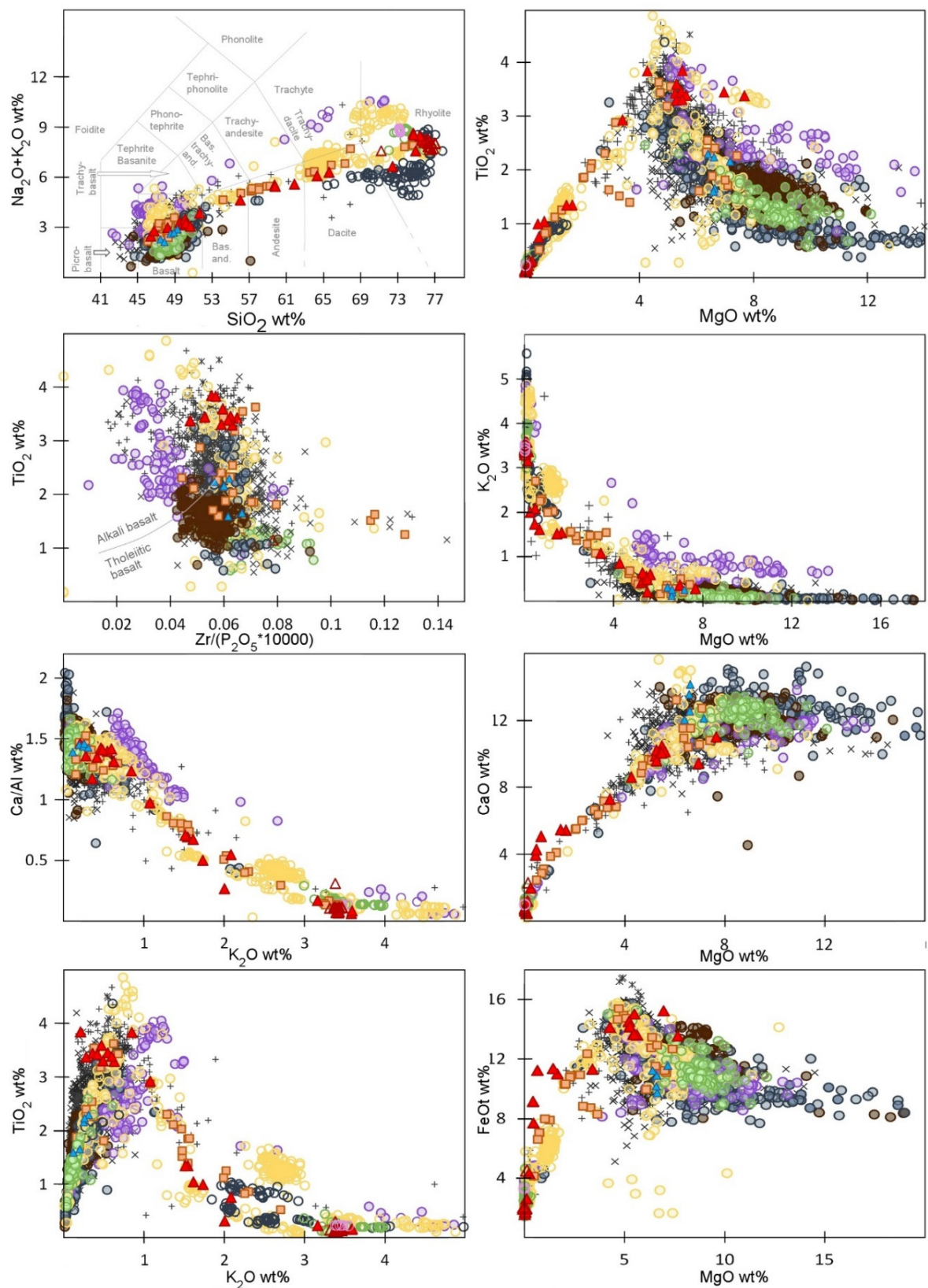
Altogether three dacitic samples are included in this study, and implications of complexities or magma heterogeneities are observed in all three samples. Two of these samples document composite dacite/rhyolitic ignimbrite, with dacitic pumice recorded in otherwise rhyolitic ignimbrite in one of these two samples. The third dacite sample, from a dacitic lava, contains a xenolith consisting of primitive (bytowntitic) plagioclases and coexisting augite and Mg-rich pigeonite, showing evidence of incorporation of solid primitive basaltic country rock into magma of dacitic composition. In this

same dacite sample, we observed a clear reverse zoning in a plagioclase phenocryst indicating higher temperature composition towards the rim, which may imply mixing of the hosting dacite magma with a more primitive magma during growth of the crystal.

A comparison of the whole-rock data with data from the neovolcanic zones of Iceland is presented in Fig.A2.10. The figure indicates that basalts sourced from the ToCV have high TiO_2 and FeO_t contents (~3-4 wt% and ~14-15 wt%, respectively) compared to typical products of the presently active mature rift zones of Iceland. The plateau basalts enveloping the ToCV are on the other hand similar to NVZ products. If compared to Jakobsson's (2008) compilation of whole-rock data, reflecting the compositional range of Holocene and Late Pleistocene volcanic rocks in Iceland, the Torfufell data mostly falls within the overlap of Jakobsson's (2008) definition of tholeiitic and the transitional alkalic series, often close to the Hekla samples. Similarly, compositions of the silicic rocks of the ToCV do generally not correlate with the typical low-alkali field of rhyolites of the presently active mature rift zones. Instead, they have slightly higher alkali contents (but still fall in the low-alkali rhyolite field) and correlate with lower alkali rhyolites from the EVZ and the ÖVB and with higher alkali rhyolites from the rift zones. All major elements of the rhyolitic rocks of the ToCV plot close to rhyolites from the MIB (the Prestahnúkur and Kerlingarfjöll central volcanoes) and the ÖVB (the Öraefajökull central volcano). Compared to selected tephra samples from presently active central volcanoes, the Torfufell obsidian often plots close to samples from the central volcanoes of the EVZ (Eyjafjallajökull, Hekla and Torfajökull) and the ÖVB (Öraefajökull) (Fig.A2.11).

However, even though the samples selected for this study are rather fresh/unaltered considering their Micoene age, they are unavoidable mildly altered. Therefore, as Na, K and Ca are notoriously mobile and can easily be modified even by mildest alteration, plots involving these elements are approached with caution. Thus, plots showing ratios of more immobile elements (and thus elements that are least affected during alteration) are preferred in this case and as such, the $\text{Zr}/\text{P}_2\text{O}_5$ vs. TiO_2 plot is considered important to identify magma suites. This plot (Fig.A2.5, bottom right; Fig.A2.10, second plot from top, left) demonstrates a mild alkalinity for the basalts sourced from the ToCV while lavas enveloping the central volcano plot as tholeiitic basalts. On a TiO_2 vs FeO plot (also showing ratios of more immobile elements), the Torfufell obsidian plots close to Hekla and Kerlingarfjöll rhyolites (Fig.A2.7, upper right; Figure A2.11, middle right). Hekla sits at the east end of the South Iceland Seismic Zone while the Kerlingarfjöll central volcano is situated within the MIB. This may indicate that the Torfufell basalts and rhyolites are not formed at an axial rift.

It is apparent from Fig. A2.10 that the geochemical data from the ToCV show strong similarities with the neighbouring 5 Ma Tinná central volcano. These two central volcanoes were previously considered to be of similar age and potentially the same volcano (e.g., Hjartarson, 2003; 2005). However, as the ToCV has been established to be 7 Ma (Árnadóttir et al., 2023), this hypothesis has been refuted. Furthermore, as the age progression of these two E-W aligned volcanoes (younging to the west) conflicts with concepts of unidirectional spreading, Árnadóttir et al. (2023) proposed that these two volcanoes were formed at a leaky transform zone that developed to accommodate the rift relocation in North Iceland, with the ToCV formed at its junction with the embryonic rift zone, thus providing constraints on the oldest silicic rocks formed at the incipient NVZ. While this hypothesis awaits critical testing, some support is provided by the whole-rock geochemical data.



Neogene: + East Fjords × West Fjords ✕ North Iceland ■ TiCV ▲ ToCV (this study) ▲ Basalts enveloping the ToCV
 Present rift and off-rift volcanic zones: ● NVZ ● WVZ/RVB ● EVZ ● MIB ● ÖVZ ● SVZ ● Crystalline ○ Glass

Figure A2.10. Geochemistry of the ToCV in comparison with samples from the neovolcanic zones in Iceland, the adjacent Tinná central volcano and data from the Neogene East and West fjords. Comparison data is from Clay et al. (2015), Debaille et al. (2009), Fitton et al. (1997), Flude et al. (2010), Fowler et al. (2016), Guðmundsdóttir et al. (2011), Gunnarsson et al. (1998), Harðarson (1993), Harðarson and Fitton (1997), Harðarson et al. (1997), Hjartarson (2003), Kuritani et al. (2011), Lacasse et al. (2007), Larsen et al. (1999; 2001; 2002), MacLennan et al. (2001), Martin and Sigmarsson (2007), Mattsson and Óskarsson (2005), McGarvie et al. (1990; 2007), Meara et al. (2020), Nicholson et al. (1991), Óladóttir et al. (2011), Pollock et al. (2014), Selbekk and Trönnnes, 2007, Sigvaldason (1979), Sinton et al. (2005), Slater (1996), Slater et al. (2001), Viccaro et al. (2015), and Zierenberg et al. (2013). The total alkali-silica diagram (TAS; uppermost left) shows root names from Le Bas et al. (1986). The TiO_2 vs $\text{Zr}/(\text{P}_2\text{O}_5 \cdot 10000)$ plot shows the discrimination between alkali basalts and tholeiite basalts after Winchester and Floyd (1976).

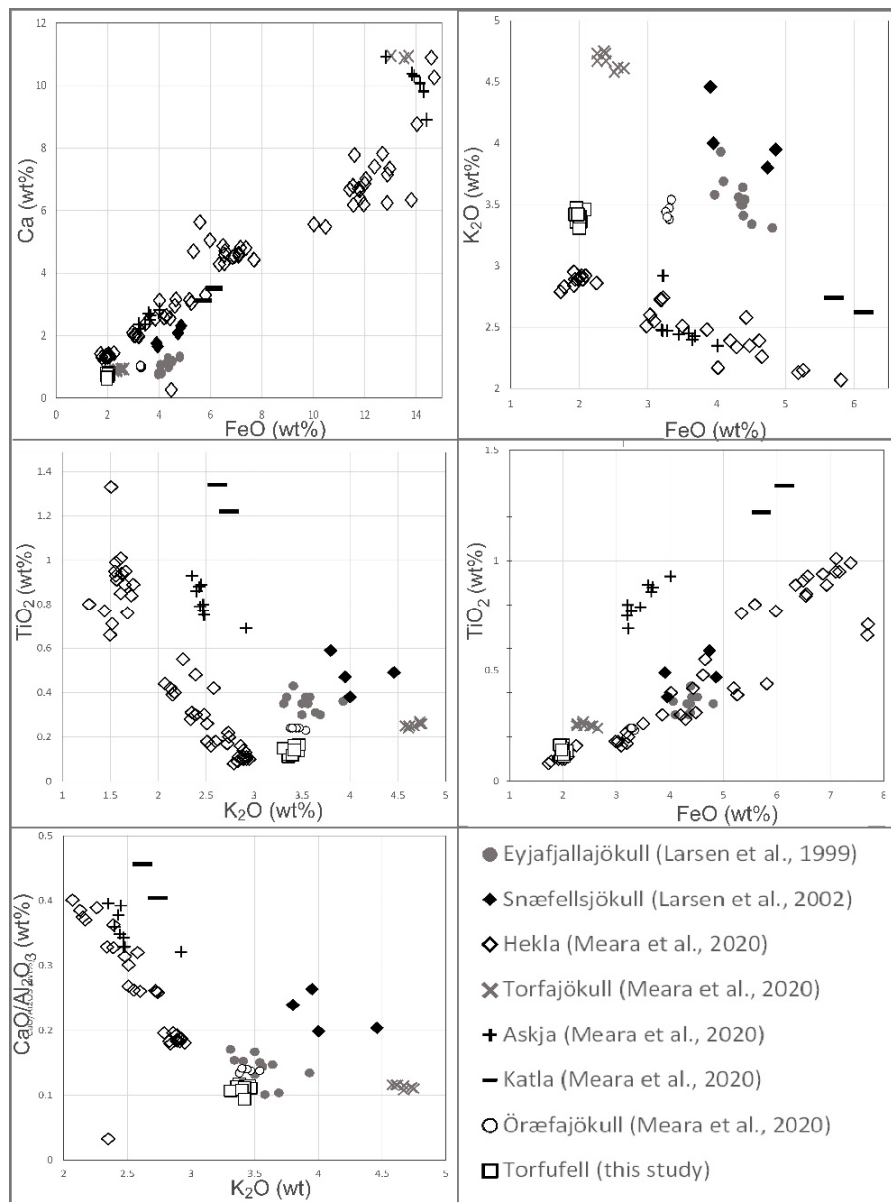


Figure A2.11. Geochemistry of the Torfufell obsidian compared with silicic tephra from several Holocene central volcanoes in Iceland. In wt%.

Conclusions

The whole-rock geochemical data presented here, ranging in SiO₂ from 46 to 76 wt%, enable us to discriminate between basaltic lavas sourced from the Torfufell central volcano and over- and underlying basaltic plateau lavas. A semi-continuous series of basaltic to rhyolitic magmas was erupted from the central volcano that deviates from the enveloping lavas by higher TiO₂, FeO_t, MnO, K₂O and P₂O₅, lower Al and Ca, and higher Y, Co and Zr. Therefore, we can conclude that the shift from thick (>5 m) grey lavas to thin (<5 m) black *ā*ʼa lavas defines the base of the central volcano, i.e., the transition from predominantly fissure-fed basalts towards basalts sourced from the central volcano. Geochemistry of minerals documents that basaltic to dacite lavas (i.e. basalt, basaltic andesite, andesite and dacite) of the central volcano comprise pyroxenes occurring in the augite phase. Two pyroxenes are only observed in the basaltic andesite and in a basaltic xenolith, where pigeonite coexists with augite. Apparently augite is the only pyroxene in the basalt, andesite and dacite. Plagioclase compositions range from An₁₆₋₂₁ in rhyolites to An₅₆₋₇₉ in the basalt, with clear reverse zoning documented in a dacite sample. Integration with previous and new age data document that these geochemical and mineralogical variations span approximately 1-1.2 Myr during the Late-Miocene. The new geochemical data show that the Torfufell central volcano features basalts that are mildly alkaline and high in Ti and Fe compared to typical products from the presently active axial rift in Iceland and rhyolites that are similar to rhyolites produced in the Mid Iceland Belt and by the east end of the South Iceland Seismic Zone.

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**A3 Paper III: U-Pb zircon age and chronology
of the Torfufell central volcano: implication
for timing of rift relocation in North Iceland**



U–Pb zircon age and chronology of the Torfufell central volcano: implications for timing of rift relocation in North Iceland

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Abstract

The Late-Miocene Torfufell central volcano (ToCV), situated between the now extinct Snæfellsnes-Húnaflói rift zone and the presently active rift in North Iceland, provides an excellent opportunity to recreate the construction history of a volcanic edifice. We present new U–Pb zircon ages from six silicic units of the ToCV. The results range from 7.15 ± 0.12 to 6.76 ± 0.02 Ma, taken here to represent a ~400 kyr time-span for silicic activity at the volcano. Before that, the central volcano had produced basaltic lavas for 600–800 kyr, implying that it was active for ~1–1.2 Myr. A stratigraphically documented ~1 Myr hiatus above the volcano is contemporaneous with, but shorter than, a major unconformity in the Flateyjarskagi peninsula, considered to result from a major rift relocation in North Iceland. The new U–Pb ages show that silicic volcanism at the ToCV took place 1–2 Myr earlier than assumed previously and nearly synchronously with the rift relocation. As the age progression of the ToCV and the neighboring 5–6 Ma Tinná central volcano conflicts with the generally established geotectonic framework of central N-Iceland, we propose that these two volcanoes were formed at a leaky transform zone that developed to accommodate the rift relocation, with the ToCV formed at its junction with the embryonic rift zone, thus marking the initiation of the presently active rift in North Iceland. Since then, the two volcanoes have drifted away from the rift system due to plate spreading and migration of the plate boundary relative to the Iceland mantle plume.

Keywords Volcano geology · Geochronology · Iceland · Torfufell · Eyjafjörður · U–Pb zircon age

Introduction

Iceland is situated at the intersection of the Mid-Atlantic Ridge (MAR) and the Iceland mantle plume and is constructed by ridge/plume interaction (e.g., Schilling 1973; Vink 1984). Today, volcanism in Iceland is confined to volcanic zones, each delineated by discrete volcanic systems (e.g., Jakobsson et al. 2008). The volcanic zones are further

subdivided into rift-zones, oblique rift-zones (or “leaky” transform zones), propagating rifts and intra-plate belts (e.g., Einarsson 2008). Approximately 30 active volcanic systems are identified within the volcanic zones, and each system features either an elongate fissure swarm, a localized central volcano, or both (e.g., Thordarson and Höskuldsson 2008; Hjartarson and Sæmundsson 2014). The fissure swarms trend subparallel to the respective volcanic zone and typically consist of monogenetic fissures erupting only basaltic magmas, while the central volcanoes are polygenetic (composite) and erupt basaltic to silicic magmas. While a typical lifetime of a volcanic system has been estimated around 0.5–1.5 Myr (Jakobsson et al. 1978; Jakobsson 1979; Sæmundsson 1978; 1979), a lifespan of 2.3–2.4 Myr was evaluated in a recent study for a fossilized volcanic system in East Iceland featuring both a fissure swarm and a central volcano, where the central volcano within the system was active for ~1 Myr (Askew et al. 2020). However, central volcanoes in Iceland appear to have potentials for longer lifetimes than that, as longevities of silicic magmatism within individual central volcanoes have been recorded to reach > 1 Myr (Flude et al.

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2008) and ≥ 1.5 Myr (Banik et al. 2018), with ≥ 2.8 Myr documented as the longest lifespan of silicic activity within an Icelandic central volcano (Carley et al. 2017). Comparably, lifespans of composite volcanoes in other geodynamic settings, such as subduction zones and extensional basins, are commonly estimated around 1–1.3 Myr or less (e.g., Hildreth 2007; Tatsumi et al. 2020; Karaoğlu et al. 2010).

Arrangement of the rift zones in Iceland is explained by the west-northwestward migration of the mid-ocean ridge system in the North Atlantic relative to the Iceland mantle plume, which has induced repeated eastward relocations of the onshore part of MAR-rift segments that are accommodated by transform zones. The present distribution of the rifting segments in Iceland is established by three principal rift zones (Fig. 1a); the $\sim$ N-S trending Northern Volcanic Zone (NVZ) in the north and two subparallel NE-SW trending branches in the south—the Eastern and Western Volcanic Zones (EVZ and WVZ) (e.g., Sæmundsson 1979; Einarsson 2008). These three segments exemplify different stages in the evolution of a rift axis across Iceland, where the southern part of the EVZ is propagating through older crust to the SW, the WVZ is waning and receding, and the NVZ may be referred to as an established (or steady-state) rift as it accommodates the full spreading rate in North Iceland (e.g., Einarsson 2008). The division between the NVZ and the EVZ is nevertheless arbitrary, as these two domains form a single continuous structural identity. Two major transform zones cross Iceland with W-E and WNW-ESE trends: the Tjörnes fracture zone (TFZ) in the north and the South Iceland seismic zone (SISZ) in the south (e.g., Sæmundsson 1979; Jóhannesson 1980). The NVZ is offset towards East from the WVZ along the transverse Mid-Iceland Belt (MIB) which has been described as a “leaky” transform fault (e.g., Óskarsson et al. 1985), i.e., comprising a small component of opening (extension), sufficient to induce local volcanism, although evidence of strike-slip movement in this belt is not apparent (e.g., Hjartardóttir and Einarsson 2021). The extension component has been proposed to be caused by the opposite sense of rotation of crustal blocks to the N and S (Karson 2017). Intra-plate volcanism occurs in the Snæfellsnes and Örafi Volcanic Belts (SVB and ÖVB), with the former representing renewed volcanism through crust formed in the now extinct Snæfellsnes-Húnaflói rift zone (SHRZ) (Harðarson et al., 1997; Sæmundsson 1979) and the latter considered as an embryonic rift (e.g., Thordarson and Höskuldsson 2002). These intra-plate volcanic zones, along with the propagating part of the EVZ, are typified by alkalic and/or transitional magmatism while the rift zone magmas are tholeiitic (e.g., Jakobsson et al. 2008).

In North Iceland, the last major rift relocation took place when the northern segment of the SHRZ shifted eastward and a new rift axis initiated at the NVZ. The classically quoted timing of the relocation, ~ 6 –7 Ma (e.g., Sæmundsson

1979; Jóhannesson 1980), appears to be further supported by new $^{40}\text{Ar}/^{39}\text{Ar}$ ages from lavas within the Tjörnes sedimentary sequence (Hall et al. 2023). The proposed alignment of the palaeo SHRZ runs along the axis of a syncline (Fig. 1a, b, c), interpreted to be induced by subsidence due to loading of erupted material, causing the volcanic successions to dip towards the then active rift (Sæmundsson 1974; 1979; Jóhannesson 1980; Harðarson et al. 2008). A major discontinuity (unconformity/hiatus) is recorded within the basaltic lava dominated stratigraphical succession along the Flateyjarskagi peninsula, west of the NVZ (Fig. 1b, c). This unconformity is interpreted to have formed because of the rift relocation, where lava flows beneath the hiatus were formed in the SHRZ and lavas above the hiatus were formed in the NVZ (Sæmundsson 1974). Campaigns undertaken to constrain the timing and length of this hiatus indicate that it spans the time from ~ 10 to ~ 6 Ma in the north while the time gap decreases towards the south where it spans the time from ~ 7 to ~ 5 Ma (Jancin et al. 1985; Cotman 1979). These age determinations, along with a number of other datings in central North Iceland (Aronson and Sæmundsson 1975; Sæmundsson et al. 1980; Everts, 1975; Kristjánsson et al. 1992; Fig. 1b, c), were obtained by the K–Ar method which, although certainly useful, has proved to be problematic in Iceland, mostly due to low concentrations of K_2O in Icelandic basalts in combination with problems arising from the mobility of K and resulting sensitivity to the thermal history of the rock. These limitations are largely overcome by the more recent $^{40}\text{Ar}/^{39}\text{Ar}$ technique (e.g., Lee 2015) which is now considered an optimal method for dating Icelandic rocks (e.g., Sigmarsson et al. 2012). This superseding method has been applied to numerous regional basaltic dykes in central North Iceland, dated in particular to provide spatio-temporal constraints on the ~ 6 –7 Ma rift relocation (Garcia et al. 2003). A number of basaltic lavas have also been dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method in the central north region, including lavas in Mt. Hólafljall (Supakulopas 2018; Fig. 1b, c; Fig. 2) that provided indications of a major hiatus in the present study area. Age determinations of silicic portions of several of the fossilized and excavated central volcanoes in the central north region of Iceland have furthermore been published, i.e., K–Ar ages from two adjacent volcanoes in the Flateyjarskagi peninsula (Jancin et al. 1985), $^{40}\text{Ar}/^{39}\text{Ar}$ ages from rhyolite lavas within the Tinná (Hjartarson 2003) and Torfufell (Supakulopas 2018) central volcanoes, and U–Pb zircon ages from intrusive units of the Víðidalur and Laxárdalur central volcanoes (Carley et al. 2020).

The age data mentioned, compiled in Fig. 1b and c, have contributed significantly to the understanding of the volcano-tectonic evolution of central North Iceland, not least by providing constraints on the Flateyjarskagi hiatus and timing of the last major rift relocation in the region. However, a closer look at these ages shows that the distribution

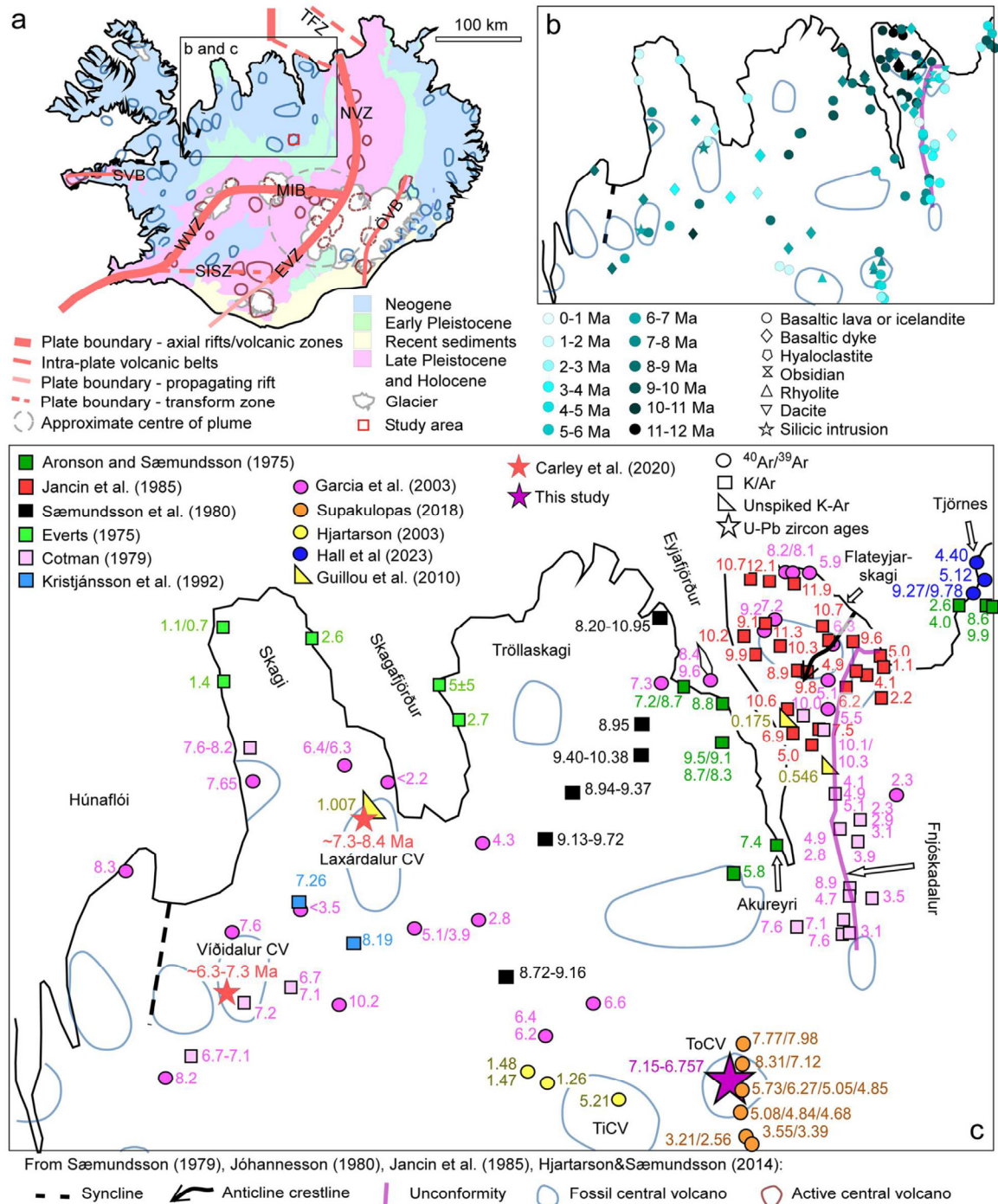


Fig. 1 **a** Generalized geological map of Iceland (modified from Hjartarson & Sæmundsson 2014; Thordarson and Höskuldsson 2008), highlighting active and fossil central volcanoes and active volcanic zones. See text for abbreviations. The approximate center of the Iceland mantle plume, as depicted by Wolfe et al. (1997), is indicated

with a gray, dotted circle. **b**, **c** Published radiometric ages from central N-Iceland (compilation aided by Hopper et al. 2014), with features related to the ~6–7 Ma rift relocation indicated (i.e., syncline axis, anticline crestline and unconformity); **b** data sorted by age and rock type; **c** data sorted by reference and dating method

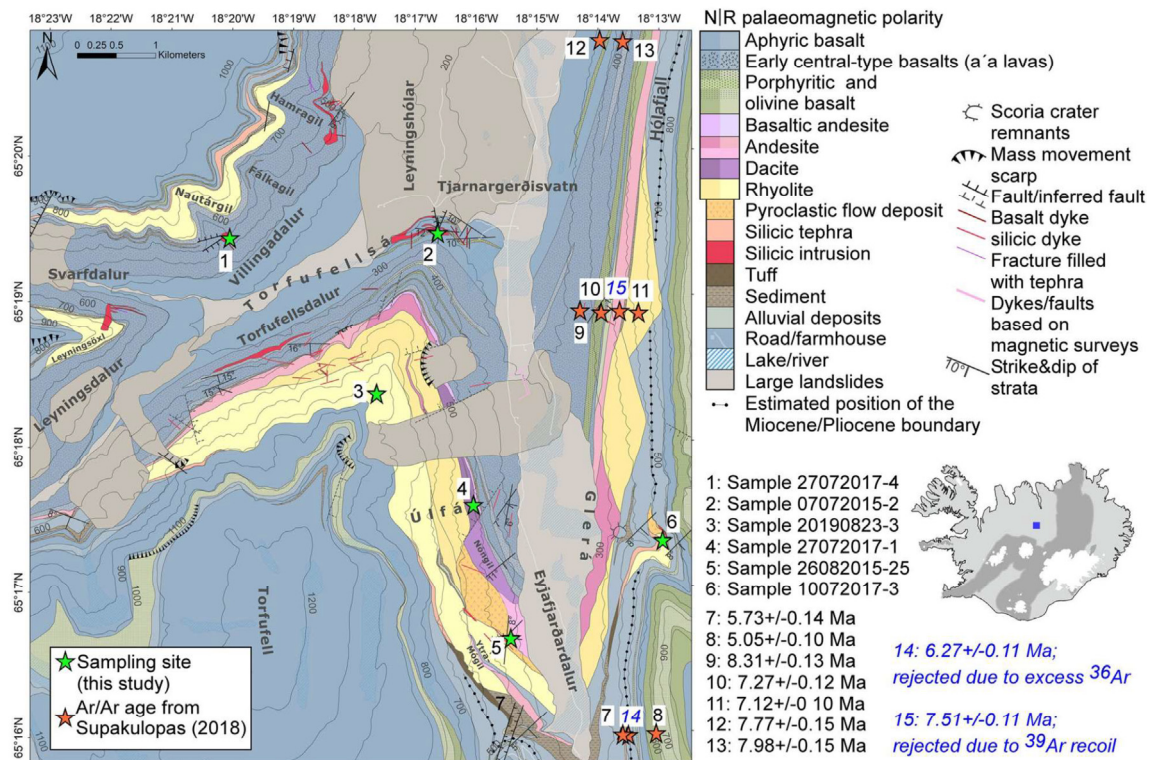


Fig. 2 Sampling sites, shown on a geological map, in comparison with $^{40}\text{Ar}/^{39}\text{Ar}$ ages in Mt. Hólafljall from Supakulopas (2018). Location of the study area is indicated with a blue box on the small image of Iceland. The geological map is based on original fieldwork, integrated with data from previous authors (stratigraphic and

polarity profiles in Mt. Hólafljall from Kristjánsson et al. 2004 and Supakulopas 2018; landslide outlines from Pétursson 1997; dykes/faults based on magnetic surveys from Flóvenz and Tómasson 1992). Basemap: Topography, lakes, rivers, roads and farms sourced from the National Land Survey of Iceland

does not follow a straightforward progression away from the NVZ as assumed for mid-ocean ridge spreading centers. The ages record a general younging to the west, from 12 to 7–7.5 Ma, in the direction away from the Flateyjarskagi unconformity and towards the SHRZ syncline, while lavas above the unconformity are 4–5 Ma. Very young ages are recorded in the Skagafjörður region (Everts 1975; Hjartarson 2003) which have been interpreted as recommenced volcanism, long after extinction of the SHRZ, while lavas of Quaternary age in the Eyjafjörður region have been assumed to be remains of large regional lava flows reaching tens of kilometers out from the NVZ (Guillou et al. 2010). In the Eyjafjörður region (west of the Flateyjarskagi unconformity), a general younging is implied by lava ages from the coastline (i.e., the northernmost Tröllaskagi and Flateyjarskagi peninsulas) and into the land which appears to be non-existent in the western part of the central North region. This younging in the Eyjafjörður region may possibly, at least to some extent, be explained by the general SE dipping of the strata pile (as measured by Jancin et al. 1985) below the

Flateyjarskagi unconformity. The apparently non-existent younging from the coastline into the land in the western part of the central North region is unexplained, although it should be noted that in the west, the age data is scarcer than in the east while a large part of the available dates are from dykes instead of lavas. A relatively wide range of ages is recorded in some locations, especially in the Flateyjarskagi peninsula, which may largely be explained by sampling at different stratigraphic levels, while some may possibly be explained by inaccuracy in the K–Ar method.

The primary objective of this study is to address the timing and longevity of silicic ($\text{SiO}_2 \geq 65$ wt%) magmatism and volcanism within the Late-Miocene Torfufell central volcano (ToCV), located in the region of the Eyjafjörður fjord, by the Tröllaskagi peninsula's southern end (Figs. 1c and 2), between the presently active NVZ and the northern segment of the palaeo SHRZ. This is a key area in the evolving understanding of rift transfer in North Iceland, allowing us to explore a potential continuation of the Flateyjarskagi unconformity to the south and to examine an inferred

relation of the ToCV with the neighboring Tinná central volcano (TiCV), previously considered to be of similar age and potentially the same volcano (e.g., Hjartarson 2003; 2005). As the ToCV is dissected by rivers and glaciers, it provides an excellent opportunity to recreate the construction history of a volcanic edifice. Contrary to basaltic lavas that may flow tens of kilometers to be observed far away from the eruptive fissure, central volcanoes are localized features, abundantly comprising rocks with restricted spreading such as silicic intrusions and rhyolite lavas of high viscosity and inability to flow long distances, thus providing ages at or very close to the eruptive site. Accordingly, addressing the timing of silicic magmatism of ancient volcanic centers provides geometric relationships that can significantly improve our understanding of the geodynamic evolution of Iceland. Of particular interest are the rhyolites of the Trörlaskagi peninsula which—being situated between the NVZ and the northern segment of the palaeo SHRZ—may hold the key to a more refined comprehension of rift transfer in North Iceland.

This paper details new U–Pb zircon ages from six silicic formations belonging to the ToCV via secondary ion mass spectrometry (SIMS; five formations) and chemical abrasion–isotope dilution thermal ionization mass spectrometry (CA-TIMS; one formation) methods. The SIMS method is a high-spatial resolution *in situ* technique and was employed in an early stage of the study to obtain, in one batch, a reliable idea about the age of the volcano and its chronological evolution. The CA-TIMS method is a mineral-dissolution technique that results in higher attainable precision than the SIMS method and was employed in a later phase to provide accurate age data for the youngest outcropping rhyolite lava and thereby a more precise conception of the absolute longevity of rhyolite activity at the volcano and, simultaneously, better constraints on the duration of a time gap in the strata pile, indicated by earlier research and supported but abridged by the SIMS age data. The present study was conducted synchronously with field mapping and palaeomagnetic measurements in the study area, with corollary sampling and whole-rock geochemical analyses (detailed separately). In the present paper, we couple the six new U–Pb zircon ages with these observations, as well as with the abovementioned $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the study area (by Supakulopas 2018), to address the development and life-span of the ToCV and the volcano-tectonic evolution of central North Iceland.

Geological background

The region of the Eyjafjörður fjord is composed of sequences of Neogene flood basalts, commonly interbedded with thin layers of lithified sediments which are typically distinctively red and consisting largely of weathered, wind-blown tephra

mixed with ancient soils (Sæmundsson 1979; Sæmundsson et al. 1980; Roaldset 1983). As the originally sub-horizontal lava pile now tilts regionally a few degrees to the south (SW in the northern part, turning to SE in the southern part; Sæmundsson et al. 1980), the oldest lavas occur near the mouth of the fjord while strata from Early Pleistocene are present in the south at the head of the valley Eyjafjarðardalur. Several Miocene central volcanoes have been identified in the region (e.g., Hjartarson and Sæmundsson 2014). Two of these, the Torfufell and Tinná central volcanoes, are ~15 km apart and have been proposed to be related and hence of similar age, 5–6 Ma (e.g., Hjartarson 2003; 2005), while Jóhannesson (1991) suggested a higher age for the ToCV than the TiCV, i.e., 6–7 Ma. A stratigraphically constrained ToCV rhyolite yielding $^{40}\text{Ar}/^{39}\text{Ar}$ age of 7.12 ± 0.10 Ma in Mt. Hólafljall (Supakulopas 2018) indicated an even greater age than both proposals.

The present study area is approximately 40 km south of the largest town in North Iceland, Akureyri (Fig. 1a and Fig. 2). The main features of the bedrock in the area are illustrated in small-scale geological maps of Iceland (e.g., Hjartarson and Sæmundsson 2014), delineating silicic volcanic formations—centered in Mt. Torfufell and enveloped by basaltic lavas—just beneath the boundary between the Miocene and Pliocene periods. Stratigraphic profiling and palaeomagnetic measurements have demonstrated the stratigraphy of Mt. Hólafljall in the eastern part of the area in more detail (Kristjánsson et al. 2004; Supakulopas 2018). Although only partly covering the ToCV, the study by Supakulopas (2018) indicated a ~1.5 Ma hiatus between the rhyolite lavas of the ToCV and the overlying basalts.

Field mapping and sample selection

The present study was a part of a field mapping (including stratigraphic and geomagnetic profiling) and geochemical investigation in the area around Mt. Torfufell (detailed separately). The field observations demonstrate that tectonic uplift and glacial erosion has exposed extrusive rocks and shallow intrusions of the ToCV. Outcropping silicic and intermediate extrusive units belonging to the volcano are thickest in the northern part of Mt. Torfufell (Fig. 2), where they form a ~400-m-thick succession. The lowermost ~30–60 m of this pile are composed of andesite and dacite lavas, which are overlain by thicker rhyolite lavas. Different palaeomagnetic polarities and sediments and individual basaltic to andesitic lavas separating the rhyolite lavas manifest that these are several discrete formations. Below the silicic/intermediate extrusive formations is a 200–300-m-thick stack of basaltic lavas, featuring unusually thin (individual layers typically <5 m) *ā'a* lavas. This stack is separated from the silicic/intermediate volcanic

products in several outcrops by a notable tephra-, smectite-, and fossil-bearing sediment horizon. According to our geochemical data, the composition of these unusually thin *ā*ʻa lavas is rather evolved and more evolved than underlying plateau basalts (~50–52 compared to ~48–49 wt% SiO₂; samples 24072017–0 to -3 and 20180903–1 in Table S1 of the Supplementary Material), indicating longer residence time of the magma in the shallow crust. Such unusually thin, phenocryst-free basaltic lava flows have been observed to be abundantly erupted from Icelandic central volcanoes (Sæmundsson 1979) and interpreted to be abnormally thin as they were erupted onto a sloping landscape resulting from the buildup of central volcanism (Walker 1963). Therefore, we have a reason to assume that these thin *ā*ʻa lavas below the silicic/intermediate extrusive portion of the ToCV are sourced from the central volcano and erupted during its early phases. Later activity at the central volcano was typified by effusive and explosive rhyolitic eruptions and less frequent and smaller basaltic andesite to dacite events, ceasing with a Plinian eruption. The silicic volcanism was accompanied by silicic intrusions that are exposed at shallow levels (up to ~300 m below the base of the silicic/intermediate lavas), with evidence of magma ascending through transgressive sills and erupting through sub-vertical dykes as well as sub-cylindrical conduits. Basaltic lavas were formed concurrently with the rhyolites and continued to flow alongside the volcanic edifice after the end of silicic activity, eventually burying the highest rhyolitic peaks. A swarm of basaltic dykes is recorded north of the central volcano (north of the map in Fig. 2), but no clear evidence has been observed of whether this dyke swarm belongs to the volcanic system of the ToCV or not. While dykes belonging to this swarm generally trend NNE-SSW, similar to the regional trend of basaltic dykes in the Tröllaskagi peninsula (Sæmundsson et al. 1980), silicic dykes are concentrated in the northern part of Mt. Torfufell, most often striking from ENE-WSW to ESE-WNW. Our strike and dip measurements indicate that the entire strata succession of the study area is dipping gently (from ~5 to 11°) towards southeast, while steeper (up to ~16°) and more southerly dips (SSE to SSW) are locally indicated in the central zone of the volcanic complex, i.e., in the northern and western slopes of Mt. Torfufell.

Six silicic rock samples from the ToCV were selected, on grounds of the geological mapping and in terms of stratigraphic relations, for U–Pb zircon dating by the SIMS and CA-TIMS methods. Four of the selected samples are from volcanic formations, located at different stratigraphic levels, including samples marking both the base and the top of silicic volcanic products as observed in outcrops. Three of these volcanic formations were formed in effusive eruptions (i.e., lavas) while one is the result of an explosive event (i.e., ignimbrite). The remaining two samples are from intrusive units; one of these is from a sill while the other is from the

interiors of a volcanic conduit (plug). Sampling sites are presented in Fig. 2 in comparison with previously published age data from the study area. Descriptions of the six host samples and their stratigraphic levels are presented in Table 1. Our geochemical data, available from 5 of the host samples, indicate that they span a compositional range from ~65 to 75% SiO₂. In order to provide background information on the geochemistry of the ToCV, we introduce geochemical analysis results of 27 additional rock samples from the study area (Tables S1 and S2 of the Supplementary Material; detailed separately by Árnadóttir et al., In Prep.). These samples, mostly collected from the central volcano itself while a few are obtained from enveloping lavas, demonstrate that the rhyolites of the ToCV are mildly alkalic, i.e., they have a transitional character towards alkaline rocks, and tend to have high silica contents. The geochemical data show strong similarities with the neighboring TiCV, and a comparison with data from the neovolcanic zones of Iceland indicates that basalt to rhyolite products belonging to these two volcanoes are in general more enriched than typical rift zone magmas (Fig. 3).

Zircons were identified in thin sections of four of the six rock samples; in three samples (07072015–2, 27072017–1, 26082015–25) as inclusions in plagioclase phenocrysts, and in the groundmass of one sample (10072017–3). Nevertheless, it turned out via mineral separation processes that all six host samples featured zircon crystals in different abundances. The highest zircon yield was obtained from samples 10072017–3 and 24072014–4 (~120–150 grains per kg rock) while samples 07072015–2, 20190823–3, and 26082015–25 yielded lower abundances (~40–70 grains per kg rock). The lowest yield was obtained from the dacite sample, 27072017–1 (~16 grains per kg rock). The zircons are commonly ~50–200 µm along the c-axis, elongate and prismatic, typically subhedral and less commonly euhedral, and often with pyramidal terminations (see examples in Fig. 4a). Common length-to-width ratios are from 2:1 to 3:1, while some crystals are very long (up to more than 300 µm in length) and thin, with ratios up to 6:1. Catholuminescence (CL) images, available from the CA-TIMS dated zircons (20190823–3), do typically not show very distinct brightness variations or strong CL intensities within the crystals as would be expected for well-developed zoning textures indicating distinct growth regions (Fig.S4 of the Supplementary Material). These images do, however, imply zoning in a few crystals and even rounded inherited cores; these crystals were avoided during dating (see examples of dated vs. avoided crystals in Fig. 4a). Only backscattered electron (BSE) images are available from the SIMS dated zircons (Fig.S4 of the Supplementary Material), which are not very helpful for illustrating internal zircon textures. Although test line scans (from energy-dispersive X-ray spectroscopy (EDS) analysis using a scanning electron

Table 1 Descriptions and stratigraphic position of the dated samples

Sample I.D./dating method	Latitude/longitude	Rock type/polarity	Location	Position in the stratigraphy	Sample description
24072017-4/ SIMS	65.321931/-18.335686	Intrusion/R	Nautárgil gully in Villingadalur valley	Solidified volcanic plug, exposed ~100 m below the base of the silicic portion of the volcano	Light-gray, strongly flow-banded and flaky rhyolite. Aphanitic to glassy groundmass with spherulites and sparse plagioclase phenocrysts
07072015-2/ SIMS	65.324207/-18.277519	Intrusion/uncertain	Villingadalaká river gully, southern riverbank	36-m-thick sill, intruded into the basaltic lava pile below the central volcano, ~300 m below the base of the silicic/intermediate horizon within the volcano	Light-gray, very finely grained groundmass featuring high quartz content, plagioclase, Fe-Ti oxides, sparse phenocrysts and small (<1 mm) vesicles
27072017-1/ SIMS	65.292893/-18.268749	Dacite lava/N	Úlfá, east side of Mt. Torfufell	Situated at the base of the silicic/intermediate horizon of the volcano, resting on top of an evolved basalt lava sequence, representing the early central-volcano basalt succession and overlain by thick rhyolite lavas	Dacitic, flow-banded and flaky lava. Dark-gray aphanitic to glassy groundmass with sparse phenocrysts of plagioclase and clinopyroxene
26082015-25/SIMS	65.277547/-18.259066	Ignimbrite/R	Ytra-Mógil, Mt. Torfufell southern part	Among the stratigraphically lowest silicic formations of the volcano; rests on an andesitic flow	Densely welded flow-banded rhyolitic ignimbrite. Aphanitic groundmass tephra with abundant pumice lapilli, lithics, and phenocrysts (mostly plagioclase)
10072017-3/ SIMS	65.288856/-18.218619	Rhyolite lava/R	Glerá gully, Mt. Hólaflajall southern part	Small patch of rhyolite, assumed to be an edge of a larger lava dome. Formed during later stages of silicic volcanism; overlies some of the basaltic lavas that adjoin older rhyolite domes	Flaky and flow-banded rhyolite lava. Aphanitic to glassy groundmass of quartz, alkaline feldspar, and opaque minerals; altered, often spherulitic. Sparse plagioclase phenocrysts
20190823-3/ CA-TIMS	65.305372/-18.294526	Rhyolite lava/R	Mt. Torfufell northern part	The topmost rhyolite lava present in Mt. Torfufell, marking the top of the silicic horizon within the volcano	Flaky rhyolitic lava. Aphanitic, light-gray groundmass

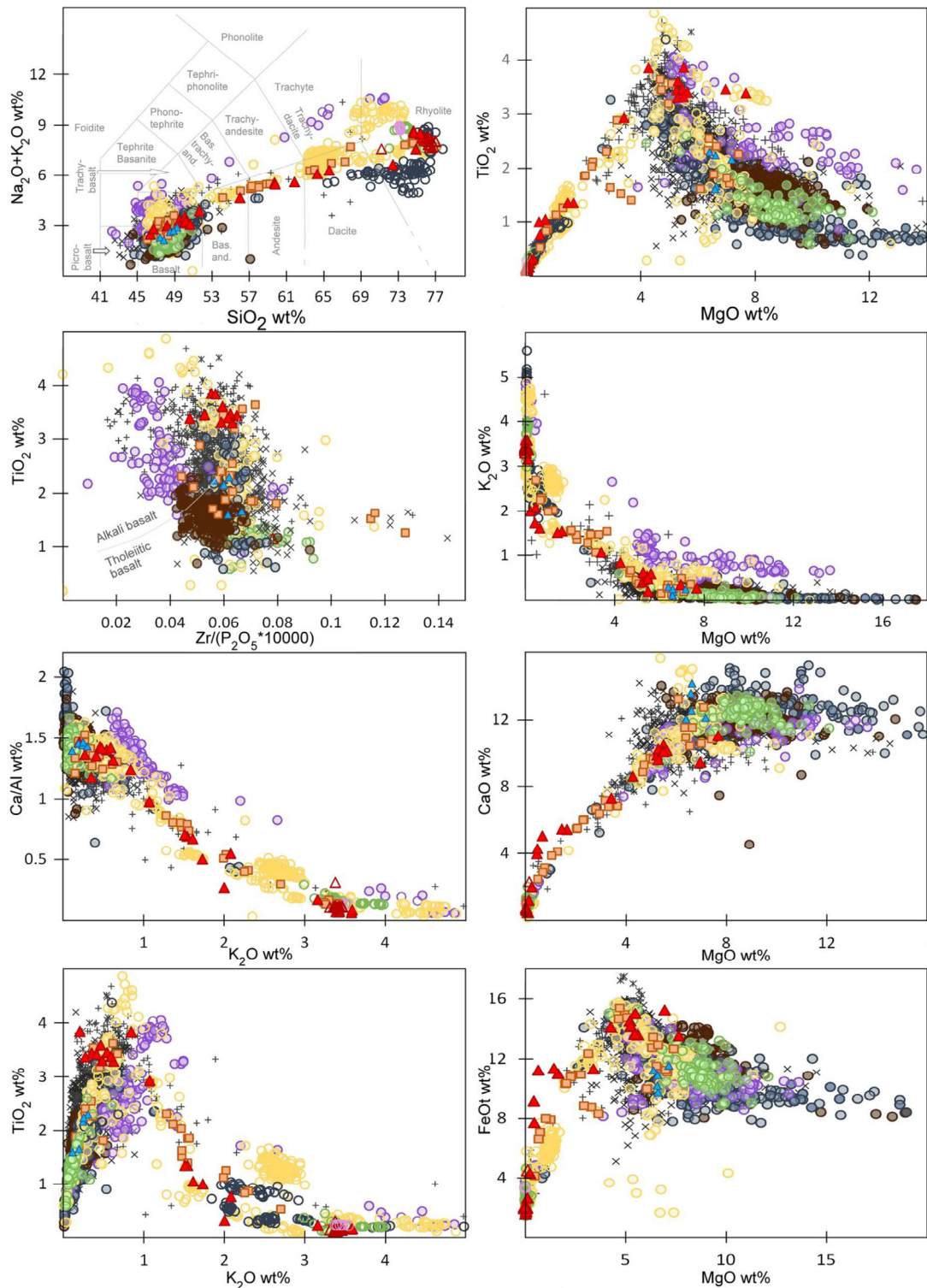


Fig. 3 Geochemistry of the ToCV in comparison with samples from the neovolcanic zones in Iceland, the TiCV and the Neogene East and West fjords. The samples dated in this study are signified with bright red diamonds. Comparison data is from Clay et al. (2015), Debaille et al. (2009), Fitton et al. (1997), Flude et al. (2010), Fowler and Zierenberg (2016), Guðmundsdóttir et al. (2011), Gunnarsson et al. (1998), Harðarson (1993), Hardarson and Fitton (1997), Hardarson et al. (1997), Hjartarson (2003), Kuritani et al. (2011), Lacasse et al. (2007), Larsen et al. (1999; 2001; 2002), MacLennan et al. (2001), Martin and Sigmarrsson (2007), Mattsson and Óskarsson (2005), McGarvie et al. (1990; 2007), Meara et al. (2020), Nicholson et al. (1991), Óladóttir et al. (2011), Pollock et al. (2014), Selbekk and Trönnnes (2007), Sigvaldason (1979), Sinton et al. (2005), Slater (1996), Slater et al. (2001), Viccaro et al. (2015), and Zierenberg et al. (2013). The total alkali-silica diagram (TAS; uppermost left) shows root names from Le Bas et al. (1986). The TiO_2 vs $\text{Zr}/(\text{P}_2\text{O}_5 \times 10,000)$ plot shows the discrimination between alkali basalts and tholeiite basalts after Winchester and Floyd (1976)

microscope (SEM)) through cross-sections of several randomly selected zircons indicate that distribution of elements within the crystals is rather homogeneous (see example in Fig. 4b), it cannot be excluded that some of the SIMS dated zircons have inherited domains. In order to reduce the influence of such domains, the zircon cores were avoided as much as possible during dating. Inclusions of other minerals are rather commonly observed in zircons from all samples (see example in Fig. 4b); these were also evaded during dating.

Analytical methods

Secondary ion mass spectrometry

U–Pb dating of zircons from host samples 20172017–1, 26082015–25, 07072015–2, 24072017–4, and 10072017–3 was carried out via *in situ* measurements using the CAMECA ims 1280 in the NordSIMS facility, Swedish Museum of Natural History, Stockholm. Zircons were separated from these five host samples using standard crushing, sieving, and density and magnetic methods by Geotrack in Australia. The zircon grains were mounted by hand onto a two-sided tape along with reference materials and then epoxy-casted and polished to expose grain interiors. The polished mount was imaged using backscattered electron signals in SEM (Hitachi TM3000 SEM at the University of Iceland) in order to carefully map the sample mount prior to dating, to confirm zircon identities of crystals, and to identify internal structures such as inclusions and cracks that were avoided during the dating. The zircon cores were also avoided during dating in order to exclude potential inheritance as possible.

The analytical and calibration procedures generally followed those described in Whitehouse and Kamber (2005) and Jeon and Whitehouse (2015), with a few differences noted in Supplementary Text S1. In total, 97 U–Pb analyses

were carried out on 92 zircon grains from the five samples (all analyzed spots are presented in Fig.S4 of the Supplementary Material) and thereof, 7 analyses were excluded, resulting in a total of 90 analyzed spots. Eleven grains were selected from sample 27072017–1 (12 spots; thereof 2 spots were discordant and excluded (assumed as contamination due to abnormally high age; 529 and > 1200 Ma)); 19 grains from sample 26082015–25 (21 spots; thereof 2 spots were discordant and excluded (assumed as contamination due to abnormally high age; 73 and > 1200 Ma)); 22 grains from 07072015–2 (22 spots; no spot excluded); 21 grains from 24072017–4 (21 spots; no spot excluded); and 19 grains from 10072017–3 (21 spots; thereof 3 spots were excluded due to outstandingly high common Pb).

Chemical abrasion–isotope dilution thermal ionization mass spectrometry

Zircons from host sample 20190823–3 were dated at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia (UBC) by CA-TIMS method. The sample was prepared at the PCIGR, including separation of zircon crystals from the host sample and CL SEM imaging. Zircon crystals were subjected to a pre-treatment combining annealing and a modified version of Mattinson's (2005) chemical abrasion method for removing zircon domains that have lost lead from the interior of grains (see Supplementary Text S1). By this, the CA-TIMS method can isolate and analyze closed-system, high-quality domains within the zircon grains and exclude discordance due to loss of lead. The mineral-dissolution method furthermore samples larger volumes of material than the SIMS method, resulting in higher attainable precision. Prior to the chemical abrasion, 33 zircon grains were selected for *in situ* determination of trace element concentrations by LA-ICPMS (the LA-ICPMS conditions are given in Supplementary Table S7; the method is described in Supplementary Text S1). Six zircon grains were then selected for CA-TIMS analysis based on the LA-ICPMS results in combination with the prismatic morphology and the absence of inclusions, avoiding those crystals with rounded edges. U–Pb geochronology methods for isotope dilution thermal ionization mass spectrometry follow those previously published by Wall et al. (2018), detailed in Supplementary Text S1. Chemical abrasion in concentrated HF at 190° for 12 h resulted in only minor dissolution of the zircon crystals.

Results

Our U–Pb zircon ages (weighted averages) range from 7.15 ± 0.12 to 6.76 ± 0.02 Ma (error is in 2σ); that is Late Miocene. Weighted mean ages for each sample are

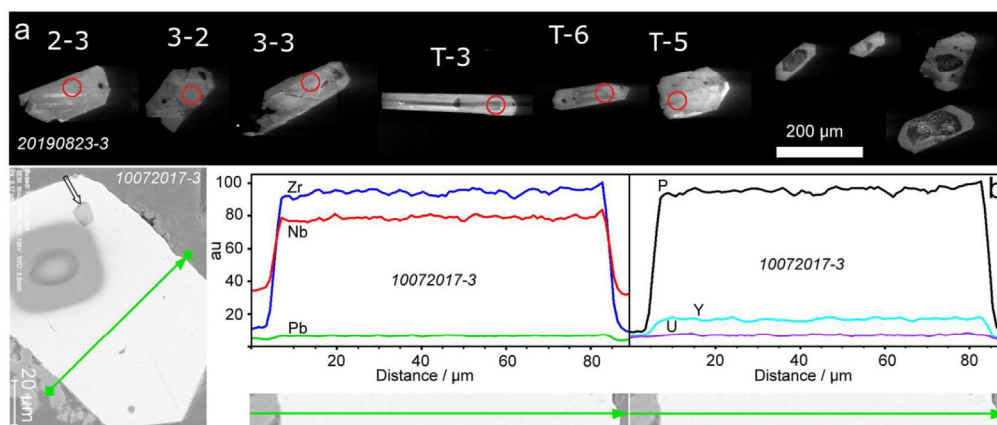


Fig. 4 **a** CL images of zircons from sample 20190823–3. Numbered zircon grains were dated with the CA-TIMS method (with red circles indicating location of laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) spots) while zircons without numbers (and without red circles) are examples of avoided grains. **b** Example of a random line scan test (from EDS analysis using a SEM) through

a cross-section of a zircon dated with the SIMS method (au=arbitrary units). The alignment of the line scan is shown to the left. The large dark area inside the crystal is a spot/crater generated by the defocused beam during SIMS dating. A ~10 μm inclusion, observed next to the spot (indicated with an arrow) is rich in Ca and rimmed by Al- and Si-rich material

Table 2 Summary of U–Pb radiometric data. Ages are given as weighted averages. Detailed results are listed in Tables S3 and S4 in the Supplementary Material

Sample ID	Rock type	Weighted average U–Pb age (Ma)/ <i>TuffZirc</i> age (Ma)	2σ	Method	Number of dated grains/analyzed spots	MSWD
24072017–4	Volcanic plug	7.015	±0.048	SIMS	21/21	1.13
07072015–2	Silicic sill	7.002	±0.064	SIMS	22/22	1.5
27072017–1	Dacite lava	7.03	±0.15	SIMS	9/10	1.8
26082015–25	Ignimbrite	7.15/7.03	±0.12/+0.18–0.07	SIMS	17/19	4.3
10072017–3	Rhyolite lava	6.85/6.93	±0.091/+0.08–0.1	SIMS	17/18	5.1
20190823–3	Rhyolite lava	6.757	±0.015	CA-TIMS	6/N.A	0.98

presented in Table 2 and Fig. 5a, while detailed results are listed in Tables S3–S4 and Figures S1–S4 of the Supplementary Material. Results of LA-ICPMS U–(Th–)Pb and trace element analysis of zircons from sample 20190823–3 are given in Tables S5–S6 of the Supplementary Material. Very similar ages were obtained for the two intrusive units, showing an age of 7.00 ± 0.06 Ma for the sill (sample 07072015–2) and 7.02 ± 0.05 Ma for the volcanic plug (sample 24072017–4). Slightly higher ages were obtained for the early silicic extrusive units: 7.03 ± 0.15 Ma for the dacite lava (sample 27072017–1) while the highest obtained U–Pb mean age is the ignimbrite age, 7.15 ± 0.12 Ma (Sample 26082015–25), although located slightly higher in the stratigraphy than the dacite. The ages of the upper rhyolite lavas are 6.85 ± 0.09 Ma for the Glerá lava (sample 10072017–3) and 6.76 ± 0.02 Ma for the uppermost rhyolite in Mt. Torfufell (sample 20190823–3). Very low 2σ and mean square weighted deviation (MSWD) were obtained

for the CA-TIMS dated sample compared to the SIMS dated samples. Four SIMS analyses were rejected to get statistically meaningful MSWD (a value under 2) and probability (higher than 0.05 for 95% confidence level), 2 rejections in 07072015–2, 1 in 27072017–1 and 1 in 26082015–25 (blue bars in Fig. 5a and Fig.S2 of the Supplementary Material). However, while MSWD is < 2 for most SIMS samples, high MSWDs (> 4) were obtained for two samples (26082015–25 and 10072017–3). The weighted averages of these two samples also have zero probability, meaning that their data are too scattered to get a statistically grouped age—and the probability density plots for these two samples show more than one peak (while the plots for the other samples show a single peak), indicating that the data from each sample consists of more than one population (Figures S2 and S3 of the Supplementary Material). Since the zircons are young and fairly low in U, it is not reasonable to assign this to Pb loss, as might be the case for older and/or U-rich zircons.

Instead, we rather assume that the dispersion in these two samples is related to recycling/mixing of older zircons into younger melts. To improve the situation, the data from these two samples were processed using the *TuffZirc* algorithm of Isoplot, which is largely insensitive to both Pb loss and inheritance and looks at the data statistically for a coherent group (Ludwig and Mundil 2002; Ludwig 2003). The ages calculated by *TuffZirc* are $7.03 \pm 0.18 / -0.07$ Ma for sample 26082015–25 (95.1% conf, from a coherent group of 12) and $6.93 \pm 0.08 / -0.1$ Ma for sample 10072017–3 (93.5% conf, from a coherent group of 11; Fig. 5a and Fig.S3 of the Supplementary Material).

Discussion

The silicic samples selected for this study are from volcanic formations, located at different stratigraphic levels, and intrusive units of the ToCV. By this, we were able to provide geochronological data that can be interpreted to represent the age range of silicic magmatism and volcanism at the volcano. We base the timing of the initiation of the ToCV on Supakulopas's (2018) $^{40}\text{Ar}/^{39}\text{Ar}$ 7.77 ± 0.15 and 7.98 ± 0.15 Ma ages, obtained from samples collected above and below the stratigraphic level of the base of the pile of thin basaltic *ā'a* lavas that we assume to define the onset of eruptions at the central volcano (Fig. 5a). However, as these two ages are inconsistent to the stratigraphic order (i.e., the higher age was obtained for the lava that is located higher in the strata pile while the lower lava gave younger age), the estimated timing of the establishment of the edifice base is quite imprecise (therefore given here as ~ 7.8 – 8.0 Ma). While no age determinations are available for intermediate formations, correlation with Supakulopas (2018) and the geomagnetic time scale provides a rough estimate, indicating that intermediate volcanism began during geomagnetic subchron C3Br.2r (i.e., somewhere on the range from ~ 7.3 to ~ 7.5 Ma; Ogg 2020).

Our oldest weighted average U–Pb age (7.15 ± 0.12 Ma) was obtained for the ignimbrite sample (26082015–25), which appears to be located higher in the strata pile than the younger dacite sample (27072017–1; 7.03 ± 0.15 Ma). As the MSWD for the ignimbrite sample is high (4.3), and as the probability density plot for this sample indicates that the data consists of more than one population (Fig.S3 of the Supplementary Material), it may be speculated that there is an older (~ 7.4 Ma) component in a ~ 7 Ma melt that could explain the higher weighted average U–Pb age, suggesting that the ignimbrite and the dacite were emplaced in close temporal proximity. The $7.03 \pm 0.18 / -0.07$ Ma age of the ignimbrite, extracted from the most-coherent population by the *TuffZirc* algorithm of Isoplot (Ludwig and Mundil 2002; Ludwig 2003), supports this idea (Fig. 5a and Fig.S3 of the

Supplementary Material). The older component in the ignimbrite may e.g., be derived from zircon inclusions in plagioclase phenocrysts, and/or from silicic lithics in the whole-rock sample, which would imply silicic magmatism as early as 7.4 Ma at the ToCV. However, as Supakulopas's (2018) 7.12 ± 0.10 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age is from the lowermost rhyolite lava in Mt. Hólaflajall, it can be considered to approximately mark the onset of silicic volcanism at the ToCV.

The two youngest weighted average ages, 6.85 ± 0.09 and 6.76 ± 0.02 , are from lavas representing late silicic volcanism at the ToCV (samples 10072017–3 and 20190823–3, respectively). The weighted average of sample 10072017–3 has zero probability; MSWD for this sample is high (5.1) and the relative probability plot indicates that the data consists of more than one population (~ 7.0 and ~ 6.8 Ma; Figures S2 and S3 of the Supplementary Material). The most-coherent group of zircon ages, determined using the *TuffZirc* algorithm of Isoplot (Ludwig and Mundil 2002; Ludwig 2003), provided an age of $6.93 \pm 0.08 / -0.1$ Ma (Fig. 5a and Fig.S3 of the Supplementary Material). While this sample is not confidently assigned to the youngest rhyolite lava at the volcano, sample 20190823–3 is collected at the highest rhyolite peak and has MSWD very close to 1 (0.98), showing decidedly that silicic activity continued at the ToCV until 6.76 ± 0.02 Ma. Field relations indicate that the rhyolite activity was succeeded by regional basaltic volcanism. Supakulopas (2018) provided a 5.73 ± 0.14 Ma age for a basaltic lava onlapping a rhyolite formation in Mt. Hólaflajall which, according to his interpretation, was formed during geomagnetic subchron C3Bn (~ 7.21 – 7.10 Ma), thereby identifying a ~ 1.5 Myr hiatus between these sequences (Fig. 5a). This hiatus is somewhat shortened by at least four lavas that are present between these two units, and due to the palaeo-landscape, the length of the hiatus may vary within the area, probably increasing in length at the highest rhyolite peak. Nevertheless, as we date the youngest rhyolite at 6.76 ± 0.02 Ma, it may be assumed that ~ 1 Myr passed from the extinction of the ToCV until basaltic lavas from nearby fissure swarms began to onlap the volcano.

The available age data indicate that the ToCV was active from ~ 7.8 – 8.0 to 6.76 ± 0.02 Ma, or for ~ 1 – 1.2 Myr, and that silicic magmatism and volcanism occurred during the last ~ 0.4 Myr of the volcano's life-span. Consistent with Supakulopas' (2018) conclusions, our age data show that the silicic rocks of the ToCV are 1–2 Myr older than suggested by earlier researchers (e.g., Hjartarson 2003; 2005). The longest hiatus in the research area appears to be between the volcano's uppermost rhyolites and the younger, succeeding basalts. Although relatively shorter than the time gap recorded in the Flateyjarskagi peninsula, it may be speculated if the hiatus observed above the ToCV is potentially an extension of this major unconformity and thereby related to a plate boundary shift. If so, and according to the general

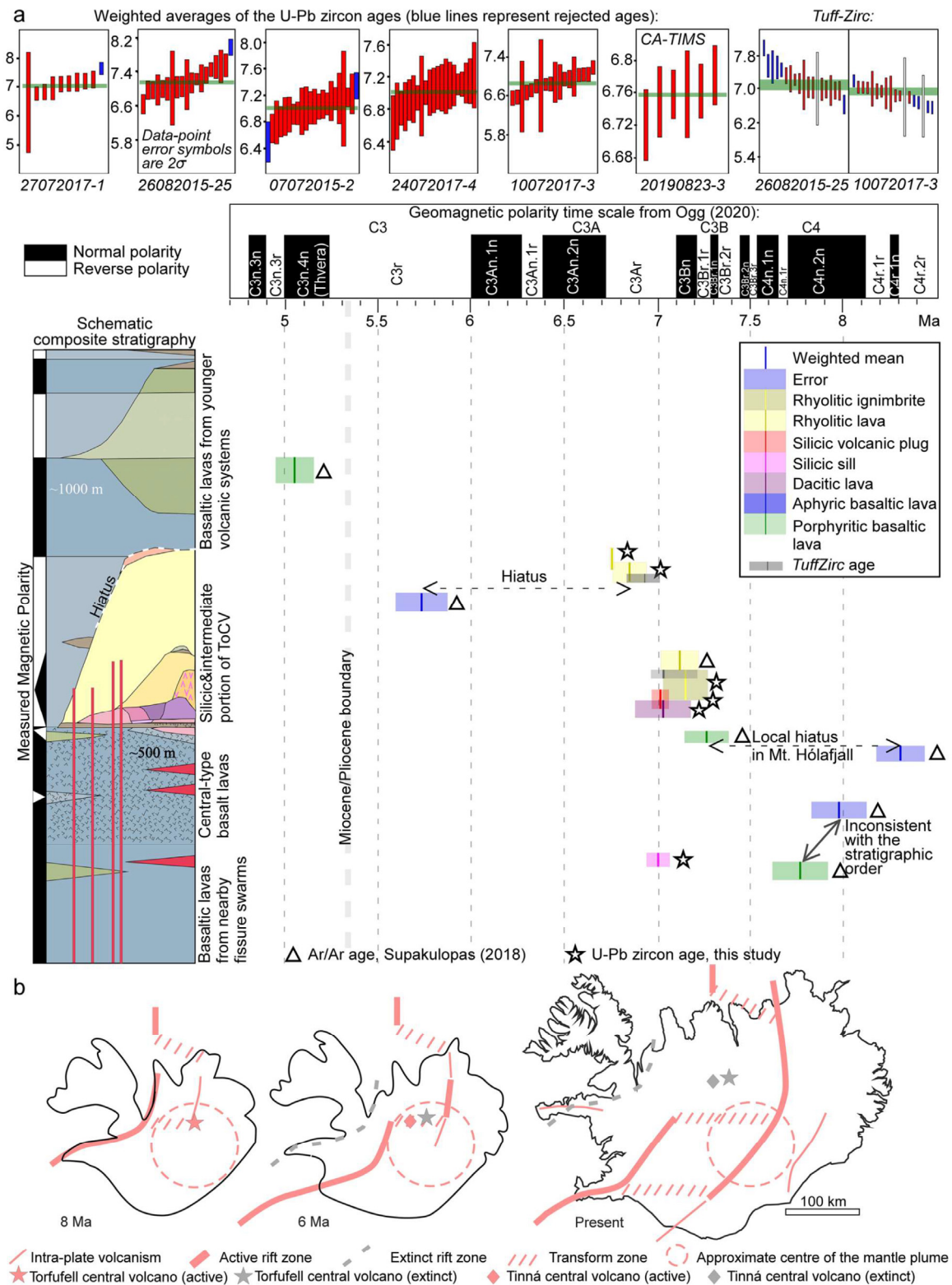


Fig. 5 **a** New U–Pb zircon ages, combined with Supakulopas ⁺ (2018) ⁴⁰Ar/³⁹Ar ages and coupling of the schematic, composite stratigraphic column with the geomagnetic polarity time scale. The schematic stratigraphic column (same color legend as in Fig. 2) is based on original fieldwork, integrated with data by Kristjánsson et al. (2004) and Supakulopas (2018) from Mt. Hólafljall. The weighted average plots were made with Isoplot (Ludwig 2012). *TuffZirc* age plots for the two high-MSWD samples are presented in the upper right corner (generated using the *TuffZirc* algorithm of Isoplot by Ludwig and Mundil 2002; detailed in Fig.S3 of the Supplementary Material). **b** Schematic illustration of our new hypothesis; proposed to explain a discrepancy (younging towards west) in the ages of TiCV and ToCV

understanding of the Flateyjarskagi unconformity, the ToCV would be formed in the now extinct SHRZ, while the basalt lavas above the hiatus would be formed in the NVZ. The Flateyjarskagi hiatus appears to span the time from ~10 to ~6 Ma in the north (i.e., by the peninsula's SE end) and from ~7 to ~5 Ma in the south (i.e., in the southern part of the Fnjóskadalur valley; Jancin et al. 1985; Cotman 1979; Fig. 1b, c), thus spanning the Miocene-Pliocene boundary (~5.3 Ma), while the lavas onlapping the ToCV record ongoing volcanism across this boundary (Figs. 2 and 5a), at least until 5.05 Ma (via stratigraphic correlation with Supakulopas's (2018) ⁴⁰Ar/³⁹Ar ages). On the other hand, the hiatus above the ToCV may simply represent a local break at the end of the volcano's active period. Assuming that the geodynamic setting since the volcano's lifetime until present was dominated by spreading, the distance between the ToCV and the present NVZ (~70 km) is consistent with origin within the NVZ and a mean spreading half-rate of ~1 cm/year (e.g., Árnadóttir et al. 2008). Furthermore, considering the general assumptions that regional lava dips in Iceland result from loading by voluminous lava flows in the respective volcanic zone (e.g., Pálmason 1973; Pálmason and Sæmundsson 1974; Walker 1960), the regional south-east dip direction of the strata in the ToCV area might be taken to indicate origin within a zone that was roughly coincident with the present NVZ. This would agree with the hiatus representing only a local break and would indicate, as no major hiatuses are present, that a time gap related to a rift relocation is non-existent in the ToCV area. If so, the new U–Pb zircon ages from the ToCV may be considered to provide timing of silicic magma erupted soon after its parent rift relocated, and thereby constrains on the oldest silicic rocks formed at the incipient rift. Similar findings of appreciable silicic material erupting soon after relocation of the parent rift (at ~5.4–3.9 Ma) are documented at the Hafnarfjall-Skarðsheiði central volcano in West Iceland which began forming nearly contemporaneously with the relocation of the southern segment of the SHRZ to the WVZ (Banik et al. 2018). However, the age progression (younging to the west) of the E–W aligned ToCV and the 5–6 Ma TiCV remains enigmatic as it conflicts with concepts of unidirectional spreading. Considering the age of the main formation

of the TiCV, ~5.5 Ma (Hjartarson 2003; 2005), it might be suggested that the TiCV originated inside the NVZ. The problem is that the volcano is 90 km west of the NVZ which would indicate a half spreading rate of 1.7 cm/year (Hjartarson 2009). Therefore, the TiCV appears to have formed outside the NVZ and to the west of the then extinct ToCV. As such, the results of our study do not align with the generally established geotectonic framework (e.g., Sæmundsson 1979; Einarsson 2008). Therefore, to provide an explanation for this discrepancy, we propose a new hypothesis (Fig. 5b).

At ~8 Ma, the center of the mantle plume was located just east of the ToCV (an assumption based on Steinthorsson et al. (1985) and Martin et al. (2011)), after having reached a critical distance from the northern segment of the SHRZ, already weakening the lithosphere, resulting in partitioned spreading between the SHRZ and the incipient NVZ. To accommodate this rearrangement, the southern end of the NVZ was linked with the SHRZ by a transverse zone which was the precursor of the MIB. Similar to the present MIB, we propose that this proto-MIB was leaky, i.e., comprising a small component of opening, producing sufficient room for magma to erupt. Volcanic activity at this transverse zone was initially most effective at the east end, at the junction of the proto-MIB with the incipient NVZ, approximately by the center of the mantle plume, then gradually migrated westward—away from the center—resulting in the observed age progression of the Torfufell and Tinná central volcanoes. Lavas from the TiCV may have flowed from the west and reached the area around the ToCV and partly or totally covered the edifice along with lavas from the NVZ flowing from the east. This interpretation requires a ~50 km southward migration of the transverse zone with time, from the proto-MIB to the present location of the MIB. While such southward advancement could probably be explained partly by the WNW migration of the tectonic plates relative to the mantle plume, it may also be a result of southward propagation of the new rift zone, similar to the indicated southward migration of the SISZ with propagation of the EVZ (e.g., Einarsson 1991; Khodayar and Franzson 2007; Karson 2017) and northward migration of the TFZ with propagation of the NVZ (e.g., Karson 2017; Karson et al. 2019).

Our hypothesis does have some support from the whole-rock geochemical data that indicate that the rock suite of the ToCV is transitional in nature (i.e., has a transitional character towards alkaline rocks) with basalts that are slightly higher in TiO₂ and K₂O compared to typical rift zone basalts and rhyolites that have higher K₂O and lower FeO than typical rift zone rhyolites (Fig. 3; Tables S1 and S2 of the Supplementary Material). A comparison with the neighboring TiCV shows strong similarities between these two central volcanoes and indicates that basalt to rhyolite products of both volcanoes are, in general, more enriched than typical rift zone magmas (Fig. 3). More

importantly, these two volcanoes feature rhyolites similar to rhyolites associated either with the MIB or those in the propagating EVZ, or even the intraplate ÖVB, while their basalts are similar to those from the junction of the WVZ with the SISZ. Nonetheless, the new hypothesis awaits critical testing that optimally will involve extensive structural mapping along the hypothesized proto-MIB, to seek evidence of potential transform-related structures that may be compared with future collection of isotopic data from zircon crystals and whole rocks of the ToCV and TiCV and may be indicators of petrogenetic environments for silicic magmas at these volcanoes (see Carley et al. 2020). To obtain more robust geometric relationships in the central north region of Iceland, we consider dating of the remaining undated silicic centers in the region to be essential. Dating of additional samples from the TiCV and the two adjacent volcanoes in the Flateyjarskagi peninsula that can confidently confirm their ages would furthermore strengthen the dataset, and a closer look at the Víðidalur central volcano would be of particular interest as recent U–Pb zircon ages (6.3–7.3 Ma; Carley et al. 2020) document silicic magmatism at the SHRZ concurrently with silicic activity at the ToCV.

Conclusions

The U–Pb zircon ages (weighted averages) presented here range from 7.15 ± 0.12 to 6.76 ± 0.02 Ma, indicating that silicic magmatism and volcanism of the Torfufell central volcano extended over ~400 kyr. Correlations with previous work predict that the life-span of the central volcano is about or just over 1 Myr, commencing with basaltic volcanism at ~7.8–8.0 Ma. A ~1 Myr volcanic hiatus is recorded between the uppermost rhyolites of the central volcano and the succeeding basaltic lavas, from 6.76 ± 0.02 to 5.73 ± 0.14 Ma, and although broadly contemporaneous with (but shorter than) the Flateyjarskagi unconformity, we propose that this hiatus represents a local break at the end of the volcano's active period. The new U–Pb age data demonstrate that the silicic portion of the Torfufell central volcano was formed nearly synchronously with a major rift relocation in North Iceland and may provide constraints on the oldest silicic rocks formed at the incipient Northern volcanic zone. After its extinction, the Torfufell central volcano was buried beneath younger formations making up the lava succession above the hiatus. We propose that these younger lavas originated from the large Tinná central volcano in the west as well as from the newly formed NVZ in the east. Our results pertain to a key area in the evolving understanding of the development of crustal accretion in Iceland and underline

the extensive room for additional high-quality radiometric dating on silicic activity in the central north region.

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Declarations

Conflict of interest There are no financial interests related to this work. It has only academic benefit and it is a part of a PhD project in the University of Iceland.

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AS1 Supplementary material of Paper I

Supporting Information for

Evolution of the Late-Miocene Torfufell central volcano, N-Iceland

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Introduction

This supporting information presents (i) details of aa-lavas and pyroclastic flows belonging to the Torfufell central volcano; presented in image and table format; (ii) results of ICP-OES whole-rock geochemical analysis representative of the Torfufell volcanic system (major elements); and (iii) results of XRD analysis on amygdules and vein fillings from the study area; (iv) XRD analysis and field descriptions of the tephra-, smectite- and fossil-bearing sediment horizon; (v) cross-sections illustrating the complexities indicated by age data in the western side of Mt. Torfufell.

Text S1.1. Description of early basaltic lavas (ā'a and pahoehoe).

In general, ā'a lavas in the observed stack are most often ~1-3 m thick (except for three lavas which are ~4-6 m thick; Fig.S1.1), and generally feature <1 m thick upper and/or basal clinker. Sediments (sandstone and sandy siltstones) are recorded at 5 lava contacts while no sediment is observed between lavas no. 2-6 and 10-12, indicating short time intervals between these flows. Chilled lava contacts are observed in two cases (see example in Fig.S1.2k and l). Waveforms at the boundary between lava no. 5 and its upper clinker suggest that the lava flowed from a westward direction. One of the uppermost ā'a lavas is quite flow-banded, with flow-banding particularly prominent within the lower part (Fig. S1.2j). The composition of this lava is more silicic than lower ā'a lavas and approaches basaltic andesite (51.70 wt% SiO₂; Table S1.2). Six pahoehoe lavas, observed above the ā'a lava pile, are generally slightly thicker (most often >4 m) than the ā'a lavas and also more primitive in composition as indicated by chemical analysis of lava no. 13 (48.24 wt% SiO₂; Table S1.2). Very sharp and distinct contact is recorded between the two lowermost pahoehoe lavas (lavas no. 13 and 14; Fig. S1.2m), while scoria and/or sediments are observed between upper lavas. The thin-layered lava pile is intruded by a silicic intrusion, ~100 m in diameter, which crops out above lava no. 18 (see section 3.2.3. of the paper).

A very thick (~40 m) pahoehoe lava lobe is observed in the Glerá profile. This lava is more primitive in composition than lava no. 13 (47 wt% SiO₂; sample 20180904-2) and rather coarse grained. Horizontal and vertical vesicular sheets are prominent within the core of the lobe (Fig.S4). A 5 m thick vesicular crust is observed at the top (Fig.S3c).

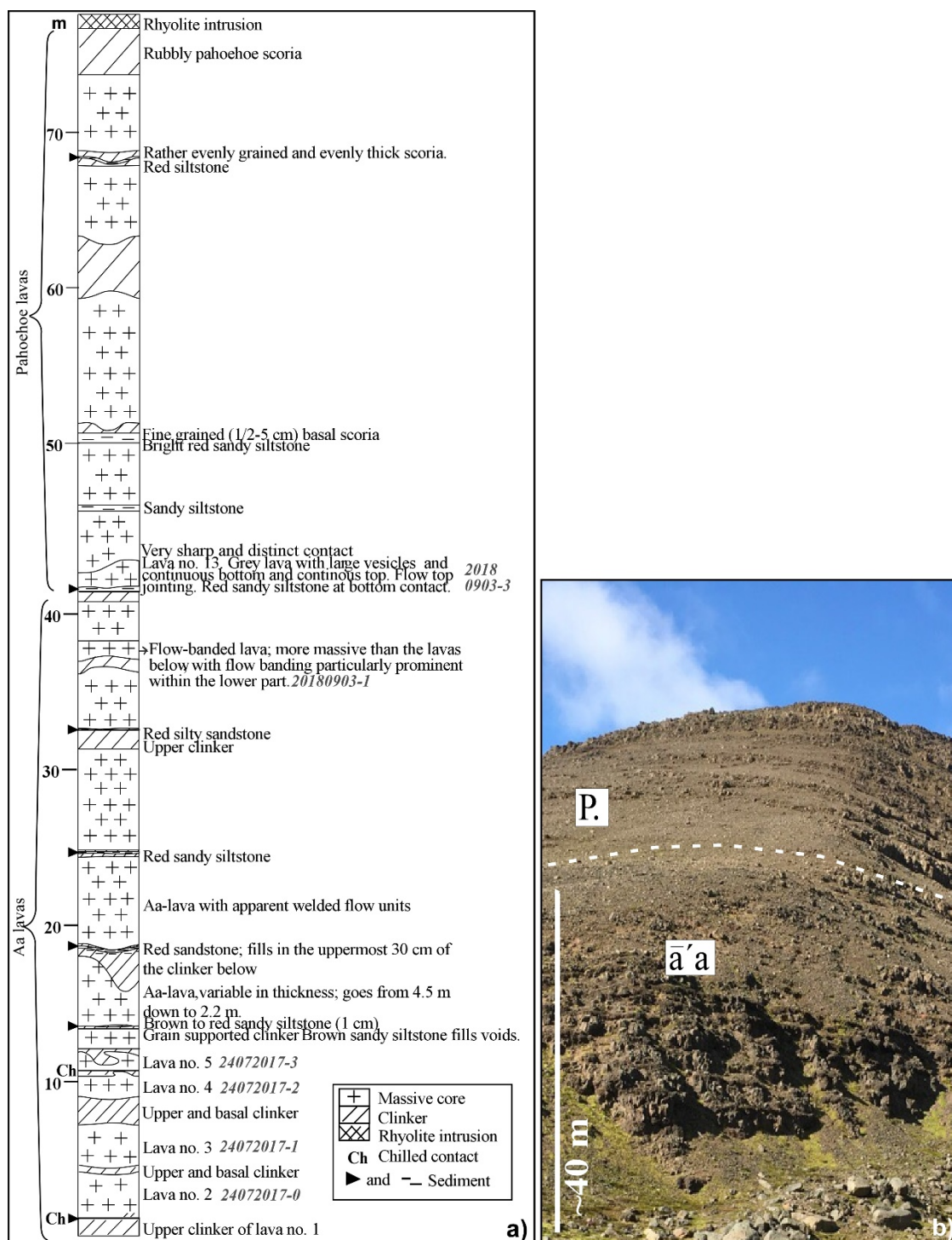


Figure S1.1. a) ā'a and pahoehoe lavas of the Torfufell central volcano, observed in the Nautárgil gully. (Coordinates of Lava no. 1: 65.321931, lon:-18.335686, ele:393). Sample Ids are indicated with italic print. Overview of the ā'a (Aa) and pahoehoe (P.) lavas, observed in the Nautárgil Gully. Dashed line indicates approximate boundary between the two types. Sample Ids are indicated with italic print.

Unit	Thickness	Internal component/thickness	Description
Scoria	40-90 cm		Top scoria of lava no. 5. Where the lava is thin, the scoria is thick, and vice versa, resulting in a wavy contact between scoria and lava. The direction of the ramping and the lava fingers indicates that the lava flowed from the West.
Lava no. 5 (ā'a lava)	35-120 cm	Vesicular zone/24-109 cm Vesicular zone/3 cm Vesicle-poor zone/5 cm Glassy bottom/2-3 cm	25-30% vesicles, larger than below; usually ca. 5 mm but up to 1 cm. Ca. 25% vesicles, small (~1 mm). Vesicle-poor (~1-2% vesicles) cryptocrystalline rock Rapidly chilled contact, sometimes glassy.
Scoria	15-20 cm		Top scoria of lava no. 4. Inside the scoria is a squeeze-out from the core of the lava.
Lava no. 4 (ā'a lava)	130-180 cm	Vesicular zone/110-160 cm Vesicle-poor zone/20 cm	Ca. 30% vesicles, with the largest vesicles are in the middle of the layer where they are from 1 mm to 20 mm in diameter. In the uppermost part, vesicles are from 1 mm to 10 mm in diameter. Vesicles are both round and elongated. Elongated vesicles occur in bands. Vesicle-poor bottom.
Scoria	150-180 cm		Top scoria of lava no. 3 and bottom scoria of lava no. 4. Grain supported scoria with 1-35 cm scoria grains. No sediment between scoria grains and not between lavas.
Lava no. 3 (ā'a lava)	2.6-2.9 m	Vesicular zone/190-220 cm Vesicle-poor zone/50 cm Vesicle-poor zone/20 cm	30-40% vesicles, up to 1x3 cm. Ca. 1 m above bottom is a very circular volcanic bomb. The bomb is vesiculated in the middle but has a dense coat. The coat has very sharp contact, both outer and inner. 5-7% vesicles, up to 4x7 mm. Ca. 25 cm above the bottom is a 17x30 cm scoria piece. Microcrystallized dark-grey rock with <5% vesicles.
Scoria	40 cm		Top scoria of Layer 2 and bottom scoria of Layer 3. Grain supported scoria with 2-12 cm scoria grains. No sediment. Lower and upper contacts are sharp but grading. The scoria is wavy but even in thickness.
Lava no. 2 (ā'a lava/blocky pahoehoe)	2.8-3 m	Vesicular zone/260-280 cm Vesicle-poor zone/15-20 cm Glassy bottom/~5 cm	Grey microcrystallized to fine grained basalt with 15-30% vesicles on the range 3-30 mm. The volume of vesicles appears to increase upwards. Pockets of up to 30% vesicles alternate with pockets of down to 15% vesicles. The largest vesicles are in the middle of the lava. By the top of the lava, vesicles are 3-15 mm on average. Microcrystallized and vesicle-poor dark-grey lava. Vesicles are <5%, most often =< 1 mm. Clusters of pipe vesicles are observed in several places, 1-2 cm wide and up to 10 cm long. These clusters cover 20-30 cm long horizontal areas. Glassy, continuous pahoehoe-bottom. Localized piece of thin scoria (up to 20 cm thick) is observed in the bottom, where the lava flowed over a small irregularity in the substrate.
Sediment	1-2 cm		Red sandstone
Scoria	110 cm		Only the top scoria of lava no. 1 is visible. The scoria grains are up to 15-20 cm in diameter. The uppermost 45 cm are infilled with red to brown sandy siltstone (reddish in the upper part but yellow-ish in the lower part). The scoria is grain supported.

Table S1.1. Detailed descriptions of 5 ā'a lavas in Nautárgil, representatives of basalts erupted during early stages of the central volcano. Coordinates of Lava no. 1: 65.321931, lon:-18.335686, ele:393.

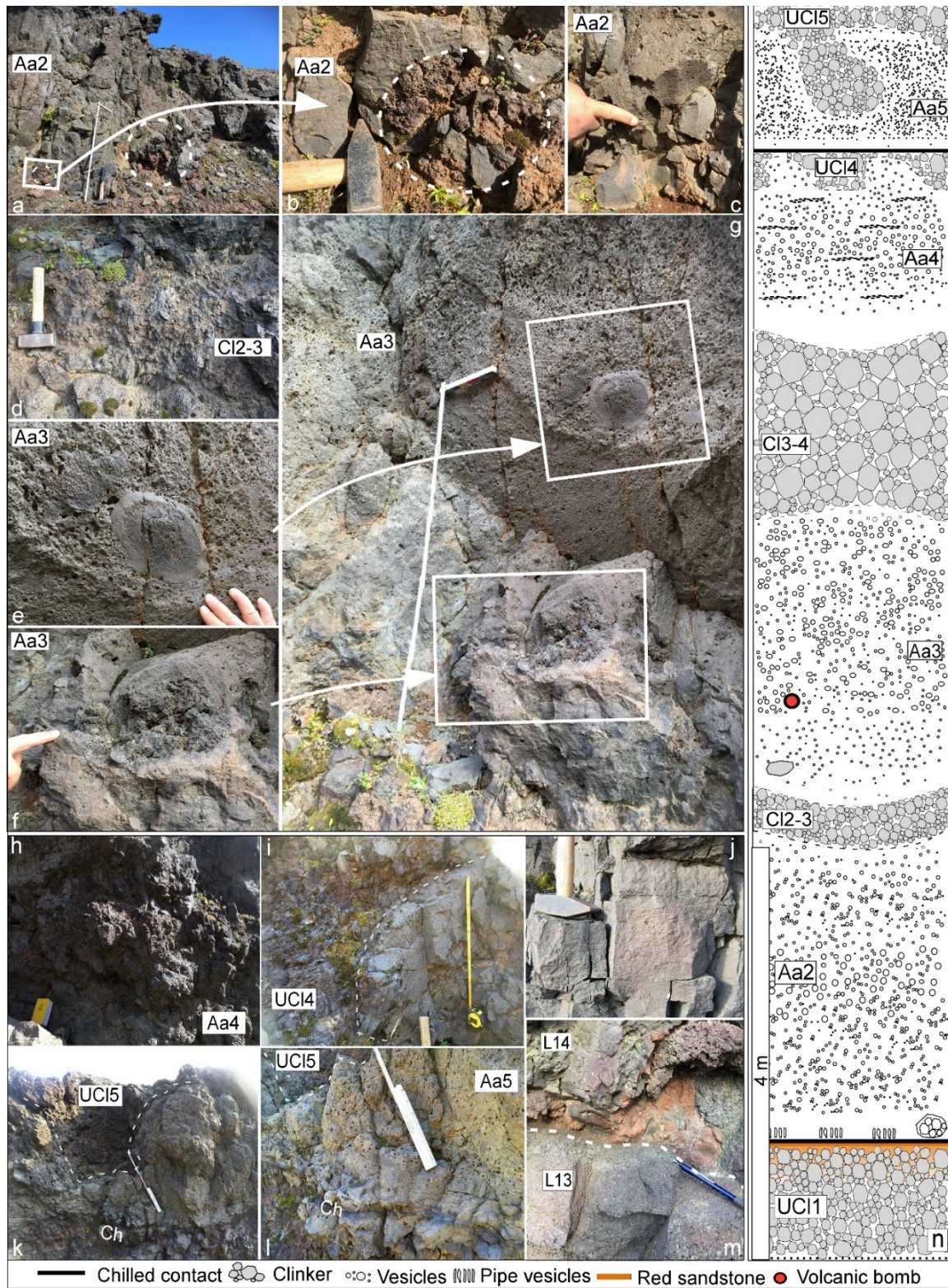


Figure S1.2. Examples of ā'a and pahoehoe lavas. a) b) and c) Lava no. 2; a) Overview (localized pockets of thin scoria at the bottom are encircled with dashed lines). b) Detail from figure a). c) Pipe vesicles in the lowermost 15-20 cm. d) Top scoria of lava no. 2 and bottom scoria of lava no. 3. e) f) and g) Lava no. 3; e) Volcanic bomb ca. 1 m above bottom (detail from figure g). The bomb is very circular and vesiculated in the middle while the coat is dense with very sharp outer and inner contacts. f) Scoria piece ca. 25 cm above bottom (detail from figure g). g) Overview of the lower part of lava no. 3. h) Lava no. 4 (ā'a lava) i) Top scoria of lava no. 4 and a squeeze-out inside the top scoria from the core. j) Prominent flow-banding in the lower part of lava no. 11 (ā'a lava). k) and l) Lava no. 5 (ā'a lava); chilled bottom contact (Ch) and wavy contact between scoria and lava finger (indicated with dashed line). m) Flow top jointing and very distinct contact (dashed line) between lavas no. 13 and 14 (pahoehoe lavas). n) Schematic log of ā'a lavas no. 1-5. UC1 = Upper clinker of lava no. 1. Aa2 = massive core of lava no. 2. Sc2-3 = Upper clinker of lava no. 2 and bottom scoria of lava no. 3. Aa3 = Massive core of lava no. 3. Cl3-4 = Upper clinker of lava no. 3 and basal clinker of lava no. 4.



Figure S1.3. Overview images of a ~40 m thick pahoehoe lava lobe in Glerá; a) Base; b) core; c) top.

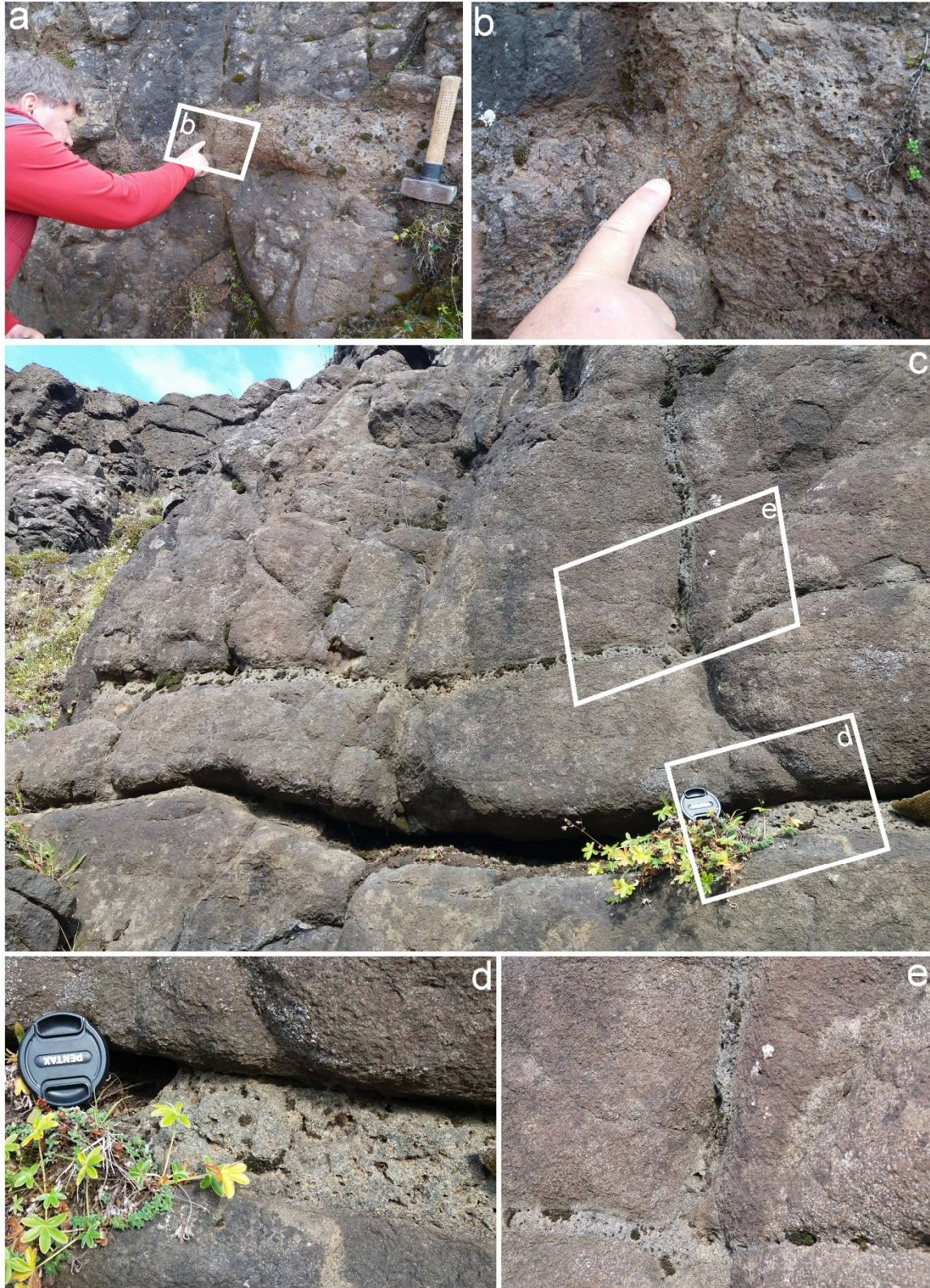


Figure S1.4. Pahoehoe lava lobe in Glerá: horizontal and vertical vesicular sheets within the core of the lobe.

Sample Id.	Lat	Long	Type	Group/ subgroup	SiO ₂	Al ₂ O ₃	FeO	MnO
27072017-5	65.2862	-18.2783	Lava	CV	46.42	14.72	13.54	0.22
20180904-2	65.289	-18.2233	Lava	CV	46.78	14.58	15.25	0.24
25072018-1	65.38694	-18.2113	Intr., P	Dyke	47.46	17.68	9.73	0.16
				Plateau				
10072017-4	65.28817	-18.2131	Lava, P	(overlying)	47.88	17.67	10.17	0.17
20180903-3	65.32288	-18.3354	Lava	CV	48.24	13.01	15.03	0.27
				Plateau				
18072017-1	65.2544	-18.2466	Lava, P	(overlying)	48.54	15.31	11.55	0.2
				Plateau (below				
14072015-12	65.4004	-18.257	Lava, P	CV)	48.92	15.57	10.88	0.2
				Plateau (below				
20072017-2	65.41463	-18.1661	Lava, P	CV)	49.3	15.31	11.23	0.18
				Plateau				
27072017-4	65.28564	-18.2841	Lava	(overlying)	49.54	13.3	14.54	0.25
24072017-0	65.32193	-18.3357	Lava	CV	49.75	13.02	14.16	0.23
24072017-3	65.32193	-18.3357	Lava	CV	50.08	13.15	13.68	0.25
				Plateau				
03072018-3	65.31565	-18.2145	Lava	(overlying)	50.12	13.24	14.2	0.25
24072017-1	65.32193	-18.3357	Lava	CV	50.22	12.98	13.6	0.24
24072017-2	65.32193	-18.3357	Lava	CV	50.69	12.95	13.65	0.23
20180903-1	65.32288	-18.3354	Lava	CV	51.7	12.63	14.12	0.25
27072017-2	65.29289	-18.2687	Lava	CV	56.04	13.59	11.33	0.2
20180904-1	65.28958	-18.2321	Lava	CV	59.76	14.29	11.01	0.24
09072015-8	65.31684	-18.2883	Lava	CV	59.83	14.11	11.36	0.27
01092016-1	65.3063	-18.3366	Lava	CV	61.91	13.69	11.25	0.28
18072017-3b	65.28641	-18.2694	Lava	CV	64.35	14.43	9.16	0.09
27072017-1	65.29289	-18.2687	Lava	CV	65.63	14.24	7.7	0.21
10082018-1	65.27755	-18.2601	Pyrocl.	CV	71.24	13.54	4.51	0.13
26082015-25	65.27755	-18.2601	Pyrocl.	CV	72.46	13.7	4.31	0.11
10072017-3	65.28886	-18.2186	Lava	CV	74.68	13.74	1.95	0.02
07072015-2	65.32421	-18.2775	Intrusion	CV	74.71	13.66	2.01	0.06
18072017-3a	65.28641	-18.2694	Lava	CV	74.95	12.95	2.63	0.14
24072017-4	65.32193	-18.3357	Feeder	CV	75.38	13.23	1.91	0.02
27072017-3	65.28667	-18.2815	Tephra	CV	75.6	13.16	2.01	0.02
14072017-2	65.30281	-18.2246	Lava	CV	75.72	12.87	1.94	0.05
14072017-1	65.30108	-18.2337	Lava	CV	75.8	13.39	1.54	0.04
20180904-3	65.28956	18.21921	BAF	CV	76.04	12.47	2.07	0.07
13072017-1	65.32597	-18.3532	Lava	CV	76.29	12.83	1.71	0.02

Table S1.2. (Continued on next page). ICP-OES whole-rock geochemical analysis results representative of the Torfufell volcanic system. Grey rows indicate samples with age determinations. P=porphyritic. CV=CV. Locations and positions in strata pile are signified in S3-profiles and S4-outcrops.

Sample Id.	MgO	CaO	Na2O	K2O	TiO2	P2O5
27072017-5	7.67	11.03	2.2	0.27	3.38	0.38
20180904-2	6.96	9.44	2.43	0.35	3.45	0.36
25072018-1	6.63	14.14	2.09	0.19	1.66	0.12
10072017-4	6.59	13.55	2.01	0.11	1.6	0.13
20180903-3	5.5	10.48	2.78	0.2	3.85	0.47
18072017-1	7.17	12.12	2.37	0.24	2.16	0.2
14072015-12	6.61	12.54	2.42	0.25	2.24	0.23
20072017-2	6.4	12.05	2.58	0.3	2.3	0.21
27072017-4	5.24	9.87	2.88	0.41	3.43	0.37
24072017-0	5.29	10.22	2.69	0.46	3.6	0.42
24072017-3	5.46	10.14	2.65	0.54	3.46	0.4
03072018-3	5.28	9.59	2.88	0.62	3.3	0.38
24072017-1	5.63	10.14	2.65	0.59	3.39	0.39
24072017-2	5.49	10.07	2.58	0.48	3.31	0.39
20180903-1	4.27	8.61	3.01	0.84	3.84	0.58
27072017-2	3.41	7.31	3.58	1.07	2.93	0.4
20180904-1	1.65	5.45	4.01	1.54	1.35	0.57
09072015-8	1.44	5.48	3.95	1.51	1.35	0.56
01092016-1	0.66	5.07	3.99	1.61	1.05	0.33
18072017-3b	0.44	3.97	4.36	1.73	1	0.28
27072017-1	0.47	4.29	4.23	2.08	0.76	0.21
10082018-1	0.14	2.31	4.22	3.38	0.31	0.02
26082015-25	0.24	2.01	4.65	2	0.32	0.03
10072017-3	0.1	0.49	5.09	3.58	0.16	0.02
07072015-2	0.01	0.64	4.98	3.59	0.17	0
18072017-3a	0.12	1.21	4.43	3.16	0.23	0.02
24072017-4	0.07	0.56	5.06	3.43	0.18	0
27072017-3	0.08	0.52	4.86	3.39	0.16	0.02
14072017-2	0.02	0.76	4.85	3.44	0.15	0.01
14072017-1	0.03	0.77	4.74	3.37	0.16	0
20180904-3	0	0.73	4.92	3.38	0.15	0
13072017-1	0.06	0.48	4.88	3.42	0.16	0.01

Table S1.2. Continued

Upper boundary (cm)	Lower boundary (cm)	Field description	Thickness
0	25	Red siltstone	25
25	27	White tephra	2
27	45	Light-brown siltstone with sand-sized grains	18
45	46	Light-colored clay with coarse sand-sized grains	1
46	66	Clay with sand. Slightly darker than the layer below.	20
66	72	Light-colored clay with sand	6
72	79	Yellow-red-brownish clay (clay-size is dominant) with minor sand-sized (up to coarse sand size) particles	7
79	107	Green-greyish clay that gets lighter in color downwards. Very little sand. Small lenses of very green clay at the bottom.	28
107	117	Greenish siltstone	10
117	120	Grey clay	3
120	132	Grey clay, very smeary/soggy. Analyzed in XRD	12
132	138	Dark-grey clay, mixed with silt	6
138	166	Light-greyish silt with clay. Analyzed in XRD	28
166	202	Green claystone with sand	36
202	211	Greyish silt with sand	9
211	235	Yellow-green-brownish silt- and claystone with coarse sand	24
235	280	Clay mixed with silt and minor sand. Changes gradually (from top to bottom) from light-colored to green	45
280	284	Very light, almost white. Mostly clay, mixed with silt and sand	4
284	302	Brown-greenish claystone mixed with silt and sand	18
302	304	Light-colored layer, mostly silt with sand	2
304	310	Brown-greenish clay mixed with silt and sand	6
310	328	Silt mixed with sand. Flickers frequently from green to dark grey	18
328	355	Green clay-, silt- and sandstone	27
355	375	Similar to layer at 310-328 cm but not as flickering	20
375	381	Darkbrown clay with sand	6
381	404	Green claystone with sand	23
404	409	Green smeary/soggy clay with sand	5
409	412	Light-colored smeary/soggy clay with sand	3
412	447	Greenish claystone with minor sand. Black fragments (fossilized wood?) are prominent.	35
447	461	Dark-green clay, sparse grains of coarse sand-size	14
461	466	Light, smeary/soggy clay mixed with sand. Analyzed in XRD	5
466	498	Yellow-brownish clay with minor silt	32
498	508	Smeary/soggy clay, minor sand-sized particles. Flickers from light-green to dark-green. Analyzed in XRD	10
508	519	Yellow-green-brownish clay. Minor sand sand-sized particles	11
519	543	Brown siltstone, mixed with sand	24
543	546	Green clay with red lenses	3
546	592	Red siltstone	46

Table S1.3. Description of the tephra-, smectite and fossil-bearing sediment horizon by Guðbjörn Margeirsson (observed at lat=65.306296, lon=-18.336557; same as Fig.A1.3c of the paper). Above the horizon at this location is an abrupt basaltic lava (olivine basalt). Above the lava is red siltstone. Samples analyzed in XRD are highlighted.

Layer no. (from top)	XRD sample Id.	Upper boundary	Lower boundary
11	SG01	120 cm	132 cm
13	SG02	138 cm	166cm
31	SG03	461 cm	466cm
33	SG04	498 cm	508cm

Table S1.4. Positions and names of four key samples from the tephra-, smectite- and fossil-bearing sediment horizon (same location as in Table S3) selected for XRD analysis.

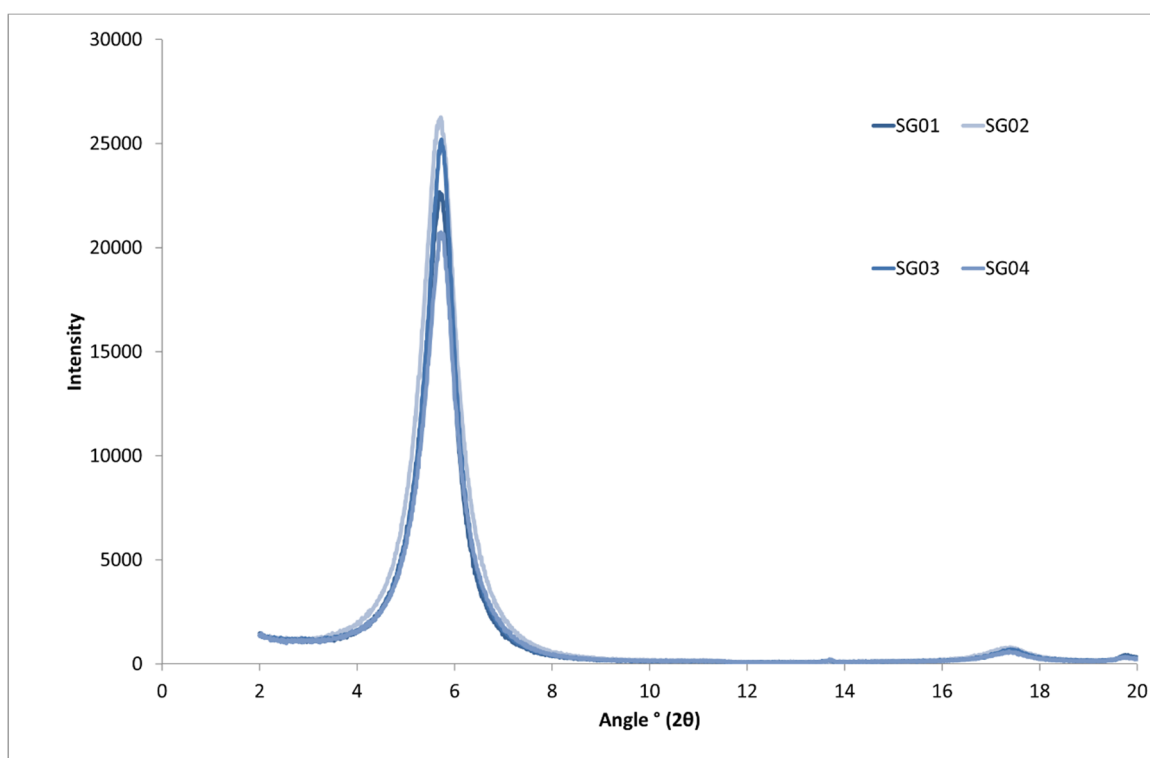


Figure S1.5. XRD analysis of four key samples from the tephra-, smectite- and fossil bearing sediment horizon. Performed by Léa Lévy and Damien Deldicque (Ecole Normale Supérieure, Paris, France). The sediment horizon was sampled in NW Mt. Torfufell (at location lat=65.306296, lon=-18.336557). The horizon consists of 37 distinct layers. Four of these were selected as key samples and analysed in XRD (Table S4).

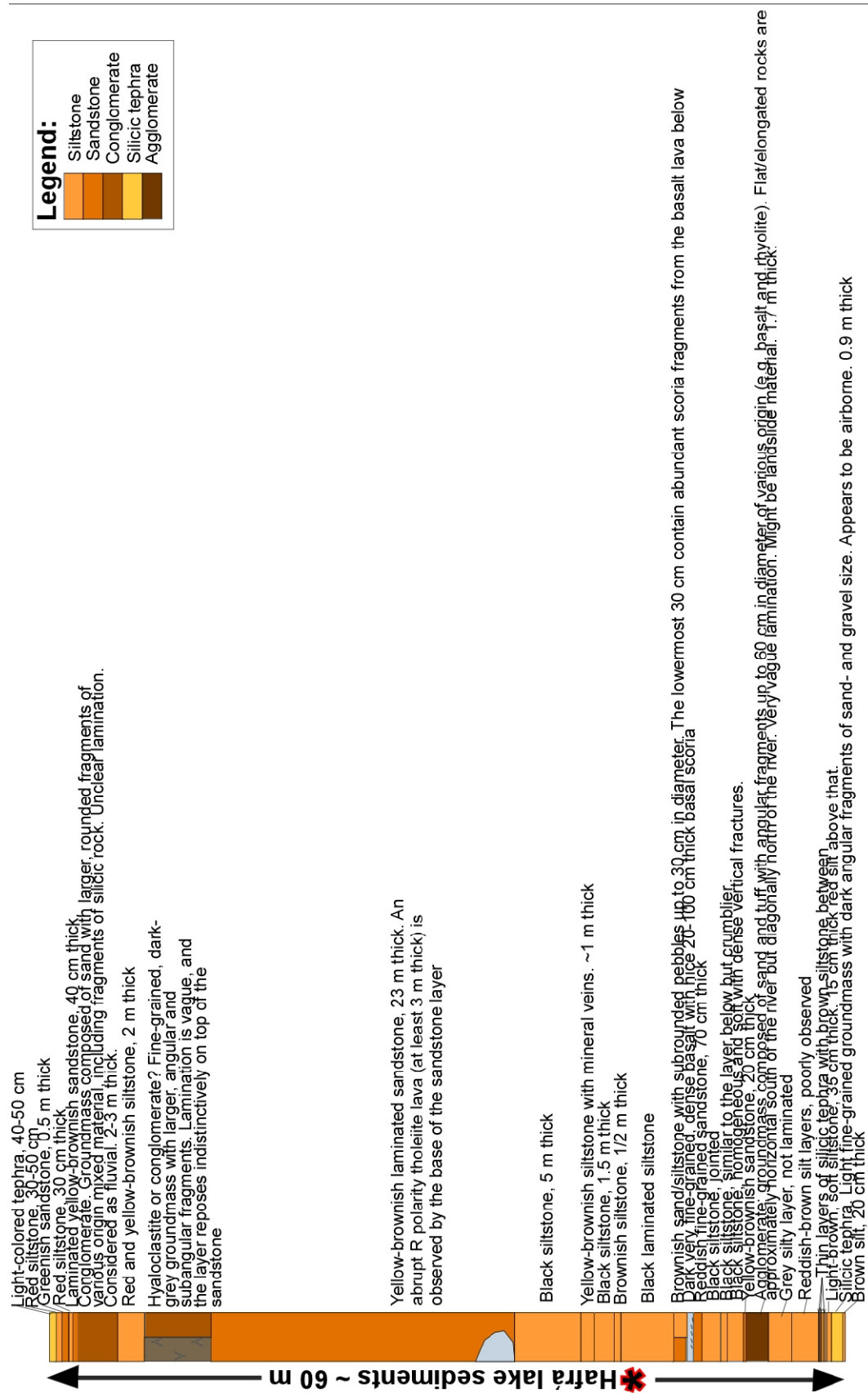


Figure S1.6. Description of the Hafrá lake sediments.

Text S1.2. Descriptions of pyroclastic flows and lahar deposits

Ignimbrite, observed in the Ytra-Mógil gully (Fig.S1.7a):

Classic black fiamme lenses with internal perlitic fractures are abundant in the lowermost 3 m of the observed outcrop (lower part of layer 1 in Fig.S1.7a), where they are strongly welded and compacted. Above this point, the color of the fiammes gradually changes from black to pale, while the groundmass color changes from reddish to grey. Pumice lapilli is still elongated in the second layer of the outcrop (layer 2 in Fig.S1.7a), although not as compacted as in the lowermost layer. In the middle of the formation (layer 3 in Fig.S1.7a), the ignimbrite becomes very densely welded and lava-like, with fewer phenocrysts, fewer and smaller lithics, and fewer discernible pumice lapilli than in lower layers. Layer 4 on the other hand displays abundant pumice lapilli which are more flattened in the upper half than in the lower half of the layer. The uppermost layers (5 and 6 in Fig.S1.7a) are lava-like in parts, generally exhibiting few discernible pumice lapilli but instead flow-bands in the groundmass that are separated by dissimilarly distinct transitions between glassy and microcrystalline material. Vesicles are larger in the uppermost layers than in lower layers, less flattened and coated with secondary minerals.

Microscopic texture throughout the ignimbrite formation is mostly eutaxitic. Lithics are most abundant (ca. 10-20%) in the lowermost 2 m of the observed outcrop but more rare (<5% to <1%) in the upper layers. Lithics are of various origin, including dacite and rhyolite, suggesting the presence of silicic intrusive or extrusive rock below the ignimbrite. Phenocrysts are plagioclase (most abundant), altered olivine (fayalite), pyroxene and opaque minerals. Phenocrysts are most abundant in the lowermost 6 m of the outcrop (mostly in layers 1a and 2, where they are 20-40%), but generally less than 2-5% in other layers. Inclusions, e.g., possible zircons, are observed in the plagioclase phenocrysts. Feldspar microlites are observed in some pumice grains.

Block-and-ash-flow (BAF) deposition, observed in Glerá (Fig.S1.7b):

The groundmass of the BAF deposition consists of fine-grained, pale (light-yellowish to white) groundmass, assumed as rhyolite dust or ash, with sparse white and dark-reddish-brown spots. Scattered within the groundmass are rounded and angular dark-grey to black clumps of needle-shaped pitchstone, often with rounded to sub-rounded pieces of jet-black fresh obsidian in the center. In the uppermost 1-2 m, fresh obsidian pieces are less abundant and the pitchstone clumps are light-grey in color, typically white at the edges while the smallest pieces are completely white. On top of the formation is a thin layer of white tephra (ash) and reddish-brown siltstone.

Lahar deposit on top of the BAF deposition in Glerá (Fig.S1.7b):

The main phase of the lahar is 10 m thick. In addition to remobilized material from the underlying BAF formation, the lahar deposit comprises rock fragments of various origins and sizes, presumably plucked by the viscous flow from the substratum. Larger pitchstone clumps within the lahar are light-grey in the center and white at the edges, with the white edges thickening upwards within the formation, while smaller clumps are completely white and fresh obsidian is rare. More alteration of the pitchstone pieces in the lahar and in the upper part of the BAF deposition in comparison with less alteration in the BAF's lower part is considered to reflect the water content, suggesting that the lower part of the BAF was dry, oppositely to the lahar, while water from the lahar may have entered its upper part. Elongated rock fragments in the lower part of the lahar are usually aligned sub-horizontally while those in the upper part of the main lahar phase are flow-oriented into variable twists, indicating significantly more viscosity than in the lower part. Early stages of spherulites are observed in pitchstone clumps in the uppermost part of the main lahar phase. Above the main lahar phase are 10 m of alternating thin sandstone layers and thin layers of the lahar material. This part is interpreted here as the last splashes from the lahar alternating with alluvial deposits as indicated by the sandstone layers. It appears that a stream has eroded a channel into the upper part of these alternating layers and then filled the channel with alluvial deposits. On top of the last splashes is a 1 m thick silicic sill intrusion.

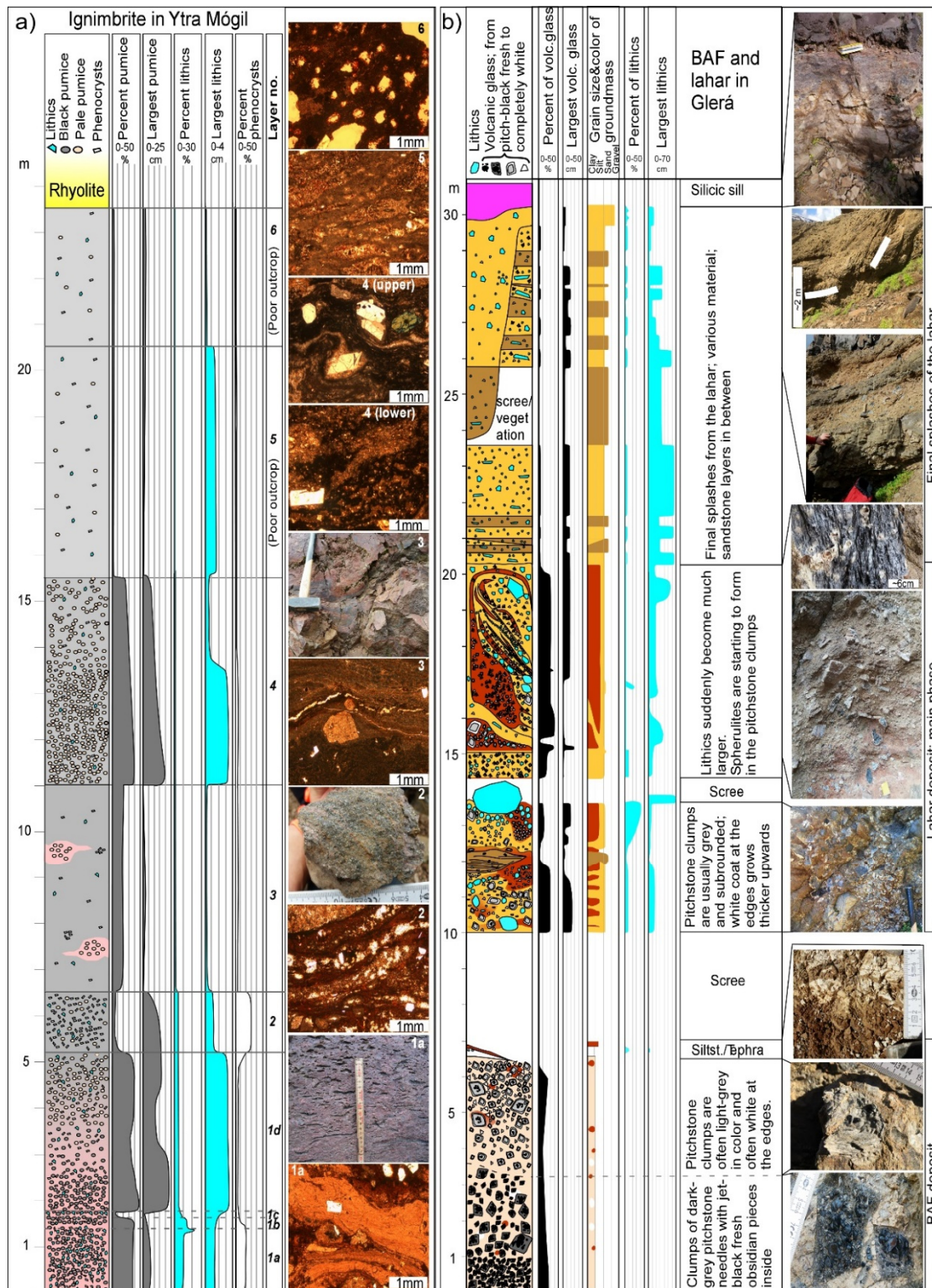


Figure S1.7. Details of pyroclastic flows. Left: BAF in Glerá, with lahar deposit on top. Right: Ignimbrite in Ytra-Mógil, eastern Mt. Torfufell.

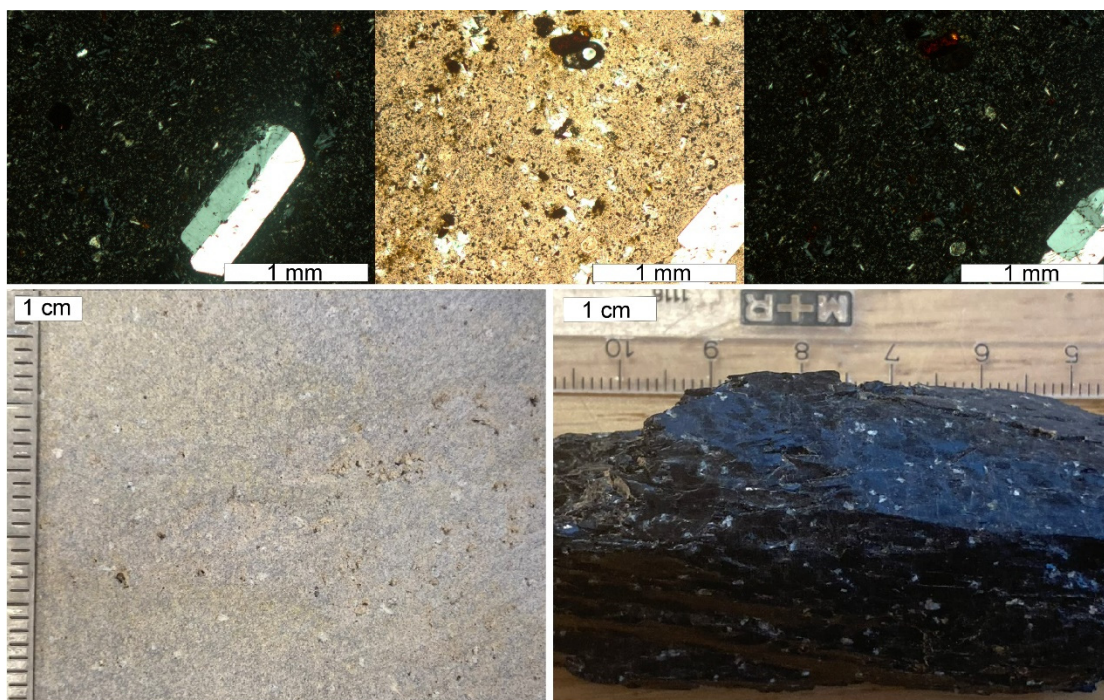


Figure S1.8. Samples from the volcanic plug in Svarfdalur. Upper row: micrographs of crystalline interior. Lower row, left: photograph of the crystalline interior (slabbed sample); right: sample from the glassy part of the margin.

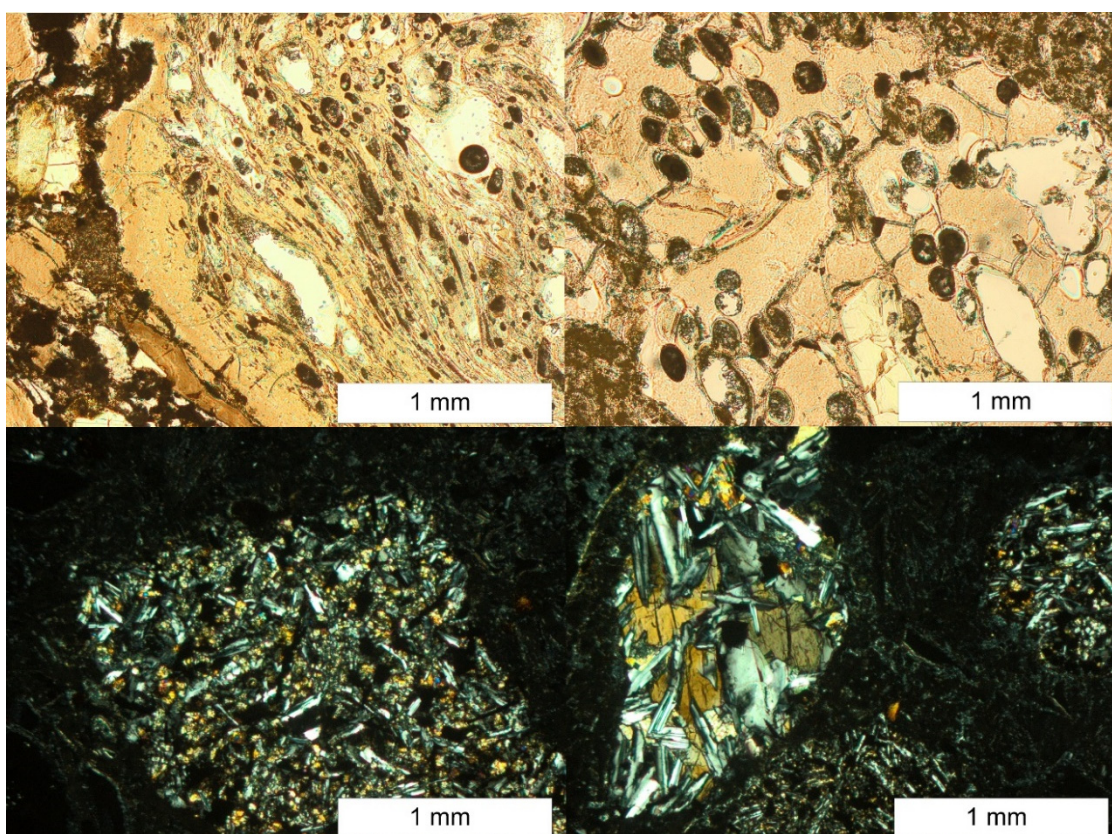


Figure S1.9. Micrographs showing glass and lithics observed inside a thin fracture near the volcanic plug in Svarfdalur.

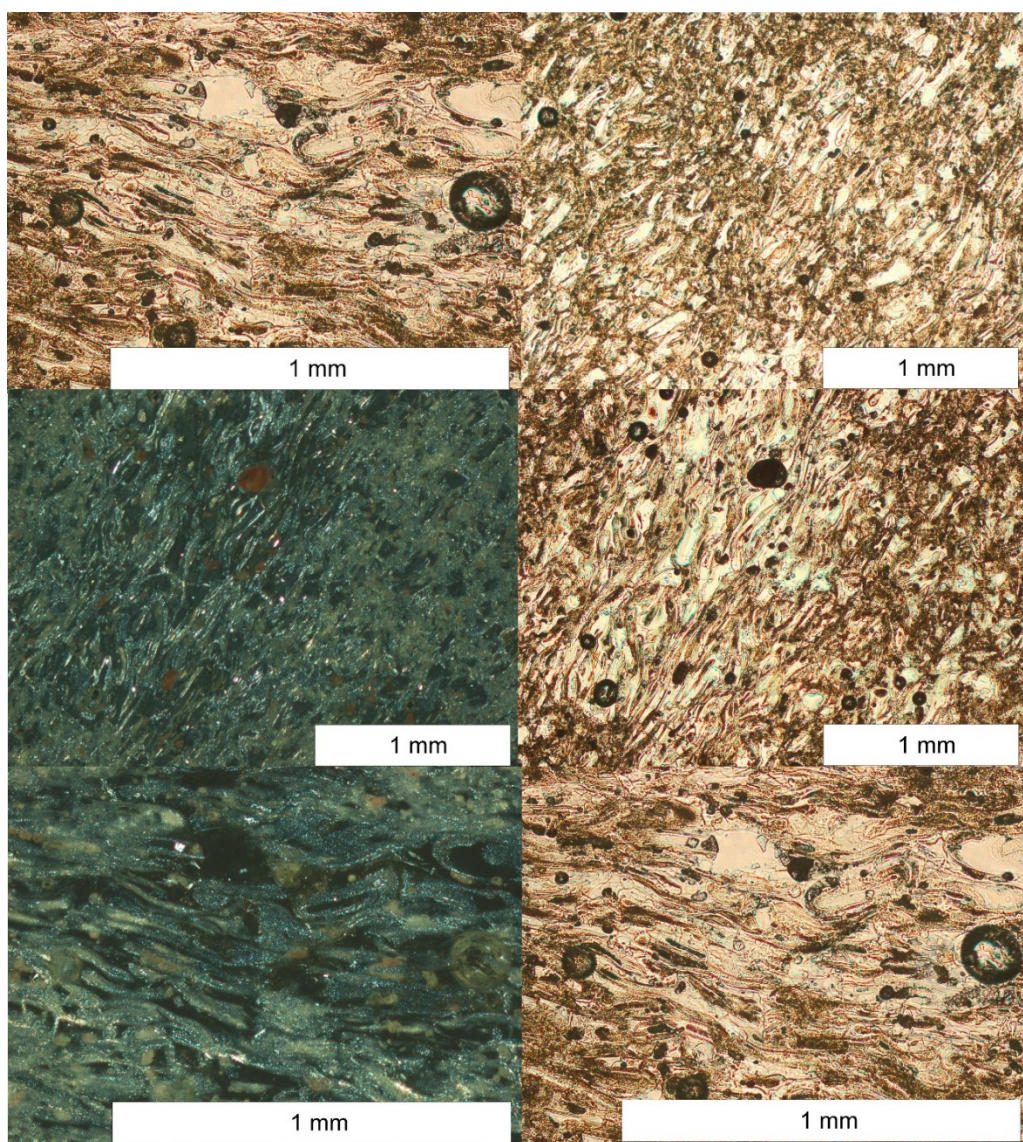


Figure S1.10. Micrographs showing consolidated ash (tuff) at the margin of the Einbúi intrusion.

Sample Id	Occurrence	Lat	Long	m.a.s.l	XRD results
14072015-11	Amygdule in porphyritic basalt below the CV	65.400445	-18.255894	120	Heulandite-Ca, Chabazite-Na
20072017-1	Amygdule in altered tholeiite below the CV	65.417534	-18.166695	108	Heulandite, Stellerite
17092015-29	Amygdule in thin-layered CV basalt	65.307792	-18.338464	380	Heulandite, Stilbite-Ca
15072015-14	Amygdule in porphyritic basalt below the CV	65.399989	-18.262564	170	Stellerite, Mordenite, syn
20180831-2	Vein filling in fault zone	65.312763	-18.304539	410	Tridymite-O, Cristobalite, syn, Albite, disordered
20180831-3	Amygdule in brecciated material in fault zone	65.312762	-18.305058	420	Tridymite-O, Cristobalite, syn, Heulandite

Table S1.5. XRD amygdule and vein filling analyses results (CV= central volcano).

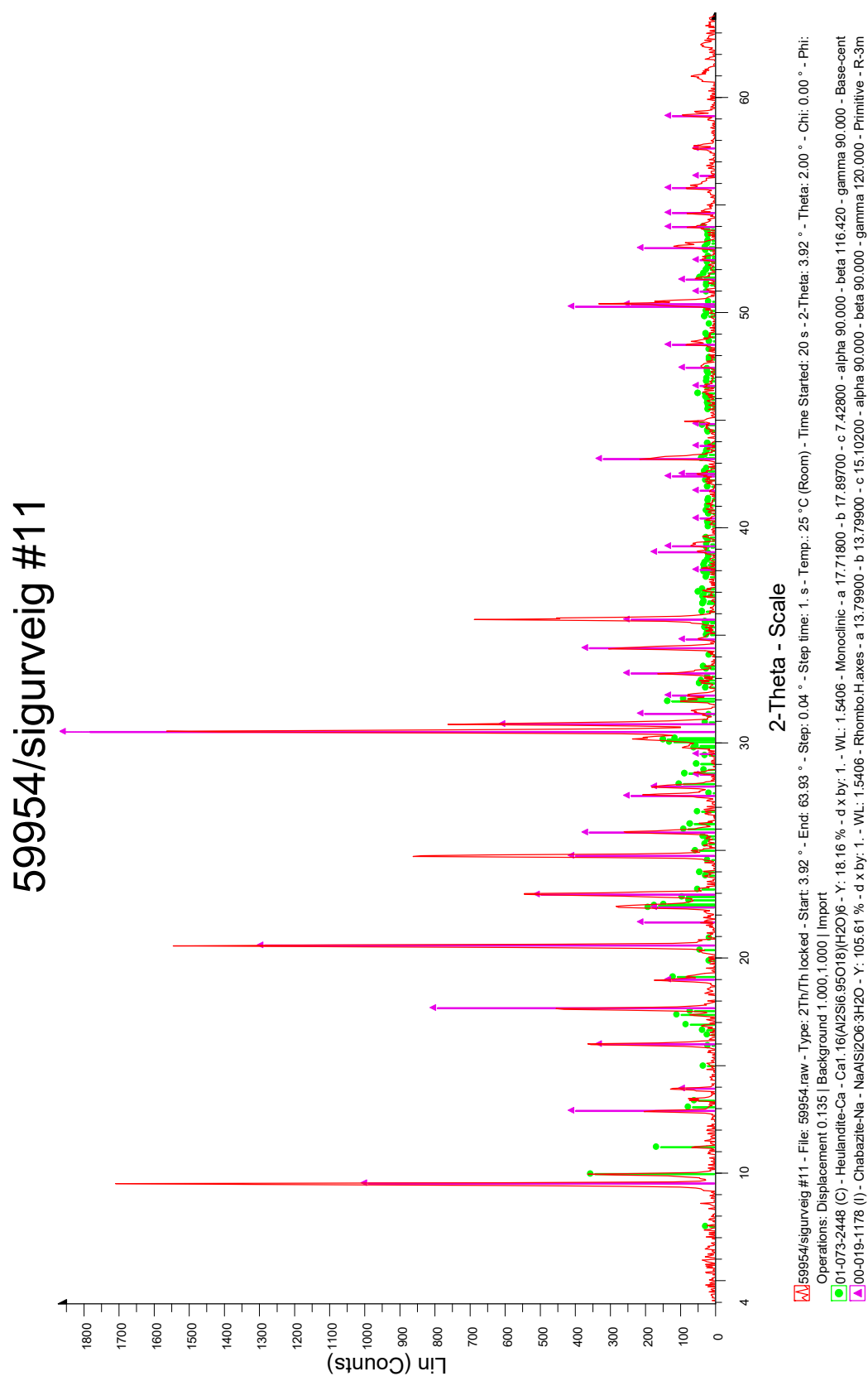


Figure S1.11. XRD analysis of sample 14072015-11 (amygdule from Gilsá profile, below the central volcano). Performed by Sigurður S. Jónsson, Iceland GeoSurvey (ISOR).

2-Theta - Scale

File: 59955\sigurveig_20072017-1 - Type: 2Th/Tl locked - Start: 3.93 ° - End: 63.94 ° - Step: 0.04 ° - Time Started: 20 s - 2-Theta: 3.93 ° - Theta: 2.00 ° - Chi: 0.00
Operations: Displacement 0.115 | Background 1.000,1.000 | Import

Phase	Symbol
Heulandite - Ca ₃ (K _{0.8} A _{0.8} S ₂ 7.4O ₇₂ 26.1H ₂ O - Y: 16.71 % - d x by: 1. - WL: 1.5406 - Monoclinic - a 17.67100 - b 17.87500 - c 7.41200 - alpha 90.000 - beta 116.390 - gamma 90.000 - Base-ce	Orange square
Stellerite - Ca ₂ A ₄ S ₁₄ O ₃₆ ·14H ₂ O - Y: 11.30 % - d x by: 1. - WL: 1.5406 - Orthorhombic - a 13.59900 - b 18.22200 - c 17.86300 - alpha 90.000 - beta 90.000 - gamma 90.000 - Face-centered - Fm	Cyan square
Ca ₂ A ₄ S ₁₄ O ₃₆ ·14H ₂ O - Y: 11.30 % - d x by: 1. - WL: 1.5406 - Orthorhombic - a 13.59900 - b 18.22200 - c 17.86300 - alpha 90.000 - beta 90.000 - gamma 90.000 - Face-centered - Fm	Blue cross

192

59956/sigurveig #29

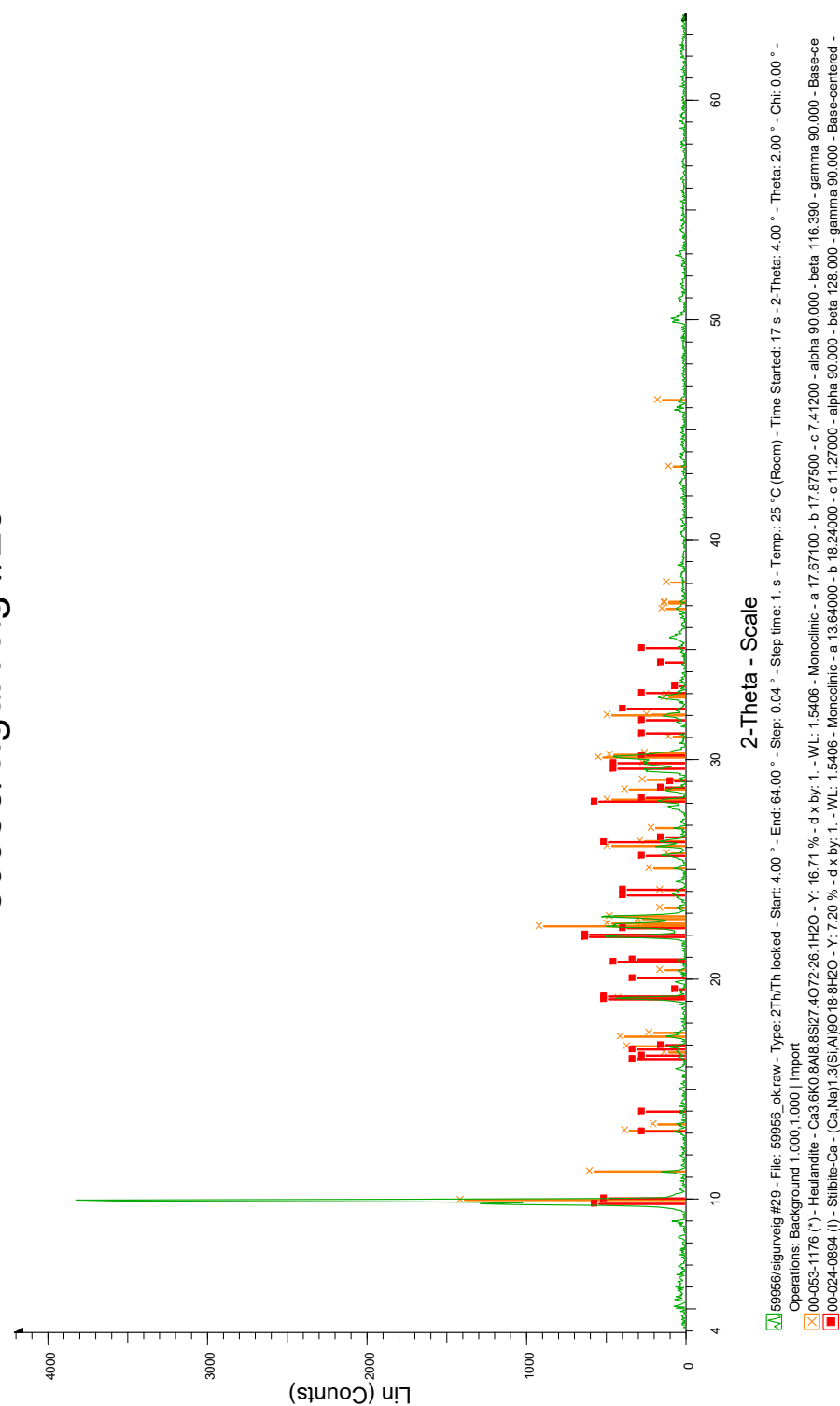


Figure S1.13. XRD analysis of sample Id. 17092015-29 (amygdule from Torfufellsdalur profile in NW Mt. Torfufell, ~80 m below the smectite-bearing sediment horizon and the silicic base). Performed by Sigurður S. Jónsson, Iceland GeoSurvey (ÍSOR).

59957/sigurveig #14

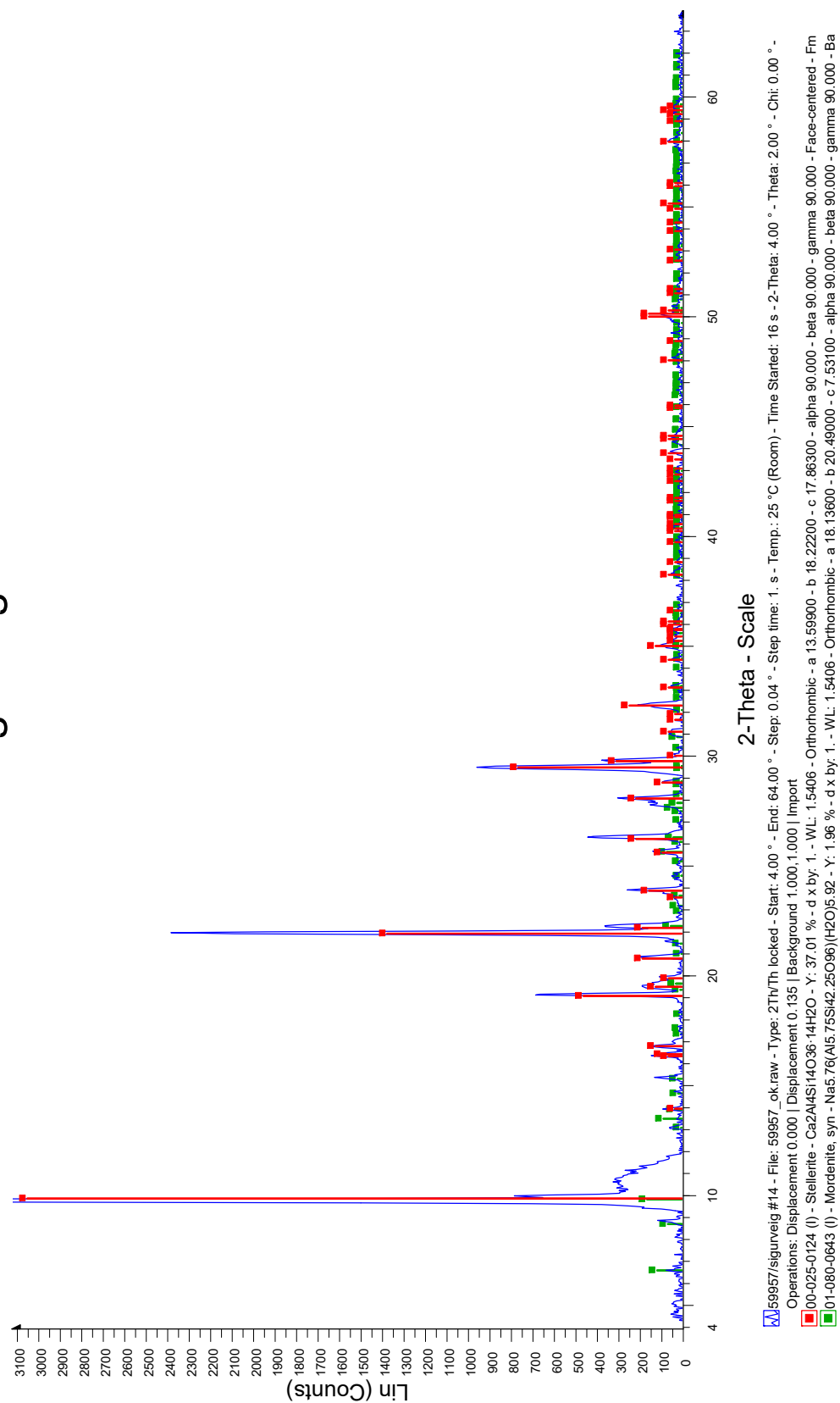


Figure S1.14. XRD analysis of sample 15072015-14 (amygdule from Gilsá, below the central volcano). Performed by Sigurður S. Jónsson, Iceland GeoSurvey (ÍSOR).

61784/SA 20180831-2

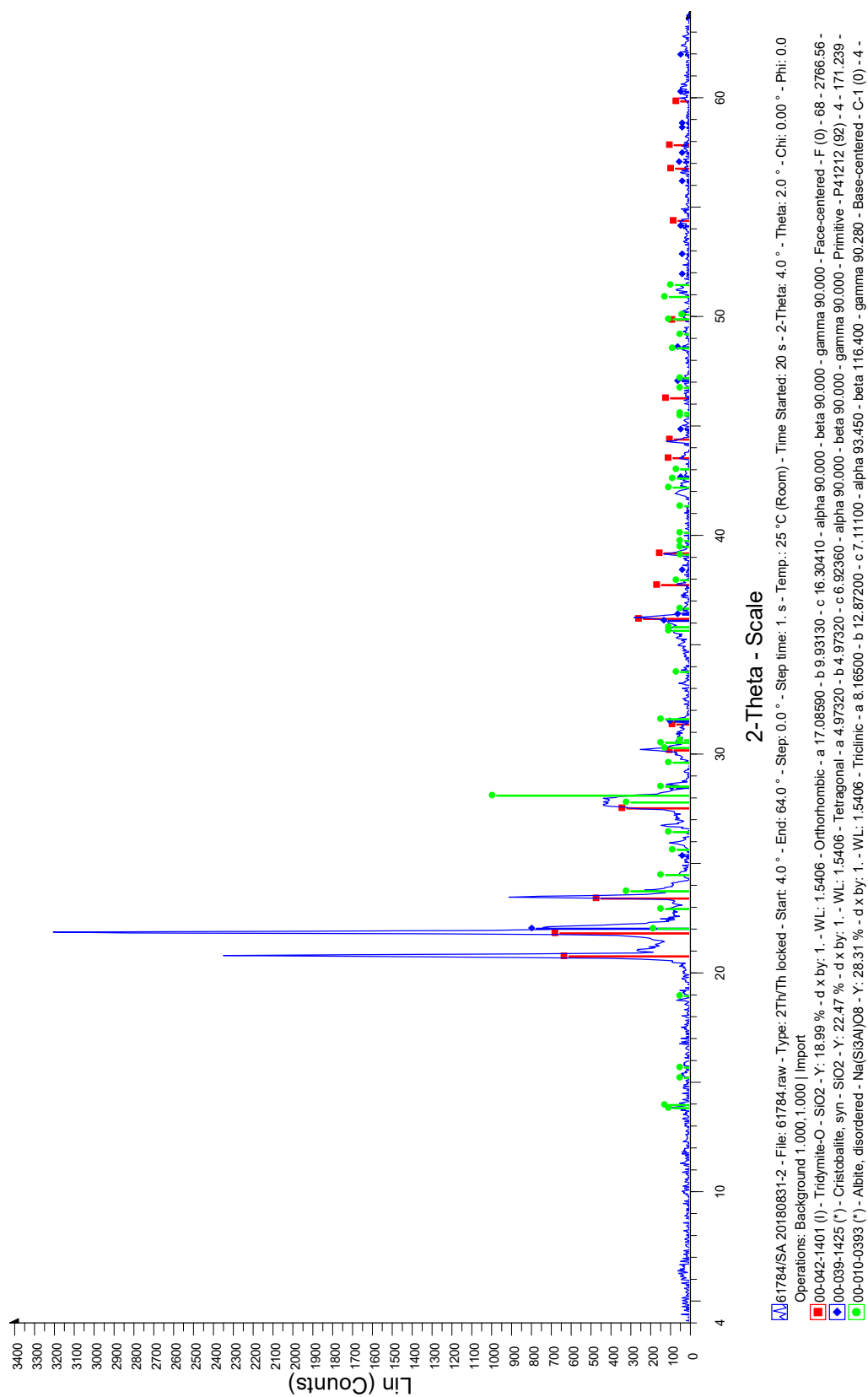


Figure S1.15. XRD analysis of sample 20180831-2 (vein filling from a fault breccia in the central zone). Performed by Sigurður S. Jónsson, Iceland GeoSurvey (ÍSOR).

61785/SA 20180831-3

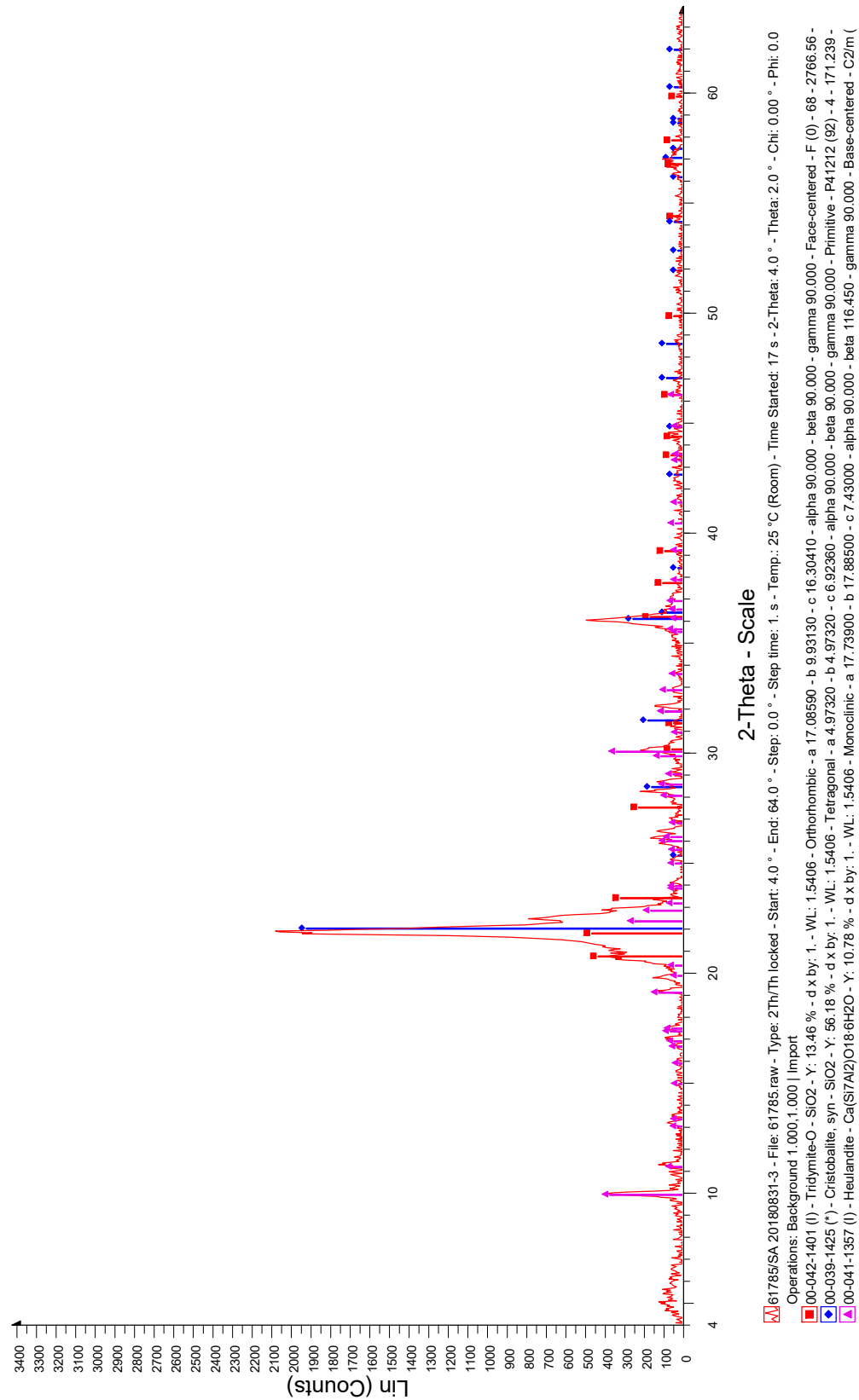
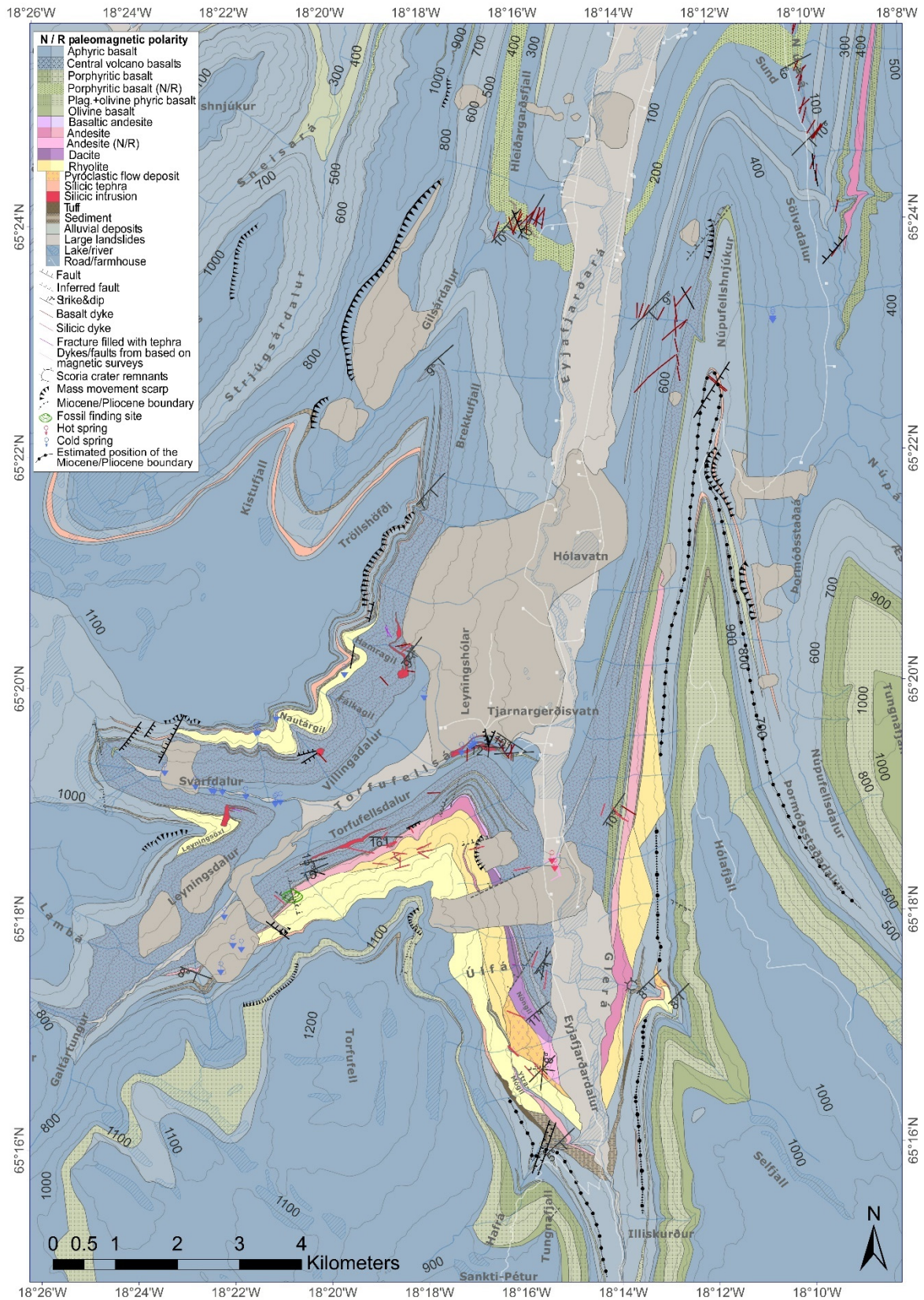
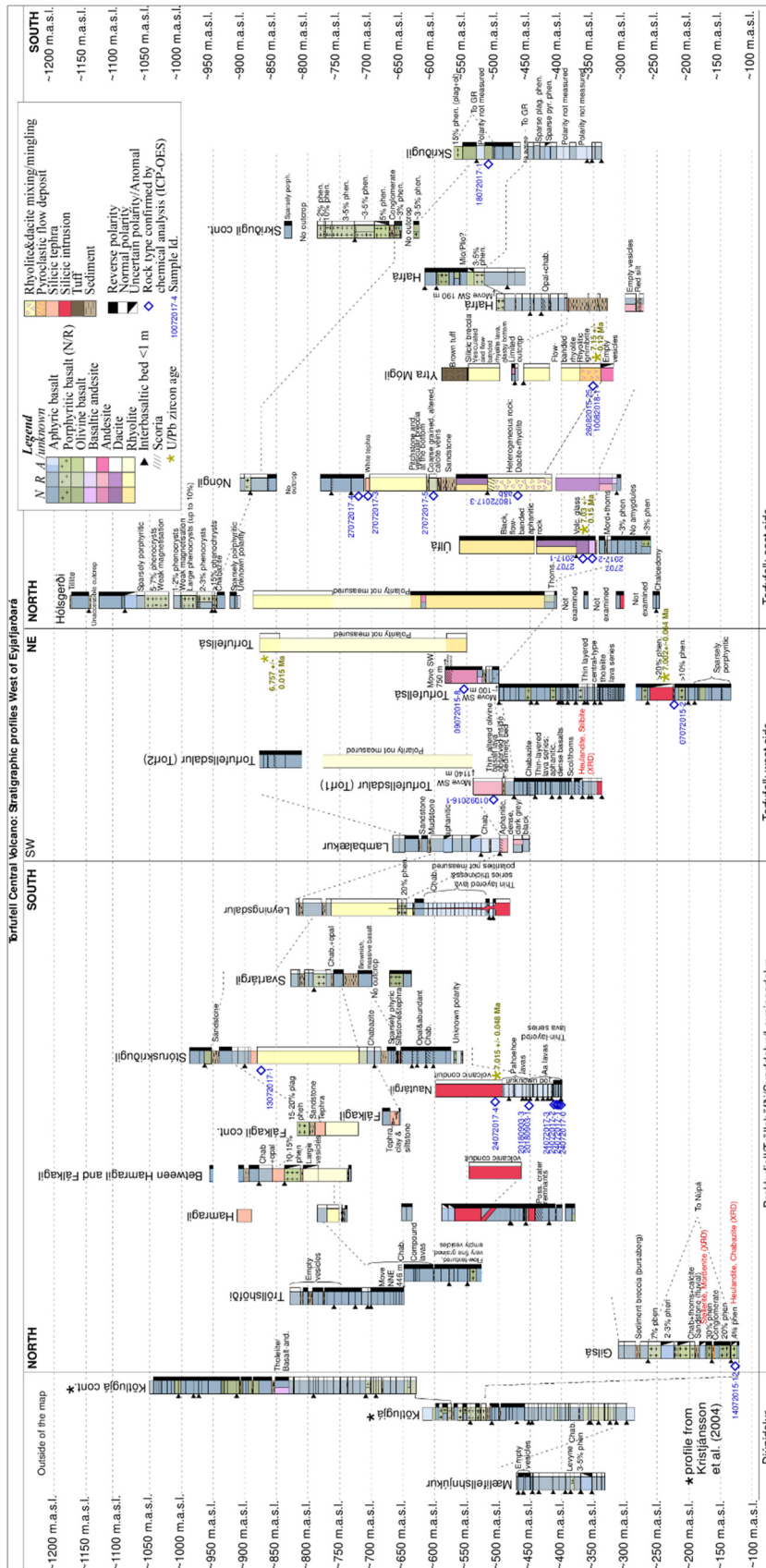


Figure S1.16. XRD analysis of sample 20180831-3 (amygdule from fault breccia in the central zone). Performed by Sigurður S. Jónsson, Iceland GeoSurvey (ÍSOR).

Figure S1.17. Geological map of the Torfufell central volcano.





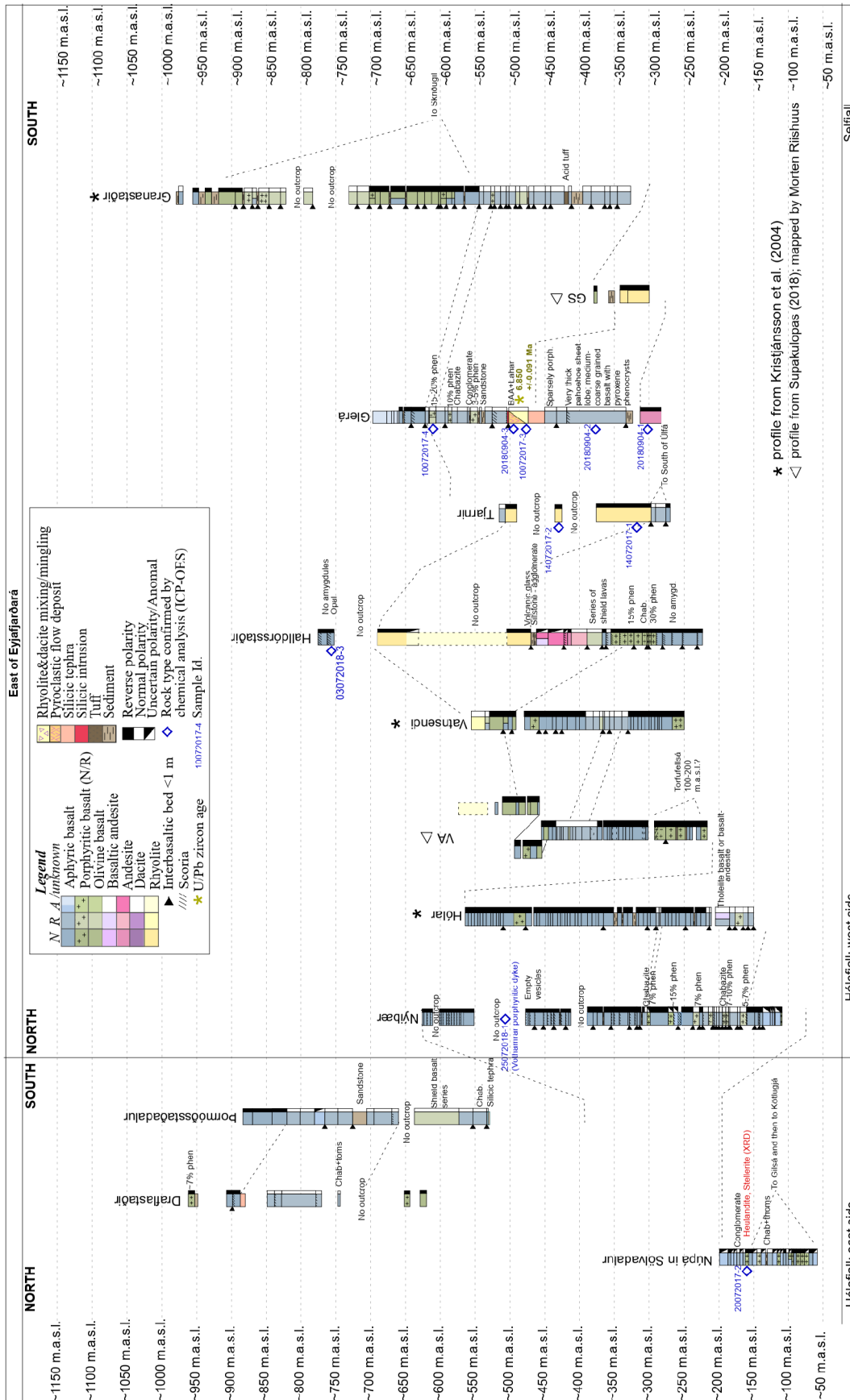


Figure S1.18. Continued.

Stratigraphic and polarity profiles and other outcrops

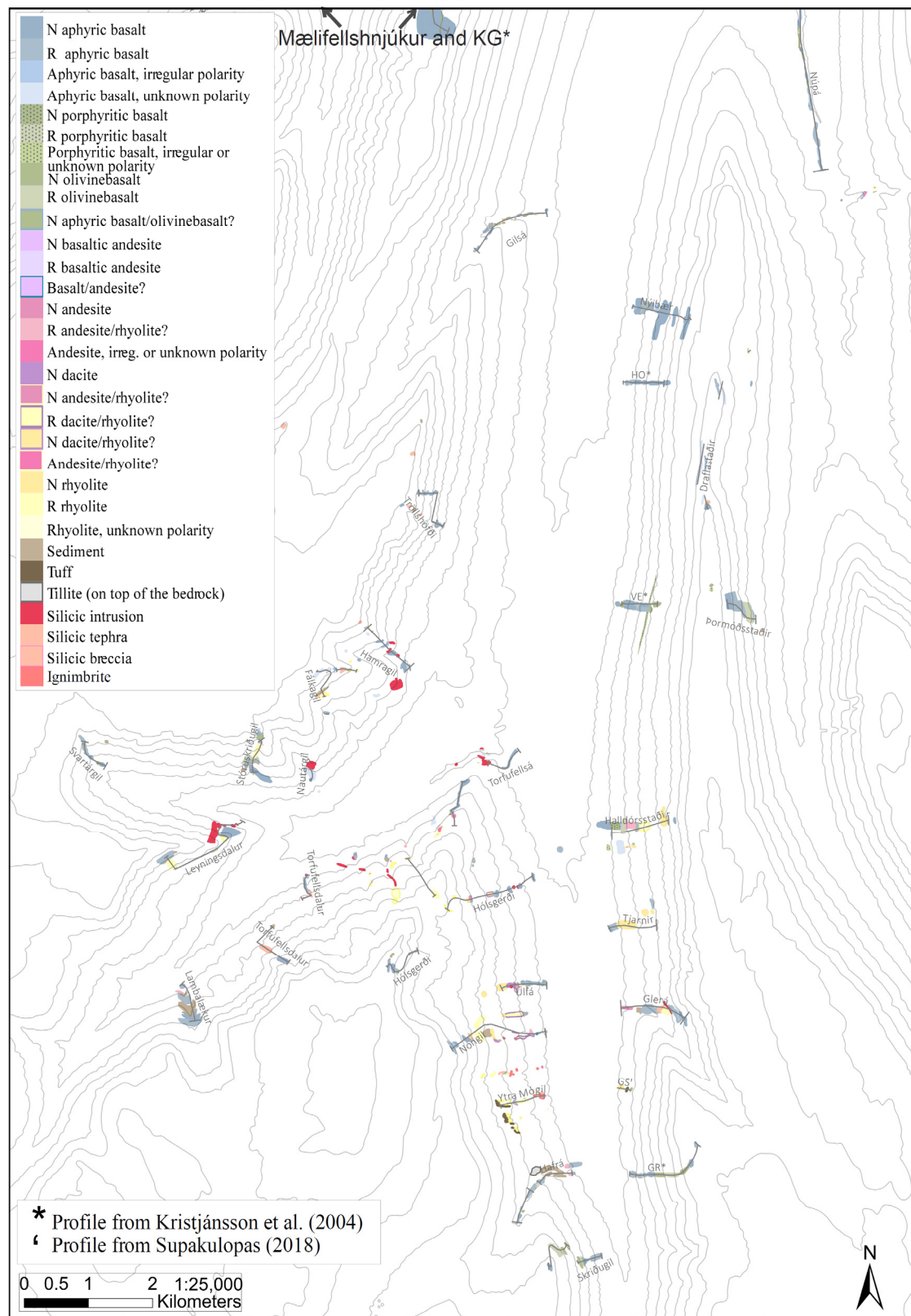


Figure S1.19. Locations of visited outcrops and sampling sites with rock types, structures, sample id's and age data indicated. Continued on next pages.

Sampling sites of ICP-OES chemical analyses and U-Pb zircon age determinations

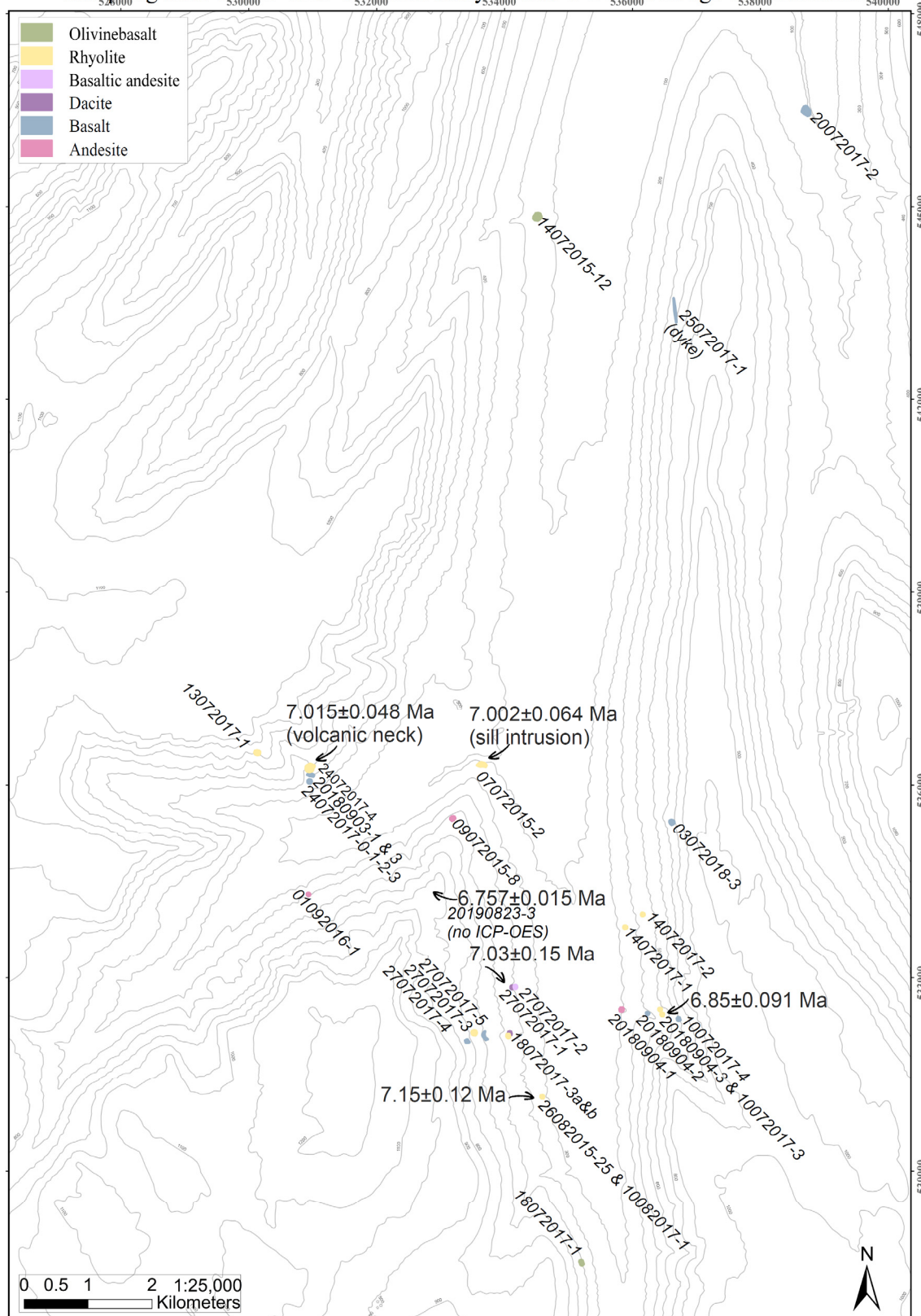


Figure S1.19. Continued.

Dikes, faults and lineaments

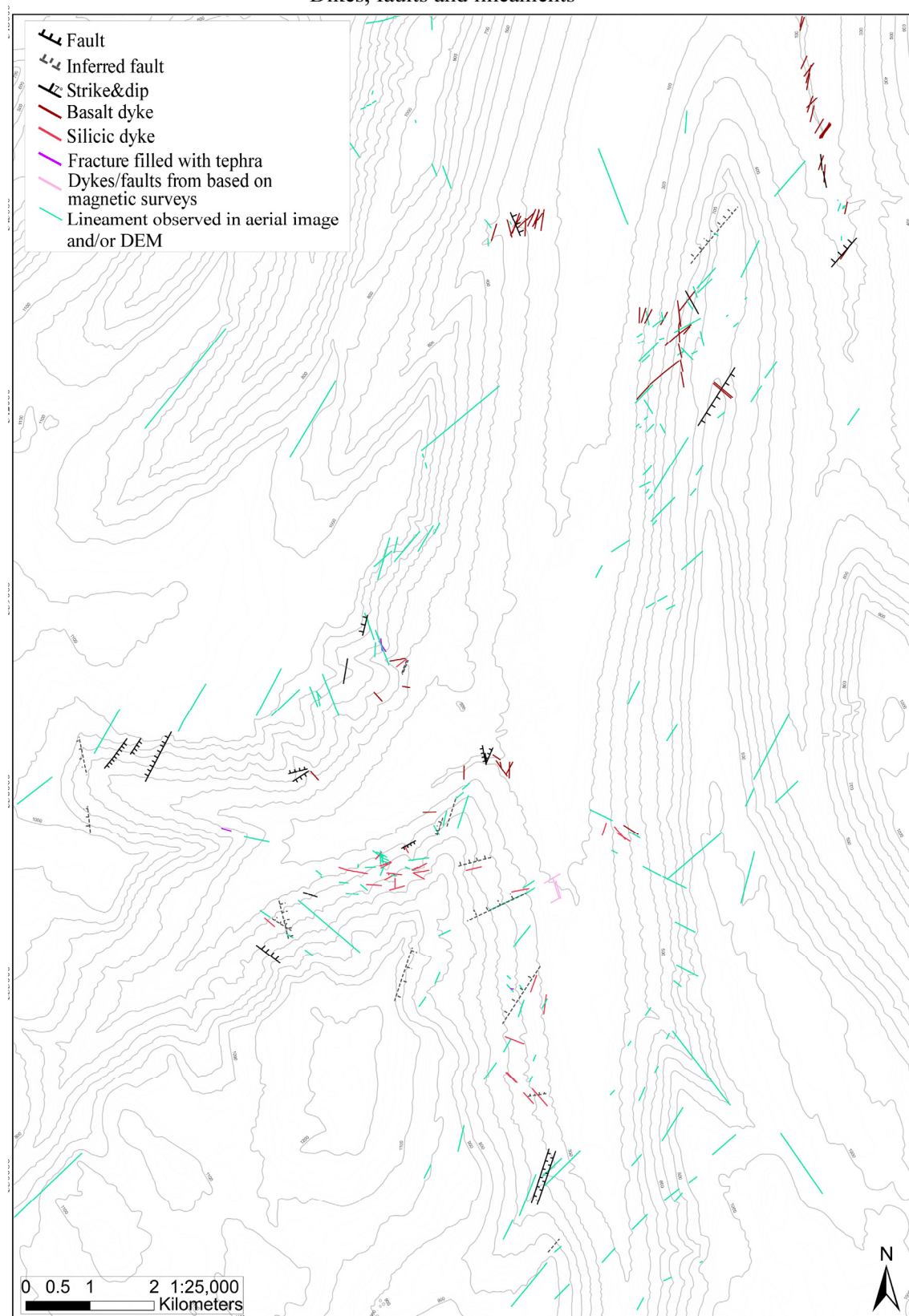
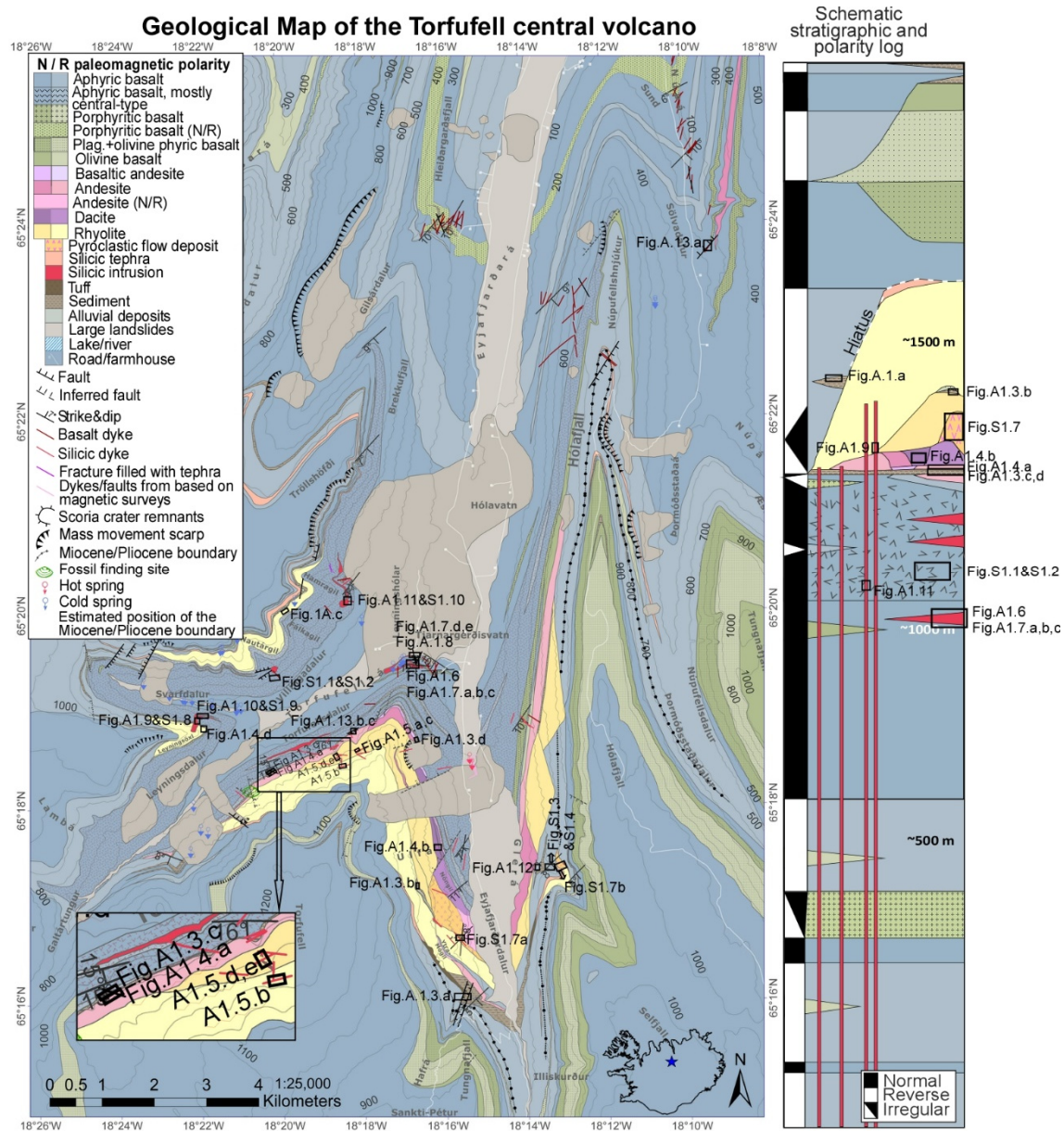


Figure S1.19. Continued.



AS2 Supplementary material of Paper II

Supplementary Figures and Tables

Geochemistry and petrography of basaltic to rhyolitic products of the Late Miocene Torfufell Central Volcano, North Iceland

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Figure S2.1.

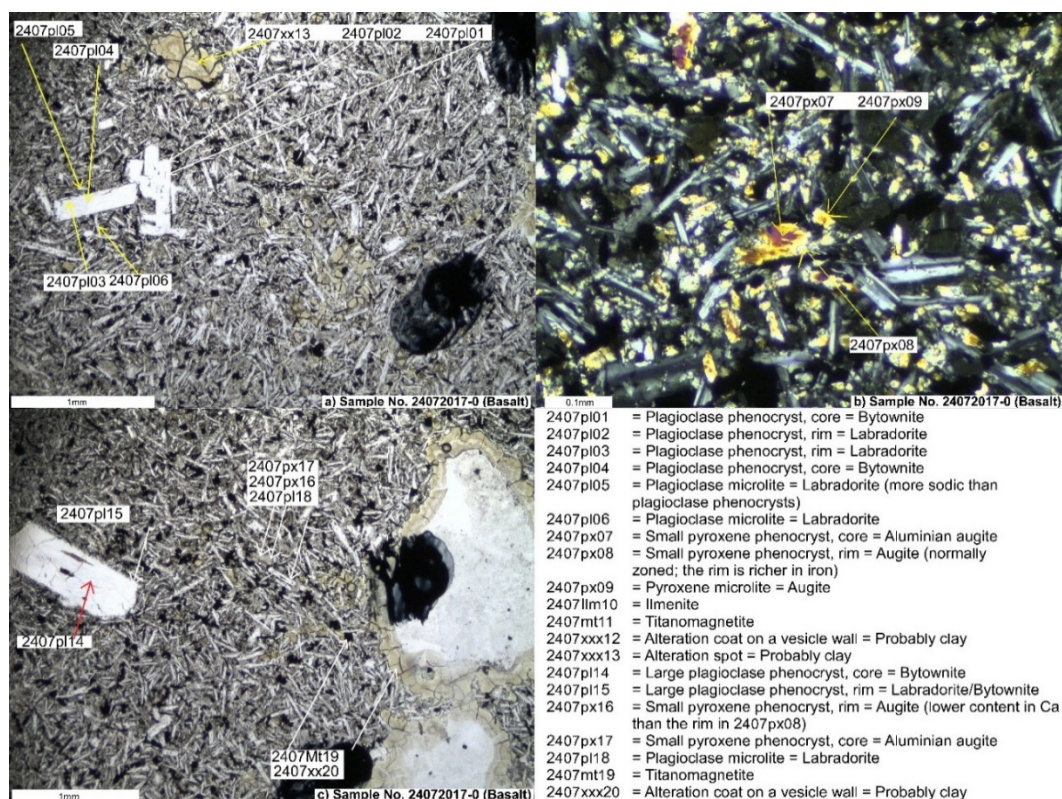


Figure S2.1. SEM/EDS analyzed spots in sample 24072017-0 (Basalt). Photomicrographs.

Figure S2.2

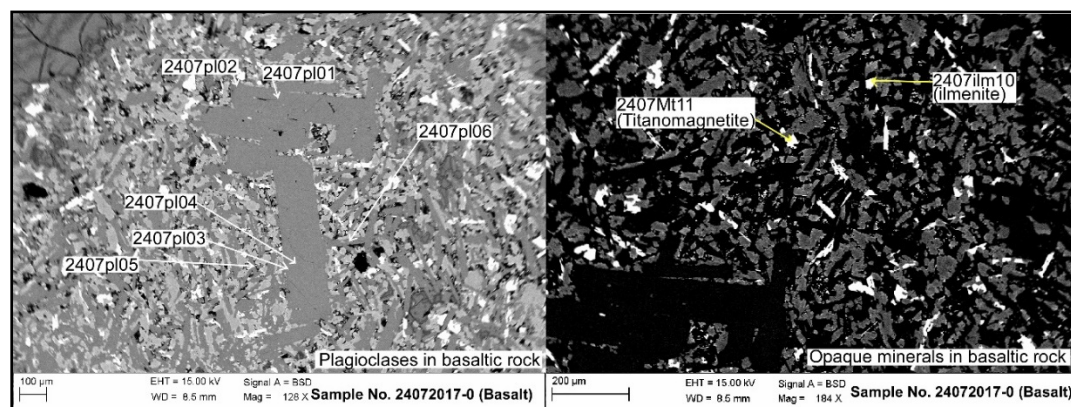


Figure S2.2. SEM/EDS analyzed spots in sample 24072017-0 (Basalt). Images from the SEM.

Figure S2.3

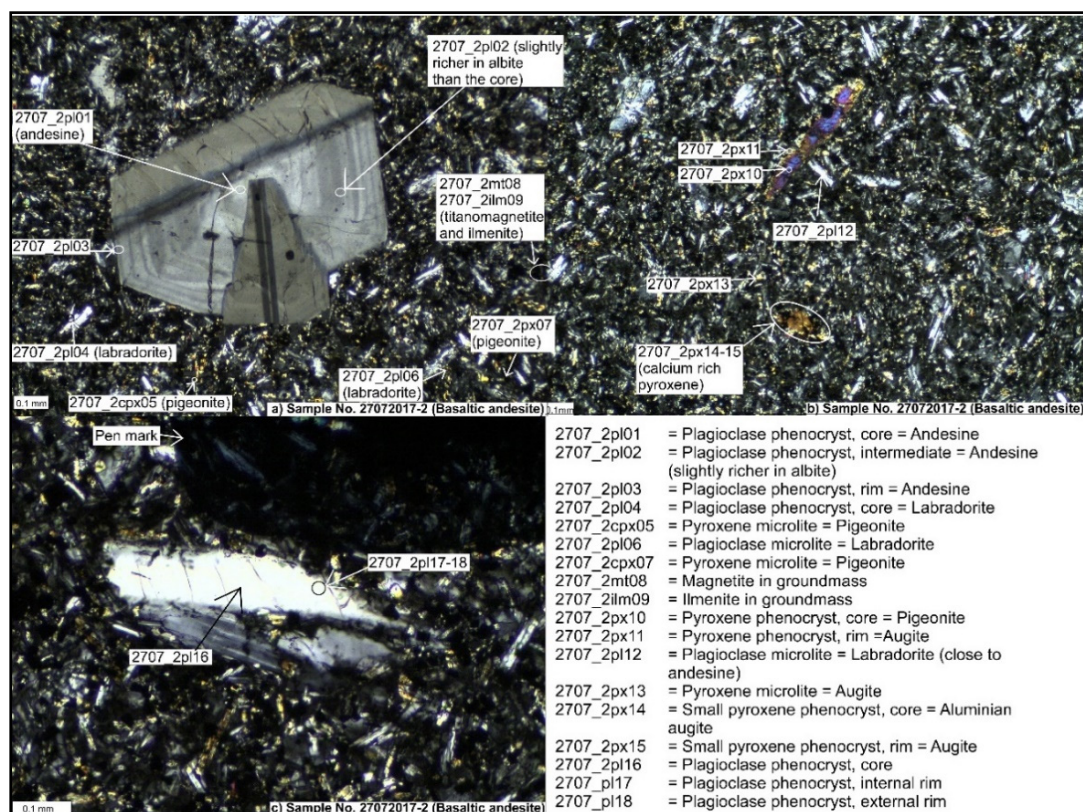


Figure S2.3. SEM/EDS analyzed spots in sample 27072017-2 (Basaltic andesite). Photomicrographs.

Figure S2.4

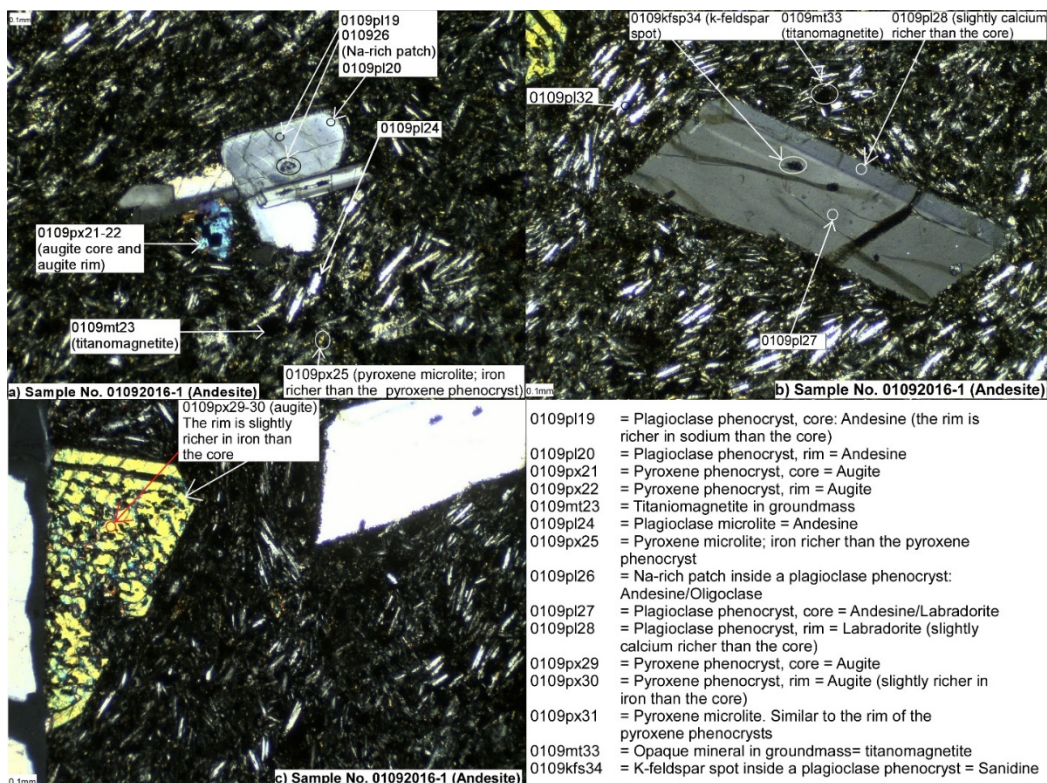


Figure S2.4. SEM/EDS analyzed spots in sample 01092016-1 (Andesite). Photomicrographs.

Figure S2.5

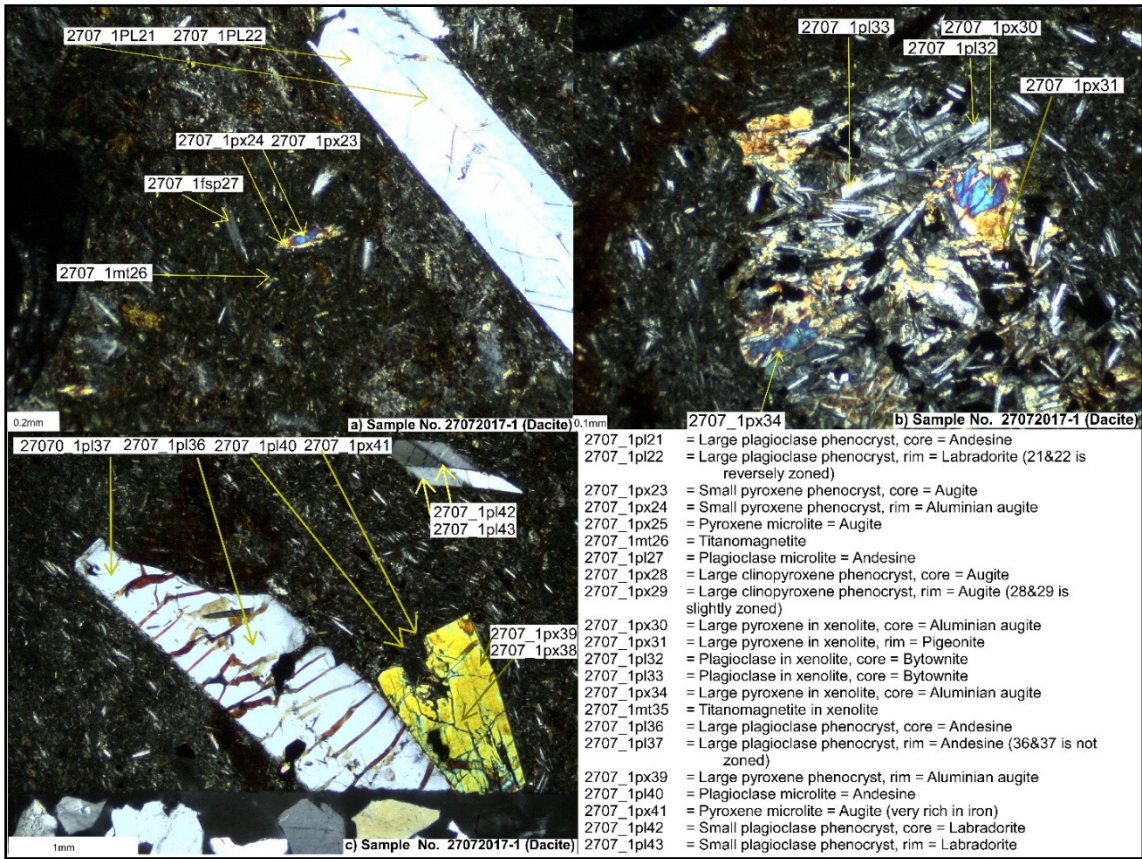


Figure S2.5. SEM/EDS Analyzed spots in sample 27072017-1 (Dacite). Photomicrographs.

Figure S2.6

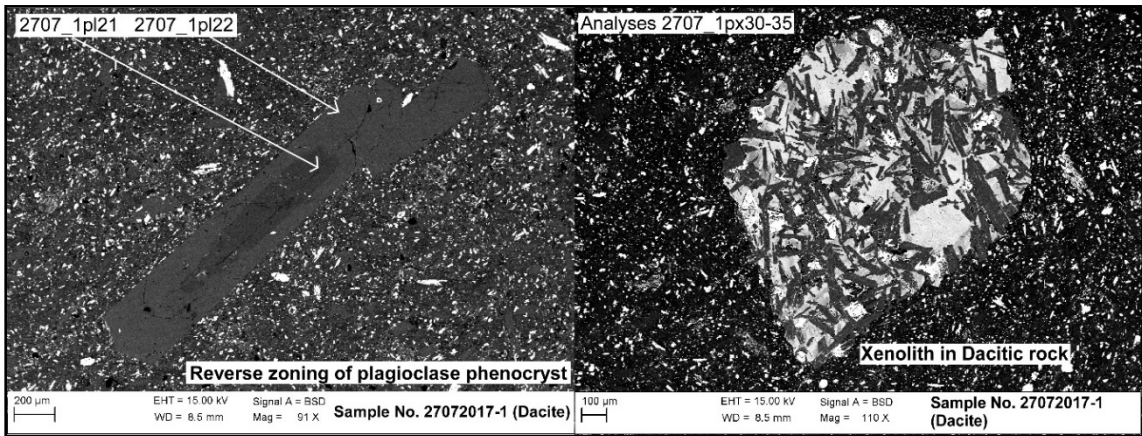


Figure S2.6. SEM/EDS analyzed spots in sample 27072017-1 (Dacite). Images from the SEM.

Figure S2.7

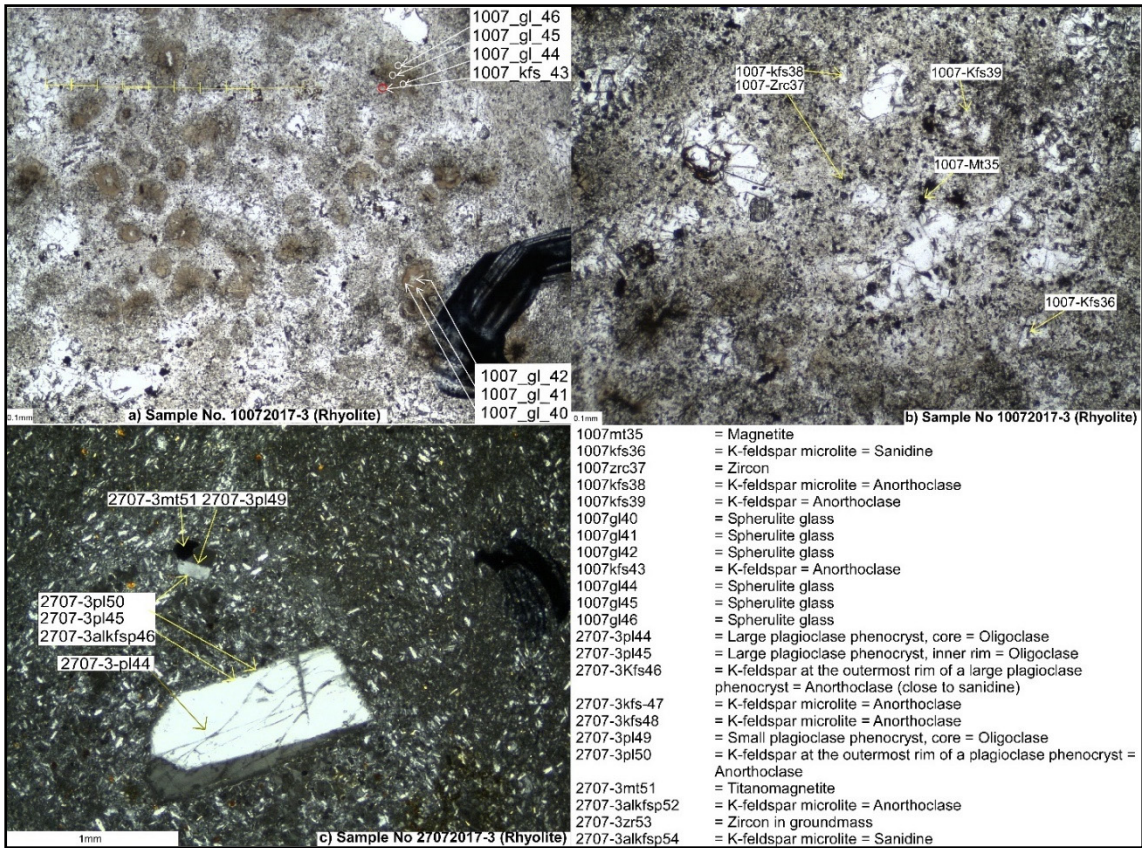


Figure S2.7. SEM/EDS analyzed spots in samples 10072017-3 and 27072017-3 (Rhyolite). Photomicrographs.

Figure S2.8

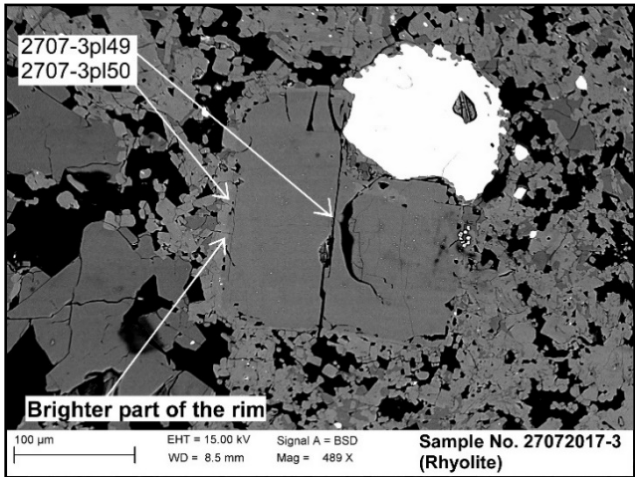


Figure S2.8. SEM/EDS analyzed spots in sample 27072017-3 (Rhyolite). Image from the SEM

Table S2.1. SEM/EDS analysis (wt%) of minerals and glass from basaltic to rhyolitic samples, representative of the Torfufell central volcano

Pyroxene:																	
Sample id	Rock type	Mineral	Analysis id.	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Total	X Wo	X En	X Fs	Mineral phase*
01092016-1	Andesite	Pyroxene Phenocryst (Core)	0109 Px 21	49.54	0.7	1.57	22.31	0.76	7.51	18.64	0.25	0	101.27	40.08	22.47	37.45	Augite
01092016-1	Andesite	Pyroxene Phenocryst (Rim)	0109 Px 22	49.16	0.29	0.79	26.46	1.18	5.45	17.34	0.23	0	100.9	38.05	16.64	45.32	Augite
01092016-1	Andesite	Pyroxene Microlite	0109 Px 25	48.5	0.55	0.84	25.59	0.99	4.96	17.91	0.19	0	99.54	39.99	15.41	44.60	Augite
01092016-1	Andesite	Pyroxene Phenocryst (Core)	0109 Px 29	48.61	0.56	1.1	22.25	0.8	6.21	19.64	0.21	0	99.37	43.03	18.93	38.05	Augite
01092016-1	Andesite	Pyroxene Phenocryst (Rim)	0109 Px 30	48.05	0.75	0.95	27.93	1.08	4.1	17.47	0.25	0	100.6	38.84	12.68	48.47	Augite
01092016-1	Andesite	Pyroxene Microlite	0109 Px 31	48.26	0.64	1.05	27.4	1.07	5.41	16.17	0.21	0	100.2	35.87	16.7	47.44	Augite
27072017-2	Bas. And.	Pyroxene Microlite	2707_2 Cpx 05	52.21	0.78	0.91	20.13	0.67	19.73	5.53	0	0	99.96	11.36	56.38	32.27	Pigeonite
27072017-2	Bas. And.	Pyroxene Microlite	2707_2 Cpx 07	52.63	0.51	0.69	20.4	0.52	20.63	3.81	0	0	99.2	7.87	59.26	32.87	Pigeonite
27072017-2	Bas. And.	Pyroxene Phenocryst (Core)	2707_2 Px 10	49.67	0	0.34	35.46	1.65	8.75	4.97	0	0	100.83	11.09	27.16	61.75	Pigeonite
27072017-2	Bas. And.	Pyroxene Phenocryst (Rim)	2707_2 Px 11	52.21	0.9	1.25	17.05	0.54	14.1	16.38	0.15	0	102.57	33.22	39.79	26.99	Augite
27072017-2	Bas. And.	Pyroxene Microlite	2707_2 Px 13	51.41	1.14	1.55	14.78	0.4	13.34	18.24	0.23	0	101.09	37.73	38.40	23.87	Augite
27072017-2	Bas. And.	Small Pyroxene Phenocryst (Core)	2707_2 Px 14	48.84	1.83	4.03	12.02	0.36	13.92	18.59	0.29	0	99.87	39.27	40.91	19.82	Aluminian
27072017-2	Bas. And.	Small Pyroxene Phenocryst (Rim)	2707_2 Px 15	51	1.16	1.15	16.38	0.4	13.01	16.95	0.22	0	100.28	35.43	37.84	26.73	Augite
27072017-1	Dacite	Small Pyroxene Phenocryst (Core)	2707_1 Px 23	48.44	1.04	1.98	20.12	0.76	8.58	18	0.2	0	99.12	39.44	26.16	34.41	Augite
27072017-1	Dacite	Small Pyroxene Phenocryst (Rim)	2707_1 Px 24	46.97	1.08	2.25	24.04	0.96	5.02	18.38	0.26	0	98.96	41.65	15.83	42.52	Aluminian
27072017-1	Dacite	Pyroxene Microlite	2707_1 Px25	45.98	1	1.97	27.59	1.13	4.27	15.46	0.2	0	97.61	36.01	13.84	50.16	Augite
27072017-1	Dacite	Large Clinopyroxene Phenocryst (Core)	2707_1 Px 28	49.11	0.65	1.02	24.01	0.9	5.97	18.61	0.19	0	100.46	40.76	18.19	41.05	Augite
27072017-1	Dacite	Large Clinopyroxene Phenocryst (Rim)	2707_1 Px 29	48.45	0.62	1.13	24.19	0.8	5.36	18.86	0.55	0	99.97	41.73	16.5	41.77	Augite
27072017-1	Dacite	Large Clinopyroxene Phenocryst (Rim)	2707_1 Px 39	45.99	1.19	2.8	26.8	0.99	4.28	16.48	0.2	0	98.73	38.01	13.74	48.25	Aluminian
27072017-1	Dacite	Pyroxene Microlite	2707_1 Px 41	47.45	0.66	1.4	27.7	1.18	3.93	16.55	0.3	0	99.18	37.92	12.53	49.55	Augite
27072017-1	Xenolith	Large Pyroxene (Core)	2707_1 Px 30	49.88	1.34	3.11	10.27	0.28	14	20.25	0.3	0	99.44	42.41	40.8	16.79	Aluminian
27072017-1	Xenolith	Large Pyroxene (Rim)	2707_1 Px 31	54.94	0.28	0.84	13.77	0.51	25.49	4.34	0	0	100.16	8.58	70.15	21.26	Pigeonite
27072017-1	Xenolith	Large Pyroxene (Core)	2707_1 Px 34	50.14	1.33	3.36	10.08	0.28	14.22	20.71	0.27	0	100.4	42.82	40.91	16.27	Aluminian
24072017-0	Basalt	Small Pyroxene Phenocryst (Core)	2407 Px 07	49.76	1.83	3.62	10.28	0	14.12	20.71	0.23	0	100.55	42.81	40.61	16.59	Augite
24072017-0	Basalt	Small Pyroxene Phenocryst (Rim)	2407 Px 08	49.69	1.19	1.55	19.52	0.48	10.35	17.17	0.27	0	100.23	36.68	30.77	32.55	Augite
24072017-0	Basalt	Pyroxene Microlite	2407 Px 09	50.82	0.69	0.98	24.32	0.58	12.56	9.66	0.14	0	99.75	20.95	37.89	41.16	Augite
24072017-0	Basalt	Small Pyroxene Phenocryst (Rim)	2407 Px 16	50.91	0.8	1.16	21.33	0.55	13.56	11.79	0	0	100.09	24.92	39.88	35.19	Augite
24072017-0	Basalt	Small Pyroxene Phenocryst (Core)	2407 Px 17	47.8	2.51	4.91	11.17	0.3	13.38	19.95	0.33	0	100.34	42.19	39.37	18.44	Aluminian

* Nomenclature of pyroxenes were derived from the PX-NOM Microsoft Excel spreadsheet program by Sturm (2002)

Table S2.1. Continued.

Plagioclase:																	
Sample id	Rock type	Mineral	Analysis id.	SiO2	TiO2	Al2O3	FeO	MnO	MgO	Na2O	K2O	CaO	Total	X Or	X Ab	X An	Classification
01092016-1	Andesite	Plag. Phenocryst (Core)	0109 PI 19	57.42	0.00	26.81	0.59	0.00	0.00	5.95	0.25	9.96	100.99	1.39	50.11	48.5	Andesine
01092016-1	Andesite	Plag. Phenocryst (Rim)	0109 PI 20	58.95	0	25.72	0.37	0	0	6.72	0.35	8.4	100.51	1.96	57.18	40.86	Andesine
01092016-1	Andesite	Plag. Microlite Patch inside a Plag.	0109 PI 24	57.91	0	26.26	1.07	0	0	6.07	0.42	9.29	101.02	2.31	50.83	46.86	Andesine
01092016-1	Andesite	Phen. Plag. Phenocryst (Core)	0109 PI 26	62.64	0	22.39	1.12	0	0	7.66	0.75	5.75	100.31	4.18	64.94	30.99	Andesine
01092016-1	Andesite	Plag. Phen. (Rim)	0109 PI 27	56.4	0	26.66	0.48	0	0	5.63	0.25	10.21	99.64	1.41	48.35	50.24	Labradorite (close to andesine)
01092016-1	Andesite	Plag. Microlite	0109 PI 28	55.57	0	27.44	0.47	0	0	5.26	0.22	11.14	100.09	1.23	44.71	54.06	Labradorite
01092016-1	Bas.	Plag. Phen. (Core)	0109 PI 32	56.55	0	25.63	1.74	0	0	5.84	0.42	9.36	99.55	2.3	48.51	49.2	Labradorite/andesite
27072017-2	And. Bas.	Plag. Phen. (Core)	2707_2 PI 01	57.74	0	26.29	0.28	0	0	6.08	0.3	9.2	99.89	1.72	52.95	45.33	Andesine
27072017-2	And. Bas.	Plag. Phen. (Intermediate)	2707_2 PI 02	59.83	0	25.63	0.24	0	0	6.77	0.36	8.27	101.1	2.03	57.96	40.01	Andesine
27072017-2	And. Bas.	Plag. Phen. (Rim)	2707_2 PI 03	58.8	0	25.12	0.32	0	0	6.39	0.32	8.45	99.41	1.85	56.01	42.14	Andesine
27072017-2	And. Bas.	Plag. Microlite	2707_2 PI 04	56.61	0	26.65	1.05	0	0.13	5.55	0.27	10.38	100.64	1.48	46.19	52.34	Labradorite
27072017-2	And. Bas.	Plag. Microlite	2707_2 PI 06	55.69	0	27.21	1.02	0	0	5.2	0.31	11.05	100.48	1.71	43.51	54.78	Labradorite
27072017-2	And. Bas.	Plag. Microlite	2707_2 PI 12	56.77	0	26.86	1.04	0	0	5.66	0.36	10.34	101.03	1.96	46.93	51.1	Labradorite
27072017-2	And. Bas.	Plag. Phen. (Core)	2707_2 PI 16	59.05	0	24.96	0.33	0	0	6.47	0.4	8.25	99.47	2.3	56.58	41.12	Andesine
27072017-2	And. Bas.	Plag. Phen. (Internal Rim)	2707_2 PI 17	62.09	0	23.14	0.33	0	0	7.29	0.57	6.17	99.59	3.34	64.99	31.67	Andesine
27072017-2	And. Bas.	Plag. Phen. (External Rim)	2707_2 PI 18	55.54	0	26.94	0.93	0	0	5.27	0.26	11.03	99.98	1.43	44.15	54.42	Labradorite
27072017-3	Rhyolite	Large Plag. Phen. (Core)	2707_3 PI 44	64.27	0	22.91	0	0	0	8.71	0.68	4.46	101.03	3.85	74.94	21.21	Oligoclase
27072017-3	Rhyolite	Large Plag. Phen. (Inner Rim)	2707_3 PI 45	64.1	0	22.67	0	0	0	8.39	1.13	4.25	100.54	6.48	73.07	20.45	Oligoclase
27072017-3	Rhyolite	Small Plag. Phen. (Core)	2707_3 PI 49	65.05	0	21.6	0.24	0	0	8.67	1.59	3.23	100.38	9.02	74.71	16.27	Oligoclase
24072017-0	Basalt	Plag. Phen. (Core)	2407 PI 01	50.71	0	30.88	0.73	0	0.15	3.09	0.13	15.22	100.92	0.71	25.71	73.57	Bytownite
24072017-0	Basalt	Plag. Phen. (Rim)	2407 PI 02	55.15	0	27.43	1.28	0	0.15	4.85	0.3	11.65	100.8	1.62	39.91	58.47	Labradorite
24072017-0	Basalt	Plag. Phen. (Rim)	2407 PI 03	53.49	0	27.93	0.85	0	0.2	4.36	0.17	12.39	99.39	0.94	36.83	62.23	Labradorite

Table S2.1. Continued.

Plagioclase:																	
Sample id	Rock type	Mineral	Analysis id.	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Total	X Or	X Ab	X An	Classification
24072017-0	Basalt	Plag. Phen. (Core)	2407 PI 04	48.87	0	31.25	0.68	0	0.16	16.05	2.49	0	99.51	0	21.14	78.86	Bytownite
24072017-0	Basalt	Plag. Microlite	2407 PI 05	54.88	0.31	26.2	1.6	0	0.17	10.71	4.92	0.36	99.14	1.99	41.36	56.65	Labradorite
24072017-0	Basalt	Plag. Microlite	2407 PI 06	55.48	0	26.95	0.94	0	0.13	11.19	5.1	0.29	100.09	1.59	42.57	55.84	Labradorite
24072017-0	Basalt	Large Plag. Phen. (Core)	2407 PI 14	49.03	0	31.47	0.69	0	0.15	16.21	2.56	0	100.11	0	21.46	78.54	Bytownite
24072017-0	Basalt	Large Plag. Phen. (Rim)	2407 PI 15	51.49	0	29.64	0.84	0	0.12	14.24	3.49	0.13	99.94	0.72	29.33	69.95	Bytownite
24072017-0	Basalt	Plag. Microlite	2407 PI 18	53.87	0	28.14	1.11	0	0.21	12.78	4.4	0.18	100.71	0.97	36	63.03	/labradorite
27072017-1	Dacite	Large Plag. Phen. (Core)	2707_1 PI 21	60.31	0	25.59	0	0	0	8.15	6.79	0.29	101.12	1.66	59.12	39.22	Labradorite
27072017-1	Dacite	Large Plag. Phen. (Rim)	2707_1 PI 22	56.07	0	27.58	0.43	0	0	10.95	5.31	0.18	100.52	1.02	45.52	53.46	Andesine
27072017-1	Dacite	Plag. Microlite	2707_1 PI 27	57.26	0	26.81	0.47	0	0	9.87	5.95	0.25	100.61	1.4	50.55	48.06	Labradorite
27072017-1	Dacite	Large Plag. Phen. (Core)	2707_1 PI 36	58.69	0	25.87	0.39	0	0	8.94	6.37	0.26	100.52	1.47	54.68	43.85	Andesine
27072017-1	Dacite	Large Plag. Phen. (Rim)	2707_1 PI 37	58.18	0	26.09	0.41	0	0	9.27	6.23	0.25	100.43	1.41	53.27	45.32	Andesine
27072017-1	Dacite	Plag. Microlite	2707_1 PI 40	56.75	0	26.12	0.73	0	0	9.45	6.19	0.29	99.53	1.6	51.94	45.46	Andesine
27072017-1	Dacite	Small Plag. Phen. (Core)	2707_1 PI 42	56.4	0	27.2	0.45	0	0	10.67	5.6	0.23	100.55	1.28	47.29	51.43	Andesine
27072017-1	Dacite	Small Plag. Phen. (Rim)	2707_1 PI 43	55.43	0	27.69	0.55	0	0	10.8	5.37	0.23	100.07	1.29	45.79	52.92	Labradorite
27072017-1	Xenolith	Plag. (Core)	2707_1 PI 32	50.91	0	30.58	0.61	0	0.24	15.15	3.25	0	100.74	0	26.93	73.07	Bytownite
27072017-1	Xenolith	Plag. (Core)	2707_1 PI 33	50.2	0	31.04	0.63	0	0.16	15.4	3.04	0	100.47	0	25.45	74.55	Bytownite

Table S2.1. Continued.

K-Feldspar:																	
Sample id	Rock type	Mineral	Analysis id.	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total	X Or	X Ab	X An	Classification
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 36	68.87	0	18.32	0.31	0	0	0.3	6.55	6.86	101.21	39.72	57.64	2.64	Sanidine
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 38	67.74	0	19.98	0.45	0	0	1.59	8.16	3.6	101.52	20.42	70.34	9.25	Anorthoclase
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 39	66.91	0	18.66	0.43	0	0	0.59	7.07	6.23	99.89	35.09	60.53	4.38	Anorthoclase
10072017-3	Rhyolite	K-feldspar Microlite	1007 Kfs 43	68.24	0	18.27	0.6	0	0	0.74	7.18	5.23	100.27	30.48	63.6	5.92	Anorthoclase
27072017-3	Rhyolite	K-feldspar (outermost rim of plag. phen.)	2707_3 Alk- Fs 46	67.18	0	18.66	0.52	0	0	0.6	6.99	5.96	99.92	34.2	60.96	4.85	Anorthoclase
27072017-3	Rhyolite	K-feldspar Microlite	2707_3 Alk- Fs 47	67.23	0	19.5	0.45	0	0	1.12	8.16	3.8	100.25	21.79	71.12	7.09	Anorthoclase
27072017-3	Rhyolite	K-feldspar Microlite	2707_3 Alk- Fs 48	66.47	0	20.37	0.3	0	0	1.97	8.29	3.37	100.77	18.91	70.7	10.39	Anorthoclase
27072017-3	Rhyolite	K-feldspar (outermost rim of plag. phen.)	2707_3 Alk- Fs 50	66.91	0	18.76	0.48	0	0	0.67	7.06	5.85	99.74	33.51	61.46	5.03	Anorthoclase
27072017-3	Rhyolite	K-feldspar Microlite	2707_3 Alk- Fs 52	67.69	0	18.84	0.48	0	0	0.6	7.43	5.63	100.68	31.74	63.65	4.61	Anorthoclase
27072017-3	Rhyolite	K-feldspar Microlite	2707_3 Alk- Fs 54	66.15	0.22	18.41	0.61	0	0	0.58	6.55	6.79	99.34	38.51	56.46	5.03	Sanidine
01092016-1	Andesite	K-feldspar (patch inside a plag. phen.)	0109 Kfs 34	67	0	18.23	0.58	0	0	0.39	4.26	10.07	100.52	58.59	37.37	4.04	Sanidine

Table S2.1. Continued.

Sample id	Rock type	Mineral	Analysis id.	SiO2	TiO2	Al2O3	FeO*	MnO	MgO	CaO	ZnO	ZrO2	Nb2O3	HfO2	V2O5	Total
01092016-1	Andesite	Titanomagnetite	0109 Mt 33	0	24.11	0.74	69.15	0.94	0.18	0	-	-	-	-	-	95.12
01092016-1	Andesite	Titanomagnetite	0109 Mt 23	0.21	24.17	1.09	69.32	0.72	0.3	0	-	-	-	-	-	95.81
24072017-0	Basalt	Titanomagnetite	2407 Mt 11	0.27	24.69	1.7	64	0.44	0.57	0.23	-	-	-	-	1.18	93.09
24072017-0	Basalt	Titanomagnetite	2407 Mt 19	0	25.63	1.85	66.18	0.43	0.65	0	-	-	-	-	1.32	96.06
24072017-0	Basalt	Ilmenite	2407 Ilm 10	0	51.33	0.2	47.35	0.66	0.61	0.16	-	-	-	-	-	100.31
			2707_2 Mt													
27072017-2	Bas.and.	Titanomagnetite	08	0.21	24.93	1.5	67.23	0.49	0.62	0.15	-	-	-	-	0.87	96
27072017-2	Bas.and.	Ilmenite	2707 Ilm 09	0.36	51.93	-	46.43	0.61	0.54	0.35	-	-	-	-	-	100.22
			2707_1 Mt													
27072017-1	Dacite	Titanomagnetite	26	2.63	17.32	0.75	67.96	1.13	0	0	-	-	-	-	-	89.80
10072017-3	Rhyolite	Titanomagnetite	1007 Mt 35	0.36	13.93	0.4	71.02	1.02	0	0	-	-	0.39	-	-	87.12
			2707_3 Mt													
27072017-3	Rhyolite	Titanomagnetite	51	0.31	16.76	0.74	67.78	1.04	0	0	0.96	-	1.13	-	-	88.72
		Zircon in	2707_3 Zrc													
27072017-3	Rhyolite	groundmass	53	31.88	0	0	0	0	0	0	-	64.87	-	1.64	-	98.39
		Zircon in														
10072017-3	Rhyolite	groundmass	1007 Zrc 37	32.33	-	-	-	-	-	-	-	68.91	-	0.99	-	102.24
			2707_1 Mt													
27072017-1	Xenolith	Titanomagnetite	35	0.23	13.84	3.65	74.76	0.42	0.8	0	-	-	-	-	-	93.71

*Low totals in titanomagnetite depends on the fact that a consistent part of iron is ferric (i.e., Fe_2O_3).

Table S2.1. Continued.

Glass and alteration:													
Sample id	Rock type	Mineral	Analysis id.	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Total
10072017-3	Rhyolite	Spherulite Glass	1007 gl 40	73.9	0	12.6	1.14	0	0	0.78	5.54	2.66	96.62
10072017-3	Rhyolite	Spherulite Glass	1007 gl 41	74.45	0	12.18	0.62	0	0	0.73	5.19	2.99	96.16
10072017-3	Rhyolite	Spherulite Glass (center)	1007 gl 42	75.63	0	10.85	0.72	0	0	0.77	4.83	2.08	94.87
10072017-3	Rhyolite	Spherulite Glass	1007 gl 44	75.06	0	12.38	0.76	0	0	0.41	4.91	3.81	97.32
10072017-3	Rhyolite	Spherulite Glass	1007 gl 45	76.61	0	11.69	0.95	0	0	0.42	4.58	3.46	97.72
10072017-3	Rhyolite	Spherulite Glass	1007 gl 46	77.99	0	11.69	0.54	0	0	0.52	4.5	3.61	98.84
24072017-0	Basalt	Alteration coat on a vesicle wall	2407 XXX 20	50.2	0.2	7.25	16.84	0	7.73	3.13	0	0.26	85.61
24072017-0	Basalt	Alteration coat on a vesicle wall	2407 XXX 12	48.53	0	6.99	16.72	0	7.32	3.15	0	0.2	82.9
24072017-0	Basalt	Alteration spot	2407 XXX 13	51.41	0	7.53	16.99	0	7.39	3.12	0	0.26	86.7

Table S2.2. Results of microprobe analysis (EPMA) of obsidian from Glerá (sample 20180904-3). ATHO is standard.

Sample	Point	Comment	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Sum
ATHO pt1	1	Standard	75.87	0.241	11.82	3.37	0.099	0.083	1.65	4.48	2.63	0.065	100.31
ATHO pt2	2	Standard	75.85	0.266	12.20	3.40	0.099	0.114	1.66	4.56	2.70	0.028	100.88
ATHO pt3	3	Standard	75.18	0.194	12.04	3.28	0.066	0.079	1.69	4.61	2.69	0.051	99.88
ATHO pt4	4	Standard	75.62	0.185	12.40	3.23	0.117	0.099	1.67	4.48	2.63	0.030	100.46
ATHO pt5	5	Standard	75.14	0.285	12.47	3.28	0.123	0.076	1.65	4.54	2.59	0.041	100.19
20180904-3	6	Torfufell-1	76.26	0.136	12.27	2.02	0.083	0.011	0.79	4.47	3.38	0.000	99.42
20180904-3	7	Torfufell-2	76.67	0.163	12.27	2.01	0.085	0.000	0.77	4.26	3.43	0.017	99.68
20180904-3	8	Torfufell-3	76.21	0.137	12.21	2.08	0.082	0.017	0.77	4.59	3.46	0.000	99.55
20180904-3	9	Torfufell-4	76.87	0.110	12.08	2.02	0.110	0.009	0.72	4.39	3.36	0.002	99.67
20180904-3	10	Torfufell-5	77.01	0.120	12.28	1.96	0.061	0.016	0.77	4.72	3.36	0.000	100.29
20180904-3	11	Torfufell-6	76.71	0.164	12.28	1.96	0.063	0.010	0.75	4.56	3.47	0.000	99.96
20180904-3	12	Torfufell-7	76.52	0.149	12.42	2.00	0.065	0.013	0.73	4.52	3.31	0.000	99.72
20180904-3	13	Torfufell-8	76.42	0.163	12.34	1.94	0.090	0.000	0.76	4.43	3.42	0.037	99.60
20180904-3	14	Torfufell-9	76.38	0.119	12.32	2.01	0.126	0.008	0.73	4.27	3.40	0.000	99.36
20180904-3	15	Torfufell-10	77.08	0.142	12.25	1.98	0.057	0.002	0.63	4.61	3.42	0.000	100.17

Table S2.2. Continued

Sample	Point	Comment	Na+K	Ti/Fe	Ti/Mg	Mg#	Ca/Al	Ca/Mg
ATHO pt1	1	Standard	7.11	0.071	2.92	0.042	0.254	19.98
ATHO pt2	2	Standard	7.26	0.078	2.33	0.056	0.247	14.54
ATHO pt3	3	Standard	7.30	0.059	2.46	0.041	0.255	21.42
ATHO pt4	4	Standard	7.11	0.057	1.87	0.052	0.245	16.89
ATHO pt5	5	Standard	7.13	0.087	3.73	0.040	0.241	21.63
20180904-3	6	Torfufell-1	7.85	0.067	11.92	0.010	0.117	69.39
20180904-3	7	Torfufell-2	7.69	0.081		0.000	0.115	
20180904-3	8	Torfufell-3	8.05	0.066	8.25	0.014	0.114	46.30
20180904-3	9	Torfufell-4	7.75	0.055	11.86	0.008	0.109	77.61
20180904-3	10	Torfufell-5	8.08	0.061	7.72	0.014	0.113	49.36
20180904-3	11	Torfufell-6	8.03	0.084	16.95	0.009	0.111	77.10
20180904-3	12	Torfufell-7	7.83	0.074	11.71	0.011	0.107	57.33
20180904-3	13	Torfufell-8	7.85	0.084		0.000	0.112	
20180904-3	14	Torfufell-9	7.67	0.059	15.61	0.007	0.108	96.34
20180904-3	15	Torfufell-10	8.03	0.072	67.57	0.002	0.094	300.86

Table S2.2. Continued

ALL	Group: Thorvaldur	Sample: Thorvaldur _0001_QN T										
Point	Comment	SiO2 (Mass%)	TiO2 (Mass %)	Al2O3 (Mass%)	FeO (Mass%)	MnO (Mass %)	MgO (Mass %)	CaO (Mass %)	Na2O (Mass %)	K2O (Mass%)	P2O5 (Mass %)	Total (Mass%)
1	ATHO pt1	75.87	0.24	11.82	3.37	0.10	0.08	1.65	4.48	2.63	0.07	100.31
2	ATHO pt2	75.85	0.27	12.20	3.40	0.10	0.11	1.66	4.56	2.70	0.03	100.88
3	ATHO pt3	75.18	0.19	12.04	3.28	0.07	0.08	1.69	4.61	2.69	0.05	99.88
4	ATHO pt4	75.62	0.18	12.40	3.23	0.12	0.10	1.67	4.48	2.63	0.03	100.46
5	ATHO pt5	75.14	0.28	12.47	3.28	0.12	0.08	1.65	4.54	2.59	0.04	100.19
6	Torfufell-1	76.26	0.14	12.27	2.02	0.08	0.01	0.79	4.47	3.38	0.00	99.42
7	Torfufell-2	76.67	0.16	12.27	2.01	0.09	0.00	0.77	4.26	3.43	0.02	99.68
8	Torfufell-3	76.21	0.14	12.21	2.08	0.08	0.02	0.77	4.59	3.46	0.00	99.55
9	Torfufell-4	76.87	0.11	12.08	2.02	0.11	0.01	0.72	4.39	3.36	0.00	99.67
10	Torfufell-5	77.01	0.12	12.28	1.96	0.06	0.02	0.77	4.72	3.36	0.00	100.29
11	Torfufell-6	76.71	0.16	12.28	1.96	0.06	0.01	0.75	4.56	3.47	0.00	99.96
12	Torfufell-7	76.52	0.15	12.42	2.00	0.07	0.01	0.73	4.52	3.31	0.00	99.72
13	Torfufell-8	76.42	0.16	12.34	1.94	0.09	0.00	0.76	4.43	3.42	0.04	99.60
14	Torfufell-9	76.38	0.1186	12.32	2.01	0.1263	0.0076	0.7322	4.27	3.4	0	99.3647
15	Torfufell-10	77.08	0.1419	12.25	1.98	0.0565	0.0021	0.6318	4.61	3.42	0	100.1723
16	ATHO-6	0.2947	0.0125	0.1155	0	0	0.0064	0	0.0795	0	0.0235	0.5321
17	ATHO-7	0.2783	0	0.1113	0.0078	0	0.0044	0.0011	0.0573	0.0032	0.0213	0.4847
Minimum		0.2783	0	0.1113	0	0	0	0	0.0573	0	0	0.4847
Maximum		77.08	0.2848	12.47	3.4	0.1263	0.1142	1.69	4.72	3.47	0.0651	100.8767
Average		67.3155	0.1521	10.8163	2.1499	0.0779	0.0322	0.9261	3.978	2.7796	0.0185	88.2461
Sigma		25.2353	0.0745	4.0313	1.0071	0.0365	0.0397	0.5473	1.4762	1.1015	0.0208	33.0257

Table S2.2. Continued.

ALL	Group: Thorvaldur											
Point	Comment	SiO2 (Norm%)	TiO2 (Norm%)	Al2O3 (Norm%)	FeO (Norm%)	MnO (Norm%)	MgO (Norm%)	CaO (Norm%)	Na2O (Norm%)	K2O (Norm%)	P2O5 (Norm%)	Total (Norm%)
1	ATHO pt1	75.64	0.240	11.78	3.36	0.098	0.08	1.64	4.47	2.62	0.065	100
2	ATHO pt2	75.19	0.264	12.09	3.37	0.098	0.11	1.65	4.52	2.68	0.027	100
3	ATHO pt3	75.27	0.194	12.05	3.28	0.066	0.08	1.69	4.62	2.69	0.051	100
4	ATHO pt4	75.27	0.184	12.34	3.22	0.116	0.10	1.66	4.46	2.62	0.030	100
5	ATHO pt5	74.99	0.284	12.45	3.27	0.122	0.08	1.65	4.53	2.59	0.041	100
6	Torfufell-1	76.70	0.137	12.34	2.03	0.084	0.01	0.80	4.50	3.40	0.000	100
7	Torfufell-2	76.92	0.164	12.31	2.02	0.086	0.00	0.78	4.27	3.44	0.017	100
8	Torfufell-3	76.55	0.138	12.26	2.09	0.082	0.02	0.77	4.61	3.48	0.000	100
9	Torfufell-4	77.12	0.111	12.12	2.03	0.110	0.01	0.72	4.40	3.37	0.002	100
10	Torfufell-5	76.79	0.119	12.24	1.95	0.061	0.02	0.76	4.71	3.35	0.000	100
11	Torfufell-6	76.74	0.165	12.28	1.96	0.063	0.01	0.75	4.56	3.47	0.000	100
12	Torfufell-7	76.73	0.149	12.45	2.01	0.065	0.01	0.73	4.53	3.32	0.000	100
13	Torfufell-8	76.73	0.164	12.39	1.95	0.091	0.00	0.76	4.45	3.43	0.037	100
14	Torfufell-9	76.87	0.119	12.40	2.02	0.127	0.01	0.74	4.30	3.42	0.000	100
15	Torfufell-10	76.95	0.142	12.23	1.98	0.056	0.00	0.63	4.60	3.41	0.000	100
16	ATHO-6	55.38	2.349	21.71	0.00	0.000	1.20	0.00	14.94	0.00	4.417	100
17	ATHO-7	57.42	0.000	22.96	1.61	0.000	0.91	0.23	11.82	0.66	4.395	100
Minimum		55.38	0.000	11.78	0.00	0.000	0	0	4.2737	0	0.000	100
Maximum		77.12	2.349	22.96	3.37	0.127	1.20	1.69	14.94	3.48	4.417	100
Average		73.96	0.290	13.44	2.24	0.078	0.16	0.94	5.55	2.82	0.534	100
Sigma		6.66	0.535	3.36	0.85	0.037	0.34	0.52	3.00	1.01	1.457	0

Table S2.2. Continued.

ALL	Group: Thorvaldur										ALL	Group: Thorvaldur
Point	Comment	SiO2 (Cation)	TiO2 (Cation)	Al2O3 (Cation)	FeO (Cation)	MnO (Cation)	MgO (Cation)	CaO (Cation)	Na2O (Cation)	K2O (Cation)	P2O5 (Cation)	Total (Cation)
1	ATHO pt1	9.90	0.024	1.82	0.367	0.01	0.016	0.230	1.14	0.437	0.007	13.94
2	ATHO pt2	9.85	0.026	1.87	0.369	0.01	0.022	0.231	1.15	0.447	0.003	13.98
3	ATHO pt3	9.86	0.019	1.86	0.360	0.01	0.015	0.237	1.17	0.451	0.006	13.99
4	ATHO pt4	9.85	0.018	1.90	0.352	0.01	0.019	0.233	1.13	0.437	0.003	13.96
5	ATHO pt5	9.82	0.028	1.92	0.358	0.01	0.015	0.231	1.15	0.431	0.005	13.97
6	Torfufell-1	9.97	0.013	1.89	0.221	0.01	0.002	0.111	1.13	0.564	0.000	13.92
7	Torfufell-2	9.99	0.016	1.88	0.219	0.01	0.000	0.108	1.08	0.570	0.002	13.87
8	Torfufell-3	9.97	0.014	1.88	0.227	0.01	0.003	0.108	1.16	0.577	0.000	13.95
9	Torfufell-4	10.01	0.011	1.86	0.220	0.01	0.002	0.101	1.11	0.559	0.000	13.88
10	Torfufell-5	9.98	0.012	1.88	0.212	0.01	0.003	0.106	1.19	0.555	0.000	13.94
11	Torfufell-6	9.98	0.016	1.88	0.213	0.01	0.002	0.104	1.15	0.575	0.000	13.93
12	Torfufell-7	9.97	0.015	1.91	0.218	0.01	0.003	0.102	1.14	0.550	0.000	13.91
13	Torfufell-8	9.97	0.016	1.90	0.211	0.01	0.000	0.107	1.12	0.570	0.004	13.90
14	Torfufell-9	9.98	0.012	1.90	0.220	0.01	0.002	0.103	1.08	0.568	0.000	13.88
15	Torfufell-10	10.00	0.014	1.87	0.215	0.01	0.000	0.088	1.16	0.566	0.000	13.92
16	ATHO-6	7.46	0.237	3.44	0.000	0.00	0.240	0.000	3.90	0.000	0.503	15.78
17	ATHO-7	7.68	0.000	3.62	0.179	0.00	0.180	0.032	3.06	0.114	0.498	15.36
Minimum		7.46	0.000	1.82	0.000	0.00	0.000	0.000	1.08	0.000	0.000	13.87
Maximum		10.01	0.237	3.62	0.369	0.01	0.240	0.237	3.90	0.577	0.503	15.78
Average		9.66	0.029	2.08	0.245	0.01	0.031	0.131	1.41	0.469	0.061	14.12
Sigma		0.79	0.054	0.55	0.094	0.00	0.069	0.073	0.79	0.167	0.166	0.55

Table S2.2. Continued.

Point	Comment	SiO2 (mole %)	TiO2 (mole %)	Al2O3 (mole %)	FeO (mole %)	MnO (mole %)	MgO (mole %)	CaO (mole %)	Na2O (mole %)	K2O (mole %)	P2O5 (mole %)	Total (mole %)	X	Y	Z
1	ATHO pt1	80.83	0.193	7.42	3.00	0.089	0.131	1.88	4.63	1.79	0.029	100	29.81	-24.57	11.37
2	ATHO pt2	80.46	0.212	7.63	3.02	0.089	0.181	1.89	4.69	1.83	0.012	100	29.81	-24.53	11.36
3	ATHO pt3	80.53	0.156	7.60	2.94	0.060	0.126	1.94	4.79	1.84	0.023	100	29.81	-24.48	11.36
4	ATHO pt4	80.59	0.148	7.79	2.88	0.105	0.157	1.91	4.63	1.79	0.014	100	29.81	-24.42	11.36
5	ATHO pt5	80.36	0.229	7.86	2.93	0.111	0.122	1.89	4.71	1.77	0.018	100	29.82	-24.36	11.36
6	Torfufell-1	82.26	0.110	7.80	1.82	0.076	0.018	0.91	4.67	2.33	0.000	100	26.28	12.59	10.62
7	Torfufell-2	82.50	0.132	7.78	1.81	0.078	0.000	0.89	4.44	2.35	0.008	100	25.69	12.24	10.62
8	Torfufell-3	82.10	0.111	7.75	1.87	0.075	0.027	0.89	4.79	2.38	0.000	100	25.40	12.14	10.62
9	Torfufell-4	82.62	0.089	7.65	1.82	0.100	0.015	0.83	4.57	2.30	0.001	100	25.30	12.10	10.62
10	Torfufell-5	82.28	0.096	7.73	1.75	0.056	0.025	0.88	4.89	2.29	0.000	100	25.30	12.02	10.62
11	Torfufell-6	82.30	0.133	7.76	1.76	0.057	0.016	0.86	4.74	2.37	0.000	100	25.37	12.00	10.62
12	Torfufell-7	82.30	0.120	7.87	1.80	0.059	0.020	0.84	4.71	2.27	0.000	100	24.35	23.46	10.64
13	Torfufell-8	82.33	0.132	7.83	1.75	0.082	0.000	0.88	4.63	2.35	0.017	100	24.30	23.45	10.64
14	Torfufell-9	82.46	0.096	7.84	1.81	0.116	0.012	0.85	4.47	2.34	0.000	100	24.22	23.41	10.64
15	Torfufell-10	82.49	0.114	7.73	1.77	0.051	0.003	0.72	4.78	2.33	0.000	100	24.19	23.47	10.64
16	ATHO-6	62.87	2.006	14.52	0.00	0.000	2.035	0.00	16.44	0.00	2.122	100	29.50	-24.30	10.62
17	ATHO-7	65.52	0.000	15.44	1.54	0.000	1.544	0.28	13.08	0.48	2.123	100	29.48	-24.30	10.62
Minimum		62.87	0.000	7.42	0.00	0.000	0.000	0.00	4.44	0.00	0.000	100	24.19	-24.57	10.62
Maximum		82.62	2.006	15.44	3.02	0.116	2.035	1.94	16.44	2.38	2.123	100	29.82	23.47	11.37
Average		79.69	0.240	8.59	2.02	0.071	0.261	1.08	5.86	1.93	0.257	100	26.97	-0.24	10.85
Sigma		5.91	0.458	2.41	0.76	0.033	0.585	0.60	3.40	0.69	0.702	0	2.44	21.31	0.35

Table S2.2. Continued.

Point	Comment	SiO2 (K-ratio)	TiO2 (K-ratio)	Al2O3 (K-ratio)	FeO (K-ratio)	MnO (K-ratio)	MgO (K-ratio)	CaO (K-ratio)	Na2O (K-ratio)	K2O (K-ratio)	P2O5(K-ratio)	Total(K-ratio)
1	ATHO pt1	0.00	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.00	0.000	0.00
2	ATHO pt2	75.58	0.261	12.03	3.33	0.095	0.115	1.633	4.69	2.62	0.021	100.38
3	ATHO pt3	74.87	0.191	11.88	3.21	0.064	0.080	1.662	4.74	2.61	0.039	99.36
4	ATHO pt4	75.31	0.181	12.25	3.16	0.113	0.100	1.642	4.61	2.55	0.023	99.94
5	ATHO pt5	74.75	0.280	12.31	3.21	0.118	0.077	1.622	4.67	2.51	0.031	99.57
6	Torfufell-1	76.18	0.133	12.21	1.98	0.080	0.012	0.776	4.68	3.27	0.000	99.32
7	Torfufell-2	76.67	0.160	12.22	1.96	0.082	-0.001	0.759	4.45	3.32	0.013	99.64
8	Torfufell-3	76.13	0.134	12.15	2.03	0.079	0.017	0.754	4.80	3.35	0.000	99.43
9	Torfufell-4	76.91	0.108	12.03	1.97	0.106	0.010	0.708	4.58	3.25	0.002	99.68
10	Torfufell-5	77.01	0.117	12.22	1.91	0.059	0.016	0.751	4.94	3.24	0.000	100.27
11	Torfufell-6	76.69	0.161	12.22	1.92	0.060	0.010	0.734	4.77	3.35	0.000	99.92
12	Torfufell-7	76.43	0.146	12.36	1.95	0.063	0.013	0.714	4.73	3.20	0.000	99.61
13	Torfufell-8	76.38	0.160	12.29	1.89	0.087	-0.006	0.747	4.63	3.31	0.028	99.52
14	Torfufell-9	76.32	0.116	12.28	1.96	0.122	0.008	0.718	4.46	3.29	0.000	99.28
15	Torfufell-10	77.09	0.139	12.20	1.94	0.055	0.002	0.620	4.83	3.31	0.000	100.17
16	ATHO-6	0.25	0.012	0.11	0.00	0.000	0.006	0.000	0.08	0.00	0.018	0.48
17	ATHO-7	0.24	0.000	0.10	0.01	0.000	0.004	0.001	0.06	0.00	0.017	0.44
Minimum		0.00	0.000	0.00	0.00	0.000	-0.006	0.000	0.00	0.00	0.000	0.00
Maximum		77.09	0.280	12.36	3.33	0.122	0.115	1.662	4.94	3.35	0.039	100.38
Average		62.75	0.135	10.05	1.91	0.070	0.027	0.814	3.87	2.54	0.011	82.18
Sigma		29.87	0.078	4.76	1.06	0.039	0.039	0.548	1.83	1.25	0.013	39.07

Table S2.2. Continued.

Point	Comment	SiO2 (K-raw)	TiO2 (K-raw)	Al2O3 (K-raw)	FeO (K- raw)	MnO (K-raw)	MgO (K-raw)	CaO (K- raw)	Na2O (K-raw)	K2O (K- raw)	P2O5 (K-raw)	Total (K-raw)
1	ATHO pt1	99.92	5.01	32.39	20.29	0.394	0.473	6.55	92.10	22.55	0.122	279.80
2	ATHO pt2	99.78	5.54	33.40	20.47	0.394	0.654	6.61	93.73	23.17	0.052	283.79
3	ATHO pt3	98.84	4.04	32.97	19.78	0.264	0.452	6.72	94.84	23.13	0.095	281.13
4	ATHO pt4	99.42	3.84	33.99	19.45	0.466	0.567	6.64	92.27	22.55	0.056	279.24
5	ATHO pt5	98.68	5.92	34.16	19.74	0.490	0.437	6.56	93.30	22.21	0.076	281.58
6	Torfufell-1	100.57	2.82	33.89	12.17	0.332	0.066	3.14	93.52	28.96	0.000	275.46
7	Torfufell-2	101.22	3.39	33.93	12.06	0.341	-0.006	3.07	88.99	29.35	0.032	272.37
8	Torfufell-3	100.50	2.84	33.71	12.51	0.327	0.096	3.05	95.93	29.62	0.000	278.57
9	Torfufell-4	101.53	2.29	33.39	12.14	0.437	0.054	2.86	91.68	28.77	0.004	273.15
10	Torfufell-5	101.66	2.48	33.92	11.77	0.245	0.090	3.03	98.84	28.71	0.000	280.74
11	Torfufell-6	101.24	3.41	33.93	11.80	0.250	0.056	2.97	95.40	29.68	0.000	278.73
12	Torfufell-7	100.90	3.08	34.31	12.02	0.259	0.073	2.89	94.64	28.32	0.000	276.50
13	Torfufell-8	100.83	3.38	34.11	11.66	0.360	-0.034	3.02	92.64	29.31	0.069	275.35
14	Torfufell-9	100.75	2.46	34.08	12.08	0.504	0.044	2.90	89.23	29.14	0.000	271.20
15	Torfufell-10	101.77	2.94	33.86	11.91	0.226	0.012	2.51	96.53	29.25	0.000	279.00
16	ATHO-6	0.34	0.26	0.29	0.00	0.000	0.035	0.00	1.68	0.00	0.045	2.65
17	ATHO-7	0.32	0.00	0.29	0.05	0.000	0.024	0.00	1.20	0.03	0.040	1.95
Minimum		0.32	0.00	0.29	0.00	0.000	-0.034	0.00	1.20	0.00	0.000	1.95
Maximum		101.77	5.92	34.31	20.47	0.504	0.654	6.72	98.84	29.68	0.122	283.79
Average		88.72	3.16	29.80	12.94	0.311	0.182	3.68	82.74	23.81	0.035	245.37
Sigma		33.28	1.55	11.12	6.07	0.146	0.230	2.18	30.70	9.43	0.039	91.55

Table S2.2. Continued.

Point	Comment	Si(Net)	Ti(Net)	Al(Net)	Fe(Net)	Mn(Net)	Mg(Net)	Ca(Net)	Na(Net)	K(Net)	P(Net)
1	ATHO pt1	6.19E+05	1.14E+03	9.31E+04	1.89E+04	5.40E+02	5.80E+02	1.01E+04	1.79E+04	3.67E+04	1.20E+02
2	ATHO pt2	6.18E+05	1.26E+03	9.61E+04	1.90E+04	5.40E+02	7.80E+02	1.01E+04	1.82E+04	3.77E+04	4.00E+01
3	ATHO pt3	6.12E+05	9.20E+02	9.48E+04	1.84E+04	3.60E+02	5.40E+02	1.03E+04	1.84E+04	3.76E+04	8.00E+01
4	ATHO pt4	6.16E+05	8.79E+02	9.78E+04	1.81E+04	6.40E+02	6.80E+02	1.02E+04	1.79E+04	3.67E+04	6.00E+01
5	ATHO pt5	6.11E+05	1.36E+03	9.83E+04	1.84E+04	6.80E+02	5.20E+02	1.01E+04	1.81E+04	3.62E+04	7.99E+01
6	Torfufell-1	6.23E+05	6.40E+02	9.75E+04	1.13E+04	4.60E+02	7.99E+01	4.82E+03	1.82E+04	4.71E+04	-4.00E+01
7	Torfufell-2	6.27E+05	7.79E+02	9.76E+04	1.12E+04	4.79E+02	0.00E+00	4.71E+03	1.73E+04	4.78E+04	2.00E+01
8	Torfufell-3	6.22E+05	6.39E+02	9.69E+04	1.16E+04	4.60E+02	1.20E+02	4.67E+03	1.87E+04	4.82E+04	-2.00E+01
9	Torfufell-4	6.29E+05	5.19E+02	9.60E+04	1.13E+04	5.99E+02	5.99E+01	4.39E+03	1.78E+04	4.68E+04	0.00E+00
10	Torfufell-5	6.30E+05	5.59E+02	9.75E+04	1.09E+04	3.40E+02	9.98E+01	4.65E+03	1.92E+04	4.67E+04	-7.99E+01
11	Torfufell-6	6.27E+05	7.79E+02	9.76E+04	1.10E+04	3.40E+02	5.99E+01	4.55E+03	1.86E+04	4.83E+04	-2.00E+01
12	Torfufell-7	6.25E+05	6.99E+02	9.87E+04	1.12E+04	3.60E+02	7.99E+01	4.43E+03	1.84E+04	4.61E+04	0.00E+00
13	Torfufell-8	6.24E+05	7.79E+02	9.81E+04	1.08E+04	4.99E+02	-3.99E+01	4.63E+03	1.80E+04	4.77E+04	5.99E+01
14	Torfufell-9	6.24E+05	5.59E+02	9.80E+04	1.12E+04	6.99E+02	5.99E+01	4.45E+03	1.73E+04	4.74E+04	-5.99E+01
15	Torfufell-10	6.30E+05	6.79E+02	9.74E+04	1.11E+04	3.19E+02	2.00E+01	3.85E+03	1.88E+04	4.76E+04	-3.99E+01
16	ATHO-6	2.08E+03	5.99E+01	8.38E+02	-5.99E+01	-7.98E+01	3.99E+01	-2.00E+01	3.19E+02	-2.00E+01	3.99E+01
17	ATHO-7	1.98E+03	3.99E+01	8.18E+02	3.99E+01	-7.98E+01	2.00E+01	0.00E+00	2.40E+02	3.99E+01	3.99E+01
Minimum		1.98E+03	3.99E+01	8.18E+02	-5.99E+01	-7.98E+01	-3.99E+01	-2.00E+01	2.40E+02	-2.00E+01	-7.99E+01
Maximum		6.30E+05	1.36E+03	9.87E+04	1.90E+04	6.99E+02	7.80E+02	1.03E+04	1.92E+04	4.83E+04	1.20E+02
Average		5.49E+05	7.18E+02	8.57E+04	1.20E+04	4.21E+02	2.18E+02	5.64E+03	1.61E+04	3.88E+04	1.65E+01
Sigma		2.06E+05	3.60E+02	3.20E+04	5.65E+03	2.23E+02	2.76E+02	3.34E+03	5.97E+03	1.53E+04	5.53E+01

Table S2.2. Continued.

Point	Comment	Si(BG-)	Ti(BG-)	Al(BG-)	Fe(BG-)	Mn(BG-)	Mg(BG-)	Ca(BG-)	Na(BG-)	K(BG-)	P(BG-)
1	ATHO pt1	1,24E+03	1,12E+03	1,30E+03	9,99E+02	0,00E+00	6,20E+02	6,99E+02	2,80E+02	8,59E+02	7,99E+01
2	ATHO pt2	1,60E+03	1,18E+03	1,18E+03	1,20E+03	0,00E+00	6,20E+02	7,80E+02	4,00E+02	7,60E+02	1,40E+02
3	ATHO pt3	1,72E+03	1,34E+03	1,02E+03	1,34E+03	0,00E+00	6,40E+02	7,40E+02	3,20E+02	9,00E+02	1,60E+02
4	ATHO pt4	1,56E+03	1,24E+03	1,10E+03	1,24E+03	0,00E+00	6,60E+02	6,80E+02	3,20E+02	7,99E+02	1,40E+02
5	ATHO pt5	1,56E+03	9,39E+02	1,02E+03	1,18E+03	0,00E+00	8,39E+02	9,39E+02	4,40E+02	8,19E+02	1,20E+02
6	Torfufell-1	1,28E+03	1,28E+03	1,20E+03	1,06E+03	0,00E+00	6,00E+02	8,80E+02	2,40E+02	9,00E+02	1,80E+02
7	Torfufell-2	1,52E+03	1,28E+03	1,30E+03	1,20E+03	0,00E+00	7,19E+02	5,19E+02	4,79E+02	7,99E+02	9,99E+01
8	Torfufell-3	1,44E+03	1,34E+03	1,18E+03	1,30E+03	0,00E+00	6,79E+02	6,99E+02	5,19E+02	9,59E+02	1,60E+02
9	Torfufell-4	1,32E+03	1,24E+03	1,26E+03	1,28E+03	0,00E+00	6,79E+02	7,59E+02	2,00E+02	9,19E+02	1,20E+02
10	Torfufell-5	1,40E+03	1,26E+03	9,78E+02	1,24E+03	0,00E+00	5,79E+02	7,39E+02	3,59E+02	7,99E+02	1,60E+02
11	Torfufell-6	1,36E+03	1,26E+03	1,14E+03	1,18E+03	0,00E+00	6,79E+02	7,79E+02	4,39E+02	7,99E+02	1,60E+02
12	Torfufell-7	1,52E+03	9,99E+02	1,28E+03	1,38E+03	0,00E+00	6,99E+02	6,19E+02	3,99E+02	7,99E+02	1,80E+02
13	Torfufell-8	1,48E+03	1,12E+03	9,98E+02	1,30E+03	0,00E+00	6,59E+02	7,39E+02	3,20E+02	7,79E+02	7,99E+01
14	Torfufell-9	1,36E+03	1,28E+03	9,98E+02	1,12E+03	0,00E+00	7,59E+02	6,99E+02	3,19E+02	7,99E+02	1,80E+02
15	Torfufell-10	1,08E+03	1,04E+03	1,22E+03	1,16E+03	0,00E+00	6,99E+02	7,99E+02	3,59E+02	8,19E+02	1,60E+02
16	ATHO-6	5,99E+02	9,98E+01	2,40E+02	2,40E+02	0,00E+00	1,80E+02	5,99E+01	1,20E+02	1,60E+02	3,99E+01
17	ATHO-7	2,79E+02	9,98E+01	2,00E+02	1,40E+02	0,00E+00	1,60E+02	1,40E+02	1,60E+02	9,98E+01	3,99E+01
Minimum		2,79E+02	9,98E+01	2,00E+02	1,40E+02	0,00E+00	1,60E+02	5,99E+01	1,20E+02	9,98E+01	3,99E+01
Maximum		1,72E+03	1,34E+03	1,30E+03	1,38E+03	0,00E+00	8,39E+02	9,39E+02	5,19E+02	9,59E+02	1,80E+02
Average		1,31E+03	1,06E+03	1,04E+03	1,09E+03	0,00E+00	6,16E+02	6,63E+02	3,34E+02	7,51E+02	1,29E+02
Sigma		3,66E+02	3,81E+02	3,26E+02	3,53E+02	0,00E+00	1,79E+02	2,32E+02	1,10E+02	2,40E+02	4,64E+01

Table S2.2. Continued.

Point	Comment	Si(BG+)	Ti(BG+)	Al(BG+)	Fe(BG+)	Mn(BG+)	Mg(BG+)	Ca(BG+)	Na(BG+)	K(BG+)	P(BG+)
1	ATHO pt1	1.36E+03	1.02E+03	1.02E+03	8.99E+02	9.59E+02	6.20E+02	6.40E+02	1.60E+02	7.59E+02	1.40E+02
2	ATHO pt2	1.56E+03	1.08E+03	9.39E+02	1.02E+03	8.80E+02	5.00E+02	7.60E+02	4.40E+02	5.40E+02	1.20E+02
3	ATHO pt3	1.64E+03	9.60E+02	1.02E+03	1.02E+03	9.00E+02	6.00E+02	6.20E+02	4.00E+02	6.40E+02	1.20E+02
4	ATHO pt4	1.48E+03	1.02E+03	1.06E+03	1.16E+03	8.19E+02	5.00E+02	7.39E+02	3.60E+02	8.59E+02	1.20E+02
5	ATHO pt5	1.56E+03	9.59E+02	1.06E+03	1.02E+03	8.99E+02	4.60E+02	7.79E+02	2.40E+02	9.99E+02	1.20E+02
6	Torfufell-1	1.20E+03	1.18E+03	1.14E+03	1.02E+03	8.20E+02	4.60E+02	6.00E+02	1.60E+02	9.99E+02	1.20E+02
7	Torfufell-2	1.48E+03	9.99E+02	1.04E+03	9.39E+02	8.39E+02	6.19E+02	6.59E+02	1.20E+02	7.79E+02	1.60E+02
8	Torfufell-3	1.04E+03	1.08E+03	7.79E+02	1.14E+03	8.39E+02	4.79E+02	6.99E+02	4.40E+02	6.59E+02	1.20E+02
9	Torfufell-4	9.99E+02	1.12E+03	9.59E+02	1.04E+03	7.19E+02	5.79E+02	6.19E+02	5.19E+02	7.79E+02	9.99E+01
10	Torfufell-5	1.56E+03	1.12E+03	1.08E+03	9.59E+02	8.79E+02	4.79E+02	6.59E+02	4.39E+02	6.99E+02	1.20E+02
11	Torfufell-6	1.44E+03	9.79E+02	9.79E+02	1.20E+03	9.39E+02	4.79E+02	7.39E+02	2.40E+02	6.79E+02	2.00E+02
12	Torfufell-7	1.28E+03	9.39E+02	6.99E+02	1.10E+03	8.39E+02	4.79E+02	5.39E+02	4.79E+02	6.99E+02	1.40E+02
13	Torfufell-8	1.44E+03	9.98E+02	9.98E+02	1.18E+03	8.99E+02	5.39E+02	7.39E+02	2.00E+02	7.19E+02	1.20E+02
14	Torfufell-9	1.92E+03	9.58E+02	9.38E+02	9.78E+02	7.79E+02	4.79E+02	7.59E+02	3.19E+02	6.99E+02	1.80E+02
15	Torfufell-10	1.36E+03	1.10E+03	8.39E+02	1.04E+03	9.78E+02	4.79E+02	8.19E+02	2.40E+02	6.19E+02	2.00E+02
16	ATHO-6	3.19E+02	7.98E+01	1.40E+02	2.00E+02	2.00E+02	1.80E+02	1.40E+02	7.98E+01	1.20E+02	9.98E+01
17	ATHO-7	3.99E+02	1.40E+02	2.00E+02	1.80E+02	2.20E+02	1.40E+02	5.99E+01	7.98E+01	7.98E+01	3.99E+01
Minimum		3.19E+02	7.98E+01	1.40E+02	1.80E+02	2.00E+02	1.40E+02	5.99E+01	7.98E+01	7.98E+01	3.99E+01
Maximum		1.92E+03	1.18E+03	1.14E+03	1.20E+03	9.78E+02	6.20E+02	8.19E+02	5.19E+02	9.99E+02	2.00E+02
Average		1.29E+03	9.25E+02	8.76E+02	9.46E+02	7.89E+02	4.75E+02	6.22E+02	2.89E+02	6.66E+02	1.30E+02
Sigma		4.14E+02	3.15E+02	2.88E+02	2.97E+02	2.27E+02	1.31E+02	2.10E+02	1.46E+02	2.45E+02	3.87E+01

Table S2.2. Continued.

Point	Comment	Si(L-value)	Ti(L-value)	Al(L-value)	Fe(L-value)	Mn(L-value)	Mg(L-value)	Ca(L-value)	Na(L-value)	K(L-value)	P(L-value)	Current
1	ATHO pt1	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.00E+00
2	ATHO pt2	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.00E+00
3	ATHO pt3	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.00E+00
4	ATHO pt4	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.00E+00
5	ATHO pt5	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.00E+00
6	Torfufell-1	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.00E+00
7	Torfufell-2	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
8	Torfufell-3	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
9	Torfufell-4	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
10	Torfufell-5	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
11	Torfufell-6	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
12	Torfufell-7	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
13	Torfufell-8	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
14	Torfufell-9	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
15	Torfufell-10	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
16	ATHO-6	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
17	ATHO-7	7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
Minimum		7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.00E+00
Maximum		7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
Average		7.73E+01	8.82E+01	9.06E+01	1.35E+02	1.46E+02	1.08E+02	1.08E+02	1.30E+02	1.20E+02	1.97E+02	5.01E+00
Sigma		5.00E-03	0.00E+00	7.00E-03	4.00E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.60E-02	0.00E+00	0.00E+00

Table S2.2. Continued.

Point	Comment	Si (Error%)	Ti (Error%)	Al (Error%)	Fe (Error%)	Mn (Error%)	Mg (Error%)	Ca (Error%)	Na (Error%)	K (Error%)	P (Error%)	Total (Error%)
1	ATHO pt1	0.400	11.22	0.86	1.71	18.33	15.21	2.74	3.38	1.19	37.59	92.63
2	ATHO pt2	0.400	10.53	0.84	1.71	17.84	11.37	2.75	3.39	1.17	86.69	136.69
3	ATHO pt3	0.410	13.84	0.85	1.75	25.00	15.74	2.70	3.36	1.18	51.78	116.61
4	ATHO pt4	0.400	14.34	0.83	1.77	15.33	12.75	2.73	3.41	1.19	78.07	130.82
5	ATHO pt5	0.410	9.41	0.83	1.74	15.09	16.11	2.78	3.37	1.20	57.38	108.32
6	Torfufell-1	0.400	19.36	0.84	2.29	20.13	82.24	4.25	3.35	1.05	100.00	233.91
7	Torfufell-2	0.400	16.00	0.84	2.30	19.72	100.00	4.20	3.44	1.04	132.05	279.99
8	Torfufell-3	0.400	19.16	0.84	2.28	20.54	59.61	4.30	3.36	1.03	100.00	211.52
9	Torfufell-4	0.400	23.05	0.84	2.30	15.50	107.58	4.46	3.43	1.05	869.87	1028.48
10	Torfufell-5	0.400	21.44	0.84	2.34	26.45	61.70	4.31	3.30	1.05	100.00	221.83
11	Torfufell-6	0.400	15.83	0.84	2.35	26.72	99.68	4.42	3.34	1.03	100.00	254.61
12	Torfufell-7	0.400	16.37	0.83	2.33	24.91	77.15	4.36	3.38	1.06	100.00	230.79
13	Torfufell-8	0.400	15.56	0.83	2.38	19.37	100.00	4.35	3.37	1.04	59.58	206.88
14	Torfufell-9	0.400	21.16	0.83	2.29	14.22	129.16	4.45	3.46	1.04	100.00	277.01
15	Torfufell-10	0.400	17.65	0.84	2.32	29.56	453.98	4.95	3.31	1.04	100.00	614.05
16	ATHO-6	8.750	57.50	10.59	100.00	100.00	93.64	100.00	31.14	100.00	73.49	675.11
17	ATHO-7	9.030	100.00	11.02	97.09	100.00	119.97	556.78	40.44	72.86	69.80	1176.99
Minimum		0.400	9.41	0.83	1.71	14.22	11.37	2.70	3.30	1.03	37.59	92.63
Maximum		9.030	100.00	11.02	100.00	100.00	453.98	556.78	40.44	100.00	869.87	1176.99
Average		1.400	23.67	2.01	13.47	29.92	91.52	42.03	7.19	11.13	130.37	352.72
Sigma		2.820	22.38	3.31	32.03	26.76	101.91	134.68	10.89	28.74	192.03	325.51

Table S2.3. ICP-OES whole-rock geochemical analysis (wt%) of rock samples from the study area; major elements and selected trace elements (samples are arranged in order of position in the strata pile; from lowermost (top of table) to uppermost). CV=central volcano.

Sample Id.	Lat	Long	Type	Comment	Group	U-Pb zircon age (Ma)*	SiO ₂ Wt. %	Al ₂ O ₃ Wt. %	FeO Wt. %
20072017-2	65.41463	-18.1661	Basalt	Lava, porphyritic	Plateau (below CV)		49.30	15.31	11.23
14072015-12	65.4004	-18.257	Basalt	Lava, porphyritic	Plateau (below CV)		48.92	15.57	10.88
24072017-0	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)	CV		49.75	13.02	14.16
24072017-1	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)	CV		50.22	12.98	13.60
24072017-2	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)	CV		50.69	12.95	13.65
24072017-3	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)	CV		50.08	13.15	13.68
20180903-1	65.32288	-18.3354	Basalt	Lava (ā'a; unusually thin)	CV		51.70	12.63	14.12
20180903-3	65.32288	-18.3354	Basalt	Lava (pahoehoe; unusually thin)	CV		48.24	13.01	15.03
27072017-2	65.29289	-18.2687	Basaltic andesite	Lava	CV		56.04	13.59	11.33
01092016-1	65.3063	-18.3366	Andesite	Lava	CV		61.91	13.69	11.25
20180904-1	65.28958	-18.2321	Andesite	Lava	CV		59.76	14.29	11.01
09072015-8	65.31684	-18.2883	Andesite	Lava	CV		59.83	14.11	11.36
27072017-1	65.29289	-18.2687	Dacite	Lava	CV	7.03±0.15	65.63	14.24	7.70
18072017-3b	65.28641	-18.2694	Dacite	Pyroclastic	CV		64.35	14.43	9.16
18072017-3a	65.28641	-18.2694	Rhyolite	Pyroclastic	CV		74.95	12.95	2.63
07072015-2	65.32421	-18.2775	Rhyolite	Intrusion (sill)	CV	7.002±0.064	74.71	13.66	2.01
24072017-4	65.32193	-18.3357	Rhyolite	Feeder (interiors of a conduit)	CV	7.015±0.048	75.38	13.23	1.91
26082015-25	65.27755	-18.2601	Rhyolite	Pyroclastic	CV	7.15±0.12	72.46	13.70	4.31
10082018-1	65.27755	-18.2601	Dacite	Pyroclastic (pumice)	CV		71.24	13.54	4.51
14072017-1	65.30108	-18.2337	Rhyolite	Lava	CV		75.80	13.39	1.54
20180904-2	65.289	-18.2233	Basalt	Lava (thick pahoehoe lobe)	CV		46.78	14.58	15.25
14072017-2	65.30281	-18.2246	Rhyolite	Lava	CV		75.72	12.87	1.94
27072017-5	65.2862	-18.2783	Basalt	Lava (between rhyolite lavas)	CV		46.42	14.72	13.54
10072017-3	65.28886	-18.2186	Rhyolite	Lava	CV	6.85±0.091	74.68	13.74	1.95
20180904-3	65.28956	18.21921	Rhyolite	Pyroclastic (obsidian)	CV		76.04	12.47	2.07
13072017-1	65.32597	-18.3532	Rhyolite	Lava	CV		76.29	12.83	1.71
27072017-3	65.28667	-18.2815	Rhyolite	Lava	CV		75.60	13.16	2.01
03072018-3	65.31565	-18.2145	Basalt	Lava	CV (just above the rhyolite lavas)		50.12	13.24	14.20
27072017-4	65.28564	-18.2841	Basalt	Lava	CV (just above the rhyolite lavas)		49.54	13.30	14.54
10072017-4	65.28817	-18.2131	Basalt	Lava, porphyritic	Plateau (overlying)		47.88	17.67	10.17
25072018-1	65.38694	-18.2113	Basalt	Intrusion (feeder), porphyritic	Dyke (overlying)		47.46	17.68	9.73
18072017-1	65.2544	-18.2466	Basalt	Lava, porphyritic	Plateau (overlying)		48.54	15.31	11.55

Table S2.3. Continued.

Sample Id.	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
20072017-2	0.18	6.40	12.05	2.58	0.30	2.30	0.21
14072015-12	0.20	6.61	12.54	2.42	0.25	2.24	0.23
24072017-0	0.23	5.29	10.22	2.69	0.46	3.60	0.42
24072017-1	0.24	5.63	10.14	2.65	0.59	3.39	0.39
24072017-2	0.23	5.49	10.07	2.58	0.48	3.31	0.39
24072017-3	0.25	5.46	10.14	2.65	0.54	3.46	0.40
20180903-1	0.25	4.27	8.61	3.01	0.84	3.84	0.58
20180903-3	0.27	5.50	10.48	2.78	0.20	3.85	0.47
27072017-2	0.20	3.41	7.31	3.58	1.07	2.93	0.40
01092016-1	0.28	0.66	5.07	3.99	1.61	1.05	0.33
20180904-1	0.24	1.65	5.45	4.01	1.54	1.35	0.57
09072015-8	0.27	1.44	5.48	3.95	1.51	1.35	0.56
27072017-1	0.21	0.47	4.29	4.23	2.08	0.76	0.21
18072017-3b	0.09	0.44	3.97	4.36	1.73	1.00	0.28
18072017-3a	0.14	0.12	1.21	4.43	3.16	0.23	0.02
07072015-2	0.06	0.01	0.64	4.98	3.59	0.17	0.00
24072017-4	0.02	0.07	0.56	5.06	3.43	0.18	0.00
26082015-25	0.11	0.24	2.01	4.65	2.00	0.32	0.03
10082018-1	0.13	0.14	2.31	4.22	3.38	0.31	0.02
14072017-1	0.04	0.03	0.77	4.74	3.37	0.16	0.00
20180904-2	0.24	6.96	9.44	2.43	0.35	3.45	0.36
14072017-2	0.05	0.02	0.76	4.85	3.44	0.15	0.01
27072017-5	0.22	7.67	11.03	2.20	0.27	3.38	0.38
10072017-3	0.02	0.10	0.49	5.09	3.58	0.16	0.02
20180904-3	0.07	0.00	0.73	4.92	3.38	0.15	0.00
13072017-1	0.02	0.06	0.48	4.88	3.42	0.16	0.01
27072017-3	0.02	0.08	0.52	4.86	3.39	0.16	0.02
03072018-3	0.25	5.28	9.59	2.88	0.62	3.30	0.38
27072017-4	0.25	5.24	9.87	2.88	0.41	3.43	0.37
10072017-4	0.17	6.59	13.55	2.01	0.11	1.60	0.13
25072018-1	0.16	6.63	14.14	2.09	0.19	1.66	0.12
18072017-1	0.20	7.17	12.12	2.37	0.24	2.16	0.20

Table S2.3. Continued.

Sample Id.	Ba ppm	Co ppm	Cr ppm	Cu ppm	Ni ppm	Sc ppm	Sr ppm	V ppm	Y ppm	Zn ppm	Zr ppm	Σ Norm %	Σ Run %
20072017-2	72.39	58.80	46.69	138.33	66.31	38.07	287.02	311.66	27.25	107.57	131.04	100	96.1
14072015-12	67.37	56.89	137.99	130.65	69.91	39.91	289.76	309.38	26.94	106.87	132.42	100	95.5
24072017-0	95.53	70.66	40.54	113.27	50.17	43.06	267.32	437.34	50.85	137.68	254.18	100	98.0
24072017-1	112.15	68.88	45.49	124.70	44.50	41.78	261.36	414.97	48.32	132.06	242.43	100	100.3
24072017-2	110.90	67.74	44.48	107.57	47.50	41.43	259.93	420.84	47.82	134.11	232.31	100	97.1
24072017-3	326.83	68.27	40.66	156.13	42.45	41.83	264.88	408.14	52.73	138.78	247.26	100	97.2
20180903-1	179.72	64.28	7.78	28.61	8.78	37.48	282.87	325.79	67.60	148.18	330.17	100	101.7
20180903-3	78.75	76.43	27.35	194.91	44.21	45.23	278.80	440.16	53.55	181.97	258.70	100	99.0
27072017-2	232.80	48.43	4.20	39.46	3.52	29.92	236.04	239.50	60.69	124.60	287.37	100	97.0
01092016-1	313.50	11.38	4.19	24.63	5.03	39.86	212.80	4.49	93.39	159.52	606.15	100	94.6
20180904-1	287.95	19.43	3.39	22.49	4.95	30.04	218.25	3.31	85.64	150.16	415.60	100	99.7
09072015-8	286.52	19.24	4.19	31.08	2.77	31.25	224.54	2.29	92.59	157.06	455.61	100	94.3
27072017-1	351.15	7.39	4.49	22.66	5.06	29.20	191.41	5.15	83.76	133.51	713.73	100	98.4
18072017-3b	341.61	10.34	5.24	21.74	4.62	33.49	214.67	7.87	93.54	180.30	713.30	100	94.9
18072017-3a	575.44	1.29	5.28	25.24	15.16	6.35	101.06	10.49	78.05	80.94	377.12	100	94.8
07072015-2	633.07	0.42	5.54	17.28	6.43	1.19	80.00	7.21	124.83	142.42	387.38	100	92.1
24072017-4	603.53	0.48	5.28	21.27	8.27	1.48	73.67	15.75	55.24	125.42	381.36	100	98.5
26082015-25	476.12	1.30	4.05	16.16	3.55	7.44	144.60	8.78	115.31	132.47	594.91	100	97.3
10082018-1	498.08	1.13	3.97	16.35	4.71	7.69	144.37	6.23	127.52	139.71	640.67	100	93.6
14072017-1	605.47	0.30	3.48	36.61	37.93	0.62	87.83	6.67	54.33	132.77	353.35	100	96.0
20180904-2	82.16	80.02	64.98	207.09	99.92	38.26	213.25	486.16	43.96	147.39	190.93	100	95.1
14072017-2	621.91	0.11	4.49	14.46	5.19	0.77	90.27	10.27	113.92	138.58	379.74	100	89.3
27072017-5	77.21	75.53	178.43	150.72	138.95	43.68	277.22	386.54	38.13	128.90	176.52	100	95.8
10072017-3	638.86	0.72	6.60	21.06	6.54	1.38	68.45	18.42	112.21	136.41	367.47	100	93.1
20180904-3	598.27	0.18	4.56	15.87	4.35	0.95	63.08	4.52	138.54	141.40	392.99	100	101.6
13072017-1	606.78	0.00	4.88	16.05	4.28	1.30	74.70	12.56	58.71	128.40	377.15	100	92.7
27072017-3	599.02	0.00	5.98	16.04	4.92	1.36	74.21	17.43	95.95	128.89	375.15	100	98.6
03072018-3	128.62	67.15	43.98	93.15	36.32	41.50	209.43	435.00	56.56	137.63	236.89	100	96.5
27072017-4	182.10	68.48	37.77	113.97	36.31	41.68	213.47	457.46	54.25	135.66	237.04	100	99.7
10072017-4	35.31	52.56	171.02	164.85	142.67	42.54	196.98	286.48	22.88	89.95	84.39	100	95.5
25072018-1	38.68	50.87	209.76	142.26	73.71	43.61	195.70	313.56	20.50	87.14	76.19	100	98.9
18072017-1	70.96	58.29	111.80	97.38	89.35	41.85	220.02	322.16	27.58	99.13	123.22	100	102.1

*Árnadóttir et al. (2023)

Table S2.3. Continued.

Standards	SiO2 Wt. %	Al2O3 Wt. %	FeO Wt. %	MnO Wt. %	MgO Wt. %	CaO Wt. %	Na2O Wt. %	K2O Wt. %	TiO2 Wt. %	P2O5 Wt. %
A-THO	74.33	12.57	3.36	0.11	0.07	1.68	4.66	2.76	0.25	0.02
B-THO	47.61	15.43	10.16	0.17	10.20	13.53	1.75	0.01	0.98	0.02
B-ALK	47.47	13.01	14.72	0.23	5.13	10.32	3.07	0.74	4.59	0.54
B-ALK	47.93	12.75	14.62	0.22	5.24	10.21	3.04	0.73	4.55	0.54
RGM-1	72.74	14.86	1.69	0.04	0.27	1.20	4.36	4.36	0.28	0.04
RGM-1	73.09	14.61	1.69	0.04	0.27	1.18	4.25	4.38	0.28	0.04
RGM-1	73.29	14.38	1.70	0.04	0.28	1.17	4.26	4.38	0.29	0.04
K1919	50.08	13.72	10.88	0.17	7.14	11.77	2.36	0.53	2.89	0.28
K1919	50.08	13.62	10.89	0.17	7.17	11.90	2.40	0.53	2.80	0.28
K1919	50.41	13.78	10.91	0.17	6.89	11.73	2.38	0.54	2.75	0.28

Table S2.3. Continued.

Standards	Ba	Co	Cr	Cu	Ni	Sc Wt. %	Sr	V	Y	Zn	Zr	Σ Norm %	Σ Run %
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	%	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	%	%
A-THO	583.93	1.60	3.72	21.51	2.00	4.80	98.00	6.35	108.35	124.72	514.28	100	98.9
B-THO	6.39	55.11	407.00	118.00	191.70	45.62	107.08	310.70	12.58	82.76	19.55	100	98.6
B-ALK	181.19	79.85	15.06	40.43	27.86	32.43	409.48	432.30	36.84	138.17	229.72	100	101.0
B-ALK	180.58	79.53	15.44	40.40	27.73	32.32	407.81	423.20	36.18	134.44	228.07	100	101.1
RGM-1	858.92	2.63	5.07	21.72	11.28	4.34	106.11	14.55	21.65	50.17	220.91	100	98.3
RGM-1	870.25	2.68	4.93	21.62	12.92	4.30	106.78	14.14	20.65	49.21	221.26	100	98.2
RGM-1	874.52	2.89	4.89	21.55	12.55	4.35	107.18	14.85	21.16	48.47	221.38	100	100.8
K1919	132.92	65.03	205.05	130.69	100.83	33.02	384.58	309.81	24.75	102.00	166.72	100	100.2
K1919	133.29	63.44	203.00	129.33	97.27	32.30	382.31	302.18	24.54	102.84	167.70	100	101.6
K1919	135.11	63.55	205.07	130.73	100.12	32.68	385.51	303.56	24.53	102.46	170.56	100	101.2

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AS3 Supplementary material of Paper III

Supplementary Text and Figures

U-Pb zircon age and chronology of the Torfufell central volcano: implication for timing of rift relocation in North Iceland

Bulletin of Volcanology

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Text S1: Details of analytical methods

SIMS (secondary ion mass spectrometry)

U-Pb zircon dating of zircons from host samples 20172017-1, 26082015-25, 07072015-2, 24072017-4 and 10072017-3 was carried out using the CAMECA ims 1280 in the NordSIMS facility, Swedish Museum of Natural History, Stockholm. The analytical and calibration procedures generally followed those described in Whitehouse and Kamber (2005) and Jeon and Whitehouse (2015), with a few differences noted here. A defocused O₂-primary beam generated by a Hyperion H201 RF Plasma source was used to project the image of a 200 µm aperture onto the sample, generating elliptical, flat-bottomed craters of nominal ca. 20 µm. Complete U–Th–Pb analyses at a mass resolution (M/ΔM) of ca. 5400 were performed using a peak switching routine, with a single ion-counting electron multiplier (EM) as the detection device. An energy window of 45 eV was used throughout, with energy adjustments made using the ²³⁸U¹⁶O peak. Pb/U ratios, elemental concentrations and Th/U ratios were calibrated relative to the Geostandards zircon 91500 reference, which has an age of 1065 Ma (Wiedenbeck et al., 1995). The 4.4 Ma (Li et al., 2010) Penglai zircon was also analysed as unknowns to monitor the accuracy of the Pb/U calibration. Individual ages in the data table (Table S3) were calculated using simple basic decay equations. Isoplot (vers. 4.15, Ludwig, 2012) was used to make the plots and regressions.

CA-TIMS (chemical abrasion – isotope dilution thermal ionization mass spectrometry)

Sample 20190823-3 was dated by Dr. Corey Wall at PCIGR, UBC by chemical abrasion - isotope dilution thermal ionization mass spectrometry (CA-TIMS) method. The sample was prepared at PCIGR, including zircon separation and catholuminescence (CL) scanning electron microscope (SEM) imaging. Following is Dr. Wall's Report of Investigation, detailing the pre-treatment and analytical method:

An abundant population of relatively large, (approximately 100-150 micron in long dimension), elongate, prismatic zircon crystals was separated from a hand sample by conventional density and magnetic methods. The entire zircon separate was placed in a muffle furnace at 900°C for 60 hours in quartz beakers to anneal minor radiation damage; annealing enhances cathodoluminescence (CL) emission (Nasdala et al., 2002), promotes more reproducible interelement fractionation during laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) (Allen and Campbell, 2012), and prepares the crystals for subsequent chemical abrasion (Mattinson, 2005). Following annealing, individual grains from all samples were hand-picked based on morphology, clarity, and the absence of inclusions.

Mounted grains of zircon were imaged for internal structure at the Electron Microbeam/X-Ray Diffraction Facility (EMXDF) at UBC, Vancouver, using a Philips XI-30 scanning electron microscope (SEM). Zircon grains were imaged using a Robinson cathodoluminescence (CL) detector, using a Bruker Quanta 200 energy-dispersion X-ray microanalysis system with XFlash 6010 SDD detector at a voltage of 15 kV. Trace element concentrations were determined in zircon by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at UBC using a Resonetics (now ASI) RESOLUTION M-50-LR Class I laser ablation system coupled to an Agilent 7700x quadrupole ICP-MS. Ablations were carried out with the 193nm excimer laser, using a beam energy of 100 mJ and a pit diameter of 34 µm, with a pulse rate of 5 Hz for a duration of 30 seconds followed by 20 seconds of gas blank. Spots were chosen based on grain-scale variations observed in CL images and grain size, with typically two analyses per grain. For zircon, measurements were conducted on the masses ⁷Li, ²⁹Si, ³¹P, ⁴⁵Sc, ⁴⁹Ti, ⁸⁹Y, ⁹¹Zr, ⁹³Nb, ¹³⁹La, ¹⁴⁰Ce, ¹⁴¹Pr, ¹⁴⁶Nd, ¹⁴⁷Sm, ¹⁵³Eu, ¹⁵⁷Gd, ¹⁵⁹Tb, ¹⁶³Dy, ¹⁶⁵Ho, ¹⁶⁶Er, ¹⁶⁹Tm, ¹⁷²Yb, ¹⁷⁵Lu, ¹⁷⁷Hf, ¹⁸⁸Ta, ²⁰²Hg (as a monitor for Pb), Pb (²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb), ²³²Th, and U (²³⁵U and ²³⁸U); these masses were chosen based on high relative isotopic abundances and the absence of interferences. Sample-standard bracketing was carried out with spot analyses of synthetic glasses NIST 612 and NIST 610 between zircon analyses and the natural zircon reference materials

91500, Plesovice (PL), and Temora2 (TEM) were also analyzed. Data were reduced using Iolite 4 software running within the Igor Pro environment using the Trace Elements IS data reduction scheme (Paton et al., 2011). For zircon, NIST 612 was used as the standard and the average Zr contents (by sample) determined by EPMA were employed as an internal standard value for the unknowns. All concentrations are reported in ppm with uncertainties of 2 standard deviation. U-Pb geochronology methods for isotope dilution thermal ionization mass spectrometry follow those previously published by Wall et al. (2018). Zircon crystals were subjected to a modified version of the chemical abrasion method of Mattinson (2005), whereby single crystal fragments plucked from grain mounts were individually abraded in a single step with concentrated HF at 190°C for 12 hours. All analyses were undertaken on crystals previously mounted, polished and imaged by CL, and selected on the basis of zoning patterns. Zircon was put into 3 mL Teflon PFA beakers and loaded into 300 µL Teflon PFA microcapsules. Fifteen microcapsules were placed in a large-capacity Parr vessel and the zircon partially dissolved in 120 µL of 29 M HF for 12 hours at 190°C. Zircon was returned to 3 mL Teflon PFA beakers, the HF was removed, and the zircon was immersed in 3.5 M HNO₃, ultrasonically cleaned for an hour, and fluxed on a hotplate at 80°C for an hour. The HNO₃ was removed, and zircon was rinsed twice in ultrapure H₂O before being reloaded into the 300 µL Teflon PFA microcapsules and spiked with the EARTHTIME mixed ²³³U-²³⁵U-²⁰⁵Pb tracer solution (ET535). Zircon as dissolved in Parr vessels in 120 µL of 29 M HF with a trace of 3.5 M HNO₃ at 220°C for 48 hours, dried to fluorides, and re-dissolved in 6 M HCl at 180°C overnight. U and Pb were separated from the zircon matrix using HCl-based anion-exchange chromatographic procedure (Krogh, 1973), eluted together and dried with 2 µL of 0.05 N H₃PO₄.

The U-Pb aliquots were loaded in a silica gel emitter (Gerstenberger and Haase, 1997) to outgassed, zone-refined Re filaments. Isotopic determinations were performed using a Nu Instruments TIMS. A correction for mass-dependent Pb fractionation was applied based on repeated measurements of NBS 982 (Catanzaro et al., 1968) Pb on both the Daly ion counter [$0.16 (\pm 0.03\%) \text{ amu}^{-1}; 1 \text{ s}$] and the Faraday cups [$0.10 \times (1 \pm 0.02\%) \text{ amu}^{-1}; 1 \text{ s}$]. Uranium was run as an oxide (UO₂) and measured in static mode on Faraday detectors equipped with 1012 Ω resistors. The U mass fractionation for the same analyses was calculated using the ²³³U/²³⁵U ratio of the double spike solution ($0.99506\% \pm 0.01\%$, 1 s).

U-Pb dates and uncertainties for each analysis were calculated using the algorithms of Schmitz and Schoene (2007) and the U decay constants of Jaffey et al. (1971). Uncertainties are based upon non-systematic analytical errors, including counting statistics, instrumental fractionation, tracer subtraction, and blank subtraction. These error estimates should be considered when comparing our ²⁰⁷Pb/²⁰⁶U dates with those from other laboratories that used tracer solutions calibrated against the EARTHTIME gravimetric standards. When comparing our dates with those derived from other decay schemes (e.g., ⁴⁰Ar/³⁹Ar, ¹⁸⁷Re-¹⁸⁷Os), the uncertainties in tracer calibration (0.03%; Condon et al., 2015; McLean et al., 2015) and U decay constants (0.108%; Jaffey et al., 1971) should be added to the internal error in quadrature. Quoted errors for calculated weighted means are thus of the form $\pm X [Z]$, where X is solely analytical uncertainty and Z is the combined analytical and ²³⁸U and ²³⁵U decay constant uncertainties. Six zircon grains were selected for CA-TIMS analysis on the basis of LA-ICPMS results in combination with the prismatic morphology and the absence of inclusions, avoiding those crystals with rounded edges. Chemical abrasion in concentrated HF at 190° for 12 hours resulted in only minor dissolution of the zircon crystals. All six analyses are concordant and equivalent, with a weighted mean ²⁰⁶Pb/²³⁸U date of $6.757 \pm 0.015(0.02)[0.02] \text{ Ma}$ (MSWD = 0.98), which is interpreted as dating the eruption and depositional age of this rhyolite.

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Figure S1

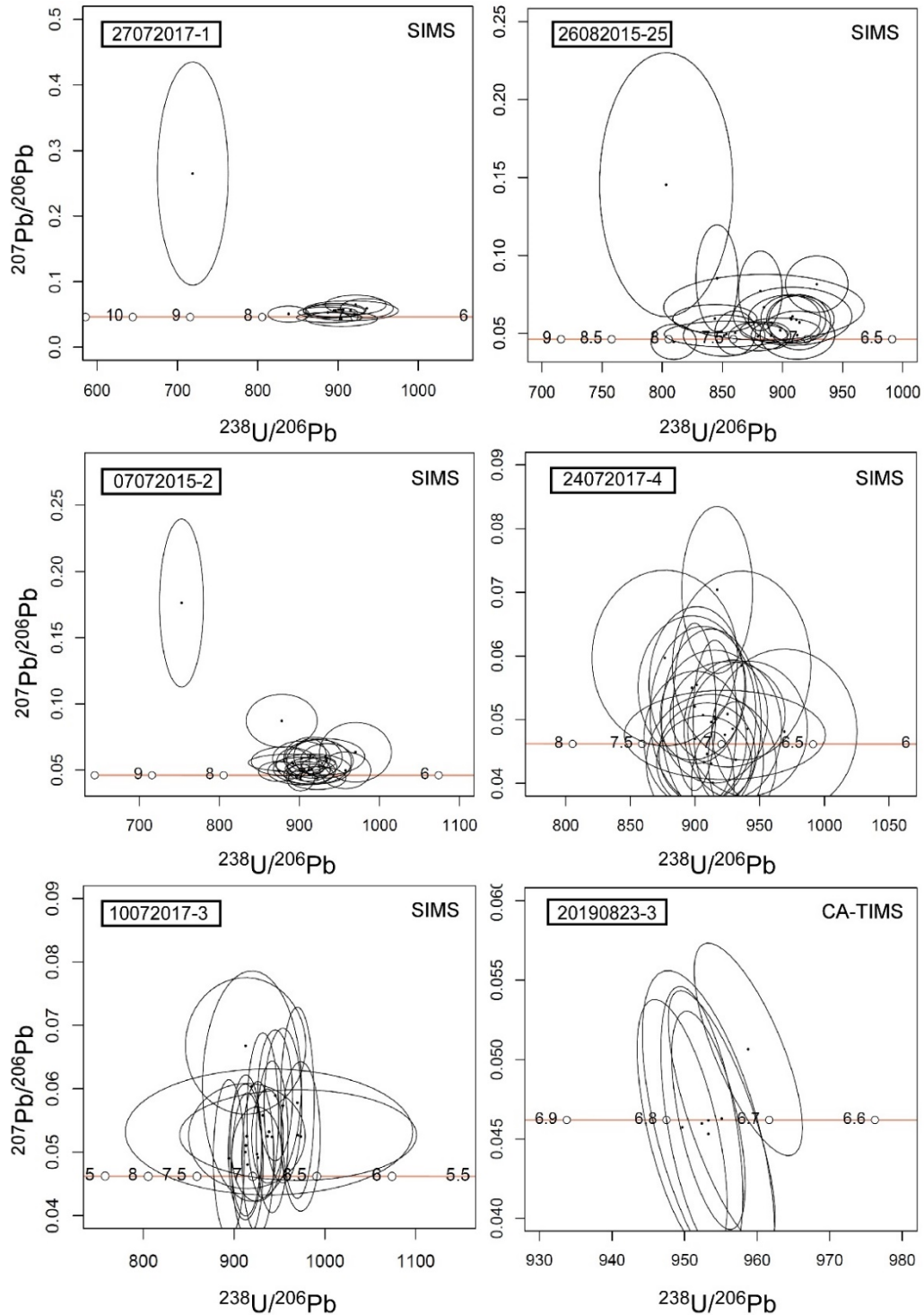


Figure S1 - Tera-Wasserburg Concordia diagrams of the six dated samples, plotted by IsoplotR (Vermeesch, 2018). Diagrams of the SIMS data use the common Pb uncorrected data; diagrams of the CA-TIMS data use radiogenic isotopic ratios corrected from fractionation, spike and common Pb. Data-point error ellipses are 2σ .

Reference:

Vermeesch, P., 2018, IsoplotR: a free and open toolbox for geochronology: *Geoscience Frontiers*, v. 9, p. 1479-1493, <https://doi.org/10.1016/j.gsf.2018.04.001>.

Figure S2

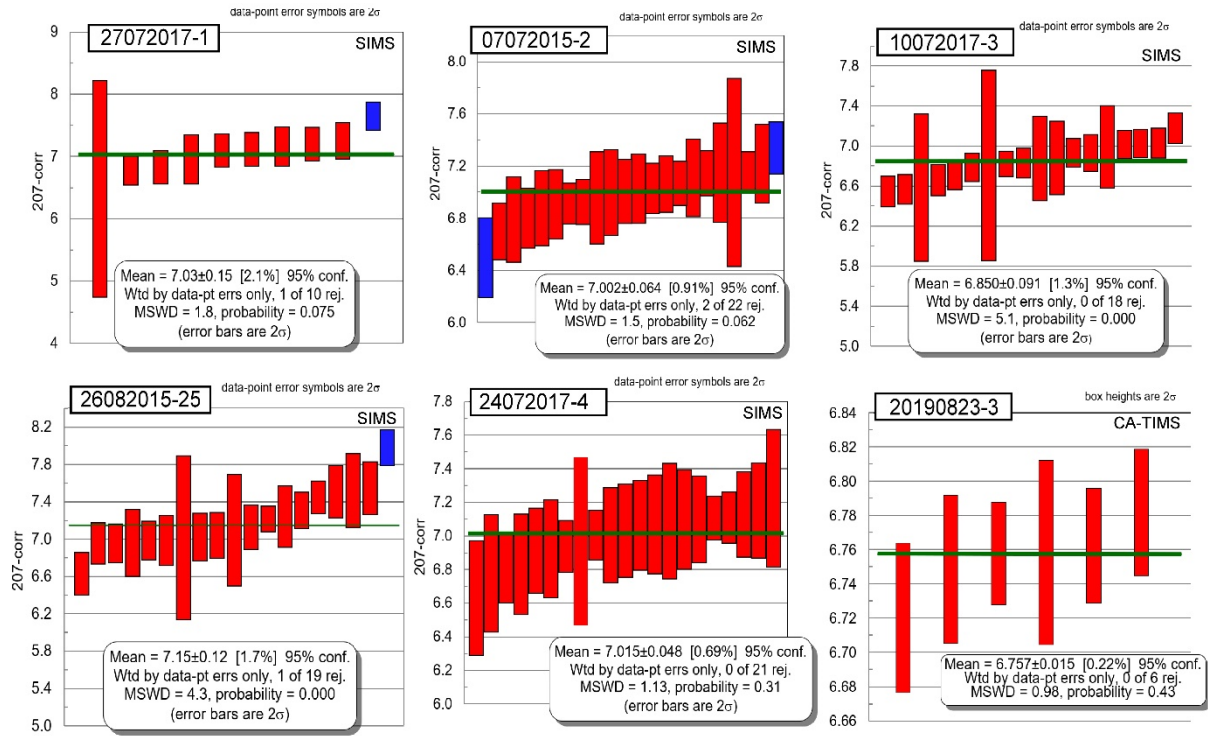


Figure S2 - Weighted average U-Pb ages for the six dated samples, detailed. Blue bars represent ages rejected to get statistically meaningful MSWD and probability. Note the high MSWD's of 26082015-25 and 10072017-3; the weighted averages of these two samples also have zero probabilities, meaning that its data are scattered too much to get a statistically grouped age. The probability density plots for these two samples show more than one peak (see Figure S3). The Y-axes represent 207-corrected $^{206}\text{Pb}/^{238}\text{U}$ dates. SIMS data: individual ages calculated using simple basic decay equations; weighted averages and MSWDs used Isoplot (Ludwig).

Figure S3

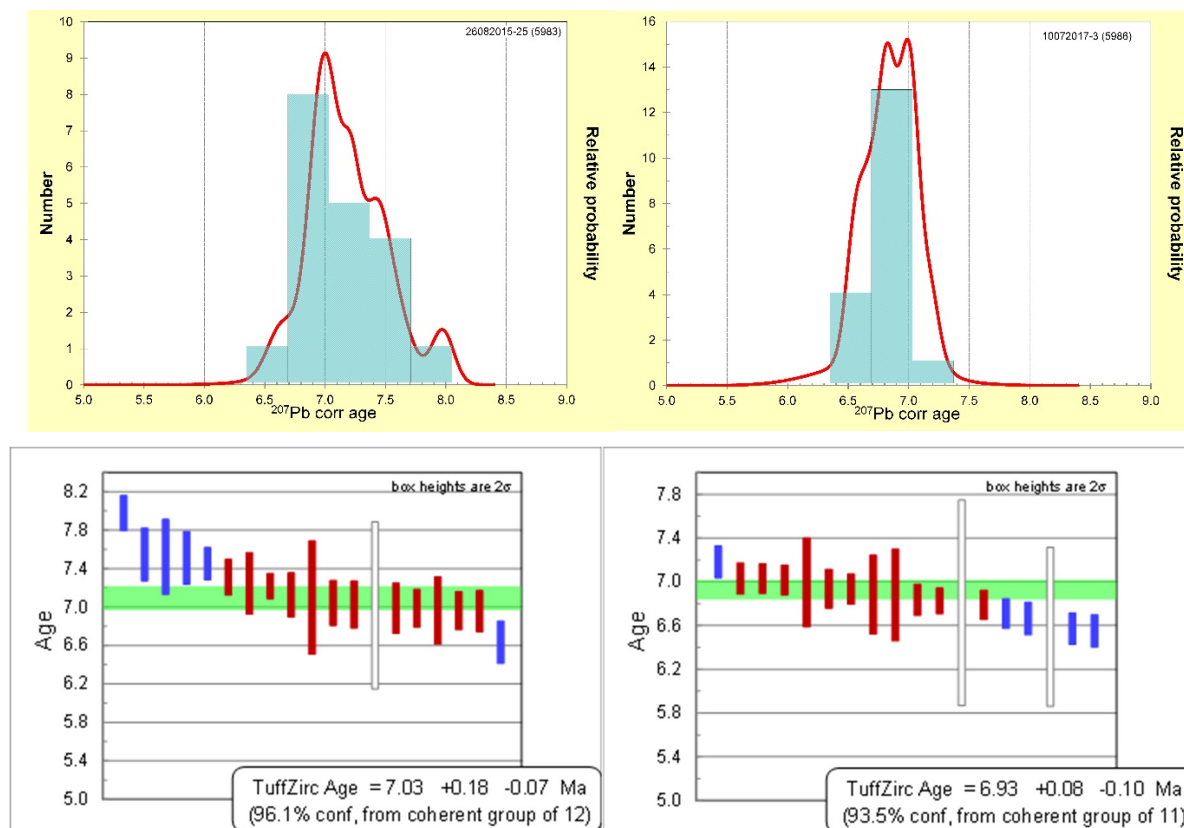


Figure S3 - High-MSWD samples. Above: Probability density plots for samples 26082015-25 (left) and 10072017-3 (right) show more than one peak (while other samples having larger probability show a single peak), indicating that the data consists of more than one population. The x-axes represent 207-corrected $^{206}\text{Pb}/^{238}\text{U}$ dates. Plotted by Isoplot (Ludwig). Below: "TuffZirc" age plots for samples 26082015-25 (left) and 10072017-3 (right) using the "TuffZirc" algorithm of Isoplot (Ludwig and Mundil, 2002; Ludwig, 2003). Red boxes are error bars for the coherent group extracted by "TuffZirc", and thereby the arguable syngenetic zircons. Blue boxes are error bars for zircons regarded by "TuffZirc" as high uncertainty dates that may skew the calculation. White boxes are error bars for zircons rejected by the "TuffZirc" algorithm due to large error.

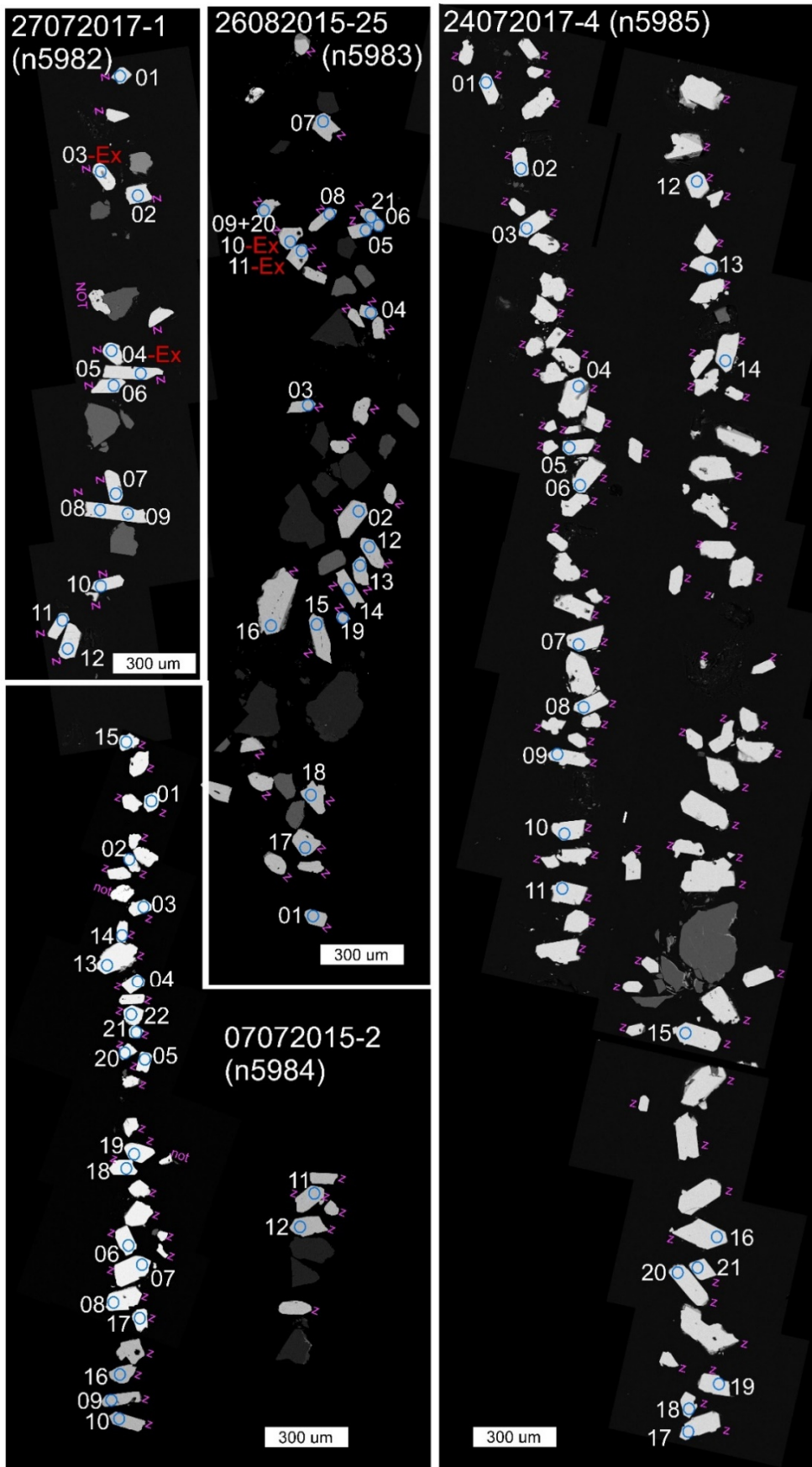
References:

Ludwig, K.R., 2003. User's Manual for Isoplot 3.00: a Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication 4.

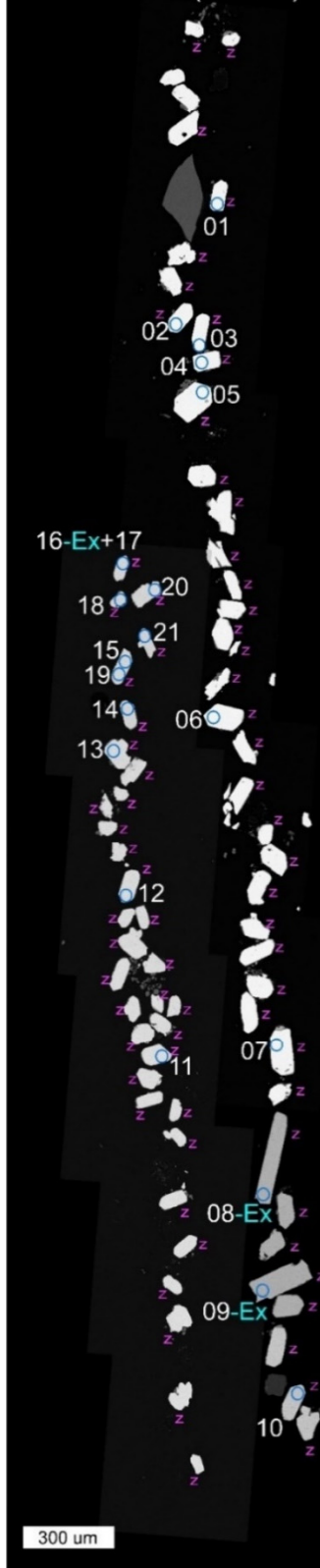
Ludwig, K.R., Mundil, R., 2002. Extracting reliable U-Pb ages and errors from complex populations of zircons from Phanerozoic tuffs. *Geochimica et Cosmochimica Acta* 66(15A), A463-A463.

Figure S4

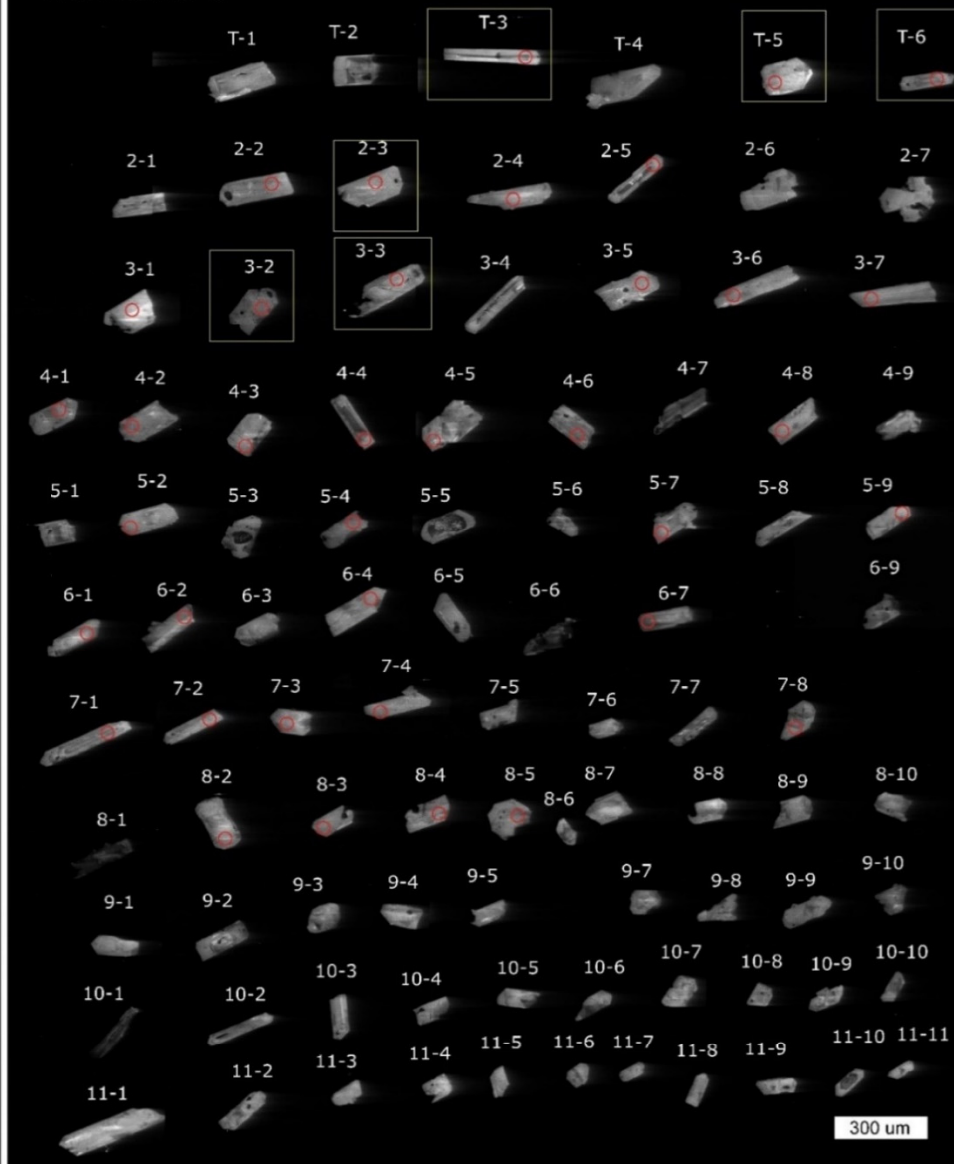
Figure S4 - SEM backscattered electron microscope and catholuminescence images of all zircon crystals separated from the six samples. Locations of SIMS analyzed spots are indicated with red circles and numbers while blue circles indicate Laser-ablation-ICP-MS spots of the CA-TIMS dated sample, performed prior to the chemical abrasion to identify the best grains for isotope dilution - thermal ionization mass spectrometry.



10072017-3 (n5986)



20190823-3



- Grains selected for CA-TIMS dating
- Laser ablation ICP-MS spots
- SIMS analyzed spot
- Z Confirmed zircon
- Ex Excluded; abnormally high age
- Ex Excluded; outstandingly high common Pb

27072017-1, 26082015-25, 07072015-2, 24072017-4 & 10072017-3:
Backscattered electron microscope (SEM) images
20190823-3: Cathodoluminescence (CL) images

Table S3.1. Background geochemical data from the ToCV area: ICP-OES whole-rock geochemical analysis results (dated samples are highlighted)

Sample Id.	Lat	Long	Type	Comment
27072017-5	65.2862	-18.2783	Basalt	Lava (between rhyolite lavas)
20180904-2	65.289	-18.2233	Basalt	Lava (thick pahoehoe lobe)
25072018-1	65.38694	-18.2113	Basalt	Intrusion (feeder) porphyritic
10072017-4	65.28817	-18.2131	Basalt	Lava, porphyritic
20180903-3	65.32288	-18.3354	Basalt	Lava (pahoehoe; unusually thin)
18072017-1	65.2544	-18.2466	Basalt	Lava, porphyritic
14072015-12	65.4004	-18.257	Basalt	Lava, porphyritic
20072017-2	65.41463	-18.1661	Basalt	Lava, porphyritic
27072017-4	65.28564	-18.2841	Basalt	Lava
24072017-0	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)
24072017-3	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)
03072018-3	65.31565	-18.2145	Basalt	Lava
24072017-1	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)
24072017-2	65.32193	-18.3357	Basalt	Lava (ā'a; unusually thin)
20180903-1	65.32288	-18.3354	Basalt	Lava (ā'a; unusually thin)
27072017-2	65.29289	-18.2687	Basaltic andesite	Lava
20180904-1	65.28958	-18.2321	Andesite	Lava
09072015-8	65.31684	-18.2883	Andesite	Lava
01092016-1	65.3063	-18.3366	Andesite	Lava
18072017-3b	65.28641	-18.2694	Dacite	Pyroclastic
27072017-1	65.29289	-18.2687	Dacite	Lava
10082018-1	65.27755	-18.2601	Dacite	Pyroclastic (pumice)
26082015-25	65.27755	-18.2601	Rhyolite	Pyroclastic
10072017-3	65.28886	-18.2186	Rhyolite	Lava
07072015-2	65.32421	-18.2775	Rhyolite	Intrusion (sill)
18072017-3a	65.28641	-18.2694	Rhyolite	Pyroclastic
24072017-4	65.32193	-18.3357	Rhyolite	Feeder (interiors of a conduit)
27072017-3	65.28667	-18.2815	Rhyolite	Lava
14072017-2	65.30281	-18.2246	Rhyolite	Lava
14072017-1	65.30108	-18.2337	Rhyolite	Lava
20180904-3	65.28956	18.21921	Rhyolite	Pyroclastic (obsidian)
13072017-1	65.32597	-18.3532	Rhyolite	Lava

Table S3.1, continued.

Sample Id.	Group	SiO2 Wt. %	Al2O3 Wt. %	FeO Wt. %	MnO Wt. %	MgO Wt. %	CaO Wt. %
27072017-5	Central Volcano	46.42	14.72	13.54	0.22	7.67	11.03
20180904-2	Central Volcano	46.78	14.58	15.25	0.24	6.96	9.44
25072018-1	Dyke (overlying) Plateau	47.46	17.68	9.73	0.16	6.63	14.14
10072017-4	(overlying)	47.88	17.67	10.17	0.17	6.59	13.55
20180903-3	Central Volcano	48.24	13.01	15.03	0.27	5.5	10.48
18072017-1	Plateau (overlying)	48.54	15.31	11.55	0.2	7.17	12.12
14072015-12	Plateau (below CV)	48.92	15.57	10.88	0.2	6.61	12.54
20072017-2	Plateau (below CV)	49.3	15.31	11.23	0.18	6.4	12.05
27072017-4	Central Volcano	49.54	13.3	14.54	0.25	5.24	9.87
24072017-0	Central Volcano	49.75	13.02	14.16	0.23	5.29	10.22
24072017-3	Central Volcano	50.08	13.15	13.68	0.25	5.46	10.14
03072018-3	Central Volcano	50.12	13.24	14.2	0.25	5.28	9.59
24072017-1	Central Volcano	50.22	12.98	13.6	0.24	5.63	10.14
24072017-2	Central Volcano	50.69	12.95	13.65	0.23	5.49	10.07
20180903-1	Central Volcano	51.7	12.63	14.12	0.25	4.27	8.61
27072017-2	Central Volcano	56.04	13.59	11.33	0.2	3.41	7.31
20180904-1	Central Volcano	59.76	14.29	11.01	0.24	1.65	5.45
09072015-8	Central Volcano	59.83	14.11	11.36	0.27	1.44	5.48
01092016-1	Central Volcano	61.91	13.69	11.25	0.28	0.66	5.07
18072017-3b	Central Volcano	64.35	14.43	9.16	0.09	0.44	3.97
27072017-1	Central Volcano	65.63	14.24	7.7	0.21	0.47	4.29
10082018-1	Central Volcano	71.24	13.54	4.51	0.13	0.14	2.31
26082015-25	Central Volcano	72.46	13.7	4.31	0.11	0.24	2.01
10072017-3	Central Volcano	74.68	13.74	1.95	0.02	0.1	0.49
07072015-2	Central Volcano	74.71	13.66	2.01	0.06	0.01	0.64
18072017-3a	Central Volcano	74.95	12.95	2.63	0.14	0.12	1.21
24072017-4	Central Volcano	75.38	13.23	1.91	0.02	0.07	0.56
27072017-3	Central Volcano	75.6	13.16	2.01	0.02	0.08	0.52
14072017-2	Central Volcano	75.72	12.87	1.94	0.05	0.02	0.76
14072017-1	Central Volcano	75.8	13.39	1.54	0.04	0.03	0.77
20180904-3	Central Volcano	76.04	12.47	2.07	0.07	0	0.73
13072017-1	Central Volcano	76.29	12.83	1.71	0.02	0.06	0.48
Standards		SiO2 Wt. %	Al2O3 Wt. %	FeO Wt. %	MnO Wt. %	MgO Wt. %	CaO Wt. %
A-THO		74.33	12.57	3.36	0.11	0.07	1.68
B-THO		47.61	15.43	10.16	0.17	10.2	13.53
B-ALK		47.47	13.01	14.72	0.23	5.13	10.32
B-ALK		47.93	12.75	14.62	0.22	5.24	10.21
RGM-1		72.74	14.86	1.69	0.04	0.27	1.2
RGM-1		73.09	14.61	1.69	0.04	0.27	1.18
RGM-1		73.29	14.38	1.7	0.04	0.28	1.17
K1919		50.08	13.72	10.88	0.17	7.14	11.77
K1919		50.08	13.62	10.89	0.17	7.17	11.9
K1919		50.41	13.78	10.91	0.17	6.89	11.73

Table S3.1, continued.

Sample Id.	Na2O Wt. %	K2O Wt. %	TiO2 Wt. %	P2O5 Wt. %	Ba Wt. %	Co Wt. %	Cr Wt. %
27072017-5	2.2	0.27	3.38	0.38	0.008	0.008	0.018
20180904-2	2.43	0.35	3.45	0.36	0.008	0.008	0.006
25072018-1	2.09	0.19	1.66	0.12	0.004	0.005	0.021
10072017-4	2.01	0.11	1.6	0.13	0.004	0.005	0.017
20180903-3	2.78	0.2	3.85	0.47	0.008	0.008	0.003
18072017-1	2.37	0.24	2.16	0.2	0.007	0.006	0.011
14072015-12	2.42	0.25	2.24	0.23	0.007	0.006	0.014
20072017-2	2.58	0.3	2.3	0.21	0.007	0.006	0.005
27072017-4	2.88	0.41	3.43	0.37	0.018	0.007	0.004
24072017-0	2.69	0.46	3.6	0.42	0.01	0.007	0.004
24072017-3	2.65	0.54	3.46	0.4	0.033	0.007	0.004
03072018-3	2.88	0.62	3.3	0.38	0.013	0.007	0.004
24072017-1	2.65	0.59	3.39	0.39	0.011	0.007	0.005
24072017-2	2.58	0.48	3.31	0.39	0.011	0.007	0.004
20180903-1	3.01	0.84	3.84	0.58	0.018	0.006	0.001
27072017-2	3.58	1.07	2.93	0.4	0.023	0.005	0
20180904-1	4.01	1.54	1.35	0.57	0.029	0.002	0
09072015-8	3.95	1.51	1.35	0.56	0.029	0.002	0
01092016-1	3.99	1.61	1.05	0.33	0.031	0.001	0
18072017-3b	4.36	1.73	1	0.28	0.034	0.001	0.001
27072017-1	4.23	2.08	0.76	0.21	0.035	0.001	0
10082018-1	4.22	3.38	0.31	0.02	0.05	0	0
26082015-25	4.65	2	0.32	0.03	0.048	0	0
10072017-3	5.09	3.58	0.16	0.02	0.064	0	0.001
07072015-2	4.98	3.59	0.17	0	0.063	0	0.001
18072017-3a	4.43	3.16	0.23	0.02	0.058	0	0.001
24072017-4	5.06	3.43	0.18	0	0.06	0	0.001
27072017-3	4.86	3.39	0.16	0.02	0.06	0	0.001
14072017-2	4.85	3.44	0.15	0.01	0.062	0	0
14072017-1	4.74	3.37	0.16	0	0.061	0	0
20180904-3	4.92	3.38	0.15	0	0.06	0	0
13072017-1	4.88	3.42	0.16	0.01	0.061	0	0
Standards	Na2O Wt. %	K2O Wt. %	TiO2 Wt. %	P2O5 Wt. %	Ba Wt. %	Co Wt. %	Cr Wt. %
A-THO	4.66	2.76	0.25	0.02	583.93	1.599	3.72
B-THO	1.75	0.01	0.98	0.02	6.39	55.113	406.995
B-ALK	3.07	0.74	4.59	0.54	181.19	79.851	15.059
B-ALK	3.04	0.73	4.55	0.54	180.58	79.532	15.441
RGM-1	4.36	4.36	0.28	0.04	858.922	2.626	5.074
RGM-1	4.25	4.38	0.28	0.04	870.248	2.684	4.927
RGM-1	4.26	4.38	0.29	0.04	874.522	2.891	4.887
K1919	2.36	0.53	2.89	0.28	132.918	65.033	205.052
K1919	2.4	0.53	2.8	0.28	133.293	63.441	202.996
K1919	2.38	0.54	2.75	0.28	135.109	63.551	205.066

Table S3.1, continued.

Sample Id.	Cu Wt. %	Ni Wt. %	Sc Wt. %	Sr Wt. %	V Wt. %
27072017-5	0.015	0.014	0.004	0.028	0.039
20180904-2	0.021	0.01	0.004	0.021	0.049
25072018-1	0.014	0.007	0.004	0.02	0.031
10072017-4	0.016	0.014	0.004	0.02	0.029
20180903-3	0.019	0.004	0.005	0.028	0.044
18072017-1	0.01	0.009	0.004	0.022	0.032
14072015-12	0.013	0.007	0.004	0.029	0.031
20072017-2	0.014	0.007	0.004	0.029	0.031
27072017-4	0.011	0.004	0.004	0.021	0.046
24072017-0	0.011	0.005	0.004	0.027	0.044
24072017-3	0.016	0.004	0.004	0.026	0.041
03072018-3	0.009	0.004	0.004	0.021	0.043
24072017-1	0.012	0.004	0.004	0.026	0.041
24072017-2	0.011	0.005	0.004	0.026	0.042
20180903-1	0.003	0.001	0.004	0.028	0.033
27072017-2	0.004	0	0.003	0.024	0.024
20180904-1	0.002	0	0.003	0.022	0
09072015-8	0.003	0	0.003	0.022	0
01092016-1	0.002	0.001	0.004	0.021	0
18072017-3b	0.002	0	0.003	0.021	0.001
27072017-1	0.002	0.001	0.003	0.019	0.001
10082018-1	0.002	0	0.001	0.014	0.001
26082015-25	0.002	0	0.001	0.014	0.001
10072017-3	0.002	0.001	0	0.007	0.002
07072015-2	0.002	0.001	0	0.008	0.001
18072017-3a	0.003	0.002	0.001	0.01	0.001
24072017-4	0.002	0.001	0	0.007	0.002
27072017-3	0.002	0	0	0.007	0.002
14072017-2	0.001	0.001	0	0.009	0.001
14072017-1	0.004	0.004	0	0.009	0.001
20180904-3	0.002	0	0	0.006	0
13072017-1	0.002	0	0	0.007	0.001
Standards	Cu Wt. %	Ni Wt. %	Sc Wt. %	Sr Wt. %	V Wt. %
A-THO	21.511	1.995	4.797	98	6.354
B-THO	118.005	191.699	45.621	107.08	310.702
B-ALK	40.433	27.863	32.435	409.479	432.295
B-ALK	40.403	27.733	32.325	407.811	423.197
RGM-1	21.723	11.275	4.343	106.107	14.551
RGM-1	21.618	12.924	4.299	106.777	14.139
RGM-1	21.55	12.553	4.345	107.182	14.851
K1919	130.693	100.833	33.019	384.576	309.806
K1919	129.331	97.27	32.298	382.31	302.181
K1919	130.733	100.116	32.677	385.506	303.558

Table S3.1, continued.

Sample Id.	Y Wt. %	Zn Wt. %	Zr Wt. %	Σ Norm %	Σ Run %
27072017-5	0.004	0.013	0.018	100	95.8
20180904-2	0.004	0.015	0.019	100	95.1
25072018-1	0.002	0.009	0.008	100	98.9
10072017-4	0.002	0.009	0.008	100	95.5
20180903-3	0.005	0.018	0.026	100	99
18072017-1	0.003	0.01	0.012	100	102.1
14072015-12	0.003	0.011	0.013	100	95.5
20072017-2	0.003	0.011	0.013	100	96.1
27072017-4	0.005	0.014	0.024	100	99.7
24072017-0	0.005	0.014	0.025	100	98
24072017-3	0.005	0.014	0.025	100	97.2
03072018-3	0.006	0.014	0.024	100	96.5
24072017-1	0.005	0.013	0.024	100	100.3
24072017-2	0.005	0.013	0.023	100	97.1
20180903-1	0.007	0.015	0.033	100	101.7
27072017-2	0.006	0.012	0.029	100	97
20180904-1	0.009	0.015	0.042	100	99.7
09072015-8	0.009	0.016	0.046	100	94.3
01092016-1	0.009	0.016	0.061	100	94.6
18072017-3b	0.009	0.018	0.071	100	94.9
27072017-1	0.008	0.013	0.071	100	98.4
10082018-1	0.013	0.014	0.064	100	93.6
26082015-25	0.012	0.013	0.059	100	97.3
10072017-3	0.011	0.014	0.037	100	93.1
07072015-2	0.012	0.014	0.039	100	92.1
18072017-3a	0.008	0.008	0.038	100	94.8
24072017-4	0.006	0.013	0.038	100	98.5
27072017-3	0.01	0.013	0.038	100	98.6
14072017-2	0.011	0.014	0.038	100	89.3
14072017-1	0.005	0.013	0.035	100	96
20180904-3	0.014	0.014	0.039	100	101.6
13072017-1	0.006	0.013	0.038	100	92.7
Standards	Y Wt. %	Zn Wt. %	Zr Wt. %	Σ Norm %	Σ Run %
A-THO	108.352	124.716	514.28	100	98.9
B-THO	12.58	82.761	19.547	100	98.6
B-ALK	36.835	138.173	229.719	100	101
B-ALK	36.182	134.438	228.073	100	101.1
RGM-1	21.647	50.174	220.915	100	98.3
RGM-1	20.651	49.206	221.26	100	98.2
RGM-1	21.157	48.471	221.383	100	100.8
K1919	24.747	101.996	166.718	100	100.2
K1919	24.539	102.838	167.695	100	101.6
K1919	24.528	102.457	170.563	100	101.2

Table S3.2. Background geochemical data from the ToCV area: EPMA glass (obsidian) analysis (in mass%)

Sample	Point	Comment	SiO2	TiO2	Al2O3	FeO	MnO	MgO
ATHO pt1	1	Standard	75.87	0.241	11.82	3.37	0.099	0.083
ATHO pt2	2	Standard	75.85	0.266	12.20	3.40	0.099	0.114
ATHO pt3	3	Standard	75.18	0.194	12.04	3.28	0.066	0.079
ATHO pt4	4	Standard	75.62	0.185	12.40	3.23	0.117	0.099
ATHO pt5	5	Standard	75.14	0.285	12.47	3.28	0.123	0.076
20180904-3	6	Torfufell-1	76.26	0.136	12.27	2.02	0.083	0.011
20180904-3	7	Torfufell-2	76.67	0.163	12.27	2.01	0.085	0.000
20180904-3	8	Torfufell-3	76.21	0.137	12.21	2.08	0.082	0.017
20180904-3	9	Torfufell-4	76.87	0.110	12.08	2.02	0.110	0.009
20180904-3	10	Torfufell-5	77.01	0.120	12.28	1.96	0.061	0.016
20180904-3	11	Torfufell-6	76.71	0.164	12.28	1.96	0.063	0.010
20180904-3	12	Torfufell-7	76.52	0.149	12.42	2.00	0.065	0.013
20180904-3	13	Torfufell-8	76.42	0.163	12.34	1.94	0.090	0.000
20180904-3	14	Torfufell-9	76.38	0.119	12.32	2.01	0.126	0.008
20180904-3	15	Torfufell-10	77.08	0.142	12.25	1.98	0.057	0.002

Sample	Point	Comment	CaO	Na2O	K2O	P2O5	Sum
ATHO pt1	1	Standard	1.65	4.48	2.63	0.065	100.31
ATHO pt2	2	Standard	1.66	4.56	2.70	0.028	100.88
ATHO pt3	3	Standard	1.69	4.61	2.69	0.051	99.88
ATHO pt4	4	Standard	1.67	4.48	2.63	0.030	100.46
ATHO pt5	5	Standard	1.65	4.54	2.59	0.041	100.19
20180904-3	6	Torfufell-1	0.79	4.47	3.38	0.000	99.42
20180904-3	7	Torfufell-2	0.77	4.26	3.43	0.017	99.68
20180904-3	8	Torfufell-3	0.77	4.59	3.46	0.000	99.55
20180904-3	9	Torfufell-4	0.72	4.39	3.36	0.002	99.67
20180904-3	10	Torfufell-5	0.77	4.72	3.36	0.000	100.29
20180904-3	11	Torfufell-6	0.75	4.56	3.47	0.000	99.96
20180904-3	12	Torfufell-7	0.73	4.52	3.31	0.000	99.72
20180904-3	13	Torfufell-8	0.76	4.43	3.42	0.037	99.60
20180904-3	14	Torfufell-9	0.73	4.27	3.40	0.000	99.36
20180904-3	15	Torfufell-10	0.63	4.61	3.42	0.000	100.17

Sample	Point	Comment	Na+K	Ti/Fe	Ti/Mg	Mg#	Ca/Al	Ca/Mg
ATHO pt1	1	Standard	7.11	0.071	2.92	0.042	0.254	19.98
ATHO pt2	2	Standard	7.26	0.078	2.33	0.056	0.247	14.54
ATHO pt3	3	Standard	7.30	0.059	2.46	0.041	0.255	21.42
ATHO pt4	4	Standard	7.11	0.057	1.87	0.052	0.245	16.89
ATHO pt5	5	Standard	7.13	0.087	3.73	0.040	0.241	21.63
20180904-3	6	Torfufell-1	7.85	0.067	11.92	0.010	0.117	69.39
20180904-3	7	Torfufell-2	7.69	0.081		0.000	0.115	
20180904-3	8	Torfufell-3	8.05	0.066	8.25	0.014	0.114	46.30
20180904-3	9	Torfufell-4	7.75	0.055	11.86	0.008	0.109	77.61
20180904-3	10	Torfufell-5	8.08	0.061	7.72	0.014	0.113	49.36
20180904-3	11	Torfufell-6	8.03	0.084	16.95	0.009	0.111	77.10
20180904-3	12	Torfufell-7	7.83	0.074	11.71	0.011	0.107	57.33
20180904-3	13	Torfufell-8	7.85	0.084		0.000	0.112	
20180904-3	14	Torfufell-9	7.67	0.059	15.61	0.007	0.108	96.34
20180904-3	15	Torfufell-10	8.03	0.072	67.57	0.002	0.094	300.86

Table S3.3. Detailed SIMS results.

Sample ID	NordSIM sample name/spot #	Concentration (µg/g)			Th/U _{meas} ¹	²⁰⁶ Pb/ ²⁰⁴ Pb	f ₂₀₆ (%) ²
		U	Th	²⁰⁶ Pb*			
27072017-1	n5982_@09	54	32	0.04	0.59	35.6	52.58
27072017-1	n5982_@02	110	79	0.08	0.69	54.2	34.53
27072017-1	n5982_@05	97	59	0.07	0.61	54.3	34.44
27072017-1	n5982_@1	77	39	0.07	0.51	114	16.35
27072017-1	n5982_@06	160	120	0.15	0.77	108	17.33
27072017-1	n5982_@11	210	220	0.21	1	188	9.96
27072017-1	n5982_@12	230	240	0.24	1	240	7.79
27072017-1	n5982_@10	110	83	0.10	0.73	124	15.06
27072017-1	n5982_@07	240	240	0.24	1	177	10.55
27072017-1	n5982_@08	100	71	0.07	0.71	46.7	40.08
27072017-1	n5982_@03	140	71	53.81	0.51	102000	0.02
27072017-1	n5982_@04	120	130	10.24	1	10900	0.17
26082015-25	n5983_@20	78	38	0.04	0.49	36.7	50.94
26082015-25	n5983_@1	100	72	0.06	0.7	40.1	46.68
26082015-25	n5983_@09	72	36	0.04	0.51	37.3	50.17
26082015-25	n5983_@12	100	60	0.10	0.59	163	11.48
26082015-25	n5983_@13	110	70	0.07	0.61	43.3	43.15
26082015-25	n5983_@14	77	46	-0.06	0.6	11.1	168.75
26082015-25	n5983_@05	62	25	0.04	0.4	39.2	47.74
26082015-25	n5983_@16	36	12	0.01	0.35	26.2	71.49
26082015-25	n5983_@03	64	28	0.06	0.44	61	30.67
26082015-25	n5983_@21	290	230	0.29	0.78	164	11.42
26082015-25	n5983_@19	61	29	0.06	0.47	125	14.94
26082015-25	n5983_@07	180	120	-0.05	0.66	15.3	122.47
26082015-25	n5983_@08	460	470	0.20	1	29.4	63.59
26082015-25	n5983_@02	240	230	0.19	0.97	62.5	29.94
26082015-25	n5983_@15	110	69	0.03	0.63	24.4	76.51
26082015-25	n5983_@06	190	170	0.21	0.88	315	5.94
26082015-25	n5983_@17	190	130	-0.18	0.72	10.3	181.85
26082015-25	n5983_@18	200	140	-0.22	0.69	9.77	191.47
26082015-25	n5983_@04	93	58	0.05	0.62	35.5	52.76
26082015-25	n5983_@10	1100	810	12.46	0.72	9120	0.2
26082015-25	n5983_@11	100	30	32.40	0.3	3040	0.62
07072015-2	n5984_@16	86	34	0.07	0.4	71.8	26.06
07072015-2	n5984_@05	160	77	0.12	0.49	63.9	29.29
07072015-2	n5984_@10	100	42	0.07	0.41	59.1	31.62
07072015-2	n5984_@06	99	39	0.08	0.39	76.2	24.55
07072015-2	n5984_@11	350	210	0.23	0.61	47.9	39.01
07072015-2	n5984_@02	230	150	0.12	0.67	37	50.55
07072015-2	n5984_@04	100	42	0.08	0.42	69.6	26.87
07072015-2	n5984_@09	130	60	0.11	0.46	84	22.26
07072015-2	n5984_@1	230	160	0.18	0.69	67.6	27.67
07072015-2	n5984_@12	120	56	0.12	0.45	186	10.06
07072015-2	n5984_@13	170	92	0.15	0.53	91.7	20.39
07072015-2	n5984_@20	98	40	0.08	0.4	62.9	29.71
07072015-2	n5984_@22	110	49	0.10	0.44	91.8	20.37
07072015-2	n5984_@07	250	150	0.23	0.61	110	17.07
07072015-2	n5984_@14	390	360	-0.59	0.92	8	233.75
07072015-2	n5984_@15	520	450	-0.46	0.86	10.3	180.72
07072015-2	n5984_@18	150	74	0.09	0.48	39.8	47.03
07072015-2	n5984_@21	130	64	0.11	0.48	85.9	21.78
07072015-2	n5984_@03	120	54	0.10	0.45	52.4	35.68
07072015-2	n5984_@08	180	89	0.19	0.5	306	6.11
07072015-2	n5984_@17	170	100	0.07	0.58	29.1	64.17
07072015-2	n5984_@19	250	150	0.21	0.61	67.6	27.68
24072017-4	n5985_@06	89	35	0.08	0.39	167	11.2

Table S3.3. Continued.

Sample ID	NordSIM sample name/spot #	Concentration (µg/g)			Th/U _{meas} ¹	²⁰⁶ Pb/ ²⁰⁴ Pb	f ₂₀₆ (%) ²
		U	Th	²⁰⁶ Pb*			
24072017-4	n5985_@02	180	120	0.17	0.64	205	9.12
24072017-4	n5985_@08	120	60	0.08	0.49	51.6	36.23
24072017-4	n5985_@21	120	52	0.11	0.43	149	12.57
24072017-4	n5985_@1	170	86	0.13	0.51	67.8	27.58
24072017-4	n5985_@05	230	140	0.23	0.59	247	7.58
24072017-4	n5985_@18	180	93	-0.10	0.51	12.3	152.58
24072017-4	n5985_@09	280	170	-0.44	0.61	7.65	244.64
24072017-4	n5985_@04	140	63	0.13	0.45	116	16.1
24072017-4	n5985_@11	170	92	0.16	0.53	142	13.15
24072017-4	n5985_@19	150	70	-0.04	0.46	15.1	123.9
24072017-4	n5985_@17	220	130	0.22	0.57	200	9.37
24072017-4	n5985_@03	200	110	0.20	0.56	178	10.54
24072017-4	n5985_@07	130	53	0.12	0.42	128	14.62
24072017-4	n5985_@10	170	95	0.01	0.56	20.3	91.94
24072017-4	n5985_@12	210	110	0.21	0.56	170	10.99
24072017-4	n5985_@13	130	77	-0.02	0.59	16.7	111.94
24072017-4	n5985_@14	110	51	0.10	0.46	102	18.31
24072017-4	n5985_@15	110	47	0.10	0.42	124	15.08
24072017-4	n5985_@16	120	56	0.11	0.45	105	17.82
24072017-4	n5985_@20	120	69	-0.11	0.56	10.4	179
10072017-3	n5986_@14	83	34	0.02	0.41	24.2	77.37
10072017-3	n5986_@17	420	440	-0.73	1.1	6.98	267.95
10072017-3	n5986_@05	130	92	-0.06	0.68	13	144.21
10072017-3	n5986_@02	190	99	-0.08	0.52	13.4	139.82
10072017-3	n5986_@21	150	80	0.06	0.53	30.3	61.76
10072017-3	n5986_@1	320	240	0.01	0.76	19	98.4
10072017-3	n5986_@04	120	56	-0.01	0.47	18	104.16
10072017-3	n5986_@06	130	75	0.02	0.56	22.5	83.07
10072017-3	n5986_@15	180	110	-0.34	0.62	6.79	275.47
10072017-3	n5986_@13	220	150	-0.30	0.69	8.38	223.31
10072017-3	n5986_@18	290	210	-0.24	0.72	10.6	176.17
10072017-3	n5986_@07	180	110	-0.21	0.59	9.05	206.75
10072017-3	n5986_@16	260	190	-0.87	0.73	4.54	412.02
10072017-3	n5986_@19	110	53	0.02	0.48	23.6	79.1
10072017-3	n5986_@20	250	150	-0.34	0.61	8.29	225.48
10072017-3	n5986_@03	330	250	0.07	0.74	22.9	81.7
10072017-3	n5986_@10	120	53	-0.02	0.45	16.3	114.7
10072017-3	n5986_@11	140	71	0.05	0.51	26.8	69.71
10072017-3	n5986_@08	360	320	-1.57	0.9	3.84	487.29
10072017-3	n5986_@12	150	79	0.04	0.55	24.6	76.07
10072017-3	n5986_@09	140	100	-0.76	0.74	3.25	575.75
	Penglai_4std- mt_@1	14	6.4	0.00	0.47	22.3	83.77
	Penglai_4std- mt_@2	10	4.3	#VALUE!	0.41	29.2	[64.06]

Table S3.3. Continued.

Sample ID	Total (uncorrected) ratio				207-corr age ⁴
	²³⁸ U/ ²⁰⁶ Pb	± σ (%)	²⁰⁷ Pb/ ²⁰⁶ Pb	± σ (%)	
27072017-1	719.4	10.	0.265	26.	6.5 ± 1.1
27072017-1	921.7	3.5	0.0648	9.2	6.8 ± 0.2
27072017-1	935.5	2.9	0.0593	10.	6.8 ± 0.2
27072017-1	915.8	3.7	0.0557	11.	7.0 ± 0.3
27072017-1	896.9	2.4	0.0560	7.9	7.1 ± 0.2
27072017-1	895.3	2.1	0.0555	6.8	7.1 ± 0.2
27072017-1	887.3	2.0	0.0530	6.5	7.2 ± 0.1
27072017-1	904.2	2.7	0.0432	11.	7.2 ± 0.2
27072017-1	888.9	2.3	0.0453	6.9	7.3 ± 0.2
27072017-1	838.2	2.8	0.0504	10.	7.6 ± 0.2
27072017-1	2.6	1.4	0.13242	0.30	2089 ± 30
27072017-1	11.7	1.2	0.05741	0.99	529 ± 6
26082015-25	928.5	3.7	0.0815	9.4	6.6 ± 0.3
26082015-25	914.1	3.2	0.0571	13.	7.0 ± 0.2
26082015-25	911.6	3.4	0.0587	11.	7.0 ± 0.2
26082015-25	908.3	2.8	0.0609	13.	7.0 ± 0.2
26082015-25	906.6	2.7	0.0597	10.	7.0 ± 0.2
26082015-25	907.4	3.2	0.0591	11.	7.0 ± 0.2
26082015-25	912.4	4.5	0.0488	13.	7.0 ± 0.3
26082015-25	881.8	4.6	0.077	14.	7.0 ± 0.3
26082015-25	803.2	5.8	0.145	25.	7.0 ± 0.6
26082015-25	897.7	1.9	0.0519	6.4	7.1 ± 0.1
26082015-25	885	5.4	0.0667	13.	7.1 ± 0.4
26082015-25	890.5	2.2	0.0484	7.5	7.2 ± 0.2
26082015-25	845.3	3.1	0.085	17.	7.2 ± 0.3
26082015-25	879.5	1.9	0.0481	8.2	7.3 ± 0.1
26082015-25	860.6	5.5	0.0502	12.	7.4 ± 0.4
26082015-25	853.2	2.9	0.0495	7.0	7.5 ± 0.2
26082015-25	851.8	2.3	0.0486	12.	7.5 ± 0.2
26082015-25	843.9	2.0	0.0594	6.5	7.5 ± 0.2
26082015-25	809.7	2.8	0.0445	11.	8.0 ± 0.2
26082015-25	88.1	2.3	0.04775	1.2	72.7 ± 1.7
26082015-25	3.1	6.4	0.13457	0.44	1761 ± 113
07072015-2	969.9	3.4	0.0635	15.	6.5 ± 0.2
07072015-2	957.9	2.4	0.0498	12.	6.7 ± 0.2
07072015-2	934.6	2.8	0.0571	9.6	6.8 ± 0.2
07072015-2	932	3.7	0.0601	9.6	6.8 ± 0.3
07072015-2	924.2	1.9	0.0526	5.5	6.9 ± 0.1
07072015-2	913.2	2.2	0.0605	9.2	6.9 ± 0.2
07072015-2	916.6	2.9	0.0595	11.	6.9 ± 0.2
07072015-2	924.2	2.9	0.0565	12.	6.9 ± 0.2
07072015-2	911.6	2.0	0.0506	7.4	7.0 ± 0.1
07072015-2	878	2.6	0.0873	9.7	7.0 ± 0.2
07072015-2	922.5	2.4	0.0440	8.3	7.0 ± 0.2
07072015-2	902.5	3.1	0.0588	9.5	7.0 ± 0.2
07072015-2	915.8	3.4	0.0507	9.6	7.0 ± 0.2
07072015-2	911.6	1.9	0.0470	6.6	7.1 ± 0.1
07072015-2	890.5	1.6	0.0556	5.0	7.1 ± 0.1
07072015-2	905.8	1.5	0.0511	4.5	7.1 ± 0.1
07072015-2	892.1	2.3	0.0549	8.7	7.1 ± 0.2
07072015-2	902.5	3.0	0.0493	8.9	7.1 ± 0.2
07072015-2	752.4	3.3	0.176	15.	7.1 ± 0.4
07072015-2	881.1	2.2	0.0567	8.1	7.2 ± 0.2
07072015-2	901.7	2.4	0.0446	9.7	7.2 ± 0.2
07072015-2	874.9	2.0	0.0490	6.5	7.3 ± 0.2
24072017-4	969	3.0	0.0481	11.	6.6 ± 0.2

Table S3.3. Continued.

Sample ID	Total (uncorrected) ratio				207-corr age ⁴
	²³⁸ U/ ²⁰⁶ Pb	± σ (%)	²⁰⁷ Pb/ ²⁰⁶ Pb	± σ (%)	
24072017-4	936.3	2.9	0.0585	11.	6.8 ± 0.2
24072017-4	917.4	2.6	0.0704	7.9	6.8 ± 0.2
24072017-4	940.7	2.6	0.0486	9.2	6.8 ± 0.2
24072017-4	929.4	3.0	0.0486	9.4	6.9 ± 0.2
24072017-4	925.1	2.3	0.0509	6.9	6.9 ± 0.2
24072017-4	932	2.3	0.0437	8.8	6.9 ± 0.2
24072017-4	923.4	1.8	0.0476	6.2	7.0 ± 0.1
24072017-4	914.9	2.6	0.0505	8.7	7.0 ± 0.2
24072017-4	912.4	2.3	0.0496	12.	7.0 ± 0.2
24072017-4	914.9	2.3	0.0501	10.	7.0 ± 0.2
24072017-4	906.6	2.0	0.0433	7.1	7.1 ± 0.1
24072017-4	909.1	2.1	0.0446	7.6	7.1 ± 0.2
24072017-4	897.7	2.6	0.0550	8.7	7.1 ± 0.2
24072017-4	914.1	3.3	0.0401	8.4	7.1 ± 0.2
24072017-4	901.7	2.1	0.0555	9.4	7.1 ± 0.2
24072017-4	899.3	2.5	0.0520	11.	7.1 ± 0.2
24072017-4	905.8	2.7	0.0508	12.	7.1 ± 0.2
24072017-4	912.4	3.1	0.0431	11.	7.1 ± 0.2
24072017-4	900.1	2.6	0.0470	9.6	7.2 ± 0.2
24072017-4	876.4	4.2	0.0597	9.8	7.2 ± 0.3
10072017-3	969.9	3.1	0.0578	11.	6.5 ± 0.2
10072017-3	970.9	2.2	0.0527	5.6	6.6 ± 0.1
10072017-3	973.7	2.5	0.0525	9.2	6.6 ± 0.2
10072017-3	945.2	2.1	0.0590	7.2	6.7 ± 0.1
10072017-3	953.3	3.1	0.0574	8.7	6.7 ± 0.2
10072017-3	937.2	1.8	0.0525	5.8	6.8 ± 0.1
10072017-3	941.6	2.7	0.0524	9.3	6.8 ± 0.2
10072017-3	932	2.6	0.0558	9.5	6.8 ± 0.2
10072017-3	939	2.4	0.0532	7.6	6.8 ± 0.2
10072017-3	912.4	2.0	0.0668	6.6	6.9 ± 0.1
10072017-3	925.1	1.8	0.0497	6.1	6.9 ± 0.1
10072017-3	920	2.2	0.0604	12.	6.9 ± 0.2
10072017-3	930.2	2.3	0.0517	6.5	6.9 ± 0.2
10072017-3	925.9	2.7	0.0491	10.	6.9 ± 0.2
10072017-3	914.1	1.9	0.0525	6.5	7.0 ± 0.1
10072017-3	913.2	2.3	0.0511	8.9	7.0 ± 0.2
10072017-3	914.9	3.4	0.0481	9.6	7.0 ± 0.2
10072017-3	912.4	3.8	0.0500	8.8	7.0 ± 0.3
10072017-3	888.9	1.7	0.0550	6.5	7.2 ± 0.1
10072017-3	894.5	2.4	0.0490	10.	7.2 ± 0.2
10072017-3	877.2	2.4	0.0431	16.	7.4 ± 0.2
Penglai_4std- mt_@1	1612.9	9.9	0.080	36.	3.8 ± 0.4
Penglai_4std- mt_@2	1587	11.	0.042	42.	4.1 ± 0.4

(1) Based on measured Th and U signals.

(2) f206 is the percentage of common Pb estimated from 204Pb counts; in parentheses where these are insignificant;

(3) Ratios after subtraction of common Pb (if detected)

(4) Age based on projecting a line in inverse concordia space from assumed common Pb through the total (uncorrected) ratios onto concordia (Ludwig, 2001)

Table S3.4. CA-TIMS U-Pb isotopic data.

Compositional Parameters								
Sample (a)	$\frac{\text{Th}}{\text{U}}$ (b)	$^{206}\text{Pb}^*$ $\times 10^{-13}$ mol (c)	mol % $^{206}\text{Pb}^*$ (c)	$\frac{\text{Pb}^*}{\text{Pb}_c}$ (c)	Pb_c (pg) (c)	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$ (d)		
20190823-3								
T-3	0.718	0.0053	79.50%	1	0.11	90		
T-5	0.765	0.0036	76.83%	1	0.09	80		
T-6	0.622	0.0052	83.18%	2	0.09	110		
2-3	0.674	0.0068	67.10%	1	0.27	56		
3-2	0.767	0.0103	69.90%	1	0.36	61		
3-3	0.843	0.0090	72.08%	1	0.29	66		
Radiogenic Isotope Ratios								
Sample (a)	$\frac{^{208}\text{Pb}}{^{206}\text{Pb}}$ (e)	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ (e)	% err (f)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (e)	% err (f)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (e)	% err (f)	corr. coef.
20190823-3								
T-3	0.233	0.04597	15.354	0.006653	15.619	0.001050	0.486	0.553
T-5	0.249	0.04574	14.385	0.006637	14.717	0.001053	0.534	0.627
T-6	0.202	0.04617	12.172	0.006678	12.434	0.001049	0.434	0.612
2-3	0.219	0.04531	18.577	0.006553	19.063	0.001049	0.782	0.683
3-2	0.249	0.04628	14.237	0.006684	14.727	0.001047	0.630	0.778
3-3	0.274	0.05064	10.804	0.007284	11.283	0.001043	0.636	0.762
Isotopic Ages								
Sample (a)	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ (g)	$\pm$ (f)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$ (g)	$\pm$ (f)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$ (g)	$\pm$ (f)		
20190823-3								
T-3	-3.73	368.28	6.73	1.05	6.762	0.033		
T-5	-16.25	345.91	6.72	0.99	6.781	0.036		
T-6	6.71	291.33	6.76	0.84	6.758	0.029		
2-3	-39.10	448.52	6.63	1.26	6.759	0.053		
3-2	12.08	340.53	6.76	0.99	6.749	0.043		
3-3	224.60	248.55	7.37	0.83	6.721	0.043		

weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age = 6.757 ± 0.015 (0.02) [0.02] Ma (2s); MSWD = 0.98 (n=6) (h)

(a) z1, z2 etc. are labels for single zircon grains or fragments annealed and chemically abraded after Mattinson (2005); bold indicates results used in weighted mean calculations.

(b) Model Th/U ratio iteratively calculated from the radiogenic $^{208}\text{Pb}/^{206}\text{Pb}$ ratio and $^{206}\text{Pb}/^{238}\text{U}$ age.

(c) Pb^* and Pb_c represent radiogenic and common Pb, respectively; mol % $^{206}\text{Pb}^*$ with respect to radiogenic, blank and initial common Pb.

(d) Measured ratio corrected for spike and fractionation only. Fractionation calculated from the measured double spike Pb and U ratios.

(e) Corrected for fractionation, spike, and common Pb; all common Pb was assumed to be procedural blank: $^{206}\text{Pb}/^{204}\text{Pb} = 18.042 \pm 0.61\%$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.537 \pm 0.52\%$;

$^{208}\text{Pb}/^{204}\text{Pb} = 37.686 \pm 0.63\%$ (all uncertainties 1-sigma).

(f) Errors are 2-sigma, propagated using the algorithms of Schmitz and Schoene (2007).

(g) Calculations are based on the decay constants of Jaffey et al. (1971) and $^{238}\text{U}/^{235}\text{U} = 137.88$.

$^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages corrected for initial disequilibrium in $^{230}\text{Th}/^{238}\text{U}$

using $\text{Th}/\text{U}(\text{magma}) = 2.8 \pm 0.05$ (1s).

(h) Age uncertainties reported as $\pm$ analytical (+tracer) [+decay constant]; MSWD = mean squared weighted deviation.

Table S3.5. Zircon U-Pb laser ablation ICP-MS analytical data.

Sample no. Analysis ID	Isotopic Ratios						2σ (abs)
	²⁰⁷ Pb/ ²³⁵ U	2σ (abs)	²⁰⁶ Pb/ ²³⁸ U	2σ (abs)	r	²⁰⁷ Pb/ ²⁰⁶ Pb	
20190823-3 T-3	0.007	0.003	0.0010	0.0001	0.22909	0.0405	0.0172
20190823-3 T-5	0.008	0.004	0.0012	0.0001	0.21021	0.0577	0.0263
20190823-3 T-6	0.004	0.002	0.0011	0.0001	0.00896	0.0324	0.0164
20190823-3 2-2	-0.001	0.000	0.0011	0.0002	0.08321	0.0001	0.0129
20190823-3 2-3	0.003	0.003	0.0011	0.0002	0.18848	0.0311	0.0333
20190823-3 2-4	0.009	0.004	0.0010	0.0001	0.09960	0.0735	0.0410
20190823-3 2-5	0.006	0.003	0.0010	0.0001	0.11176	0.0509	0.0214
20190823-3 3-2	0.005	0.004	0.0012	0.0002	0.01681	0.0497	0.0391
20190823-3 3-3	0.006	0.003	0.0010	0.0001	0.18337	0.0487	0.0247
20190823-3 3-5	0.006	0.004	0.0010	0.0002	0.01902	0.0615	0.0542
20190823-3 3-6	0.008	0.004	0.0010	0.0001	0.48832	0.0472	0.0240
20190823-3 3-7	0.024	0.011	0.0013	0.0002	0.47137	0.1473	0.0588
20190823-3 4-1	0.011	0.004	0.0010	0.0001	0.04416	0.0747	0.0334
20190823-3 4-2	0.010	0.007	0.0010	0.0002	0.04138	0.0955	0.0686
20190823-3 4-3	0.012	0.008	0.0010	0.0002	0.00443	0.1355	0.1233
20190823-3 4-4	0.009	0.004	0.0011	0.0001	0.03052	0.0706	0.0338
20190823-3 4-5	0.012	0.006	0.0010	0.0001	0.21095	0.0870	0.0417
20190823-3 4-6	0.008	0.005	0.0010	0.0002	0.09275	0.0536	0.0424
20190823-3 4-8	0.007	0.003	0.0010	0.0001	0.12706	0.0499	0.0263
20190823-3 5-2	0.007	0.006	0.0009	0.0001	0.26435	0.1165	0.1170
20190823-3 5-4	0.008	0.006	0.0009	0.0002	0.02110	0.0877	0.0648
20190823-3 5-7	0.004	0.003	0.0011	0.0002	0.04565	0.0439	0.0403
20190823-3 5-9	0.008	0.005	0.0010	0.0002	0.04810	0.0619	0.0389
20190823-3 6-1	0.009	0.003	0.0011	0.0001	0.20722	0.0641	0.0223
20190823-3 6-2	0.005	0.005	0.0010	0.0002	0.35989	0.1800	0.2230
20190823-3 6-7	0.009	0.005	0.0012	0.0002	0.00107	0.0547	0.0319
20190823-3 7-1	0.006	0.003	0.0010	0.0001	0.05078	0.0398	0.0169
20190823-3 7-2	0.006	0.003	0.0010	0.0001	0.05206	0.0527	0.0338
20190823-3 7-3	0.007	0.005	0.0012	0.0002	0.06439	0.0741	0.0532
20190823-3 7-8	0.011	0.006	0.0010	0.0001	0.24623	0.0800	0.0552
20190823-3 8-2	0.017	0.009	0.0009	0.0002	0.13917	0.2042	0.1098
20190823-3 8-3	0.006	0.004	0.0010	0.0002	0.10129	0.0528	0.0409
20190823-3 8-5	0.002	0.005	0.0011	0.0003	0.41958	0.0798	0.0824
91500	1.854	0.216	0.1790	0.0058	0.03712	0.0754	0.0065
91500	1.838	0.222	0.1814	0.0054	0.20960	0.0737	0.0066
91500	1.857	0.225	0.1782	0.0041	0.11790	0.0756	0.0068
91500	1.853	0.222	0.1773	0.0045	0.08199	0.0752	0.0066
91500	1.832	0.211	0.1809	0.0049	0.21423	0.0739	0.0059
91500	1.915	0.232	0.1794	0.0046	0.03016	0.0785	0.0071
91500	1.794	0.219	0.1798	0.0055	0.02243	0.0716	0.0068
91500	1.868	0.225	0.1801	0.0047	0.23241	0.0758	0.0064
91500	1.910	0.242	0.1817	0.0047	0.06965	0.0768	0.0074
91500	1.804	0.212	0.1770	0.0038	0.02785	0.0725	0.0063
91500	1.884	0.226	0.1792	0.0041	0.14486	0.0762	0.0067
91500	1.859	0.219	0.1790	0.0039	0.21990	0.0759	0.0063
91500	1.813	0.235	0.1789	0.0046	0.33313	0.0734	0.0069
91500	1.860	0.234	0.1819	0.0045	0.12401	0.0740	0.0066
91500	1.841	0.218	0.1766	0.0045	0.17396	0.0755	0.0064

Table S3.5. Continued.

Sample no. Analysis ID	Isotopic Ratios						2σ (abs)
	²⁰⁷ Pb/ ²³⁵ U	2σ (abs)	²⁰⁶ Pb/ ²³⁸ U	2σ (abs)	r	²⁰⁷ Pb/ ²⁰⁶ Pb	
91500	1.889	0.235	0.1799	0.0045	0.39413	0.0761	0.0068
91500	1.821	0.219	0.1795	0.0045	0.42989	0.0736	0.0065
91500	1.871	0.223	0.1805	0.0044	0.29563	0.0755	0.0063
91500	1.814	0.239	0.1791	0.0044	0.18607	0.0732	0.0073
91500	1.881	0.240	0.1773	0.0038	0.08498	0.0770	0.0075
91500	1.833	0.233	0.1799	0.0044	0.08141	0.0738	0.0074
91500	1.849	0.222	0.1810	0.0052	0.20394	0.0746	0.0065
91500	1.849	0.225	0.1799	0.0042	0.56566	0.0748	0.0066
91500	1.883	0.256	0.1783	0.0047	0.29192	0.0770	0.0079
91500	1.837	0.223	0.1796	0.0046	0.01969	0.0740	0.0065
91500	1.872	0.246	0.1775	0.0053	0.09884	0.0761	0.0078
91500	1.826	0.217	0.1784	0.0044	0.12800	0.0737	0.0062
91500	1.906	0.247	0.1815	0.0046	0.15646	0.0776	0.0080
91500	1.838	0.224	0.1781	0.0049	0.02404	0.0743	0.0069
PL	0.365	0.042	0.0544	0.0012	0.23232	0.0486	0.0039
PL	0.395	0.046	0.0540	0.0010	0.33709	0.0529	0.0042
PL	0.411	0.048	0.0543	0.0013	0.16731	0.0548	0.0045
PL	0.396	0.045	0.0543	0.0011	0.10174	0.0527	0.0041
PL	0.386	0.044	0.0544	0.0011	0.22903	0.0516	0.0040
PL	0.380	0.044	0.0538	0.0011	0.00227	0.0518	0.0043
PL	0.439	0.052	0.0536	0.0012	0.16288	0.0584	0.0048
PL	0.396	0.044	0.0535	0.0010	0.30026	0.0541	0.0039
PL	0.405	0.047	0.0543	0.0010	0.02937	0.0538	0.0041
PL	0.412	0.049	0.0539	0.0012	0.03981	0.0536	0.0045
PL	0.396	0.045	0.0538	0.0011	0.17152	0.0532	0.0041
PL	0.401	0.046	0.0542	0.0011	0.07000	0.0538	0.0042
PL	0.415	0.048	0.0536	0.0011	0.07961	0.0563	0.0045
PL	0.401	0.046	0.0540	0.0011	0.05261	0.0546	0.0045
PL	0.369	0.045	0.0539	0.0011	0.17141	0.0495	0.0043
PL	0.358	0.043	0.0539	0.0011	0.11595	0.0483	0.0041
PL	0.398	0.047	0.0542	0.0011	0.14464	0.0530	0.0045
PL	0.410	0.048	0.0535	0.0011	0.10215	0.0559	0.0046
PL	0.404	0.047	0.0540	0.0010	0.16723	0.0548	0.0045
PL	0.386	0.046	0.0548	0.0012	0.19382	0.0507	0.0043
PL	0.399	0.046	0.0544	0.0011	0.20168	0.0528	0.0042
PL	0.400	0.046	0.0536	0.0012	0.09422	0.0546	0.0045
PL	0.381	0.043	0.0544	0.0011	0.08182	0.0513	0.0040
PL	0.402	0.047	0.0539	0.0012	0.09508	0.0545	0.0045
PL	0.416	0.048	0.0537	0.0011	0.28749	0.0559	0.0044
PL	0.424	0.049	0.0534	0.0011	0.11324	0.0569	0.0045
PL	0.430	0.049	0.0526	0.0011	0.17017	0.0588	0.0045
PL	0.376	0.045	0.0530	0.0011	0.02378	0.0521	0.0044
PL	0.389	0.046	0.0528	0.0010	0.12445	0.0528	0.0044
TEM	0.482	0.061	0.0681	0.0017	0.15333	0.0529	0.0058
TEM	0.509	0.072	0.0664	0.0022	0.29310	0.0556	0.0062
TEM	0.473	0.061	0.0662	0.0020	0.07039	0.0530	0.0058
TEM	0.525	0.067	0.0673	0.0020	0.02512	0.0571	0.0057
TEM	0.511	0.069	0.0658	0.0020	0.23180	0.0569	0.0064
TEM	0.467	0.092	0.0659	0.0029	0.10654	0.0515	0.0093
TEM	0.534	0.081	0.0665	0.0019	0.29297	0.0596	0.0080

Table S3.5. Continued.

Sample no.		Isotopic Ratios					
Analysis ID	$^{207}\text{Pb}/^{235}\text{U}$	2σ (abs)	$^{206}\text{Pb}/^{238}\text{U}$	2σ (abs)	r	$^{207}\text{Pb}/^{206}\text{Pb}$	2σ (abs)
TEM	0.525	0.075	0.0655	0.0019	0.00126	0.0571	0.0068
TEM	0.583	0.091	0.0665	0.0022	0.46962	0.0641	0.0080
TEM	0.521	0.072	0.0659	0.0020	0.23356	0.0576	0.0067
TEM	0.546	0.080	0.0658	0.0020	0.07211	0.0613	0.0076
TEM	0.483	0.074	0.0665	0.0021	0.03048	0.0529	0.0069
TEM	0.488	0.071	0.0657	0.0021	0.15823	0.0540	0.0069
TEM	0.534	0.075	0.0687	0.0024	0.16351	0.0569	0.0070
TEM	0.514	0.080	0.0659	0.0022	0.20560	0.0548	0.0072
TEM	0.524	0.077	0.0687	0.0020	0.15626	0.0552	0.0070
TEM	0.478	0.067	0.0669	0.0019	0.08960	0.0523	0.0060
TEM	0.514	0.091	0.0674	0.0022	0.17333	0.0560	0.0087
TEM	0.591	0.093	0.0674	0.0026	0.00986	0.0637	0.0086
TEM	0.487	0.071	0.0664	0.0022	0.06312	0.0533	0.0068
TEM	0.499	0.093	0.0667	0.0025	0.32951	0.0538	0.0083
TEM	0.437	0.072	0.0661	0.0025	0.17072	0.0512	0.0085
TEM	0.482	0.072	0.0657	0.0023	0.08388	0.0529	0.0068

Table S3.5. Continued.

Sample no.			
Analysis ID	U/Th	~U ppm	²⁰⁷ Pb/ ²³⁵ U
20190823-3 T-3	1.0113	374.0347	7.0
20190823-3 T-5	1.2260	303.2913	8.3
20190823-3 T-6	1.0433	331.5667	4.3
20190823-3 2-2	2.2961	95.0484	-0.8
20190823-3 2-3	2.0394	134.9393	3.2
20190823-3 2-4	1.3464	243.0284	8.6
20190823-3 2-5	0.9939	586.9195	6.5
20190823-3 3-2	1.5727	189.4248	4.9
20190823-3 3-3	1.2821	395.6135	6.5
20190823-3 3-5	2.3021	123.3936	5.5
20190823-3 3-6	1.3745	263.4932	7.7
20190823-3 3-7	1.3327	164.4284	23.4
20190823-3 4-1	1.1099	272.6672	11.0
20190823-3 4-2	2.2152	97.9186	9.7
20190823-3 4-3	2.2437	110.6340	12.1
20190823-3 4-4	0.9959	333.3709	9.2
20190823-3 4-5	1.1086	227.7373	12.2
20190823-3 4-6	1.4424	119.1574	7.6
20190823-3 4-8	1.2275	264.5058	6.8
20190823-3 5-2	2.1797	105.8926	7.2
20190823-3 5-4	2.2865	90.2727	7.7
20190823-3 5-7	1.6987	169.2341	4.0
20190823-3 5-9	1.3131	194.3244	8.5
20190823-3 6-1	0.9438	472.5932	9.4
20190823-3 6-2	2.2650	92.2173	4.6
20190823-3 6-7	1.1511	140.3291	9.2
20190823-3 7-1	1.0573	358.7041	6.2
20190823-3 7-2	1.4267	186.0247	6.2
20190823-3 7-3	1.3382	90.9680	6.5
20190823-3 7-8	1.5338	157.7695	10.9
20190823-3 8-2	2.3400	82.3076	16.7
20190823-3 8-3	2.2179	100.9933	6.0
20190823-3 8-5	1.6902	133.4567	1.8
91500	2.6646	80.0763	1059.7
91500	2.6709	79.7141	1052.1
91500	2.6652	80.3530	1058.8
91500	2.6662	79.7692	1067.7
91500	2.6672	80.0855	1052.8
91500	2.6671	79.9386	1078.8
91500	2.6690	79.8554	1036.0
91500	2.6581	80.5722	1072.7
91500	2.6812	79.2063	1074.7
91500	2.6516	80.8154	1049.7
91500	2.6791	79.5305	1068.8
91500	2.6624	80.2912	1070.1
91500	2.6667	79.7647	1038.5
91500	2.6676	80.1346	1057.7
91500	2.6675	79.8947	1054.4

Table S3.5. Continued.

Sample no.			
Analysis ID	U/Th	~U ppm	²⁰⁷ Pb/ ²³⁵ U
91500	2.6628	80.1044	1068.4
91500	2.6714	79.9614	1046.5
91500	2.6614	79.9082	1064.6
91500	2.6682	80.1629	1038.5
91500	2.6675	79.8152	1064.1
91500	2.6665	80.1553	1047.2
91500	2.6675	79.9253	1056.5
91500	2.6555	80.0998	1055.3
91500	2.6911	79.7956	1060.5
91500	2.6452	80.3577	1060.7
91500	2.6791	79.2413	1058.3
91500	2.6604	80.8089	1057.6
91500	2.6723	79.3675	1071.3
91500	2.6657	80.1430	1051.2
PL	9.8103	643.3270	315.2
PL	10.3145	665.9007	337.1
PL	10.4000	570.4720	348.5
PL	10.4264	562.0736	337.6
PL	9.9870	629.1626	330.8
PL	10.3166	622.8282	326.2
PL	10.3762	578.8969	368.5
PL	10.4323	578.3182	338.4
PL	10.2468	660.2397	344.7
PL	10.7416	500.9141	349.4
PL	10.2848	583.0015	338.1
PL	10.4046	580.2986	341.6
PL	10.4535	604.2192	351.5
PL	10.3395	581.7979	341.2
PL	10.3103	569.1113	317.7
PL	10.7616	485.2329	309.9
PL	10.4115	557.4214	339.0
PL	10.4092	566.3564	348.2
PL	10.1733	559.9008	347.3
PL	10.2441	602.1664	330.3
PL	10.1652	548.5615	339.9
PL	9.6870	628.8775	341.1
PL	9.0708	763.8076	327.4
PL	8.9257	832.6245	342.1
PL	9.4945	740.3937	352.3
PL	10.1385	645.3304	358.4
PL	10.5347	495.2255	362.3
PL	10.1290	634.1720	322.9
PL	9.6114	667.3374	332.7
TEM	1.8903	268.9137	405.7
TEM	2.3916	125.9033	412.7
TEM	2.0216	117.1233	396.4
TEM	1.8814	292.5793	427.1
TEM	2.0108	135.6408	414.8
TEM	3.7114	99.6055	383.0
TEM	1.9185	131.6374	427.6

Table S3.5. Continued.

Sample no.			
Analysis ID	U/Th	~U ppm	$^{207}\text{Pb}/^{235}\text{U}$
TEM	1.4425	150.6269	425.5
TEM	1.9217	131.6510	462.2
TEM	2.0300	130.7787	429.4
TEM	1.9298	117.2155	435.7
TEM	3.0147	102.9023	393.2
TEM	1.8425	118.2429	398.2
TEM	2.0210	132.7593	431.0
TEM	1.9524	119.0048	414.2
TEM	2.2842	115.1478	422.4
TEM	1.9069	132.8036	392.9
TEM	3.2728	92.2763	412.6
TEM	2.5350	92.2615	462.1
TEM	3.6038	124.5238	397.3
TEM	3.5308	72.4244	403.0
TEM	3.3975	83.2012	370.1
TEM	3.4277	89.5481	393.9

Table S3.5. Continued.

Sample no. Analysis ID	2σ (Ma)	²⁰⁶Pb/²³⁸U	Isotopic Ages		2σ (Ma)
			2σ (Ma)	²⁰⁷Pb/²⁰⁶Pb	
20190823-3 T-3	3.0	6.8	0.7	1362.1	422.8
20190823-3 T-5	4.0	7.5	0.8	2093.4	413.5
20190823-3 T-6	2.1	7.0	0.7	1579.9	504.8
20190823-3 2-2	0.1	7.0	1.2	3950.0	553.3
20190823-3 2-3	3.2	7.0	1.1	3173.0	688.8
20190823-3 2-4	4.0	6.7	0.9	2418.9	537.1
20190823-3 2-5	2.7	6.4	0.5	1767.2	472.1
20190823-3 3-2	4.0	7.5	1.0	2908.0	771.8
20190823-3 3-3	3.2	6.4	0.6	2013.3	542.8
20190823-3 3-5	4.2	6.7	1.3	2971.6	700.9
20190823-3 3-6	4.0	6.3	0.8	2065.7	336.4
20190823-3 3-7	10.6	8.4	1.3	3214.4	415.9
20190823-3 4-1	4.4	6.6	0.9	2195.2	483.9
20190823-3 4-2	6.6	6.5	1.3	3239.1	532.3
20190823-3 4-3	7.8	6.4	1.2	3177.2	631.5
20190823-3 4-4	4.1	6.8	0.7	2213.1	539.2
20190823-3 4-5	6.2	6.5	0.8	2600.8	525.1
20190823-3 4-6	5.2	6.7	1.2	3006.3	802.9
20190823-3 4-8	3.4	6.7	0.9	2072.3	533.8
20190823-3 5-2	5.9	5.9	0.9	3381.5	959.9
20190823-3 5-4	6.3	5.9	1.3	3377.8	761.2
20190823-3 5-7	3.2	6.8	1.1	2840.9	927.2
20190823-3 5-9	4.6	6.6	1.0	2584.9	577.3
20190823-3 6-1	3.2	6.9	0.6	1624.8	395.3
20190823-3 6-2	4.7	6.7	1.2	3646.2	600.4
20190823-3 6-7	4.9	7.5	1.0	2649.5	488.2
20190823-3 7-1	2.7	6.4	0.6	1493.2	457.9
20190823-3 7-2	3.4	6.2	0.9	2414.5	636.6
20190823-3 7-3	5.2	7.9	1.6	3581.6	462.0
20190823-3 7-8	6.4	6.4	1.0	2671.2	673.8
20190823-3 8-2	9.0	5.9	1.1	3419.1	690.9
20190823-3 8-3	4.3	6.7	1.1	3241.1	463.3
20190823-3 8-5	4.8	7.4	2.1	3760.6	718.7
91500	79.3	1060.7	31.6	1039.0	171.4
91500	80.7	1074.0	29.4	986.6	179.1
91500	79.1	1057.1	22.5	1032.6	186.2
91500	71.2	1057.2	28.0	1060.7	169.5
91500	74.8	1071.8	26.6	1011.7	164.4
91500	81.1	1063.2	24.9	1111.5	178.5
91500	80.0	1065.7	29.9	944.3	177.9
91500	88.0	1067.3	25.4	1071.8	197.5
91500	82.8	1075.8	25.4	1080.1	184.3
91500	84.9	1050.5	20.8	956.7	178.6
91500	79.3	1062.6	22.6	1053.5	180.7
91500	69.1	1061.3	21.3	1085.9	152.9
91500	84.4	1060.9	25.1	994.1	188.7
91500	81.9	1077.2	24.7	1050.1	190.4
91500	78.2	1047.9	24.5	1042.1	175.7

Table S3.5. Continued.

Sample no.		Isotopic Ages			
Analysis ID	2 σ (Ma)	²⁰⁶ Pb/ ²³⁸ U	2 σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb	2 σ (Ma)
91500	84.0	1066.2	24.7	1077.9	176.9
91500	79.6	1064.1	24.5	979.4	189.6
91500	81.4	1069.6	23.8	1042.2	182.2
91500	83.6	1061.9	23.9	1001.4	181.5
91500	83.6	1052.1	20.7	1090.2	179.9
91500	81.1	1066.0	24.2	992.1	188.5
91500	80.1	1071.8	28.4	1016.2	175.5
91500	82.8	1066.0	23.2	1014.0	188.2
91500	86.7	1057.4	25.5	1074.5	191.0
91500	90.0	1064.4	25.2	1076.8	187.7
91500	88.6	1053.0	29.0	1051.6	201.8
91500	86.3	1057.8	24.3	1018.5	191.1
91500	88.5	1075.0	25.4	1128.9	187.5
91500	81.0	1056.1	26.6	1022.2	179.9
PL	31.5	341.2	7.6	339.5	127.3
PL	33.6	339.3	6.4	436.2	137.5
PL	34.9	340.9	7.9	444.6	157.2
PL	32.8	340.6	6.9	413.0	169.0
PL	32.5	341.4	7.0	366.2	133.9
PL	32.9	337.8	7.0	399.9	139.5
PL	36.2	336.7	7.2	580.0	154.2
PL	32.1	335.9	6.3	406.9	141.8
PL	33.6	340.7	6.4	432.7	134.4
PL	35.0	338.3	7.2	437.0	139.7
PL	32.7	337.8	6.5	413.5	145.3
PL	32.7	340.3	6.9	395.4	161.9
PL	34.3	336.7	6.8	533.6	140.6
PL	33.9	338.9	6.7	455.4	150.2
PL	33.5	338.4	6.7	410.4	128.3
PL	31.8	338.2	6.7	404.2	134.9
PL	33.8	340.3	6.9	395.8	153.5
PL	34.8	336.3	6.5	521.0	148.1
PL	37.7	338.8	6.3	494.5	151.4
PL	34.1	344.1	7.2	367.8	131.9
PL	33.9	341.4	6.9	385.2	137.2
PL	33.2	336.8	7.1	460.0	148.8
PL	31.6	341.7	6.6	363.3	162.5
PL	34.0	338.2	7.2	480.1	144.2
PL	34.5	337.2	6.5	485.8	150.3
PL	34.9	335.7	6.7	543.3	144.1
PL	34.5	330.6	6.8	550.6	160.7
PL	33.0	332.8	6.8	471.8	145.5
PL	33.7	331.7	6.4	451.2	150.3
TEM	50.8	424.7	10.5	450.4	188.5
TEM	49.9	414.2	13.1	711.4	154.3
TEM	46.9	413.4	12.3	565.7	189.1
TEM	44.2	420.1	12.3	574.6	176.1
TEM	47.9	410.7	12.0	689.9	159.3
TEM	66.6	411.6	17.3	633.7	182.6
TEM	53.6	415.1	11.4	809.6	203.7

Table S3.5. Continued.

Sample no.		Isotopic Ages			
Analysis ID	2 σ (Ma)	²⁰⁶ Pb/ ²³⁸ U	2 σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb	2 σ (Ma)
TEM	50.0	408.7	11.6	670.3	184.5
TEM	58.2	414.8	13.3	788.7	210.9
TEM	53.7	411.6	12.2	695.3	221.4
TEM	53.2	411.0	12.3	827.4	182.4
TEM	52.0	415.1	12.8	638.5	190.8
TEM	48.4	410.0	12.5	665.0	194.0
TEM	48.6	428.4	14.6	610.8	228.0
TEM	53.4	411.5	13.0	826.7	221.1
TEM	51.8	428.3	12.0	663.8	185.0
TEM	45.6	417.4	11.5	637.2	183.6
TEM	60.6	420.5	13.4	908.0	228.6
TEM	59.1	420.3	15.9	953.3	203.3
TEM	49.5	414.2	13.4	617.5	197.6
TEM	62.1	415.9	15.1	680.0	215.7
TEM	56.3	412.2	15.2	731.7	250.5
TEM	49.0	410.2	13.9	709.0	199.4

Table S3.6. Zircon Trace Element Geochemistry (data from the laser experiment; calibration data excluded).

Sample no.						
Analysis ID	Zr90_CPS	Zr90_CPS_2s	Li7_ppm	Li7_ppm_2s	Si29_ppm	Si29_ppm_2s
20190823-3						
20190823-3 T-3	1.98E+08	8.8E+06	4.45	0.56	1.69E+05	2.9E+03
20190823-3 T-5	2.03E+08	9.4E+06	3.46	0.53	1.67E+05	3.6E+03
20190823-3 T-6	2.04E+08	1.0E+07	2.42	0.43	1.68E+05	3.4E+03
20190823-3 2-2	2.09E+08	1.0E+07	2.46	0.62	1.65E+05	2.5E+03
20190823-3 2-3	2.06E+08	9.6E+06	2.61	0.56	1.65E+05	3.2E+03
20190823-3 2-4	2.08E+08	8.9E+06	5.25	0.52	1.66E+05	3.3E+03
20190823-3 2-5	2.06E+08	9.3E+06	6.38	0.61	1.66E+05	3.5E+03
20190823-3 3-1	2.10E+08	9.6E+06	1.95	0.43	1.61E+05	3.0E+03
20190823-3 3-2	2.04E+08	9.0E+06	2.92	0.59	1.65E+05	3.2E+03
20190823-3 3-3	2.05E+08	8.7E+06	2.89	0.48	1.67E+05	3.2E+03
20190823-3 3-5	2.09E+08	1.0E+07	1.84	0.35	1.66E+05	2.9E+03
20190823-3 3-6	2.03E+08	1.1E+07	2.88	0.50	1.64E+05	3.6E+03
20190823-3 3-7	1.96E+08	1.3E+07	5.95	0.73	1.66E+05	3.3E+03
20190823-3 4-1	2.07E+08	1.0E+07	4.30	0.53	1.66E+05	3.4E+03
20190823-3 4-2	2.04E+08	8.9E+06	1.75	0.49	1.65E+05	3.1E+03
20190823-3 4-3	2.07E+08	9.6E+06	2.02	0.48	1.64E+05	4.4E+03
20190823-3 4-4	2.06E+08	9.3E+06	2.89	0.46	1.67E+05	3.6E+03
20190823-3 4-5	2.01E+08	1.2E+07	2.25	0.55	1.68E+05	3.8E+03
20190823-3 4-6	2.04E+08	1.1E+07	2.38	0.55	1.66E+05	3.4E+03
20190823-3 4-8	1.97E+08	1.1E+07	8.76	0.62	1.68E+05	3.6E+03
20190823-3 5-2	2.07E+08	1.0E+07	1.59	0.42	1.63E+05	3.0E+03
20190823-3 5-4	2.07E+08	1.1E+07	1.44	0.45	1.67E+05	4.1E+03
20190823-3 5-7	2.01E+08	9.8E+06	1.59	0.54	1.64E+05	2.3E+03
20190823-3 5-9	1.97E+08	1.0E+07	3.42	0.58	1.67E+05	2.7E+03
20190823-3 6-1	2.01E+08	9.3E+06	3.88	0.56	1.70E+05	2.7E+03
20190823-3 6-2	2.03E+08	9.6E+06	1.45	0.56	1.66E+05	3.3E+03
20190823-3 6-4	2.04E+08	9.9E+06	6.19	0.62	1.69E+05	2.4E+03
20190823-3 6-7	2.00E+08	1.1E+07	1.64	0.33	1.63E+05	3.0E+03
20190823-3 7-1	2.02E+08	9.7E+06	5.76	0.65	1.67E+05	3.4E+03
20190823-3 7-2	2.03E+08	9.1E+06	1.80	0.46	1.67E+05	3.3E+03
20190823-3 7-3	2.06E+08	9.7E+06	1.59	0.42	1.66E+05	2.6E+03
20190823-3 7-4	2.01E+08	9.7E+06	1.91	0.40	1.64E+05	2.6E+03
20190823-3 7-8	2.07E+08	1.1E+07	2.99	0.54	1.63E+05	4.3E+03
20190823-3 8-2	2.05E+08	9.9E+06	1.49	0.45	1.65E+05	3.1E+03
20190823-3 8-3	2.03E+08	9.7E+06	1.57	0.43	1.65E+05	2.6E+03
20190823-3 8-5	2.22E+08	1.5E+07	4.68	0.74	1.62E+05	4.9E+03

Table S3.6. Continued.

Sample no.				
Analysis ID	P31_ppm	P31_ppm_2s	Ca43_ppm	Ca43_ppm_2s
20190823-3				
20190823-3 T-3	4.96E+02	4.4E+01	1.18E+02	1.5E+02
20190823-3 T-5	4.62E+02	4.2E+01	-6.04E+01	1.1E+02
20190823-3 T-6	5.49E+02	3.5E+01	3.55E+02	1.4E+02
20190823-3 2-2	1.94E+02	2.1E+01	5.49E+01	1.3E+02
20190823-3 2-3	3.40E+02	6.5E+01	1.22E+02	1.9E+02
20190823-3 2-4	3.84E+02	4.0E+01	6.83E+01	1.1E+02
20190823-3 2-5	1.76E+03	4.2E+02	2.83E+03	9.5E+02
20190823-3 3-1	2.06E+02	2.5E+01	6.30E+01	1.3E+02
20190823-3 3-2	7.49E+02	1.3E+02	1.21E+03	3.3E+02
20190823-3 3-3	5.15E+02	4.7E+01	2.66E+01	1.1E+02
20190823-3 3-5	2.47E+02	2.2E+01	4.63E+01	9.8E+01
20190823-3 3-6	4.33E+02	3.6E+01	1.06E+02	1.3E+02
20190823-3 3-7	5.46E+02	8.6E+01	-2.40E+01	1.0E+02
20190823-3 4-1	4.14E+02	2.9E+01	2.03E+01	1.0E+02
20190823-3 4-2	2.45E+02	2.8E+01	1.67E+02	1.4E+02
20190823-3 4-3	2.59E+02	2.6E+01	-9.38E+00	1.0E+02
20190823-3 4-4	5.76E+02	3.7E+01	2.76E+02	1.4E+02
20190823-3 4-5	3.37E+02	2.4E+01	7.36E-01	9.9E+01
20190823-3 4-6	2.18E+02	2.7E+01	5.34E+01	9.2E+01
20190823-3 4-8	5.91E+02	8.1E+01	-7.23E+00	1.1E+02
20190823-3 5-2	2.44E+02	2.9E+01	-9.26E+01	7.6E+01
20190823-3 5-4	2.67E+02	4.3E+01	6.58E+01	1.1E+02
20190823-3 5-7	3.34E+02	2.1E+01	4.30E+01	1.2E+02
20190823-3 5-9	7.06E+02	1.2E+02	6.04E+02	2.9E+02
20190823-3 6-1	1.41E+03	4.7E+02	2.20E+03	1.3E+03
20190823-3 6-2	2.49E+02	2.3E+01	-1.56E+01	8.4E+01
20190823-3 6-4	3.11E+02	2.5E+01	-3.69E+01	8.3E+01
20190823-3 6-7	2.76E+02	2.4E+01	5.23E+01	9.2E+01
20190823-3 7-1	6.18E+02	3.3E+01	1.03E+00	9.9E+01
20190823-3 7-2	5.06E+02	8.3E+01	4.77E+02	2.6E+02
20190823-3 7-3	3.03E+02	1.7E+01	-4.56E+01	8.5E+01
20190823-3 7-4	3.29E+02	2.8E+01	1.24E+02	1.0E+02
20190823-3 7-8	1.62E+03	6.7E+02	3.86E+03	2.1E+03
20190823-3 8-2	2.00E+02	2.3E+01	-2.39E+01	9.3E+01
20190823-3 8-3	2.62E+02	2.5E+01	5.09E+01	1.0E+02
20190823-3 8-5	2.29E+02	3.6E+01	-1.13E+02	8.4E+01

Table S3.6. Continued.

Sample no.						
Analysis ID	Sc45_ppm	Sc45_ppm_2s	Ti49_ppm	Ti49_ppm_2s	Fe56_ppm	Fe56_ppm_2s
20190823-3						
20190823-3 T-3	3.79E+02	8.0	1.24E+01	2.4	3.47E+02	3.2E+01
20190823-3 T-5	3.63E+02	7.0	1.30E+01	3.4	3.72E+02	1.3E+02
20190823-3 T-6	3.68E+02	6.0	1.17E+01	2.2	2.62E+02	4.0E+01
20190823-3 2-2	3.66E+02	7.5	5.51E+00	1.6	1.64E+01	3.5E+00
20190823-3 2-3	3.67E+02	7.8	6.43E+00	1.9	6.53E+01	1.1E+01
20190823-3 2-4	3.69E+02	6.8	9.28E+00	2.1	3.23E+02	3.5E+01
20190823-3 2-5	3.62E+02	5.9	8.31E+00	1.6	1.36E+02	3.5E+01
20190823-3 3-1	4.16E+02	8.4	3.07E+01	3.8	2.21E+01	3.2E+00
20190823-3 3-2	3.63E+02	6.3	8.74E+00	2.1	2.29E+02	3.2E+01
20190823-3 3-3	3.64E+02	5.6	5.61E+00	1.7	2.55E+02	3.5E+01
20190823-3 3-5	3.64E+02	7.4	7.54E+00	2.3	1.25E+01	3.0E+00
20190823-3 3-6	3.58E+02	6.0	9.75E+00	2.4	3.04E+02	6.5E+01
20190823-3 3-7	3.76E+02	5.6	1.21E+01	1.9	7.92E+02	4.1E+02
20190823-3 4-1	3.65E+02	6.3	9.51E+00	2.2	2.26E+02	1.0E+01
20190823-3 4-2	3.60E+02	7.3	7.46E+00	2.1	9.47E+00	2.4E+00
20190823-3 4-3	3.53E+02	7.6	5.71E+00	1.6	-2.29E+00	3.0E+00
20190823-3 4-4	3.67E+02	9.9	1.74E+01	3.3	1.33E+03	8.6E+02
20190823-3 4-5	3.58E+02	6.3	1.08E+01	2.5	7.72E+01	1.5E+01
20190823-3 4-6	3.54E+02	6.3	5.22E+00	1.6	4.57E+01	7.4E+00
20190823-3 4-8	3.62E+02	8.1	1.16E+01	3.0	1.93E+02	3.5E+01
20190823-3 5-2	3.52E+02	4.8	6.73E+00	1.6	-1.59E+00	2.7E+00
20190823-3 5-4	3.53E+02	5.6	6.19E+00	2.0	3.94E+01	2.1E+01
20190823-3 5-7	3.53E+02	8.2	7.02E+00	1.9	1.07E+01	2.2E+00
20190823-3 5-9	3.51E+02	5.0	1.31E+01	3.4	3.09E+02	5.0E+01
20190823-3 6-1	3.69E+02	6.8	1.08E+01	2.2	2.47E+02	5.8E+01
20190823-3 6-2	3.50E+02	7.0	5.70E+00	1.4	2.62E+00	2.9E+00
20190823-3 6-4	3.63E+02	6.6	1.10E+01	2.2	1.04E+02	7.1E+00
20190823-3 6-7	3.53E+02	6.8	1.11E+01	2.2	3.41E+01	5.4E+00
20190823-3 7-1	3.56E+02	4.9	1.05E+01	1.9	2.46E+02	1.3E+01
20190823-3 7-2	3.52E+02	6.3	8.22E+00	2.0	2.24E+02	3.4E+01
20190823-3 7-3	3.67E+02	5.7	1.80E+01	2.7	2.89E+01	5.8E+00
20190823-3 7-4	3.57E+02	5.3	8.51E+00	2.3	2.83E+01	1.5E+01
20190823-3 7-8	3.49E+02	6.2	1.48E+01	2.7	1.50E+02	1.4E+01
20190823-3 8-2	3.49E+02	5.5	7.23E+00	1.9	4.45E+00	2.7E+00
20190823-3 8-3	3.53E+02	5.7	7.16E+00	1.8	1.04E+01	3.4E+00
20190823-3 8-5	3.59E+02	9.4	6.29E+00	2.1	1.14E+02	2.4E+01

Table S3.6. Continued.

Sample no.				
Analysis ID	Fe57_ppm	Fe57_ppm_2s	Y89_ppm	Y89_ppm_2s
20190823-3				
20190823-3 T-3	9.68E+01	1.1E+01	7.01E+03	2.3E+02
20190823-3 T-5	9.93E+01	3.0E+01	5.70E+03	3.1E+02
20190823-3 T-6	8.31E+01	1.4E+01	5.50E+03	7.7E+01
20190823-3 2-2	4.62E+00	2.8E+00	1.41E+03	2.0E+01
20190823-3 2-3	1.68E+01	3.8E+00	2.26E+03	5.6E+01
20190823-3 2-4	1.03E+02	1.2E+01	6.50E+03	3.7E+02
20190823-3 2-5	4.43E+01	1.3E+01	8.08E+03	2.1E+02
20190823-3 3-1	9.22E+00	2.6E+00	1.94E+03	2.5E+01
20190823-3 3-2	6.53E+01	8.2E+00	3.61E+03	1.6E+02
20190823-3 3-3	7.93E+01	1.2E+01	8.39E+03	6.1E+02
20190823-3 3-5	4.56E+00	2.6E+00	1.57E+03	1.3E+01
20190823-3 3-6	9.90E+01	2.1E+01	7.25E+03	4.8E+02
20190823-3 3-7	3.03E+02	1.6E+02	5.88E+03	2.9E+02
20190823-3 4-1	7.90E+01	7.8E+00	3.84E+03	7.3E+01
20190823-3 4-2	3.06E+00	2.7E+00	1.34E+03	1.9E+01
20190823-3 4-3	1.32E-02	2.1E+00	1.44E+03	2.2E+01
20190823-3 4-4	5.57E+02	4.4E+02	3.89E+03	1.1E+02
20190823-3 4-5	3.05E+01	8.5E+00	3.43E+03	1.0E+02
20190823-3 4-6	2.05E+01	3.7E+00	3.09E+03	2.4E+02
20190823-3 4-8	6.97E+01	1.4E+01	9.07E+03	8.2E+02
20190823-3 5-2	1.94E+00	2.5E+00	1.39E+03	1.7E+01
20190823-3 5-4	1.58E+01	8.1E+00	1.34E+03	2.0E+01
20190823-3 5-7	5.43E+00	2.3E+00	2.21E+03	3.4E+01
20190823-3 5-9	1.14E+02	1.9E+01	6.84E+03	5.3E+02
20190823-3 6-1	8.44E+01	2.1E+01	7.71E+03	2.1E+02
20190823-3 6-2	1.09E+00	2.5E+00	1.47E+03	1.7E+01
20190823-3 6-4	3.90E+01	5.4E+00	5.54E+03	1.6E+02
20190823-3 6-7	9.72E+00	3.3E+00	2.20E+03	1.4E+02
20190823-3 7-1	9.69E+01	9.6E+00	9.96E+03	2.9E+02
20190823-3 7-2	8.95E+01	1.5E+01	5.61E+03	4.3E+02
20190823-3 7-3	1.45E+01	6.4E+00	1.92E+03	1.1E+02
20190823-3 7-4	1.29E+01	6.3E+00	2.07E+03	8.0E+01
20190823-3 7-8	5.99E+01	7.3E+00	4.35E+03	1.8E+02
20190823-3 8-2	1.48E+00	2.9E+00	1.26E+03	2.6E+01
20190823-3 8-3	3.76E+00	2.4E+00	1.45E+03	1.6E+01
20190823-3 8-5	4.87E+01	9.6E+00	3.81E+03	5.3E+02

Table S3.6. Continued.

Sample no.						
Analysis ID	Zr91_ppm	Zr91_ppm_2s	Nb93_ppm	Nb93_ppm_2s	Mo95_ppm	Mo95_ppm_2s
20190823-3						
20190823-3 T-3	4.90E+05	7.2E+03	5.70E+01	3.5E+00	3.94E+00	6.2E-01
20190823-3 T-5	4.85E+05	4.5E+03	4.59E+01	5.5E+00	4.31E+00	6.5E-01
20190823-3 T-6	4.90E+05	7.1E+03	5.15E+01	1.8E+00	3.98E+00	8.7E-01
20190823-3 2-2	4.90E+05	6.1E+03	1.60E+01	5.8E-01	3.92E+00	6.8E-01
20190823-3 2-3	4.94E+05	6.3E+03	1.46E+01	6.2E-01	3.10E+00	5.2E-01
20190823-3 2-4	4.96E+05	5.8E+03	2.51E+01	2.1E+00	3.75E+00	6.2E-01
20190823-3 2-5	4.97E+05	4.8E+03	1.22E+02	7.7E+00	3.04E+00	5.8E-01
20190823-3 3-1	4.98E+05	4.5E+03	1.69E+00	1.3E-01	3.49E+00	6.0E-01
20190823-3 3-2	5.00E+05	4.6E+03	2.24E+01	3.7E+00	3.22E+00	5.5E-01
20190823-3 3-3	5.00E+05	4.2E+03	4.40E+01	2.7E+00	3.30E+00	7.0E-01
20190823-3 3-5	5.01E+05	4.8E+03	2.23E+01	6.8E-01	2.88E+00	5.3E-01
20190823-3 3-6	5.03E+05	4.7E+03	2.67E+01	2.1E+00	3.25E+00	5.3E-01
20190823-3 3-7	5.04E+05	3.9E+03	1.63E+01	9.4E-01	2.96E+00	6.6E-01
20190823-3 4-1	4.99E+05	6.2E+03	4.11E+01	2.2E+00	3.09E+00	5.0E-01
20190823-3 4-2	5.06E+05	4.8E+03	1.77E+01	7.1E-01	3.12E+00	5.1E-01
20190823-3 4-3	5.08E+05	5.4E+03	1.98E+01	7.0E-01	2.88E+00	5.3E-01
20190823-3 4-4	5.09E+05	7.2E+03	5.50E+01	1.9E+00	4.14E+00	1.1E+00
20190823-3 4-5	5.04E+05	4.1E+03	3.20E+01	1.3E+00	2.77E+00	6.1E-01
20190823-3 4-6	5.07E+05	4.3E+03	1.50E+01	9.1E-01	2.87E+00	5.9E-01
20190823-3 4-8	5.08E+05	5.7E+03	3.30E+01	3.6E+00	2.62E+00	5.8E-01
20190823-3 5-2	5.04E+05	6.1E+03	1.98E+01	5.7E-01	1.98E+00	4.1E-01
20190823-3 5-4	5.11E+05	6.1E+03	1.89E+01	7.9E-01	2.54E+00	5.2E-01
20190823-3 5-7	5.03E+05	5.3E+03	3.30E+01	7.0E-01	2.07E+00	4.4E-01
20190823-3 5-9	5.07E+05	4.4E+03	2.71E+01	2.9E+00	2.29E+00	5.0E-01
20190823-3 6-1	5.07E+05	4.7E+03	9.66E+01	3.8E+00	1.93E+00	5.2E-01
20190823-3 6-2	5.06E+05	4.6E+03	1.87E+01	5.3E-01	2.07E+00	5.1E-01
20190823-3 6-4	5.07E+05	5.5E+03	1.72E+01	9.7E-01	2.18E+00	4.7E-01
20190823-3 6-7	5.04E+05	6.0E+03	2.02E+01	1.2E+00	1.64E+00	3.8E-01
20190823-3 7-1	5.03E+05	5.8E+03	5.37E+01	2.6E+00	2.44E+00	4.5E-01
20190823-3 7-2	5.01E+05	4.1E+03	2.30E+01	1.8E+00	1.91E+00	4.6E-01
20190823-3 7-3	5.05E+05	4.8E+03	8.22E+00	5.3E-01	1.72E+00	3.9E-01
20190823-3 7-4	5.06E+05	5.0E+03	2.79E+01	1.2E+00	1.73E+00	5.1E-01
20190823-3 7-8	5.02E+05	6.6E+03	2.56E+01	6.0E+00	2.15E+00	6.8E-01
20190823-3 8-2	5.05E+05	5.6E+03	1.57E+01	5.3E-01	1.62E+00	3.6E-01
20190823-3 8-3	5.05E+05	5.8E+03	1.89E+01	5.3E-01	1.87E+00	4.6E-01
20190823-3 8-5	4.98E+05	7.5E+03	1.18E+01	2.5E+00	1.55E+00	5.1E-01

Table S3.6. Continued.

Sample no.				
Analysis ID	Mo98_ppm	Mo98_ppm_2s	La139_ppm	La139_ppm_2s
20190823-3				
20190823-3 T-3	-9.25E-05	3.9E-06	7.57E-01	1.8E-01
20190823-3 T-5	-9.18E-05	4.0E-06	9.52E-01	3.5E-01
20190823-3 T-6	1.38E-02	2.7E-02	4.62E+00	9.5E-01
20190823-3 2-2	-8.77E-05	4.2E-06	3.12E-03	4.4E-03
20190823-3 2-3	-8.80E-05	3.9E-06	5.58E+00	4.4E+00
20190823-3 2-4	-8.78E-05	3.6E-06	9.34E-01	2.4E-01
20190823-3 2-5	1.17E-02	2.3E-02	6.49E+01	2.3E+01
20190823-3 3-1	-8.61E-05	3.9E-06	3.71E-02	2.2E-02
20190823-3 3-2	-8.86E-05	3.9E-06	2.69E+01	8.4E+00
20190823-3 3-3	1.08E-02	2.2E-02	1.94E+00	4.6E-01
20190823-3 3-5	-8.64E-05	4.1E-06	3.72E-03	5.2E-03
20190823-3 3-6	-8.93E-05	4.7E-06	8.28E-01	2.0E-01
20190823-3 3-7	1.51E-02	3.0E-02	2.87E+00	1.4E+00
20190823-3 4-1	-8.61E-05	4.1E-06	2.89E-02	1.8E-02
20190823-3 4-2	-8.68E-05	3.7E-06	2.56E-02	1.2E-02
20190823-3 4-3	-8.54E-05	4.0E-06	-4.18E-05	1.9E-06
20190823-3 4-4	1.20E+00	9.3E-01	1.91E+01	3.6E+00
20190823-3 4-5	1.37E-01	1.2E-01	3.55E-02	2.4E-02
20190823-3 4-6	-8.66E-05	4.5E-06	4.20E-02	2.2E-02
20190823-3 4-8	9.71E-03	1.9E-02	2.72E-01	7.3E-02
20190823-3 5-2	-8.48E-05	4.0E-06	2.70E-01	3.4E-01
20190823-3 5-4	-8.38E-05	4.1E-06	1.11E+00	6.5E-01
20190823-3 5-7	-8.67E-05	4.1E-06	3.08E-03	4.4E-03
20190823-3 5-9	1.16E-02	2.3E-02	9.90E+00	4.3E+00
20190823-3 6-1	-8.61E-05	3.8E-06	5.14E+01	2.9E+01
20190823-3 6-2	-8.55E-05	3.9E-06	5.87E-03	6.5E-03
20190823-3 6-4	2.49E-02	3.4E-02	9.06E-02	2.5E-02
20190823-3 6-7	-8.69E-05	4.4E-06	1.51E+00	2.7E-01
20190823-3 7-1	-8.52E-05	3.9E-06	1.92E-01	4.9E-02
20190823-3 7-2	-8.42E-05	3.8E-06	8.04E+00	3.3E+00
20190823-3 7-3	-8.27E-05	3.9E-06	2.49E-02	1.5E-02
20190823-3 7-4	-8.47E-05	4.1E-06	1.54E+00	3.7E-01
20190823-3 7-8	4.01E-02	5.5E-02	4.85E+01	2.6E+01
20190823-3 8-2	-8.28E-05	3.9E-06	3.03E-02	3.4E-02
20190823-3 8-3	-8.32E-05	4.0E-06	3.71E+00	1.1E+00
20190823-3 8-5	-8.93E-05	2.5E-05	1.44E-02	1.4E-02

Table S3.6. Continued.

Sample no.						
Analysis ID	Ce140_ppm	Ce140_ppm_2s	Pr141_ppm	Pr141_ppm_2s	Nd146_ppm	Nd146_ppm_2s
20190823-3						
20190823-3 T-3	4.52E+01	3.0E+00	1.02E+00	1.4E-01	1.76E+01	1.4E+00
20190823-3 T-5	4.08E+01	5.0E+00	9.69E-01	1.3E-01	1.29E+01	1.1E+00
20190823-3 T-6	4.84E+01	2.9E+00	2.61E+00	4.9E-01	2.13E+01	2.2E+00
20190823-3 2-2	1.18E+01	4.3E-01	6.76E-02	2.7E-02	1.74E+00	2.9E-01
20190823-3 2-3	2.82E+01	1.2E+01	1.85E+00	1.5E+00	1.15E+01	6.6E+00
20190823-3 2-4	2.47E+01	2.4E+00	1.24E+00	1.9E-01	1.81E+01	1.8E+00
20190823-3 2-5	2.92E+02	6.4E+01	2.97E+01	1.0E+01	1.59E+02	5.2E+01
20190823-3 3-1	1.33E+00	1.3E-01	2.21E-01	5.5E-02	4.25E+00	5.3E-01
20190823-3 3-2	9.02E+01	2.2E+01	1.10E+01	3.4E+00	6.03E+01	1.7E+01
20190823-3 3-3	6.15E+01	4.2E+00	2.04E+00	2.2E-01	2.33E+01	1.6E+00
20190823-3 3-5	1.45E+01	4.9E-01	4.96E-02	2.8E-02	1.64E+00	3.4E-01
20190823-3 3-6	2.78E+01	1.8E+00	1.22E+00	1.6E-01	1.96E+01	2.1E+00
20190823-3 3-7	1.78E+02	8.1E+01	4.85E+00	1.9E+00	4.38E+01	1.3E+01
20190823-3 4-1	2.89E+01	1.7E+00	3.28E-01	5.3E-02	7.69E+00	6.5E-01
20190823-3 4-2	1.39E+01	4.9E-01	7.64E-02	3.2E-02	1.68E+00	3.5E-01
20190823-3 4-3	1.41E+01	3.8E-01	9.09E-02	3.1E-02	1.63E+00	3.4E-01
20190823-3 4-4	9.71E+01	1.2E+01	9.19E+00	1.8E+00	5.29E+01	9.7E+00
20190823-3 4-5	2.16E+01	7.5E-01	3.74E-01	6.5E-02	5.76E+00	6.7E-01
20190823-3 4-6	2.02E+01	1.4E+00	3.91E-01	7.3E-02	7.27E+00	9.8E-01
20190823-3 4-8	3.46E+01	4.3E+00	1.59E+00	2.3E-01	2.82E+01	3.3E+00
20190823-3 5-2	1.59E+01	1.1E+00	2.81E-01	2.2E-01	2.54E+00	1.1E+00
20190823-3 5-4	1.85E+01	2.5E+00	6.04E-01	3.3E-01	3.88E+00	1.5E+00
20190823-3 5-7	2.52E+01	6.8E-01	9.27E-02	3.5E-02	2.67E+00	5.0E-01
20190823-3 5-9	5.20E+01	1.1E+01	5.24E+00	1.8E+00	4.01E+01	8.9E+00
20190823-3 6-1	2.23E+02	8.3E+01	2.28E+01	1.3E+01	1.31E+02	6.5E+01
20190823-3 6-2	1.34E+01	4.2E-01	1.04E-01	3.3E-02	1.82E+00	3.5E-01
20190823-3 6-4	1.65E+01	7.8E-01	6.23E-01	8.9E-02	1.28E+01	9.6E-01
20190823-3 6-7	1.78E+01	1.1E+00	8.02E-01	1.4E-01	6.04E+00	7.2E-01
20190823-3 7-1	6.63E+01	4.0E+00	1.31E+00	1.2E-01	2.35E+01	1.7E+00
20190823-3 7-2	4.78E+01	9.4E+00	4.55E+00	1.6E+00	3.36E+01	9.0E+00
20190823-3 7-3	5.38E+00	1.9E-01	2.19E-01	4.0E-02	3.62E+00	5.4E-01
20190823-3 7-4	2.96E+01	4.7E+00	7.13E-01	1.4E-01	6.40E+00	9.9E-01
20190823-3 7-8	1.61E+02	7.5E+01	2.22E+01	1.2E+01	1.20E+02	6.0E+01
20190823-3 8-2	1.19E+01	4.9E-01	7.12E-02	3.1E-02	1.78E+00	3.6E-01
20190823-3 8-3	2.53E+01	3.1E+00	1.74E+00	5.1E-01	1.05E+01	2.8E+00
20190823-3 8-5	1.45E+01	1.5E+00	4.15E-01	1.2E-01	7.23E+00	1.6E+00

Table S3.6. Continued.

Sm147_ppm	Sm_ppm_2s	Eu153_ppm	Eu153_ppm_2s	Gd157_ppm	Gd157_ppm_2s
4.11E+01	2.5E+00	1.08E+01	6.5E-01	2.28E+02	1.1E+01
2.66E+01	2.5E+00	7.33E+00	5.6E-01	1.68E+02	1.2E+01
3.00E+01	1.3E+00	7.94E+00	4.6E-01	1.71E+02	5.0E+00
4.63E+00	6.6E-01	1.15E+00	1.6E-01	3.21E+01	1.7E+00
1.12E+01	2.4E+00	1.98E+00	3.0E-01	5.58E+01	3.5E+00
3.97E+01	3.1E+00	9.04E+00	7.3E-01	2.07E+02	1.3E+01
7.39E+01	1.3E+01	1.18E+01	1.3E+00	2.64E+02	1.7E+01
1.03E+01	7.2E-01	4.92E+00	2.9E-01	6.07E+01	1.7E+00
2.87E+01	4.2E+00	4.43E+00	3.3E-01	1.14E+02	5.7E+00
4.55E+01	4.4E+00	1.06E+01	1.1E+00	2.57E+02	2.2E+01
5.53E+00	5.3E-01	1.06E+00	1.3E-01	3.49E+01	1.9E+00
4.16E+01	3.6E+00	1.16E+01	9.0E-01	2.39E+02	1.9E+01
5.68E+01	1.1E+01	1.19E+01	1.1E+00	2.27E+02	2.2E+01
1.54E+01	1.2E+00	4.00E+00	3.4E-01	9.94E+01	3.6E+00
4.59E+00	4.5E-01	1.12E+00	1.3E-01	3.01E+01	1.6E+00
4.84E+00	4.8E-01	1.10E+00	1.3E-01	3.18E+01	1.3E+00
2.75E+01	3.4E+00	5.52E+00	4.9E-01	1.20E+02	5.6E+00
1.41E+01	8.6E-01	4.51E+00	4.2E-01	9.45E+01	4.4E+00
1.67E+01	1.8E+00	3.65E+00	3.7E-01	8.99E+01	8.4E+00
6.20E+01	7.0E+00	1.69E+01	2.0E+00	3.20E+02	3.3E+01
4.60E+00	5.9E-01	1.03E+00	1.5E-01	3.25E+01	1.9E+00
5.22E+00	7.9E-01	1.20E+00	1.6E-01	3.07E+01	1.2E+00
7.44E+00	6.7E-01	1.60E+00	2.1E-01	4.99E+01	1.9E+00
4.74E+01	3.8E+00	1.17E+01	1.0E+00	2.29E+02	1.8E+01
6.88E+01	1.7E+01	1.21E+01	1.7E+00	2.66E+02	1.9E+01
5.56E+00	7.6E-01	1.36E+00	2.0E-01	3.29E+01	1.6E+00
3.05E+01	2.0E+00	7.78E+00	3.7E-01	1.70E+02	6.1E+00
9.31E+00	1.1E+00	2.96E+00	3.2E-01	5.98E+01	4.8E+00
5.48E+01	3.2E+00	1.24E+01	7.1E-01	3.10E+02	1.2E+01
3.76E+01	4.3E+00	8.07E+00	8.7E-01	1.75E+02	1.6E+01
7.54E+00	9.1E-01	2.95E+00	2.9E-01	4.65E+01	3.6E+00
7.98E+00	8.5E-01	1.70E+00	2.2E-01	4.96E+01	2.9E+00
4.82E+01	1.5E+01	7.93E+00	1.6E+00	1.52E+02	1.8E+01
4.18E+00	5.0E-01	1.03E+00	1.6E-01	2.84E+01	1.5E+00
7.34E+00	9.9E-01	1.20E+00	1.8E-01	3.41E+01	1.6E+00
1.74E+01	3.3E+00	5.01E+00	1.0E+00	1.05E+02	1.8E+01

Table S3.6. Continued.

Sample no.						
Analysis ID	Tb159 ppm	Tb159_ ppm_2s	Dy163 ppm	Dy163_ ppm_2s	Ho165_ ppm	Ho165 ppm_2s
20190823-3						
20190823-3 T-3	7.03E+01	2.8E+00	7.98E+02	3.0E+01	2.66E+02	9.0E+00
20190823-3 T-5	5.41E+01	3.0E+00	6.25E+02	3.7E+01	2.12E+02	1.2E+01
20190823-3 T-6	5.41E+01	1.4E+00	6.07E+02	9.7E+00	2.10E+02	5.0E+00
20190823-3 2-2	1.14E+01	3.5E-01	1.39E+02	3.7E+00	5.11E+01	1.1E+00
20190823-3 2-3	1.88E+01	7.7E-01	2.24E+02	7.3E+00	8.33E+01	2.2E+00
20190823-3 2-4	6.45E+01	3.6E+00	7.22E+02	4.1E+01	2.42E+02	1.3E+01
20190823-3 2-5	7.98E+01	3.2E+00	8.95E+02	2.8E+01	3.00E+02	8.5E+00
20190823-3 3-1	1.87E+01	4.0E-01	2.08E+02	4.6E+00	7.04E+01	1.4E+00
20190823-3 3-2	3.45E+01	1.6E+00	3.87E+02	1.8E+01	1.35E+02	6.2E+00
20190823-3 3-3	8.16E+01	6.4E+00	9.37E+02	7.1E+01	3.18E+02	2.3E+01
20190823-3 3-5	1.23E+01	3.4E-01	1.52E+02	2.9E+00	5.76E+01	9.8E-01
20190823-3 3-6	7.22E+01	5.4E+00	8.18E+02	5.7E+01	2.76E+02	1.9E+01
20190823-3 3-7	6.37E+01	4.8E+00	6.73E+02	4.2E+01	2.18E+02	9.4E+00
20190823-3 4-1	3.42E+01	8.2E-01	4.03E+02	9.5E+00	1.42E+02	3.4E+00
20190823-3 4-2	1.03E+01	3.7E-01	1.30E+02	2.7E+00	4.86E+01	1.1E+00
20190823-3 4-3	1.12E+01	4.1E-01	1.42E+02	3.0E+00	5.26E+01	9.3E-01
20190823-3 4-4	3.65E+01	1.3E+00	4.15E+02	1.2E+01	1.46E+02	4.8E+00
20190823-3 4-5	3.06E+01	1.0E+00	3.60E+02	1.2E+01	1.27E+02	4.3E+00
20190823-3 4-6	2.94E+01	2.6E+00	3.30E+02	2.6E+01	1.14E+02	9.2E+00
20190823-3 4-8	9.49E+01	9.5E+00	1.03E+03	9.9E+01	3.46E+02	3.2E+01
20190823-3 5-2	1.12E+01	3.7E-01	1.36E+02	2.7E+00	5.01E+01	1.0E+00
20190823-3 5-4	1.04E+01	3.8E-01	1.28E+02	2.8E+00	4.86E+01	1.1E+00
20190823-3 5-7	1.78E+01	4.1E-01	2.15E+02	4.6E+00	7.99E+01	1.3E+00
20190823-3 5-9	6.84E+01	5.4E+00	7.56E+02	5.8E+01	2.55E+02	1.9E+01
20190823-3 6-1	7.68E+01	3.4E+00	8.43E+02	2.8E+01	2.87E+02	9.3E+00
20190823-3 6-2	1.18E+01	2.7E-01	1.44E+02	2.3E+00	5.49E+01	8.9E-01
20190823-3 6-4	5.28E+01	2.0E+00	5.92E+02	1.8E+01	2.04E+02	5.9E+00
20190823-3 6-7	1.95E+01	1.4E+00	2.26E+02	1.5E+01	8.17E+01	5.3E+00
20190823-3 7-1	9.72E+01	2.8E+00	1.08E+03	3.0E+01	3.67E+02	1.0E+01
20190823-3 7-2	5.46E+01	4.5E+00	6.03E+02	4.8E+01	2.06E+02	1.6E+01
20190823-3 7-3	1.54E+01	1.2E+00	1.84E+02	1.3E+01	6.81E+01	4.0E+00
20190823-3 7-4	1.67E+01	7.8E-01	2.05E+02	9.2E+00	7.50E+01	3.2E+00
20190823-3 7-8	4.21E+01	2.5E+00	4.51E+02	2.1E+01	1.58E+02	6.2E+00
20190823-3 8-2	9.94E+00	3.6E-01	1.21E+02	3.1E+00	4.55E+01	1.2E+00
20190823-3 8-3	1.10E+01	3.7E-01	1.39E+02	2.5E+00	5.28E+01	9.8E-01
20190823-3 8-5	3.37E+01	5.3E+00	3.76E+02	5.7E+01	1.33E+02	1.9E+01

Table S3.6. Continued.

Sample no.						
Analysis ID	Er166_ ppm	Er166_ ppm 2s	Tm169 ppm	Tm169_ ppm 2s	Yb172 ppm	Yb172_ ppm 2s
20190823-3						
20190823-3 T-3	1.06E+03	3.5E+01	1.90E+02	6.3E+00	1.53E+03	4.9E+01
20190823-3 T-5	8.55E+02	4.8E+01	1.52E+02	7.9E+00	1.24E+03	6.5E+01
20190823-3 T-6	8.48E+02	1.5E+01	1.53E+02	3.3E+00	1.25E+03	3.1E+01
20190823-3 2-2	2.28E+02	4.4E+00	4.33E+01	1.1E+00	3.78E+02	6.8E+00
20190823-3 2-3	3.63E+02	9.6E+00	6.96E+01	1.5E+00	5.78E+02	1.3E+01
20190823-3 2-4	1.01E+03	5.8E+01	1.79E+02	9.8E+00	1.46E+03	7.7E+01
20190823-3 2-5	1.22E+03	3.1E+01	2.13E+02	5.4E+00	1.72E+03	4.5E+01
20190823-3 3-1	3.03E+02	4.8E+00	5.59E+01	9.3E-01	4.95E+02	8.0E+00
20190823-3 3-2	5.58E+02	2.7E+01	9.99E+01	4.5E+00	8.07E+02	3.8E+01
20190823-3 3-3	1.29E+03	9.1E+01	2.27E+02	1.6E+01	1.81E+03	1.2E+02
20190823-3 3-5	2.59E+02	4.2E+00	5.02E+01	1.2E+00	4.37E+02	7.6E+00
20190823-3 3-6	1.12E+03	7.4E+01	1.97E+02	1.2E+01	1.59E+03	9.8E+01
20190823-3 3-7	8.79E+02	3.4E+01	1.57E+02	5.7E+00	1.30E+03	4.6E+01
20190823-3 4-1	5.96E+02	1.3E+01	1.09E+02	2.5E+00	8.87E+02	1.8E+01
20190823-3 4-2	2.22E+02	4.5E+00	4.28E+01	9.9E-01	3.67E+02	6.3E+00
20190823-3 4-3	2.38E+02	4.8E+00	4.58E+01	1.0E+00	3.91E+02	8.6E+00
20190823-3 4-4	6.01E+02	2.0E+01	1.08E+02	3.9E+00	8.91E+02	2.7E+01
20190823-3 4-5	5.27E+02	1.6E+01	9.54E+01	2.7E+00	7.90E+02	2.7E+01
20190823-3 4-6	4.79E+02	3.7E+01	8.58E+01	6.5E+00	6.91E+02	5.2E+01
20190823-3 4-8	1.39E+03	1.2E+02	2.43E+02	2.0E+01	1.95E+03	1.6E+02
20190823-3 5-2	2.29E+02	3.9E+00	4.41E+01	9.9E-01	3.80E+02	7.8E+00
20190823-3 5-4	2.17E+02	4.2E+00	4.24E+01	9.3E-01	3.65E+02	7.0E+00
20190823-3 5-7	3.51E+02	5.7E+00	6.59E+01	1.2E+00	5.64E+02	9.5E+00
20190823-3 5-9	1.04E+03	8.1E+01	1.83E+02	1.3E+01	1.49E+03	1.1E+02
20190823-3 6-1	1.16E+03	3.1E+01	2.05E+02	5.7E+00	1.66E+03	4.4E+01
20190823-3 6-2	2.42E+02	4.1E+00	4.60E+01	8.2E-01	4.00E+02	6.4E+00
20190823-3 6-4	8.61E+02	2.7E+01	1.54E+02	5.4E+00	1.28E+03	3.8E+01
20190823-3 6-7	3.44E+02	2.0E+01	6.38E+01	3.6E+00	5.27E+02	2.9E+01
20190823-3 7-1	1.51E+03	4.3E+01	2.65E+02	6.7E+00	2.07E+03	5.4E+01
20190823-3 7-2	8.56E+02	6.3E+01	1.52E+02	1.1E+01	1.22E+03	8.9E+01
20190823-3 7-3	3.06E+02	1.9E+01	5.79E+01	3.3E+00	5.09E+02	2.7E+01
20190823-3 7-4	3.29E+02	1.2E+01	6.16E+01	2.0E+00	5.29E+02	1.7E+01
20190823-3 7-8	6.61E+02	2.8E+01	1.18E+02	4.8E+00	9.71E+02	3.9E+01
20190823-3 8-2	2.09E+02	5.2E+00	3.98E+01	1.1E+00	3.46E+02	8.1E+00
20190823-3 8-3	2.36E+02	4.7E+00	4.54E+01	7.8E-01	3.95E+02	6.7E+00
20190823-3 8-5	5.49E+02	7.9E+01	9.99E+01	1.5E+01	8.23E+02	1.2E+02

Table S3.6. Continued.

Sample no.						
Analysis ID	Lu175_ ppm	Lu175_ ppm_2s	Hf177_ ppm	Hf177_ ppm_2s	Ta181_ ppm	Ta181_ ppm_2s
20190823-3						
20190823-3 T-3	2.74E+02	7.7E+00	1.01E+04	1.7E+02	1.10E+01	7.8E-01
20190823-3 T-5	2.22E+02	1.1E+01	1.01E+04	2.0E+02	9.44E+00	9.4E-01
20190823-3 T-6	2.22E+02	3.1E+00	9.39E+03	1.4E+02	1.11E+01	3.1E-01
20190823-3 2-2	7.14E+01	1.3E+00	1.22E+04	1.8E+02	4.93E+00	2.0E-01
20190823-3 2-3	1.10E+02	1.9E+00	1.25E+04	1.7E+02	4.51E+00	2.2E-01
20190823-3 2-4	2.63E+02	1.4E+01	1.01E+04	1.4E+02	5.20E+00	3.3E-01
20190823-3 2-5	2.93E+02	8.3E+00	1.12E+04	1.8E+02	2.02E+01	1.3E+00
20190823-3 3-1	1.00E+02	1.4E+00	7.63E+03	8.1E+01	6.17E-01	7.3E-02
20190823-3 3-2	1.44E+02	6.1E+00	1.00E+04	1.4E+02	5.74E+00	7.7E-01
20190823-3 3-3	3.15E+02	2.2E+01	1.10E+04	2.2E+02	8.33E+00	4.2E-01
20190823-3 3-5	8.06E+01	1.3E+00	1.26E+04	1.8E+02	5.94E+00	2.2E-01
20190823-3 3-6	2.81E+02	1.7E+01	1.02E+04	1.6E+02	5.66E+00	2.6E-01
20190823-3 3-7	2.42E+02	7.6E+00	8.54E+03	1.0E+02	3.63E+00	2.1E-01
20190823-3 4-1	1.62E+02	3.5E+00	1.11E+04	1.4E+02	8.74E+00	3.3E-01
20190823-3 4-2	6.88E+01	1.4E+00	1.26E+04	1.9E+02	5.66E+00	2.4E-01
20190823-3 4-3	7.45E+01	1.9E+00	1.27E+04	2.4E+02	5.88E+00	2.6E-01
20190823-3 4-4	1.63E+02	5.5E+00	1.09E+04	2.3E+02	1.30E+01	6.0E-01
20190823-3 4-5	1.45E+02	4.8E+00	1.02E+04	2.2E+02	7.94E+00	3.9E-01
20190823-3 4-6	1.23E+02	9.1E+00	1.06E+04	3.1E+02	4.22E+00	2.5E-01
20190823-3 4-8	3.45E+02	2.6E+01	9.32E+03	1.5E+02	5.55E+00	2.9E-01
20190823-3 5-2	7.20E+01	1.3E+00	1.27E+04	2.1E+02	6.11E+00	2.5E-01
20190823-3 5-4	6.81E+01	1.2E+00	1.25E+04	2.1E+02	5.77E+00	2.8E-01
20190823-3 5-7	1.04E+02	1.6E+00	1.26E+04	2.0E+02	9.51E+00	2.8E-01
20190823-3 5-9	2.66E+02	1.9E+01	9.98E+03	1.3E+02	4.84E+00	3.5E-01
20190823-3 6-1	2.96E+02	6.7E+00	1.06E+04	1.3E+02	1.71E+01	5.6E-01
20190823-3 6-2	7.48E+01	1.4E+00	1.24E+04	1.6E+02	5.43E+00	2.4E-01
20190823-3 6-4	2.37E+02	7.3E+00	9.60E+03	1.4E+02	4.14E+00	2.2E-01
20190823-3 6-7	9.73E+01	5.4E+00	1.05E+04	2.5E+02	5.61E+00	3.0E-01
20190823-3 7-1	3.59E+02	1.1E+01	1.07E+04	1.2E+02	7.89E+00	4.3E-01
20190823-3 7-2	2.17E+02	1.5E+01	1.06E+04	1.9E+02	4.84E+00	2.9E-01
20190823-3 7-3	1.01E+02	4.9E+00	8.43E+03	1.1E+02	2.83E+00	1.3E-01
20190823-3 7-4	9.71E+01	3.3E+00	1.23E+04	1.6E+02	7.37E+00	4.9E-01
20190823-3 7-8	1.77E+02	6.6E+00	1.03E+04	2.2E+02	5.97E+00	8.7E-01
20190823-3 8-2	6.62E+01	1.6E+00	1.25E+04	1.6E+02	5.16E+00	2.2E-01
20190823-3 8-3	7.33E+01	1.1E+00	1.26E+04	1.5E+02	5.76E+00	2.0E-01
20190823-3 8-5	1.43E+02	2.0E+01	1.10E+04	4.7E+02	3.77E+00	4.4E-01

Table S3.6. Continued.

Sample no.						
Analysis ID	Pb204_ ppm	Pb204_ ppm_2s	Pb206_ppm	Pb206_ ppm_2s	Pb207_ppm	Pb207_ ppm_2s
20190823-3						
20190823-3 T-3	5.74E-01	1.6E+00	1.86E+00	2.0E-01	1.06E-01	4.4E-02
20190823-3 T-5	8.35E-01	1.8E+00	1.60E+00	2.1E-01	1.07E-01	4.7E-02
20190823-3 T-6	1.12E+00	2.0E+00	1.63E+00	1.7E-01	5.18E-02	2.4E-02
20190823-3 2-2	1.64E+00	1.9E+00	4.64E-01	8.3E-02	-2.87E-03	1.4E-04
20190823-3 2-3	2.49E+00	2.2E+00	6.65E-01	1.0E-01	1.56E-02	1.6E-02
20190823-3 2-4	1.96E+00	1.6E+00	1.19E+00	1.9E-01	7.53E-02	3.4E-02
20190823-3 2-5	-5.21E-01	1.3E+00	2.50E+00	2.2E-01	1.34E-01	5.4E-02
20190823-3 3-1	6.88E-01	1.6E+00	1.64E-01	5.4E-02	9.99E-03	1.2E-02
20190823-3 3-2	4.15E-01	1.5E+00	1.06E+00	2.0E-01	3.74E-02	2.9E-02
20190823-3 3-3	-9.58E-01	1.4E+00	1.75E+00	2.0E-01	8.55E-02	3.9E-02
20190823-3 3-5	5.99E-01	1.8E+00	5.54E-01	1.1E-01	2.41E-02	1.8E-02
20190823-3 3-6	4.48E-01	1.7E+00	1.14E+00	1.5E-01	7.07E-02	3.6E-02
20190823-3 3-7	1.59E+00	2.2E+00	9.31E-01	1.3E-01	1.47E-01	6.4E-02
20190823-3 4-1	8.97E-01	1.7E+00	1.26E+00	1.9E-01	1.05E-01	4.2E-02
20190823-3 4-2	-1.71E-02	1.8E+00	4.41E-01	8.8E-02	3.25E-02	2.3E-02
20190823-3 4-3	-8.25E-01	1.6E+00	4.95E-01	9.8E-02	4.76E-02	3.0E-02
20190823-3 4-4	2.22E-01	2.0E+00	1.63E+00	1.8E-01	1.26E-01	5.5E-02
20190823-3 4-5	-3.22E-01	1.3E+00	1.09E+00	1.4E-01	1.00E-01	4.9E-02
20190823-3 4-6	1.68E+00	1.4E+00	6.23E-01	1.2E-01	3.73E-02	2.5E-02
20190823-3 4-8	-1.20E-01	1.5E+00	1.42E+00	2.1E-01	6.71E-02	3.1E-02
20190823-3 5-2	-4.45E-01	1.8E+00	4.82E-01	7.3E-02	3.75E-02	2.8E-02
20190823-3 5-4	-8.78E-01	1.4E+00	3.82E-01	7.9E-02	2.73E-02	2.2E-02
20190823-3 5-7	-2.04E-01	1.5E+00	9.00E-01	1.5E-01	2.68E-02	2.1E-02
20190823-3 5-9	1.35E+00	1.7E+00	1.05E+00	1.8E-01	7.75E-02	4.1E-02
20190823-3 6-1	1.91E-01	1.7E+00	2.57E+00	2.2E-01	1.61E-01	5.0E-02
20190823-3 6-2	9.59E-01	1.5E+00	4.93E-01	8.9E-02	1.61E-02	1.7E-02
20190823-3 6-4	4.36E-01	1.7E+00	1.16E+00	1.5E-01	1.18E-01	4.0E-02
20190823-3 6-7	-1.09E-01	1.3E+00	8.82E-01	1.3E-01	5.73E-02	3.1E-02
20190823-3 7-1	-5.23E-01	1.5E+00	1.87E+00	1.8E-01	9.05E-02	3.8E-02
20190823-3 7-2	-6.33E-01	1.3E+00	9.23E-01	1.4E-01	4.58E-02	2.4E-02
20190823-3 7-3	1.46E+00	1.8E+00	5.57E-01	1.1E-01	2.48E-02	2.0E-02
20190823-3 7-4	7.83E-01	1.8E+00	9.21E-01	1.6E-01	3.75E-02	2.1E-02
20190823-3 7-8	6.55E-01	2.1E+00	7.81E-01	1.2E-01	6.46E-02	3.7E-02
20190823-3 8-2	4.14E-01	2.1E+00	4.04E-01	7.8E-02	5.67E-02	3.2E-02
20190823-3 8-3	5.01E-01	1.6E+00	5.35E-01	8.9E-02	2.42E-02	1.7E-02
20190823-3 8-5	1.01E-02	2.3E+00	6.28E-01	1.7E-01	4.72E-03	1.5E-02

Table S3.6. Continued.

Sample no.						
Analysis ID	Pb208_ ppm	Pb208_ ppm_2s	Th232_ ppm	Th232_ ppm_2s	U235_ ppm	U235_ ppm_2s
20190823-3						
20190823-3 T-3	2.70E-01	6.4E-02	4.47E+02	4.0E+01	1.39E+03	7.9E+01
20190823-3 T-5	2.32E-01	5.2E-02	3.01E+02	4.7E+01	1.11E+03	1.1E+02
20190823-3 T-6	2.46E-01	4.6E-02	3.56E+02	1.3E+01	1.19E+03	5.8E+01
20190823-3 2-2	2.39E-02	1.4E-02	4.52E+01	1.1E+00	3.20E+02	2.5E+01
20190823-3 2-3	6.86E-02	2.1E-02	7.32E+01	3.0E+00	4.99E+02	3.3E+01
20190823-3 2-4	1.13E-01	3.0E-02	1.99E+02	1.4E+01	8.53E+02	6.5E+01
20190823-3 2-5	3.08E-01	5.7E-02	6.50E+02	5.8E+01	1.98E+03	1.2E+02
20190823-3 3-1	5.13E-03	5.7E-03	1.80E+01	4.2E-01	9.34E+01	1.6E+01
20190823-3 3-2	1.22E-01	3.5E-02	1.40E+02	1.9E+01	6.89E+02	8.4E+01
20190823-3 3-3	2.13E-01	4.4E-02	3.40E+02	3.0E+01	1.39E+03	9.4E+01
20190823-3 3-5	4.85E-02	1.9E-02	5.56E+01	8.0E-01	4.36E+02	3.0E+01
20190823-3 3-6	1.54E-01	2.9E-02	2.13E+02	2.0E+01	8.80E+02	6.2E+01
20190823-3 3-7	1.55E-01	6.5E-02	1.30E+02	5.9E+00	5.81E+02	4.9E+01
20190823-3 4-1	2.06E-01	5.0E-02	2.70E+02	2.3E+01	1.04E+03	7.5E+01
20190823-3 4-2	2.65E-02	1.4E-02	4.78E+01	1.3E+00	3.42E+02	2.6E+01
20190823-3 4-3	2.40E-02	1.3E-02	5.26E+01	8.3E-01	4.00E+02	3.0E+01
20190823-3 4-4	2.19E-01	3.3E-02	3.67E+02	1.3E+01	1.26E+03	8.4E+01
20190823-3 4-5	1.21E-01	2.8E-02	2.33E+02	1.4E+01	8.35E+02	5.2E+01
20190823-3 4-6	8.60E-02	3.0E-02	9.96E+01	9.2E+00	4.61E+02	4.7E+01
20190823-3 4-8	1.78E-01	4.4E-02	2.79E+02	3.0E+01	1.07E+03	8.9E+01
20190823-3 5-2	4.22E-02	1.9E-02	5.63E+01	1.5E+00	4.45E+02	3.8E+01
20190823-3 5-4	4.45E-02	1.8E-02	4.58E+01	1.3E+00	3.75E+02	3.2E+01
20190823-3 5-7	4.91E-02	1.7E-02	1.19E+02	2.1E+00	6.27E+02	4.3E+01
20190823-3 5-9	1.22E-01	3.6E-02	1.98E+02	2.0E+01	8.59E+02	9.1E+01
20190823-3 6-1	4.18E-01	6.4E-02	6.13E+02	3.5E+01	1.90E+03	1.0E+02
20190823-3 6-2	2.62E-02	1.2E-02	4.94E+01	8.7E-01	3.76E+02	2.9E+01
20190823-3 6-4	2.22E-01	4.0E-02	1.55E+02	6.1E+00	7.50E+02	5.9E+01
20190823-3 6-7	9.19E-02	3.1E-02	1.61E+02	1.5E+01	5.76E+02	4.8E+01
20190823-3 7-1	2.54E-01	5.0E-02	4.22E+02	1.8E+01	1.48E+03	8.1E+01
20190823-3 7-2	1.06E-01	3.4E-02	1.61E+02	1.5E+01	8.09E+02	7.2E+01
20190823-3 7-3	4.82E-02	1.9E-02	8.07E+01	2.1E+00	3.87E+02	3.4E+01
20190823-3 7-4	7.82E-02	2.9E-02	1.01E+02	1.2E+01	5.86E+02	5.4E+01
20190823-3 7-8	1.04E-01	4.0E-02	1.25E+02	2.3E+01	6.42E+02	6.0E+01
20190823-3 8-2	2.46E-02	1.3E-02	4.28E+01	2.0E+00	3.46E+02	3.7E+01
20190823-3 8-3	2.68E-02	1.3E-02	5.40E+01	1.4E+00	4.39E+02	3.0E+01
20190823-3 8-5	9.23E-02	4.8E-02	8.51E+01	1.4E+01	5.34E+02	9.3E+01

Table S3.6. Continued.

Sample no.		
Analysis ID	U238_ ppm	U238_ ppm 2s
20190823-3		
20190823-3 T-3	4.35E+02	2.3E+01
20190823-3 T-5	3.42E+02	3.2E+01
20190823-3 T-6	3.68E+02	8.7E+00
20190823-3 2-2	1.04E+02	1.9E+00
20190823-3 2-3	1.49E+02	4.1E+00
20190823-3 2-4	2.66E+02	1.4E+01
20190823-3 2-5	6.25E+02	3.1E+01
20190823-3 3-1	3.07E+01	5.5E-01
20190823-3 3-2	2.13E+02	2.2E+01
20190823-3 3-3	4.34E+02	2.8E+01
20190823-3 3-5	1.29E+02	2.2E+00
20190823-3 3-6	2.87E+02	1.6E+01
20190823-3 3-7	1.79E+02	5.2E+00
20190823-3 4-1	2.99E+02	1.4E+01
20190823-3 4-2	1.08E+02	2.4E+00
20190823-3 4-3	1.21E+02	2.3E+00
20190823-3 4-4	3.74E+02	1.4E+01
20190823-3 4-5	2.62E+02	1.2E+01
20190823-3 4-6	1.43E+02	9.2E+00
20190823-3 4-8	3.31E+02	2.0E+01
20190823-3 5-2	1.26E+02	2.6E+00
20190823-3 5-4	1.07E+02	2.1E+00
20190823-3 5-7	2.08E+02	3.8E+00
20190823-3 5-9	2.53E+02	1.7E+01
20190823-3 6-1	5.85E+02	2.0E+01
20190823-3 6-2	1.15E+02	1.4E+00
20190823-3 6-4	2.26E+02	6.2E+00
20190823-3 6-7	1.85E+02	1.2E+01
20190823-3 7-1	4.56E+02	1.5E+01
20190823-3 7-2	2.28E+02	1.6E+01
20190823-3 7-3	1.11E+02	2.4E+00
20190823-3 7-4	1.75E+02	1.1E+01
20190823-3 7-8	1.91E+02	1.4E+01
20190823-3 8-2	1.02E+02	3.7E+00
20190823-3 8-3	1.23E+02	2.4E+00
20190823-3 8-5	1.45E+02	2.0E+01

Table S3.7. Metadata for LA-ICP-MS U-(Th-)Pb and TE analyses.

Laboratory and Sample Preparation	
Laboratory name	Pacific Centre for Isotopic and Geochemical Research
Sample type/mineral	Zircon
Sample preparation	Conventional mineral separation, 1 inch resin mount, 1 um polish to finish
Imaging	CL: Phillips X1-30 SEM, 15 kV, 10 nA; Robinson CL detector
Laser ablation system	
Make, Model and type	Resonetics, UP193
Ablation cell and volume	Standard UP213 ablation cell
Laser wavelength (nm)	193 nm
Pulse width (ns)	4 ns
Fluence (J cm ⁻²)	~2 J cm ⁻²
Repetition rate (Hz)	5 Hz
Ablation duration (s)	30 s
Ablation pit depth / ablation rate	15 mm pit depth, measured by optical microscope, equivalent to 0.5 mm/s
Spot diameter (mm)	35 mm
Sampling mode / pattern	Static spot ablation
Carrier gas	100% He in the cell, Ar make-up gas combined using a Y-piece 70 cm from the torch
Cell carrier gas flow (L min ⁻¹)	0.8 L min ⁻¹
ICP-MS Instrument	
Make, Model and type	Agilent 7700x, quadrupole
Sample introduction	Ablation aerosol transported through 90 cm long, 1.5 cm dia. tygon tubing coil
RF power (W)	1400 W
Make-up gas flow (L min ⁻¹)	0.53 L min ⁻¹ Ar
Detection system	single ion-counting SEM
Masses measured and dwell times per peak (ms)	7,29,91,31,45,49,89,93,139,140,141,146,147,153,157,159,163,165,166,169,172,175,177,181,202,204,206,207,208,232,238
Integration time/data point (s)	0.895 s
IC Dead time (ns)	29 ns
Data Processing	
Gas blank	15 s on-peak zero subtracted
Calibration strategy	91500 used as primary reference material, Plešovice, Temora2 used as validation
Reference Material info	Plešovice (Slama <i>et al.</i> 2008); 336.9 Ma 91500 (Weidenbeck <i>et al.</i> 2008); 1065 Ma Temora2 (Black <i>et al.</i> , 2004); 417 Ma
Data processing package and strategy	Agilent TRA software for integrated cps acquisition; lolite 4 data reduction for internal standardisation, concentration calibration, fractionation normalisation, age calculation, and uncertainty propagation
Mass discrimination	²⁰⁷ Pb/ ²⁰⁶ Pb and ²⁰⁶ Pb/ ²³⁸ U normalised to reference material
Common-Pb correction	No common-Pb correction applied; ablation sweeps with mass 204 signals above background rejected.
Uncertainty level and propagation	Ages are quoted at 2s absolute, propagation is by quadratic addition. Systematic errors based upon reproducibility of reference material are propagated where appropriate: 2% (2s) for Pb/U and 1% (2s) for Pb/Pb.
Quality control / Validation	Plešovice – Wtd ave ²⁰⁶ Pb/ ²³⁸ U age = 338.2 ± 1.3 (2s, MSWD = 0.80, n = 29) Temora2 – Wtd ave ²⁰⁶ Pb/ ²³⁸ U age = 415.7 ± 2.7 (2s, MSWD = 0.8, n = 23)

Appendix B: Descriptions of geological formations and samples

B1 Hand specimen and thin section description

Handsample # 24072017-2**Unit, Member, Formation:** Nautárgil, 4th lava from below**Sample location:** Svarfdalur North side, Nautárgil**Sample description:****A. Sample represents** Aa-lava flows below the extrusive rhyolite complex.**Location within unit** Middle of layer**meters above base** ~0.7 ; **meters below top** ~0.7**Size of sample** 17x10x10 cm**B. Color of sample. Weathering color** Red; **true color** Medium gray**C. Texture.****Groundmass** **crystallinity (%)** 100%
mineral types Not visible
grain size Fine**Phenocrysts;** **mineral types** No phenocrysts
mode (%)
size range
habit**Fabric** Vesicular, equigranular**Homogeneity** Homogeneous grain size**D. Inclusions of foreign material** None**E. Alteration; weathering** Reddish weathering coat**other alteration** Red oxidation along fractures and occasionally along vesicle walls. Vesicles are generally coated with yellow clay (opal?)**F. Other features** Vesicles are ~20%, elongated, ca. 0.1-0.8 cm long.**Thin section# 24072101-2****Rock name:** Basalt (aa-lava)**Where sampled:** Svarfdalur Valley, Nautárgil**Grain size:** Fine-grained**Texture:** Mostly microlitic**Groundmass:** Fine-grained, pyroxene, plagioclase opaque minerals, e.g. magnetite, iron.**Phenocrysts:** No phenocrysts**Comments:** Grain size is fine, suggesting rapid cooling. Groundmass is mostly made of pyroxene. Plagioclases are elongated. Texture is mostly microlitic. Pyroxene and iron are interstitial. Very large amount of opaque minerals; some are square shaped (magnetite). Percent of phenocrysts is very low.

Handsample # 01092016-1

Unit, Member, Formation: Torfufellsdalur, lowermost part of the intermediate/silicic complex

Sample location: Western slopes of Mt. Torfufell

Sample description:

A. Sample represents Lowermost part of the intermediate/silicic complex.

Location within unit

meters above base ; meters below top

Size of sample 16x7x8 cm

B. Color of sample. Weathering color red-brown ; **true color** dark-grey

C. Texture.

Groundmass crystallinity (%) 100%

Mineral types not visible

grain size fine

Phenocrysts; mineral types plagioclase, pyroxene

mode (%) <1%

size range 0.5-2 mm

habit euhedral to subhedral

Fabric equigranular

Homogeneity homogeneous grain sizes

D. Inclusions of foreign material none

E. Alteration; weathering Reddish-brown to black weathering coat.
Weathering surface is "striated"/undulated

other alteration: Orange-red oxidation along fracture. A little alteration (orange to reddish) seen in the groundmass in some places. Otherwise fresh sample

F. Other features Very dense – no vesicles

Thin section: 01092016-1

Rock name: Andesite

Where sampled: Torfufellsdalur. Lowermost part of the intermediate/silicic complex

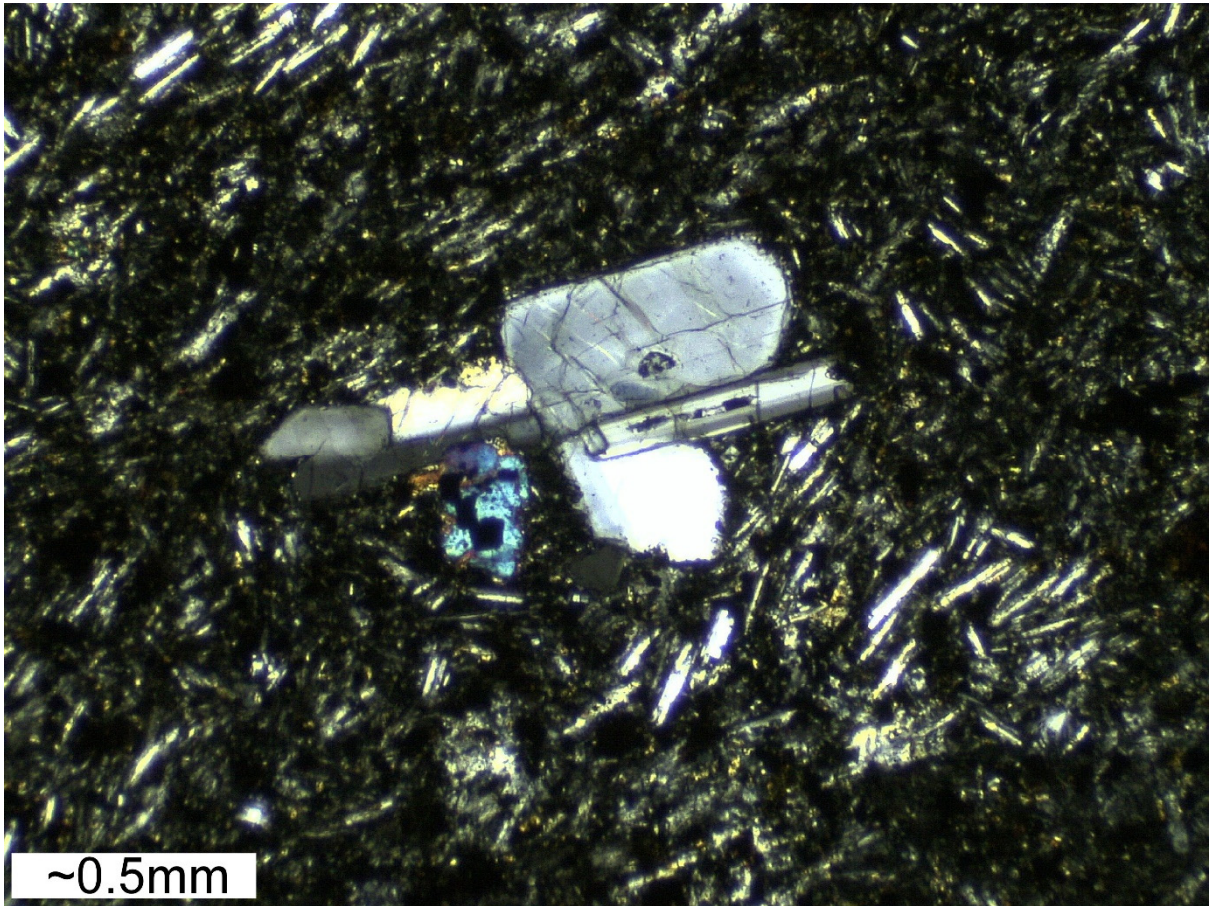
Grain size:

Texture: sub-trachytic (tendence to trachytic)

Groundmass: Plagioclase and pyroxene microlites.

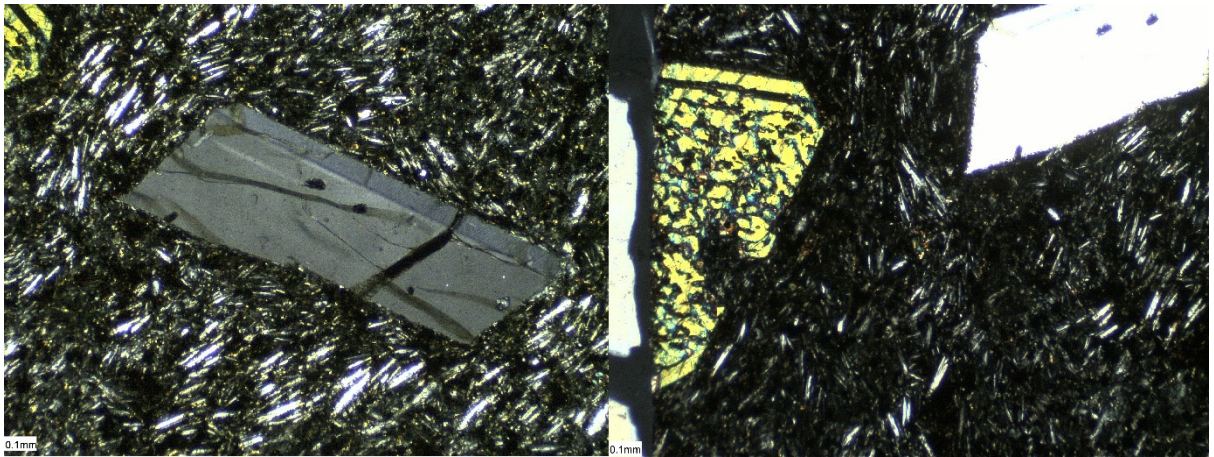
Phenocrysts: sparse feldspar, pyroxene and plagioclase (large, regular with clean margins).

Comments: Groundmass is similar to sample 24072017-2, but plagioclase phenocrysts are more evident. Also more evident is the preferred orientation of the microlites. Content of mafic minerals is also lower. No vesicles are observed. Percent of phenocrysts is low. Localized flow texture. Elongated plagioclases. A thin vein crosscuts all the thin-section, possible filled with quartz.



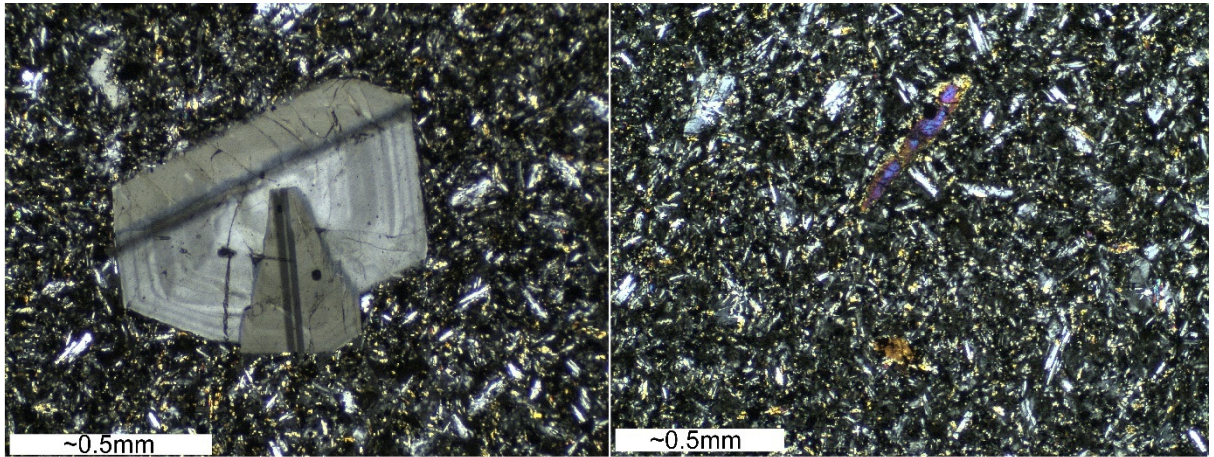
~0.5mm

01092016-1

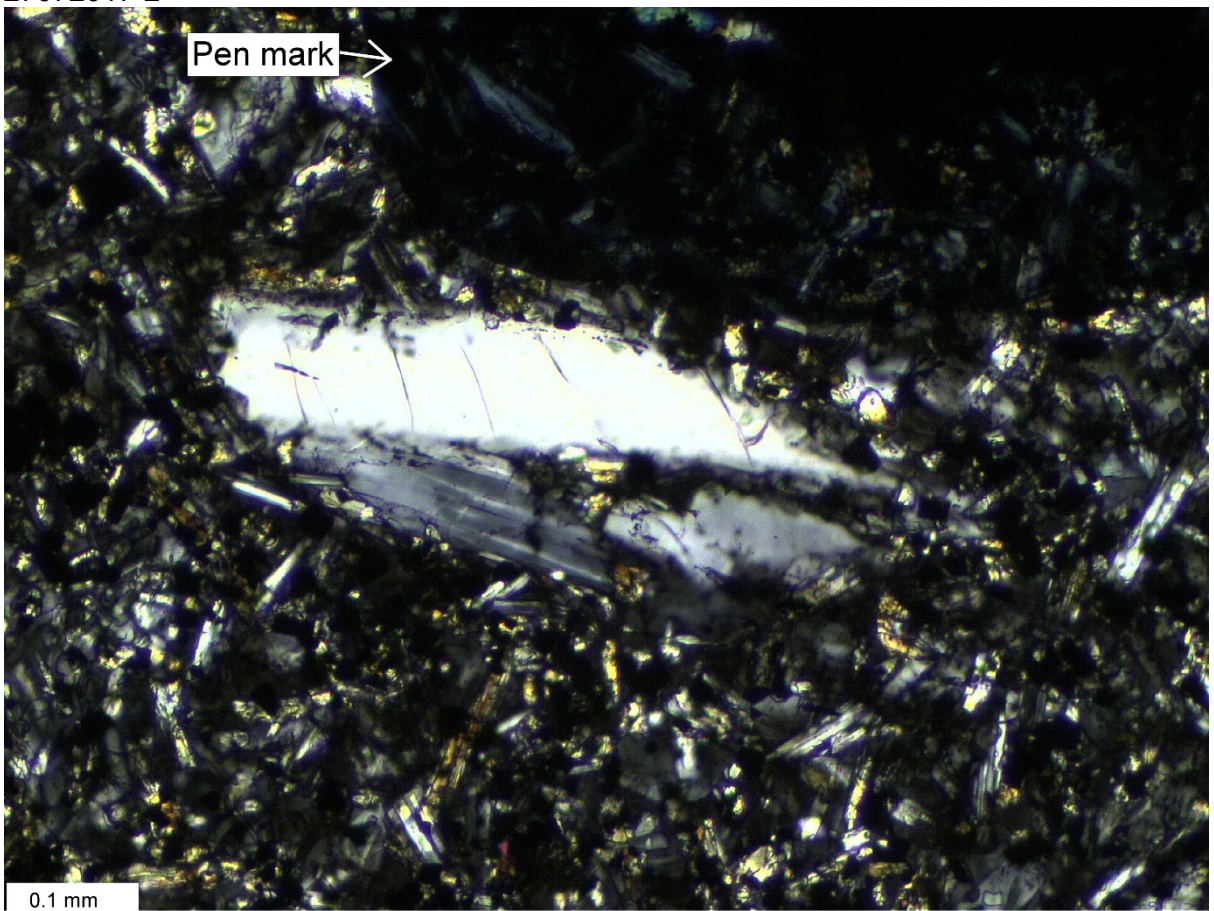


01092016-1. White bars are 0.1 mm.

Handsample # 27072017-2**Unit, Member, Formation:** Úlfá, just below the rhyolite**Sample location:** Torfufell, east side, Úlfá**Sample description:****A. Sample represents** Basalt lavas just below the intermediate/silicic complex**Location within unit****meters above base ; meters below top****Size of sample** 10x11x9 cm**B. Color of sample. Weathering color** light orange ; **true color** medium gray**C. Texture.****Groundmass crystallinity (%)** 100%**Mineral types** not visible**grain size** fine**Phenocrysts; mineral types** plagioclase and pyroxene**mode (%)** <1%**size range** ~1 mm**habit** subhedra/anhedral**Fabric** equigranular**Homogeneity** homogeneous grain sizes**D. Inclusions of foreign material** none**E. Alteration; weathering****other alteration** fresh sample**F. Other features** very dense and hard to break. Very few and small vesicles**Thin section: 27072017-2****Rock name:** Basaltic andesite**Where sampled:** Just below the intermediate/silicic extrusive complex**Grain size:** Fine**Texture:** Mostly intergranular, interstitial pyroxene**Groundmass:** Oxides (large number), plagioclase, titanomagnetite, pyroxene, ilmenite.**Phenocrysts:** plagioclase with oscillatory zoning. Pyroxenes (smaller than the plagioclase phenocrysts and with very slight green colour.**Comments:** Quite homogeneous in grain size. Mostly intergranular texture with plagioclase mostly randomly oriented (no preferred orientation). Interstitial pyroxene. Grain size is quite fine. Probably no olivine. A plagioclase phenocryst is observed to be reacting with the magma. Very low porphyritic index.



27072017-2



27072017-2

Handsample #24072017-3**Unit, Member, Formation:** Nautárgil, 5th lava from below**Sample location:** Svarfdalur north side, Nautárgil**Sample description:**

A. Sample represents Aa-lava flows below the intermediate/silicic complex
Location within unit middle of unit
meters above base ~0.5 ; **meters below top** ~0.5
Size of sample 14x10x8 cm
B. Color of sample. Weathering color red-brown ; **true color** dark grey
C. Texture.
Groundmass **crystallinity (%)** 100%
Mineral types not visible
grain size fine
Phenocrysts; mineral types no phenocrysts
mode (%)
size range
habit
Fabric vesicular, equigranular
Homogeneity homogeneous grain sizes
D. Inclusions of foreign material none
E. Alteration; weathering red-brown weathering coat
other alteration fresh sample. Vesicles are either coated or filled with opal (either light-yellowish-brown or red)
F. Other features Vesicles are ~7-10%, 0.1-0.3 cm, most often elongated

Thin section: 24072017-3**Rock name:** Basalt**Where sampled:** Nautárgil, Svarfdalur**Grain size:****Texture:****Groundmass:** Plagioclase, pyroxene, metals (e.g. magnetite)**Phenocrysts:** Former olivine**Comments:** Vesicular; all vesicles are coated with clay. Former olivine phenocrysts, all completely altered into clay, elongated and oriented into the same orientation. Flow-structures observed in the plagioclases. Elongated vesicles and remains of phenocrysts are elongated in the same orientation. Metal is very prominent in the groundmass, also plagioclase needles and pyroxene. Interstitial magnetite.

Handsample #10072017-3**Unit, Member, Formation:**

Glerá, lava no. 7 from below

Sample location:**Sample description:****A. Sample represents**

uppermost part of the rhyolite complex

Location within unit

middle of layer

meters above base ; meters below top**Size of sample**

18x13x3cm (piece with no flow-banding) and 5x4.5x4 cm (flow-banded piece)

B. Color of sample. Weathering color reddish **; true color** light yellowish-grey**C. Texture.****Groundmass** **crystallinity (%)** 80%**Mineral types**

white and dark-grey minerals. Smaller black minerals

grain size

aphanitic to classy

Phenocrysts; mineral types

feldspar

mode (%)

<1%

size range

0.5-2 mm

habit

anhedral

Fabric

Flow-banded with white and dark-grey bands

Homogeneity

The larger sample (the sample without flow-banding) is homogeneous in color. The flow-banded sample has dark-grey bands that are less crystallized than the white bands

D. Inclusions of foreign material

none

E. Alteration; weathering

reddish-brown weathering coat

other alteration

yellow to orange alteration observed in some groundmass minerals and in vesicles. Vesicles are coated with secondary crystals. Microphenocrysts are reddish

F. Other features**Thin section: 10072017-3****Rock name:**

Rhyolite

Where sampled:

Glerá, uppermost part of the rhyolite

Grain size:

Fine

Texture:

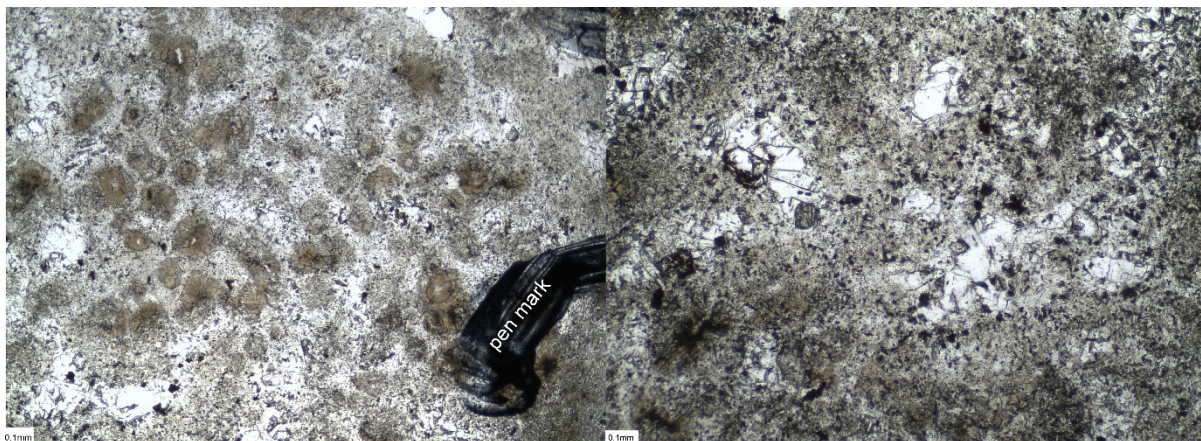
Aphanitic/spherulitic

Groundmass:

K-feldspar, spherulite glass, quartz, zircon

Phenocrysts:**Comments:**

Classic rhyolite. The groundmass is essentially composed of quartz and alkali feldspars, and some opaque minerals are seen. Some spherulitic arrangements are present which can be related to former glass (devitrification). Some minerals which are reddish in color in polarized light are seen, probably related to weathering and oxidation. Late alkali feldspar, possible chalcedony and possible zeolites are observed inside vesicles.



10072017-3. White bars are 0.1 mm.

Handsample # 13072017-1**Unit, Member, Formation:** Stóruskriðugil, lava no. 15 from above**Sample location:****Sample description:**

A. Sample represents Uppermost part of the intermediate/silicic complex
Location within unit Near upper boundary
meters above base 120 ; **meters below top** 10
Size of sample 17x11x4 cm
B. Color of sample. Weathering color reddish ; **true color** light red
C. Texture.
Groundmass crystallinity (%) 60%
Mineral types plagioclase, oxides
grain size apanitic to glassy
Phenocrysts; mineral types plagioclase
mode (%) <1%
size range plagioclase 0.5-2 mm, oxides ~0.8-1 mm
habit subhedral
Fabric flow-banded and vesicular. White bands vs. reddish bands
Homogeniety Inhomogeneous color
D. Inclusions of foreign material none
E. Alteration; weathering reddish weathering. Black, yellow and white lichens
other alteration orange to red alteration/oxidation is abundant in the groundmass
F. Other features Vesicles are ~20%, most often ~1 cm.

Thin section: 13072017-1

Rock name: Rhyolite
Where sampled: Stóruskriðugil, Svarfdalur, uppermost rhyolite
Grain size: Fine
Texture: Spherulitic
Groundmass: Former glass (brown; perlite?)
Phenocrysts: Plagioclase or eventually orthoclase
Comments: Radial arrangements of crystals; spherulites, i.e. drop-like glass. Vesicles are observed but they are empty, with orange alteration on the walls. Some of the spherulites are very large and occur in bands; i.e. there are zones which are rich in spherulites and show evidence of flow.

Handsample # 27072017-3**Unit, Member, Formation:**Nóngil, 2nd lava from above**Sample location:**

Gully south of Úlfá, Torfufell east side

Sample description:**A. Sample represents**

uppermost part of the intermediate/silicic complex

Location within unit

meters above base 20 ; meters below top 5

Size of sample

10x7x3 cm

B. Color of sample. Weathering colorred and black ; **true color** light

grey/whitish

C. Texture.**Groundmass****crystallinity (%)**

60-80%

Mineral types

plagioclase and oxides (oxides are less than 0.1 mm)

grain size

aphanitic to glassy

Phenocrysts;**mineral types**

plagioclase

mode (%)

<1%

size range

1-2 mm

habit

euhedral to subhedral

Fabric

flow-banded; white vs. light-grey bands

Homogeneity

inhomogeneous color. Grey bands less crystallized than white bands.

D. Inclusions of foreign material

none

E. Alteration; weathering

black, yellow and white lichens

other alteration

spots of orange alteration seen in several places, especially around vesicles and phenocrysts

F. Other features

dense, sparse vesicles

Thin section: 27072017-3**Rock name:**

Rhyolite

Where sampled:

Úlfá

Grain size:

Glassy

Texture:

Flow-banding

Groundmass:

Feldspar (dominant), glass, zircon, titanomagnetite

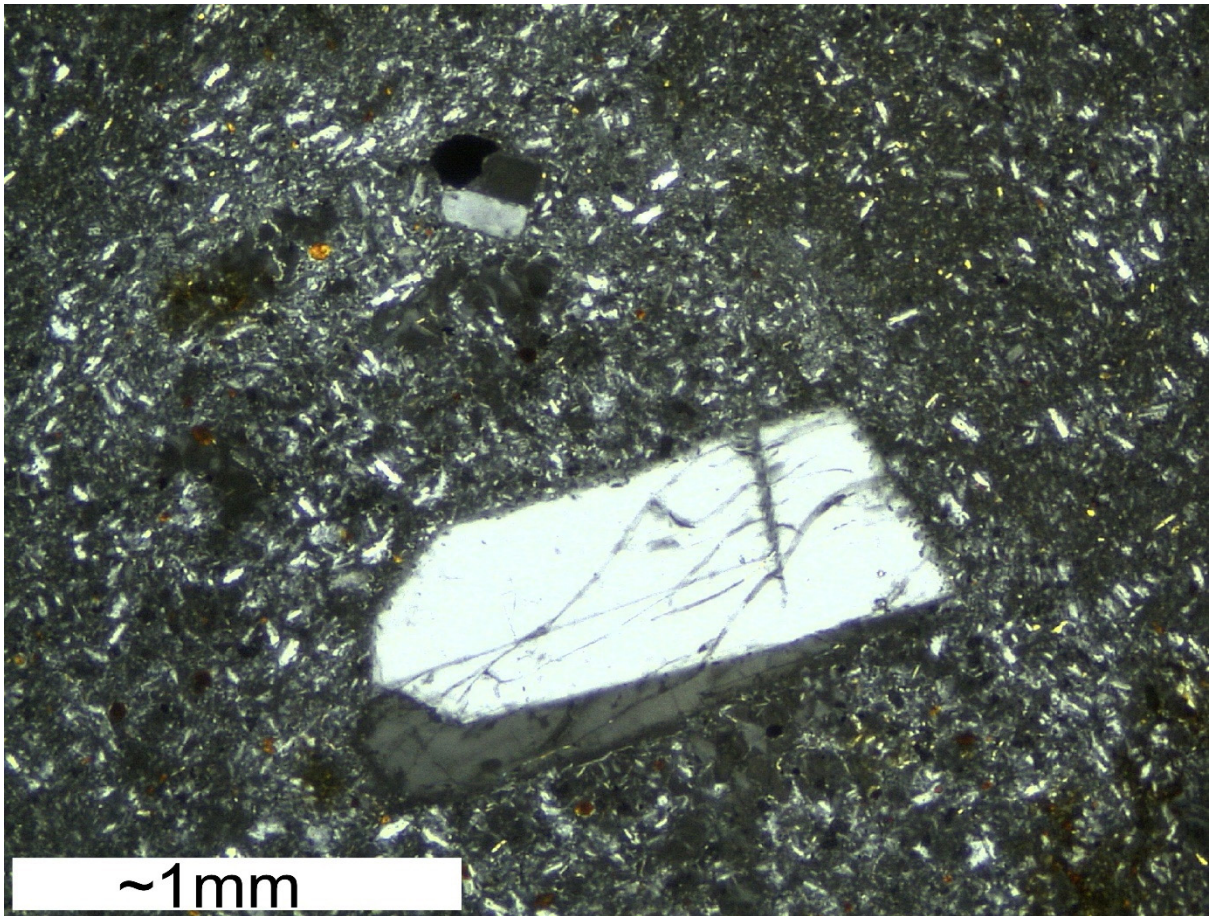
Phenocrysts:

Plagioclase (most abundant; subhedral; low extinction angle of the twins), possible sanidine, titanomagnetite (occasionally large)

Comments:

Content of phenocrysts is ca. 5-10%. Groundmass is dominated with feldspar microlites, often preferentially oriented in a flow texture. Flow-bands of different grain sizes; dark bands are finer-grained (cryptocrystalline) while light-colored bands are coarser grained. The flow-bands bend along phenocrysts. The groundmass has been rich in glass but plagioclase has been able to crystallize before the magma solidified. A crystal inclusion is observed inside a plagioclase phenocryst. Some zones are reddish in color this

is related to oxidation or alteration, maybe of iron or titanium oxides. Amygdules are present.



27072017-3

Handsample # 09072015-8**Unit, Member, Formation:** Villingadalur, uppermost layer**Sample location:** Torfufell, north side**Sample description:****A. Sample represents** lowermost part of the intermediate/silicic complex**Location within unit****meters above base ; meters below top****Size of sample** 8x7x2.5 cm**B. Color of sample. Weathering color** red ; **true color** dark grey**C. Texture.****Groundmass crystallinity (%)** 100%**Mineral types** not visible**grain size** aphanitic**Phenocrysts; mineral types** oxides, pyroxene**mode (%)** <1%**size range** ~1 mm**habit** subhedral**Fabric** equigranular**Homogeneity** homogeneous crystal sizes and
homogeneous color**D. Inclusions of foreign material** none**E. Alteration; weathering** red weathering coat**other alteration** orange alteration/weathering along flow
bands. A little orange to red alteration seen
in occasional groundmass minerals**F. Other features** flow structures. Breaks easily into flakes**Thin section: 09072015-8****Rock name:** Andesite**Where sampled:** Glerá (lowermost lava of the profile)**Grain size:** Fine**Texture:** Flow-banding**Groundmass:** Oxides, feldspar, pyroxene**Phenocrysts:** Plagioclase, pyroxene, oxides, e.g. titanomagnetite and magnetite
(microphenocrysts)**Comments:** Very flow-banded, fine-grained groundmass, rich in metals, with
plagioclase phenocrysts (most abundant) and also some pyroxene
phenocrysts. Plagioclases are parallel to the flow-bands.
Occasional plagioclase phenocrysts are dissolving. Elongated
plagioclases sometimes have wedged termination, indicating fast
cooling. Very few phenocrysts are observed. Feldspar with melt
drops inside is observed. Metals are abundant in the groundmass;
two generations of metals. An orthorhombic mineral is observed
(possible amphibole?).

Handsample # 07072015-2

Unit, Member, Formation: Villingadalur, silicic sill
Sample location: Torfufellsá, north of Mt. Torfufell

Sample description:

A. Sample represents silicic sill intruded into normal polarity basalt lavas below the intermediate/silicic complex
Location within unit near the base of the upper sill
meters above base ; meters below top
Size of sample 16x10x7 cm

B. Color of sample. Weathering color medium orange-brown ; **true color** light grey

C. Texture.

Groundmass crystallinity (%) 100%
Mineral types small black needles in otherwise light-grey and white groundmass

grain size aphanitic

Phenocrysts; mineral types plagioclase, metals
mode (%) <1%
size range plagioclase 2-5 mm, metals ~0.5 mm
habit plagioclase: subhedral, metals: euhedral to subhedral

Fabric equigranular

Homogeneity homogeneous grain size and color

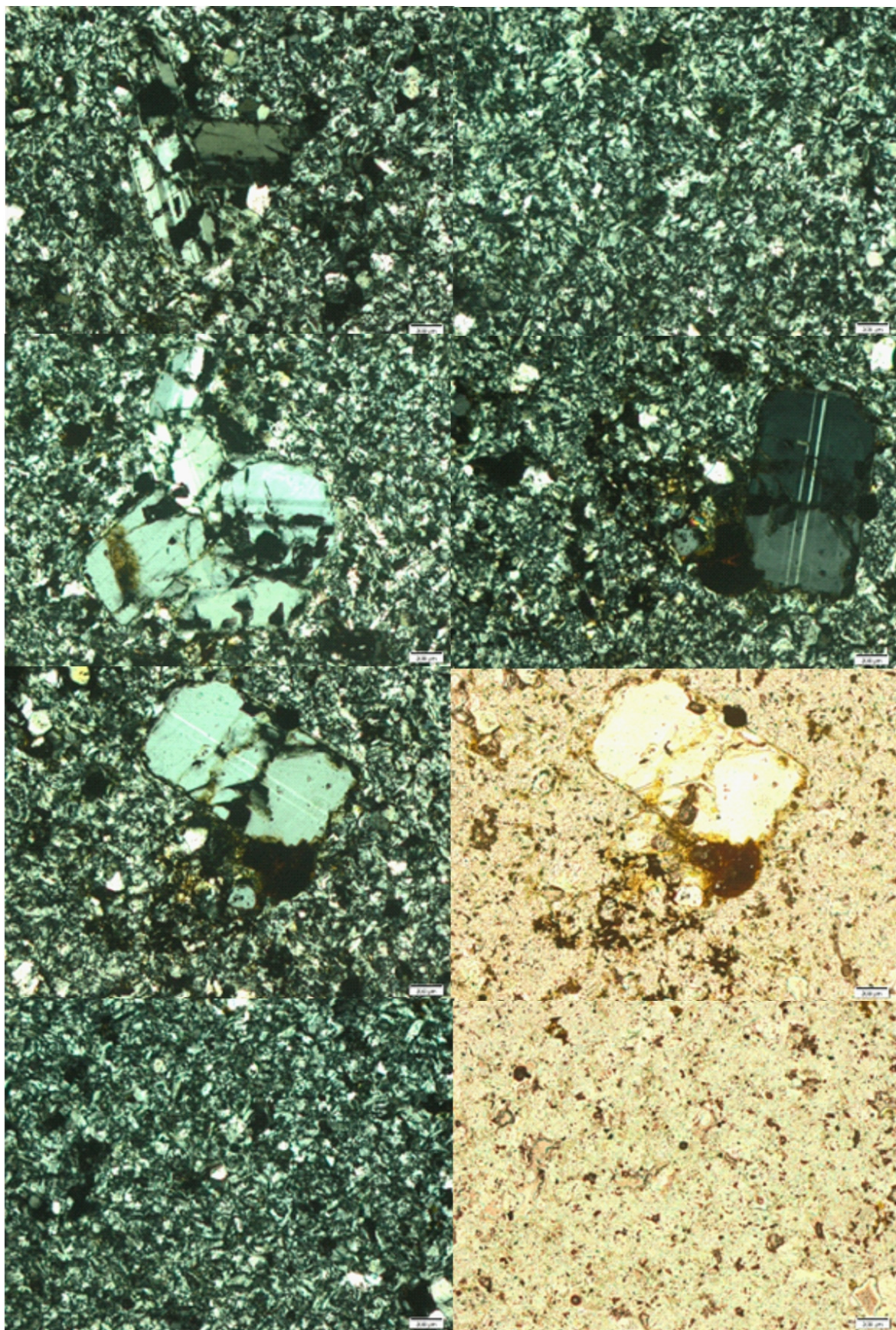
D. Inclusions of foreign material none

E. Alteration; weathering medium orange-brown weathering coat
other alteration orange to orange-red alteration along the walls of small pores and in large plagioclase phenocrysts

F. Other features small (<1 mm) pores are abundant.

Thin section: 07072015-2

Rock name: Silicic sill (rhyolitic composition)
Where sampled: Villingadalsá
Grain size: Very fine
Texture: Glomero porphyritic
Groundmass: Plagioclase, metals (e.g. Fe-Ti oxide), quartz, possible former glass altered into zeolites, possible orthopyroxene
Phenocrysts: Sparse plagioclase (occasionally with zircon inclusions) and feldspar
Comments: Very fine-grained (microcrystalline) groundmass with high quartz content and sparse phenocrysts up to 5 mm long. Aggregates of phenocrysts are seen, mostly plagioclase. Quartz content is high in the groundmass. Mafic content is very low. No evidence of flow orientation. Sparse vesicles are observed, indicating emplacement at shallow depth. Vesicles are empty and ca. 0.2-0.5 mm in diameter.



07072015-2. White bar is 200 μm .

Handsample # 24072017-4

Unit, Member, Formation: Nautárgil, uppermost unit
Sample location: Svarfdalur, north side, Nautárgil

Sample description:

A. Sample represents silicic intrusion, volcanic vent in Nautárgil in Svarfdalur
Location within unit near the base
meters above base ; meters below top
Size of sample 35x5x10 cm
B. Color of sample. Weathering color yellow ; **true color** light grey

C. Texture.

Groundmass crystallinity (%) 90%

Mineral types not visible

grain size aphanitic

Phenocrysts; mineral types plagioclase

mode (%) <1%

size range 2.2-4 mm

habit subhedral

Fabric

equigranular. Flow-banding is very prominent (narrow white bands and thicker grey bands)

Homogeneity

homogeneous grain sizes

D. Inclusions of foreign material

none

E. Alteration; weathering**other alteration**

red alteration/oxidation seen in some groundmass minerals. Yellow to orange to red alteration along flow structures; the white narrow bands are more altered than the thicker grey bands. Yellow alteration is observed in some of the phenocrysts

F. Other features

phenocrysts sometimes occur in clusters. The sample breaks very easily along flow structures into flakes.

Thin section: 24072017-4

Rock name: Silicic intrusion (rhyolitic composition)

Where sampled: Nautárgil

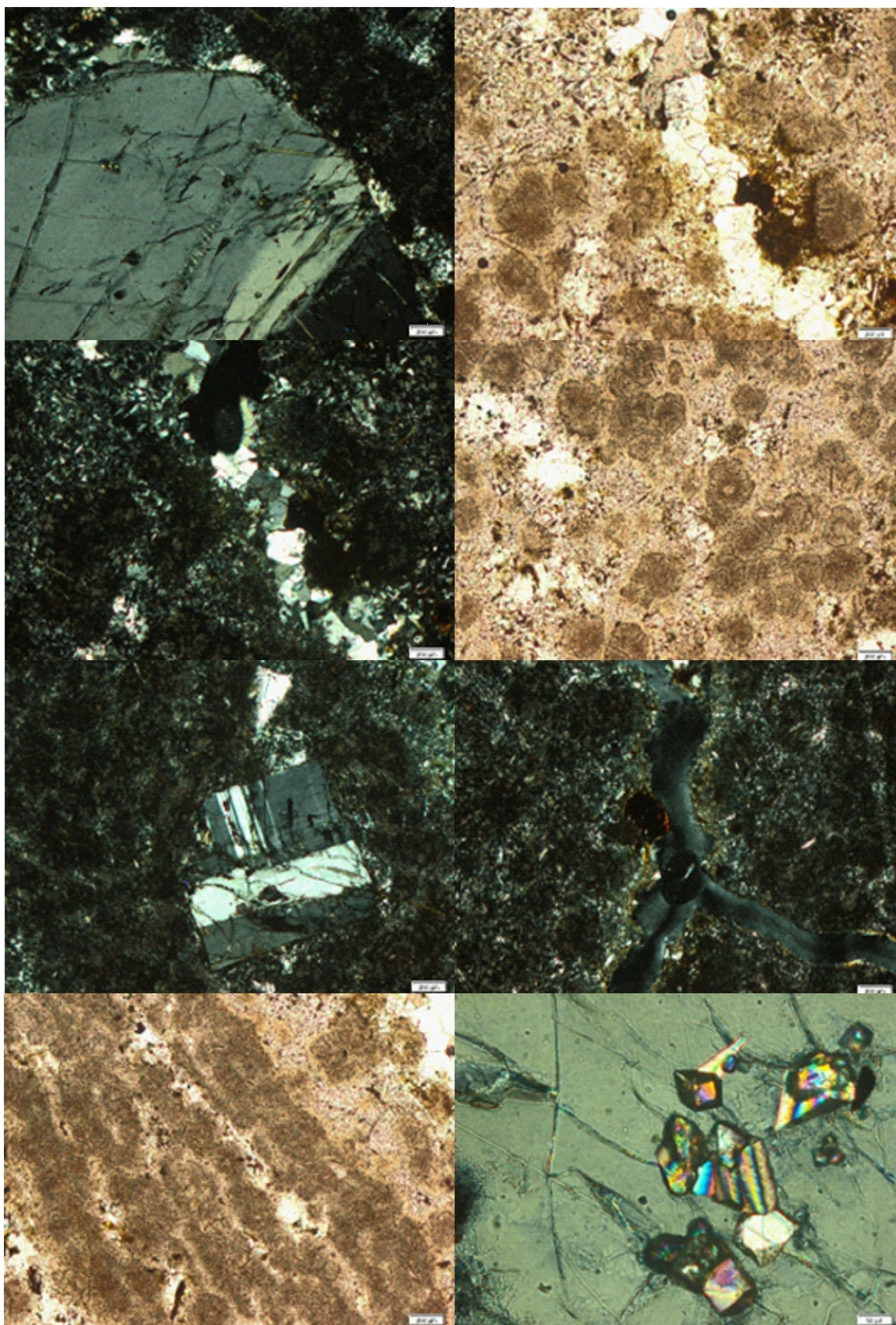
Grain size: Very fine/aphanitic

Texture: Flow-banded

Groundmass:

Phenocrysts: Feldspar

Comments: Very fine-grained/aphanitic groundmass with abundant spherulites and sparse plagioclase phenocrysts. Plagioclase phenocrysts are euhedral to subhedral. Very flow-banded. Feldspars and veins with microlitic textures. Flow-bands are visible with alternating dark and light-colored bands. Brownish crystals maybe related to weathering or hydrothermal effect. Late veins of quartz, aligned parallel to flow-bands.



24072017-4. White bars are 200 μm , except the lowermost image to the right (showing inclusions in a plagioclase phenocryst), where the white bar is 50 μm .

Handsample # 18072017-1**Unit, Member, Formation:** Skriðugil, lava no. 18 from below**Sample location:** ~1,3 km south of Hafrá, Torfufell east side,
southernmost profile on the map**Sample description:****A. Sample represents** normal polarity porphyritic basalt lavas above the
intermediate/silicic complex**Location within unit****meters above base ; meters below top****Size of sample** 19x10x7 cm**B. Color of sample. Weathering color** medium orange-brown ; **true color**
medium grey**C. Texture.**

Groundmass	crystallinity (%)	100%
	Mineral types	plagioclase, pyroxene, olivine
	grain size	fine to medium
Phenocrysts;	mineral types	olivine, plagioclase
	mode (%)	~15%
	size range	1.5-6 mm
	habit	subhedral

Fabric porphyritic**Homogeneity** inhomogeneous crystal sizes**D. Inclusions of foreign material** none**E. Alteration; weathering** medium orange-brown weathering coat
other alteration fresh sample. Some olivine crystals, both in
groundmass and phenocrysts, are slightly
reddish.**F. Other features** Small (1 mm) vesicles are abundant; the
rock is rather porous/vesiculated. Vesicles
are empty.**Thin section: 18072017-1****Rock name:** Basalt (olivine-tholeiite)**Where sampled:** Skriðugil; above the rhyolite complex**Grain size:** Coarse**Texture:** Subophitic**Groundmass:** Olivine, plagioclase**Phenocrysts:** Olivine (abundant), plagioclase (with pyroxene inclusions)**Comments:** Coarse grained olivine-bearing groundmass with abundant olivine
phenocrysts and less abundant plagioclase phenocrysts with
pyroxene inclusions. Considered as fissure-fed (i.e., eruption from
a fissure swarm) shield basalt with olivine-tholeiitic composition.

Handsample #14072015-2

Unit, Member, Formation: Gilsá, lava no. 7 from below
Sample location: Gilsá, northern part of the map

Sample description:

A. Sample represents porphyritic basalts in the lowermost part of the strata pile, where magnetic polarities are irregular

Location within unit

meters above base ; **meters below top**

Size of sample 6x4x4 cm

B. Color of sample. Weathering color medium orange-brown ; **true color** medium grey

C. Texture.

Groundmass **crystallinity (%)** 100%

Mineral types not visible

grain size fine

Phenocrysts; mineral types plagioclase, olivine

mode (%) 30%

size range plagioclase ~5 mm, olivine 1-2 mm

habit subhedral

Fabric porphyritic

Homogeneity inhomogeneous crystal sizes

D. Inclusions of foreign material none

E. Alteration; weathering orange-brown weathering coat

other alteration red oxidation occasionally observed inside vesicle walls

F. Other features Sparse large vesicles, up to 1 cm in diameter. Vesicles are nearly filled with platy zeolites. Phenocrysts are sometimes conjoined

Thin section: 14072015-12

Rock name: Basalt (porphyritic)

Where sampled: Gilsá

Grain size: Coarse

Texture: Porphyritic

Groundmass: Olivine, pyroxene, plagioclase, iron oxides

Phenocrysts: Plagioclase, olivine (relict), pyroxene

Comments: Plagioclase, pyroxene and relict olivine are observed together in a glomerocryst. Altered glass is observed in between the phenocrysts. Olivine phenocrysts are sometimes altered into clay and with rounded outlines. Plagioclase phenocrysts are ca. 25%; 1-2 mm and euhedral. Olivine phenocrysts are 3-5%, 0.5-1 mm and sub-to anhedral. Glomerocrysts are ca. 2-5 mm.

Handsample #20072017-2**Unit, Member, Formation:** Núpá, lava no. 19 from below**Sample location:** Núpá, Sölvadalur, east of Mt. Hólafljall**Sample description:****A. Sample represents** porphyritic basalt lavas in the lowermost part of the strata pile**Location within unit****meters above base** ; **meters below top****Size of sample** 15x9x9 cm**B. Color of sample. Weathering color** light orange-brown ; **true color** medium grey**C. Texture.****Groundmass** **crystallinity (%)** 100%**Mineral types** plagioclase (yellowed)**grain size** fine**Phenocrysts; mineral types** plagioclase (yellowed=**mode (%)** 10%**size range** 2-11 mm**habit** subhedral**Fabric** porphyritic**Homogeneity** inhomogeneous crystal sizes**D. Inclusions of foreign material** none**E. Alteration; weathering** light-orange-brown weathering coat with a few reddish/oxidized spots**other alteration** all plagioclase crystals (micro and macro) are yellowed. Otherwise, the sample looks fresh**F. Other features** Dense rock, no vesicles**Thin section: 20072017-2****Rock name:** Basalt (porphyritic)**Where sampled:** Núpá, Sölvadalur**Grain size:****Texture:** Porphyritic**Groundmass:****Phenocrysts:** pyroxene, relict olivine**Comments:**

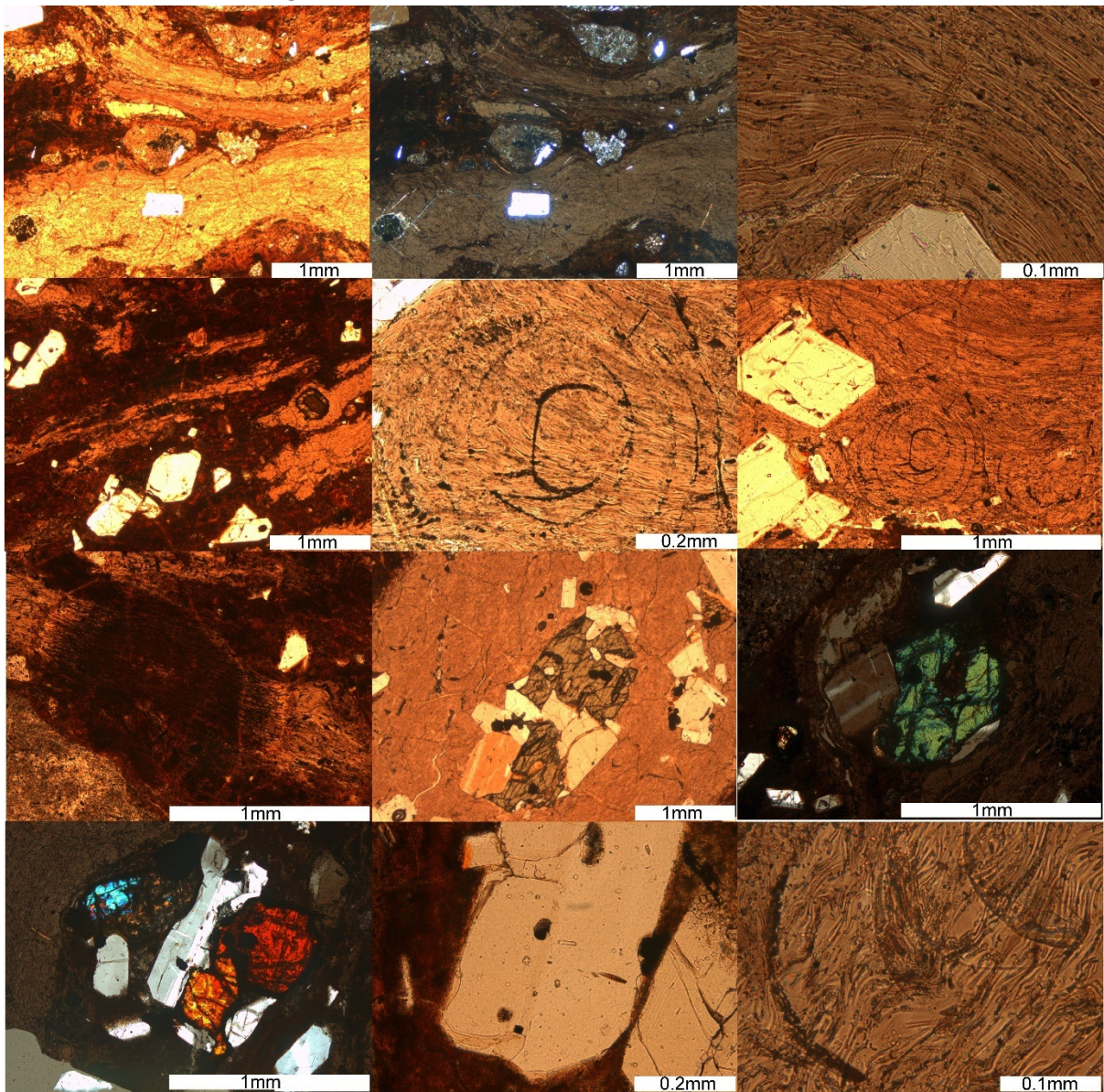
Handsample # 26082015-25**Unit, Member, Formation:** Ytra-Mógil, layer no. 2 from below**Sample location:** Torfufell east side, southern part of the map**Sample description:**

A. Sample represents	explosive volcanism by the early phases of rhyolitic activity at the volcano
Location within unit	Middle of layer
meters above base	; meters below top
Size of sample	20x10x5 cm
B. Color of sample. Weathering color	red brown ; true color brown and black
C. Texture.	
Groundmass	crystallinity (%) ~2%
	Mineral types not visible
	grain size aphanitic to glassy
Phenocrysts;	mineral types plagioclase (seen in the glassy fiamme and in the groundmass)
	mode (%) 2%
	size range ~1 mm
	habit subhedral
Fabric	pyroclastic. Fiamme grains are aligned in a preferred orientation
Homogeneity	Inhomogeneous rock; fiamme in a groundmass of fine ash
D. Inclusions of foreign material	lithics of various types
E. Alteration; weathering	red-brown weathering. White and orange. alteration minerals (vein fillings) at the weathered surface. Flat and smooth weathered surface
	other alteration Groundmass is quite altered and oxidized. Fiamme appears rather fresh
F. Other features	Sometimes the black fiamme occurs as small spheres (<0.5 mm). The fiamme is typically from 3x0.5 to 5x1 cm. Some fiammes are greyish.

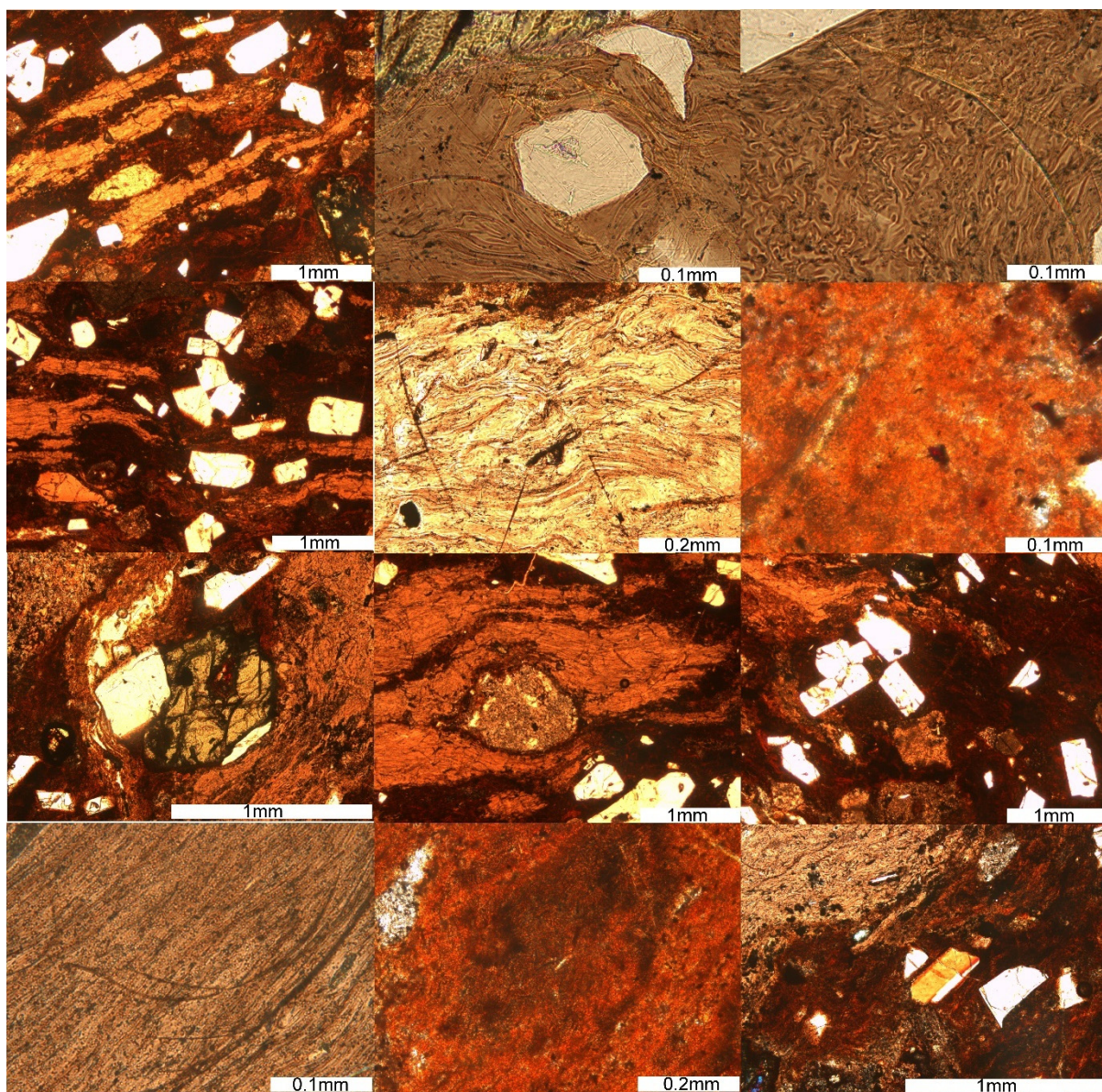
Thin section: 26082015-26

Rock name:	Ignimbrite (rhyolitic composition)
Where sampled:	Torfufell,
Grain size:	Aphanitic
Texture:	Eutaxitic
Groundmass:	fine matrix of ash/glass, opaque minerals, plagioclase
Phenocrysts:	Plagioclase, olivine (fayalite), pyroxene
Comments:	Ignimbrite rich in phenocrysts and lithics. Foliation defined by aligned, flattened, pumice lapilli. The pumice lapilli have been flattened and compacted to dark grey/black glass lenses and are separated by reddish to black matrix. Strong compaction and welding of pumice lapilli. Pumice lapilli display internal perlitic fractures (classic perlitic cracks). Flow-banding around lithics.

Elongated ash grains and elongated pumice grains. Content of lithics is ca 5-10%. Lithics are both from basalt and rhyolite. Small phenocryst crystals have preferred orientations. Very clear flow-banded texture around lithics. Fsp phenocrysts are more abundant in the groundmass matrix than in the fiammes. Fsp phenocrysts sometimes line up in a row where they are placed between fiammes and/or lithics. Fsp microlites are observed both in fiamme and in the groundmass matrix. Fsp phenocrysts sometimes have yellow-brownish color in crossed polars. Plagioclase phenocrysts are 15-20%, ca 1.5 mm, euhedral to subhedral, sometimes with inclusions e.g. zircon. Olivine (fayalite) phenocrysts are <1%, ca. 2 mm and anhedral. Pyroxene phenocrysts are <1% and subhedral to anhedral (fragments). Groundmass oxides and plagioclases are very small (<0.1 mm) and only a few crystals are visible. Groundmass is reddish and black.



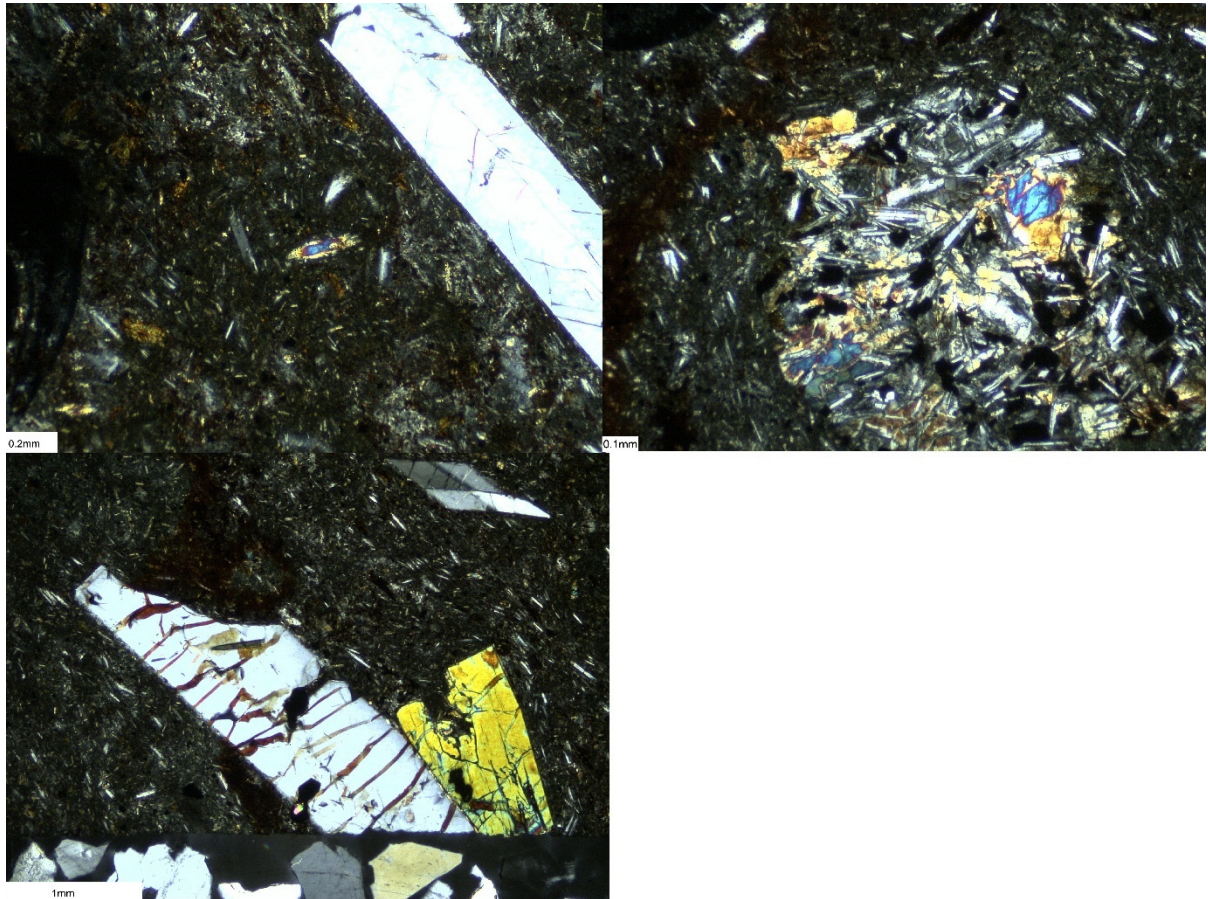
26082015-25



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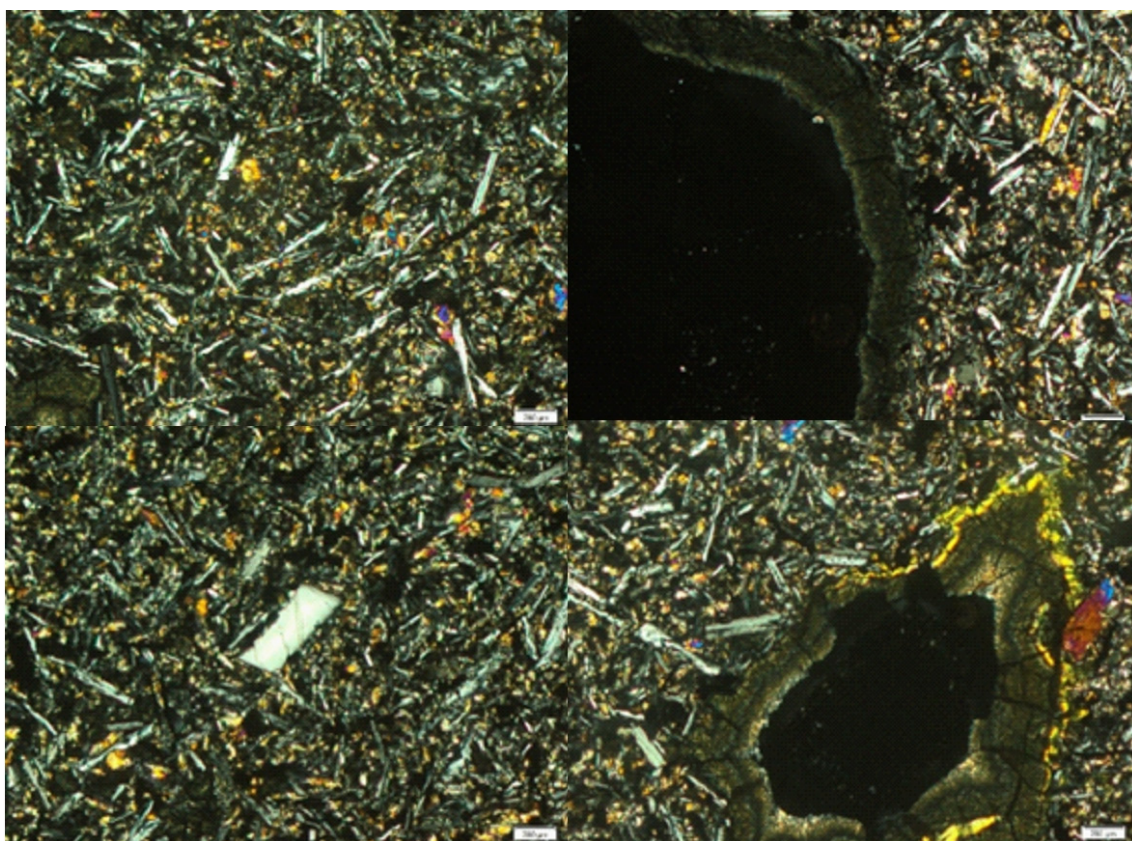
Handsample #14072017-1**Unit, Member, Formation:** Tjarnir, lava no. 4 from below**Sample location:** Hill above the Tjarnir farmhouse, Mt. Hólafljall west side**Sample description:****A. Sample represents** Lowermost part of the intermediate/silicic complex**Location within unit** Upper part**meters above base** 66 ; **meters below top** 13**Size of sample** 9x6x4 cm**B. Color of sample. Weathering color** light brown ; **true color** light grey**C. Texture.****Groundmass crystallinity (%)** 90-100%**Mineral types** not visible**grain size** aphanitic**Phenocrysts; mineral types** plagioclase**mode (%)** <1%**size range** ~1 mm**habit** subhedral**Fabric** Flow-banded, equigranular**Homogeneity** homogeneous crystal sizes**D. Inclusions of foreign material** none**E. Alteration; weathering****other alteration** orange- to red alteration along flow bands. A little orange to red alteration is also observed in the groundmass.**F. Other features** Very dense sample, no vesicles**Thin section: 14072017-1****Rock name:** Rhyolite (stony)**Where sampled:** Tjarnir (lava no. 4 in the Tjarnir profile)**Grain size:****Texture:** Flow-banded**Groundmass:** Altered glass, plagioclase, metals.**Phenocrysts:****Comments:** Very flow-banded groundmass with small spherulites. Originally rich in glass but the glass is now altered. Dark bands consist largely of glass while light-colored bands consist largely of plagioclase. Metals are widely observed throughout the sample.

Handsample # 27072017-1**Unit, Member, Formation:** Úlfá, lava no. 10 from below**Sample location:** Torfufell east side, Úlfá**Sample description:****A. Sample represents** Lowermost part of the intermediate/silicic complex in the norther part of Mt. Torfufell**Location within unit****meters above base** ; **meters below top****Size of sample** 16x19x5 cm and 15x9x8 cm**B. Color of sample. Weathering color** dark brown ; **true color** dark grey**C. Texture.****Groundmass** **crystallinity (%)** 100%**Mineral types** not visible**grain size** aphanitic**Phenocrysts; mineral types** plagioclase, pyroxene**mode (%)** <1%**size range** 0.5-3 mm**habit** euhedral to subhedral (plagioclase)**Fabric** equigranular**Homogeniety** homogeneous crystal sizes, homogeneous groundmass**D. Inclusions of foreign material** basaltic xenolites**E. Alteration; weathering****other alteration** red alteration/oxidation along fractures, orange/red alteration along some of the phenocrysts**F. Other features** flow structures**Thin section: 27072017-1****Rock name:** Dacite**Where sampled:** Úlfá, Torfufell east side, bottom of the intermediate/silicic complex**Grain size:** Fine**Texture:** Aphanitic**Groundmass:** Titanomagnetite, clinopyroxene, plagioclase**Phenocrysts:** plagioclase, pyroxene**Comments:** Aphanitic, dark groundmass, originally very glass-rich, with sparse phenocrysts. Phenocrysts are plagioclase (ca. 2 mm long) and pyroxene (ca 0.3 mm long). A vein with possible hydroxides is observed and with localized alteration close to the vein. Inclusions (e.g. opaque minerals and apatite) are observed inside plagioclase phenocrysts. A basaltic xenolite with ophitic texture, ca. 1 mm in diameter, is observed inside the sample.

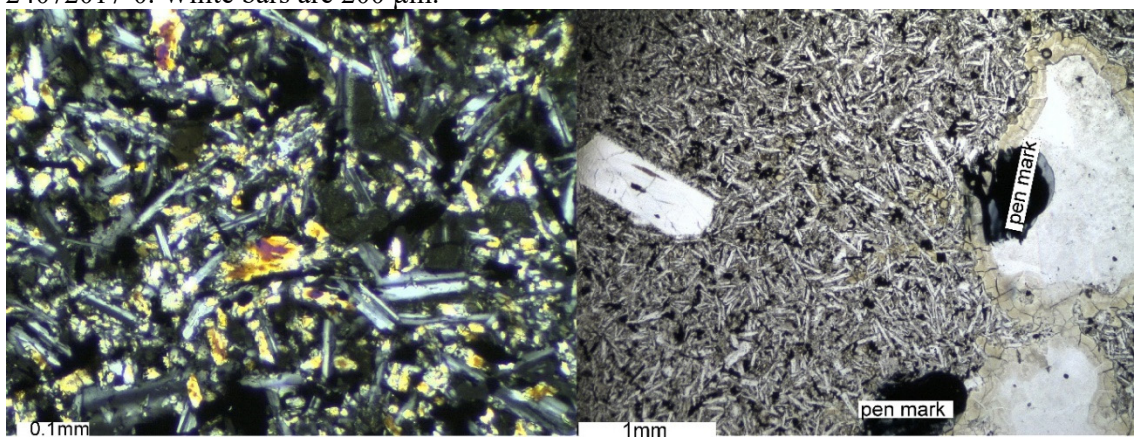


27072017-1. White bars are (from upper left) 0.2, 0.1 and 1 mm. The upper right image shows a xenolite.

Handsample # 24072017-0**Unit, Member, Formation:** Nautárgil, 2nd lava from below**Sample location:** Svarfdalur valley, north side, Nautárgil**Sample description:****A. Sample represents** aa-lava flows below the intermediate/silicic complex.**Location within unit** middle of layer**meters above base** ~1.5 ; **meters below top** ~1.5**Size of sample** 14x9x9 cm**B. Color of sample. Weathering color** red-brown ; **true color** medium grey**C. Texture.****Groundmass** **crystallinity (%)** 100%**Mineral types** not visible**grain size** fine**Phenocrysts; mineral types** plagioclase, pyroxene (microphenocrysts)**mode (%)** 3-5%**size range** <0.1 mm**habit****Fabric** vesicular, equigranular**Homogeneity** homogeneous grain sizes**D. Inclusions of foreign material** none**E. Alteration; weathering** thin red-brown weathering coat**other alteration** vesicles are either coated or filled with amorphous light-yellow material (opal). Next to the vesicle walls is orange material. Light-blue-grey material (clay) is seen in one place- could be formed along the surface of a fracture. Otherwise the sample is unaltered.**F. Other features** Vesicles are 30-40%, up to 2 cm. Elongation of vesicles is not very prominent.**Thin section: 24072017-0****Rock name:** Basalt (aa-lava)**Where sampled:** Nautárgil, Svarfdalur**Grain size:** Fine**Texture:** Intergranular**Groundmass:** Titanomagnetite, ilmenite, altered glass, plagioclase**Phenocrysts:** Plagioclase, pyroxene**Comments:** Fine-grained vesicular rock with pyroxene, interstitial iron-titanium oxide and altered interstitial glass. Intergranular texture with elongated plagioclases. Large vesicles are coated with brown material (clay). Brown clay also occurs as alteration spots in the groundmass.

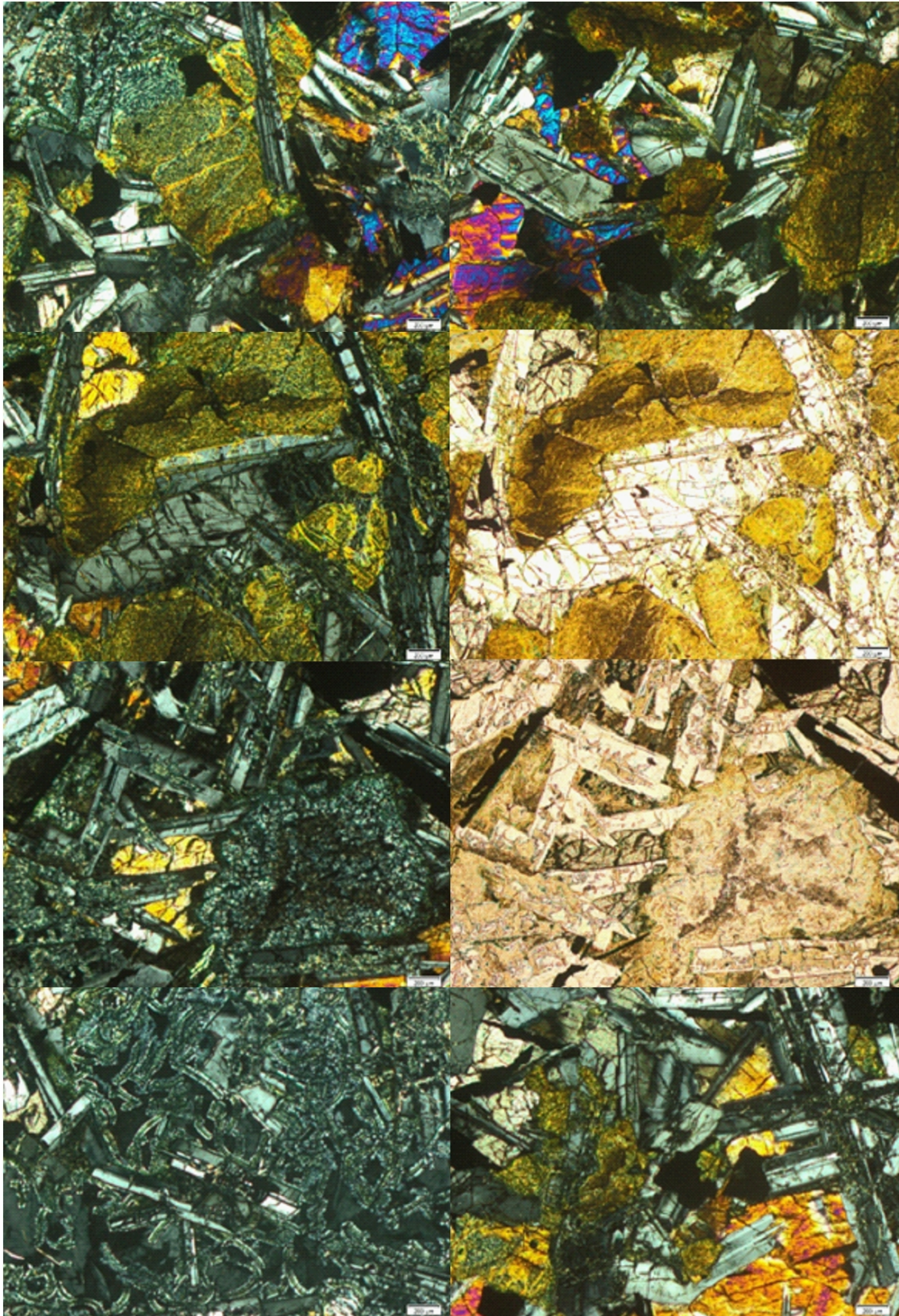


24072017-0. White bars are 200 μm .



24072017-0.

Handsample # 27072017-5**Unit, Member, Formation:** Nóngil, 8th layer from below**Sample location:** Mt. Torfufell east side, gully south of Úlfá**Sample description:****A. Sample represents** basaltic lava in the middle of the rhyolite complex – above a thick sandstone layer**Location within unit** middle of layer**meters above base** ~2.5 ; **meters below top** ~2.5**Size of sample** 6x4x4 cm and 7x5x4 cm**B. Color of sample. Weathering color** light orange-brown; **true color** dark grey**C. Texture.****Groundmass crystallinity (%)** 100%**Mineral types** not visible**grain size** fine to medium**Phenocrysts; mineral types** plagioclase, olivine, pyroxene**mode (%)** <1%**size range** plagioclase 1-2 mm, olivine ~0.8 mm, pyroxene ~1 mm**habit** plagioclase euhedral to subhedral**Fabric****Homogeneity****D. Inclusions of foreign material** none**E. Alteration; weathering****other alteration** alteration minerals at fracture surfaces. Orange alteration rather abundant in the groundmass. Olivine phenocrysts are red.**F. Other features****Thin section: 27072017-5****Rock name:** Basalt (olivine tholeiite)**Where sampled:** South of Úlfá, Torfufell east side. In the middle of the rhyolite**Grain size:** Coarse**Texture:** Intergranular/ophitic**Groundmass:** magnetite**Phenocrysts:** Pyroxene, plagioclase, olivine (former olivine; possibly serpentine or green nontronite)**Comments:** Homogenous grain size; no contrast between groundmass minerals and phenocryst sizes. Plagioclases are well formed and mostly fresh. Olivines are totally altered. Pyroxene is observed in interstitial between the plagioclases. A significant amount of pyroxene is not affected by alteration. Plagioclase is sometimes a little altered. Opaque minerals (magnetite) are abundant.



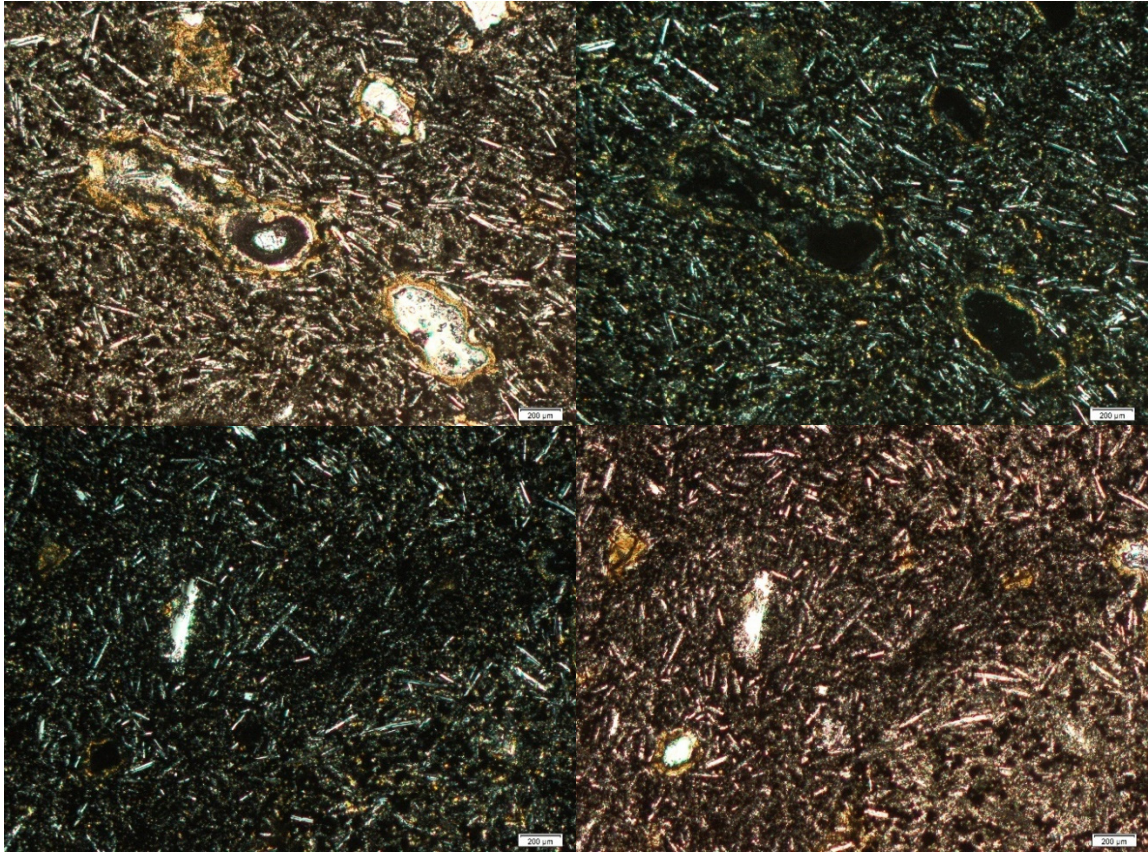
27072017-5. White bars are 200 μm .

Handsample # 27072017-4**Unit, Member, Formation:** Nóngil, uppermost layer**Sample location:** Mt. Torfufell east side, gully south of Úlfá**Sample description:****A. Sample represents** the first basalt lava (normal polarity) above the intermediate/silicic complex**Location within unit** near the base**meters above base ; meters below top****Size of sample** 12x4x7 cm**B. Color of sample. Weathering color** brown ; **true color** grey**C. Texture.****Groundmass crystallinity (%)** 100%**Mineral types** pyroxene, plagioclase, olivine**grain size** fine to medium**Phenocrysts; mineral types** plagioclase, olivine (completely altered), pyroxene**mode (%)** <1%**size range** plagioclase <0.5 mm and 1 mm, olivine 1-2 mm, pyroxene <0.5 mm**habit** subhedral to euhedral**Fabric** equigranular**Homogeneity** homogeneous grain sizes**D. Inclusions of foreign material** none**E. Alteration; weathering** very thin weathering coat**other alteration** olivine phenocrysts are completely altered. Orange alteration is often observed in the groundmass, especially around fractures and vesicles.**F. Other features** dense rock, very few vesicles**Thin section: 27072017-4****Rock name:** Basalt**Where sampled:** South of Úlfá (Torfufell east side). First basalt lava above the rhyolitic complex**Grain size:** Fine**Texture:** Intergranular**Groundmass:** Plagioclase, iron oxides, pyroxene**Phenocrysts:** plagioclase**Comments:** Fine grained groundmass with sparse (ca. 1%) plagioclase phenocrysts (0.4-1.2 mm). Almost euhedral iron oxides are interstitial.



27072017-4. White bars are 200 μm .

Handsample # 24072017-1**Unit, Member, Formation:** Nautárgil, 3rd lava from below**Sample location:** Svarfdalur valley, north side, Nautárgil**Sample description:****A. Sample represents** aa-alavas below the intermediate/silicic complex.**Location within unit** middle of layer**meters above base** ~1.4 ; **meters below top** ~1.4**Size of sample** 10x10x8 cm**B. Color of sample. Weathering color** red-brown; **true color** grey**C. Texture.****Groundmass** **crystallinity (%)** 100%**Mineral types** not visible**grain size** fine**Phenocrysts; mineral types** no phenocrysts**mode (%)****size range****habit****Fabric** vesicular, equigranular**Homogeneity** homogeneous grain sizes**D. Inclusions of foreign material** none**E. Alteration; weathering** red-brown weathering coat**other alteration** fresh groundmass. Orange-red clay in some vesicles (not filling them). Some vesicles are filled with opal and some vesicles are coated with blue-green-gray clay.**F. Other features** 15-20% vesicles, 0.1-3 mm**Thin section: 24072017-1****Rock name:** Basalt (aa-lava)**Where sampled:** Svarfdalur, Nautárgil**Grain size:** fine**Texture:** intergranular**Groundmass:** plagioclase, pyroxene, iron-titanium oxides**Phenocrysts:** no phenocrysts**Comments:** vesicular rock. vesicles are irregular (not circular) and coated with thin brown material. Vesicles are 25-30% and 0.55 mm in size. Tendency towards preferred orientation of plagioclase microlites in some places (not very prominent though). Iron-titanium oxides are abundant. Fragments of scoria are observed inside the sample.

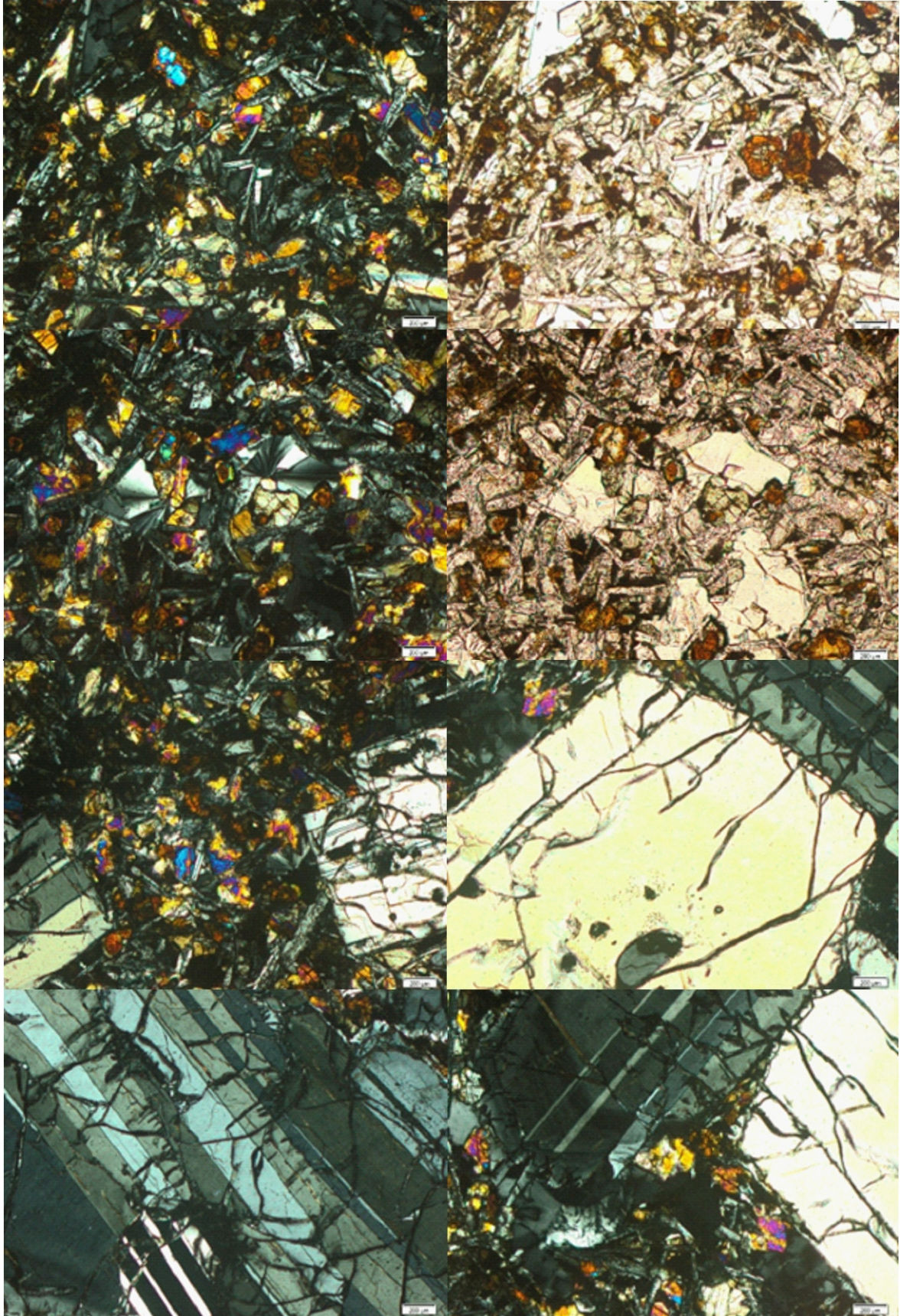


27072017-1. White bars are 200 μm .

Handsample # 10072017-4**Unit, Member, Formation:** Glerá, lava no. 17 from below**Sample location:** Glerá, Mt. Hólafljall west side**Sample description:**

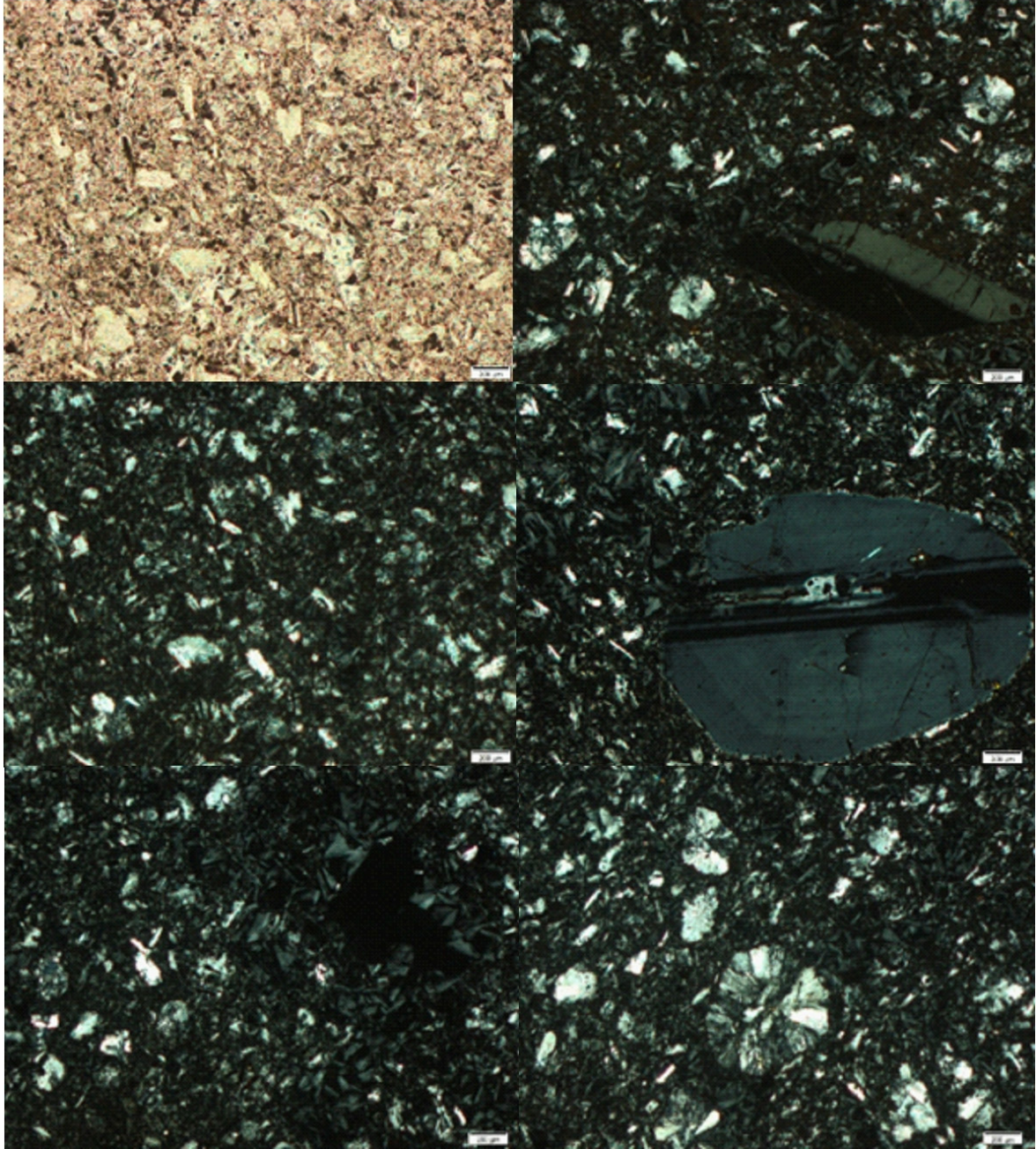
A. Sample represents porphyritic basalt lavas within reverse polarity basalts above the rhyolite complex, just below a magnetic reversal assumed as the Miocene/Pliocene boundary

Location within unit**meters above base ; meters below top****Size of sample** 18x13x5cm and 14x11x5 cm**B. Color of sample. Weathering color** light brown ; **true color****C. Texture.****Groundmass crystallinity (%)** 100%**Mineral types** pyroxene, plagioclase**grain size** fine**Phenocrysts; mineral types** plagioclase**mode (%)** 30%**size range** 1-5 mm**habit** subhedral**Fabric** porphyritic**Homogeneity** homogeneous groundmass. Various sizes of phenocrysts**D. Inclusions of foreign material** none**E. Alteration; weathering** very thin weathering coat, light brown**other alteration** plagioclase in groundmass is slightly yellowed. Plagioclase phenocrysts are slightly yellowed around the edges. Otherwise the sample is unaltered**F. Other features** dense sample with no vesicles.**Thin section: 10072017-4****Rock name:** Basalt (porphyritic)**Where sampled:** Glerá, basalt above the rhyolitic complex**Grain size:** Coarse**Texture:** Porphyritic**Groundmass:** Plagioclase, pyroxene**Phenocrysts:** Plagioclase**Comments:** Large (5-7 mm) subhedral plagioclase phenocrysts occur in clusters. Iron hydroxide and zeolites are observed in the groundmass.



10072017-4. White bars are 200 μm .

Handsample # 14072017-2**Unit, Member, Formation:** Tjarnir, lava no. 2 from above**Sample location:** Hill above the Tjarnir farmhouse, Mt. Hólafjall west side**Sample description:****A. Sample represents** lower rhyolite layer in Mt. Hólafjall**Location within unit** near the top**meters above base ; meters below top****Size of sample** 10x6x4 cm**B. Color of sample. Weathering color** red ; **true color** light grey**C. Texture.****Groundmass crystallinity (%)** 100%**Mineral types** not visible**grain size** aphanitic**Phenocrysts; mineral types** plagioclase**mode (%)** <1%**size range** 1-2 mm**habit** euhedral to subhedral**Fabric** equigranular, no flow-banding observed**Homogeneity** homogeneous grain sizes**D. Inclusions of foreign material** none**E. Alteration; weathering** red weathering coat**other alteration** orange to red alteration/oxidation is observed in a few minerals in the groundmass. Otherwise the sample is rather fresh.**F. Other features** Rather dense sample**Thin section: 14072017-2****Rock name:** Rhyolite (stony)**Where sampled:** Mt. Hólafjall, lowermost part of the rhyolite complex. Tjarnir**Grain size:** Fine**Texture:** Porphyritic**Groundmass:** Feldspar, opaque minerals, pyroxene**Phenocrysts:** Feldspar**Comments:** Fine-grained groundmass with sparse (ca. 1% -) large (1-2 mm) feldspar phenocrysts. Some of the feldspar phenocrysts are rounded while others are not rounded. The rounded phenocrysts are possibly dissolving and may be more mafic than the rounded feldspars. Several amygdules are observed. A big zircon is observed inside a phenocryst. Microlites are mostly randomly oriented (no flow texture). Sparse vesicles with zeolites.

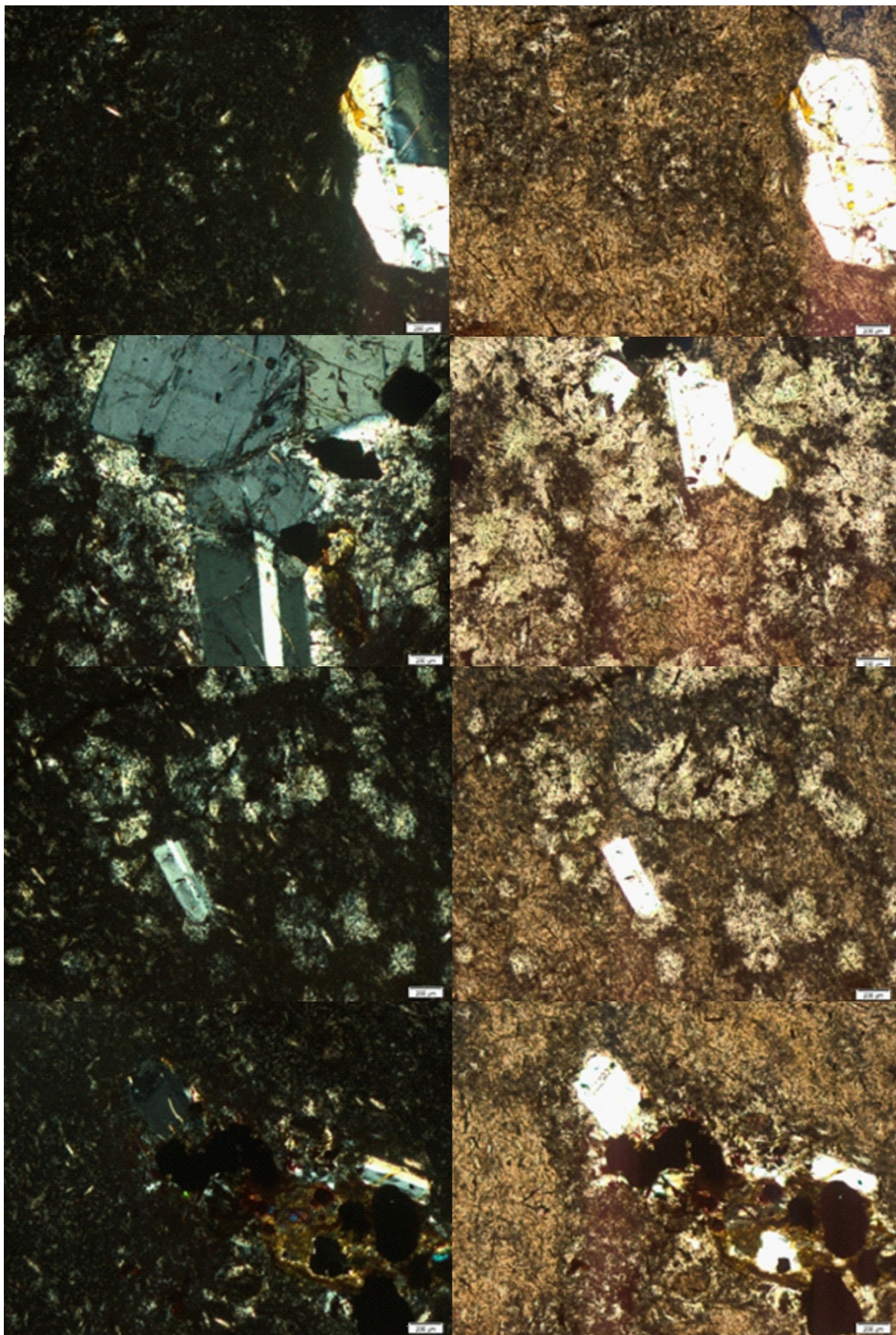


14072017-2. White bars are 200 μ m.

Handsample # 18072017-3a (rhyolitic part of an ignimbrite)**Unit, Member, Formation:** Nóngil, 5th layer from below**Sample location:** Gully south of Úlfá, Mt. Torfufell east side**Sample description:****A. Sample represents** explosive volcanism near the beginning of rhyolitic activity at the volcano**Location within unit** middle of unit**meters above base** ~50 ; **meters below top** ~50**Size of sample** 10x4x3 cm**B. Color of sample. Weathering color** dark brown to black ; **true color** purple**C. Texture.****Groundmass crystallinity (%)** 100%**Mineral types** pink and white minerals (alkali feldspar and quartz?)**grain size** medium**Phenocrysts; mineral types** feldspar (sometimes with small (0.5-3 mm) black anhedral inclusions, considered as metal oxides)**mode (%)** <1%**size range** 0.5-1.5 mm**habit** subhedral**Fabric** equigranular groundmass. Some flow-banding in part of the sample (alkali feldspar vs. quartz)**Homogeneity** homogeneous groundmass**D. Inclusions of foreign material** none**E. Alteration; weathering** dark-brown and black weathering coat**other alteration** orange alteration observed in some groundmass minerals**F. Other features**

very dense sample, no vesicles. Elongated phenocrysts are usually aligned parallel to the flow-banding while larger (and not elongated) phenocrysts are not.

Thin section: 18072017-3b (dacitic part of an ignimbrite)**Rock name:** Dacite**Where sampled:** Torfufell east side**Grain size:** Aphanitic**Texture:** Porphyritic**Groundmass:** Quartz, feldspar, titanomagnetite**Phenocrysts:** Feldspar, pyroxene**Comments:** Aphanitic (to glassy) groundmass with large (1-2 mm) feldspar phenocrysts, often occurring in clusters. Clear porphyritic texture; feldspar phenocrysts are ca. 10-15%, euhedral, well formed, zoned. Feldspar microlites are tiny and very thin (ca. 0.05-0.25 mm long). Groundmass is slightly flow-banded. Reddish color is observed along fractures in some phenocrysts. Mafic minerals are rare and completely altered (maybe originally pyroxene). Apatite is observed as inclusion in feldspar phenocryst.



18072017-3b. White bars are 200 μm .

B2 Field descriptions

~550 m.a.s.l. - - - - -

Mælifellshnjúkur

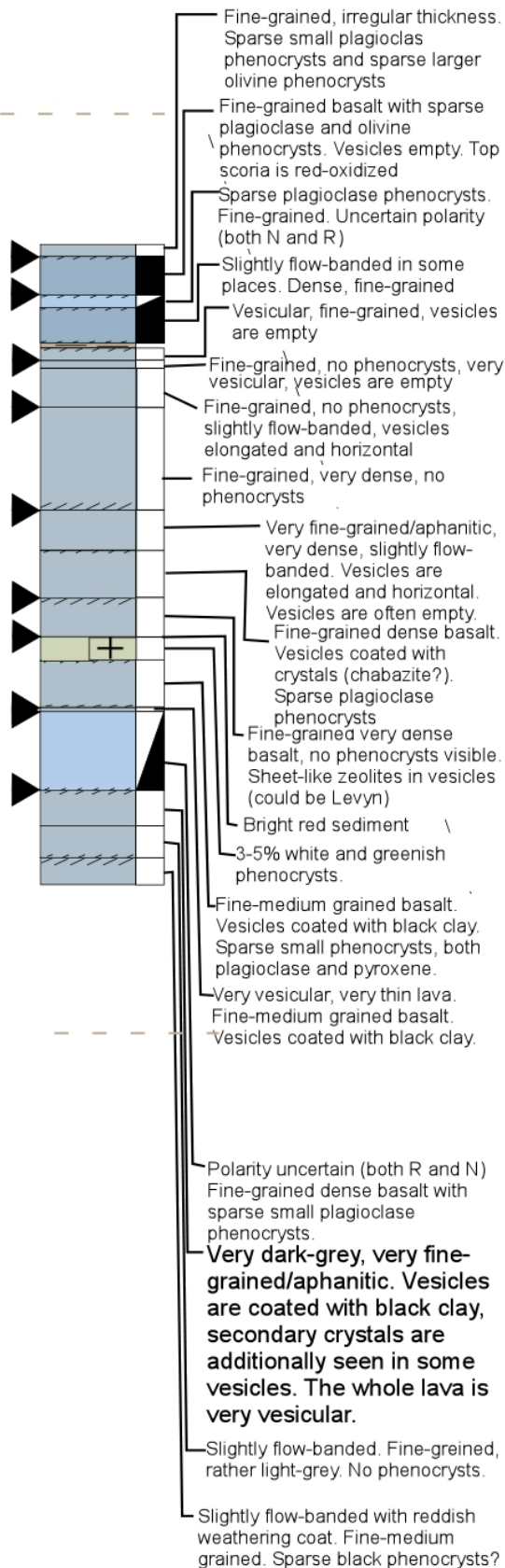
~500 m.a.s.l. - - - - -

~450 m.a.s.l.

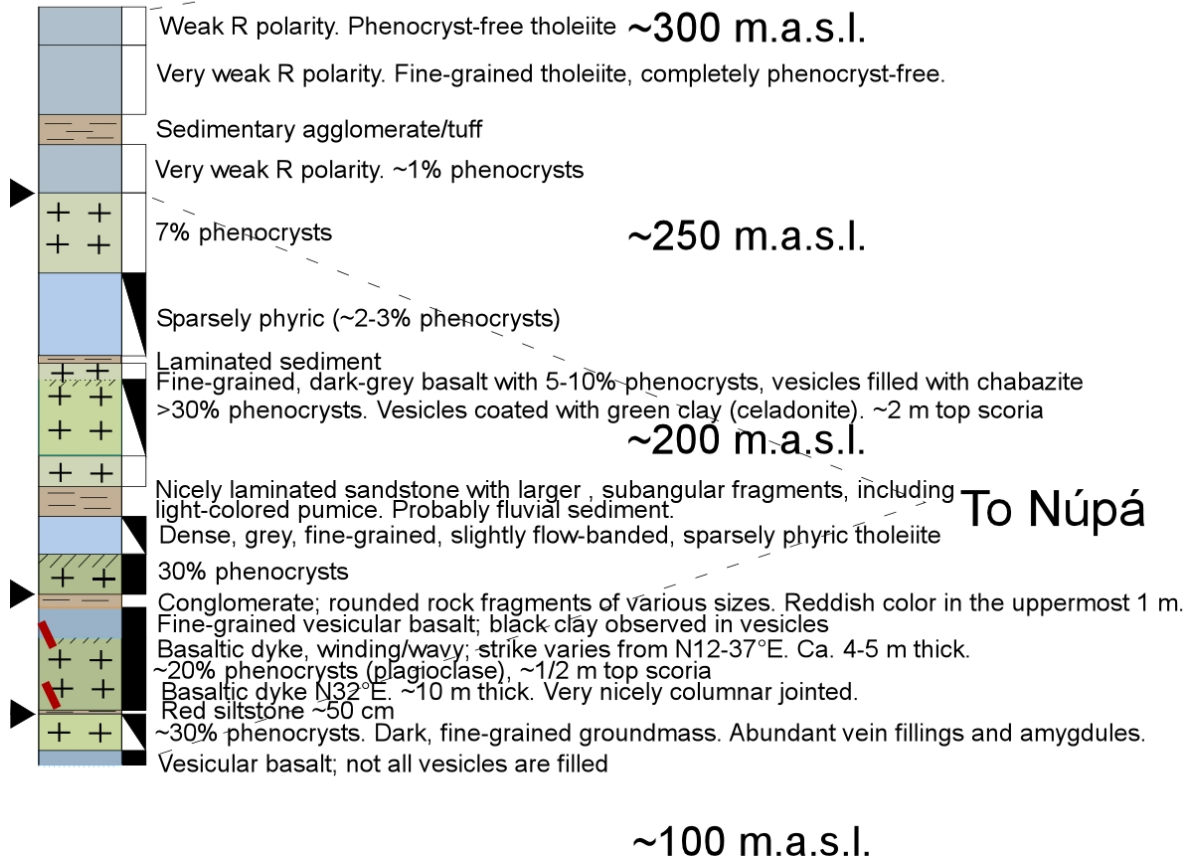
~400 m.a.s.l.

~350 m.a.s.l.

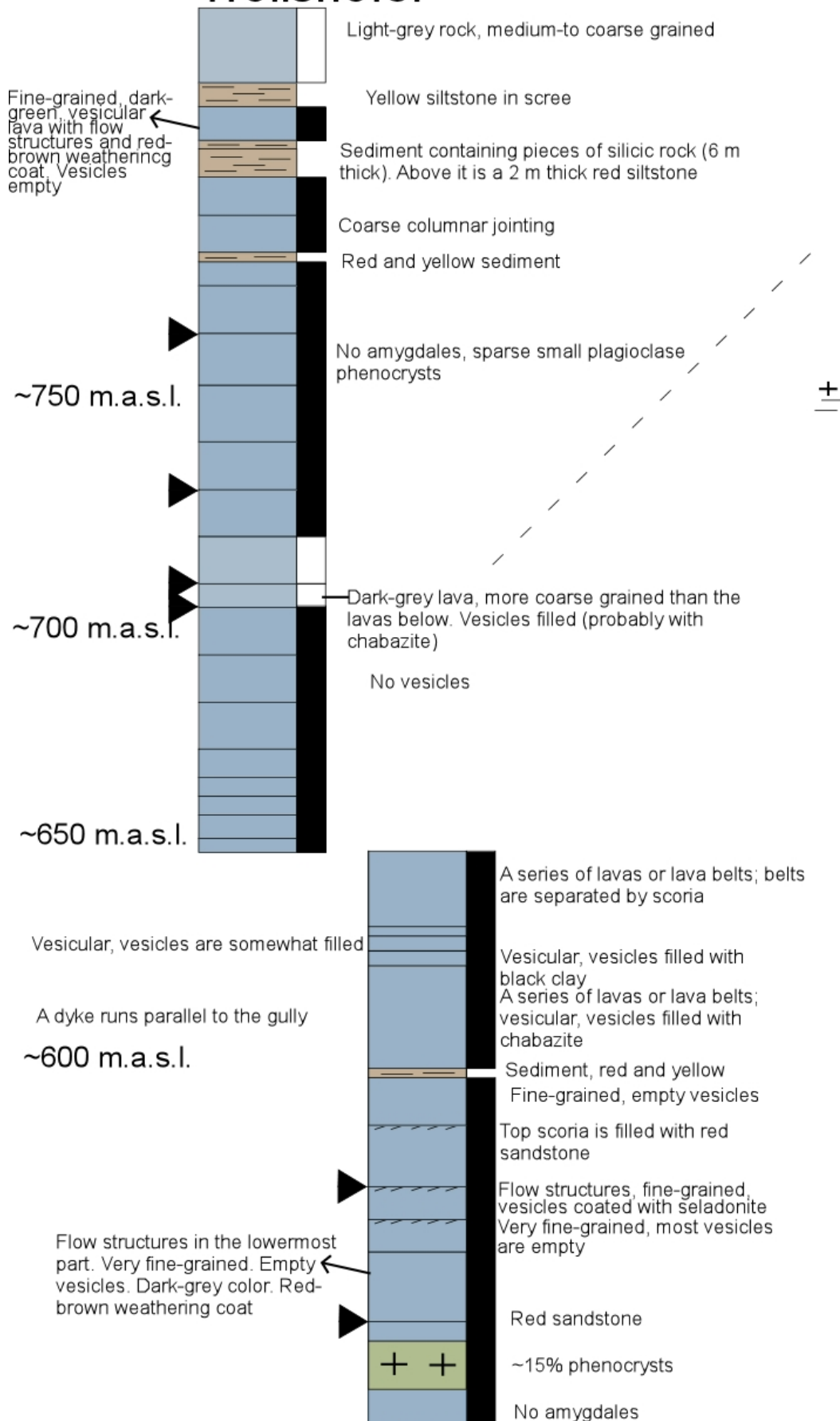
~300 m.a.s.l. - - - - -



Gilsá



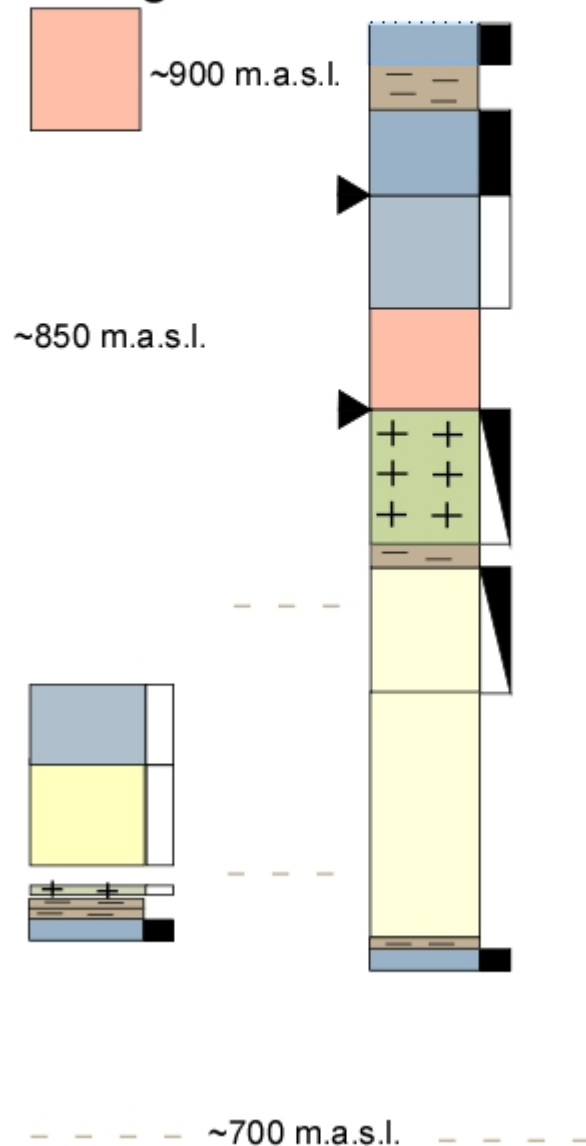
Tröllshöfði



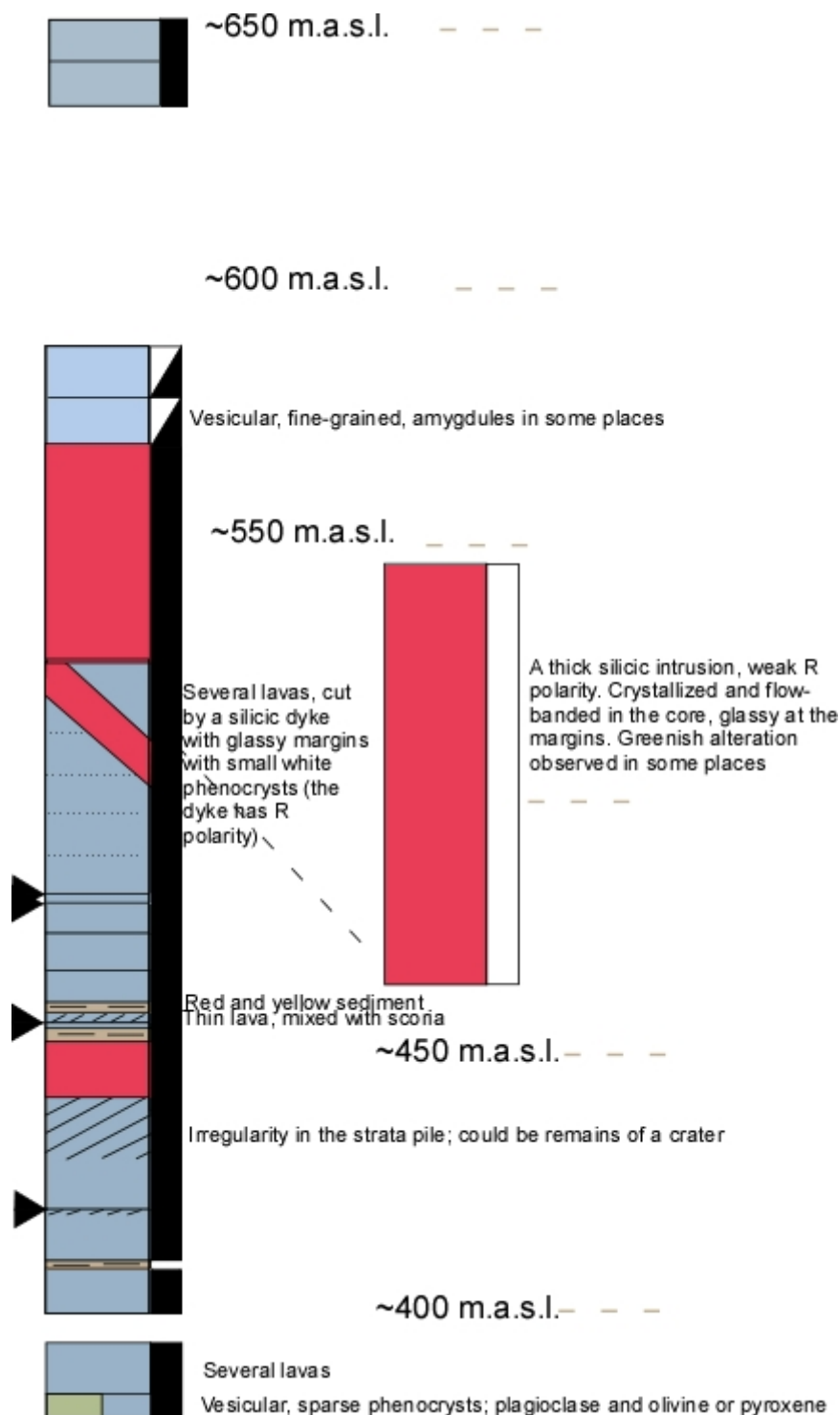
Hamragil and Between Hamragil and Fálkagil upper parts:

Between Hamragil and Fálkagil

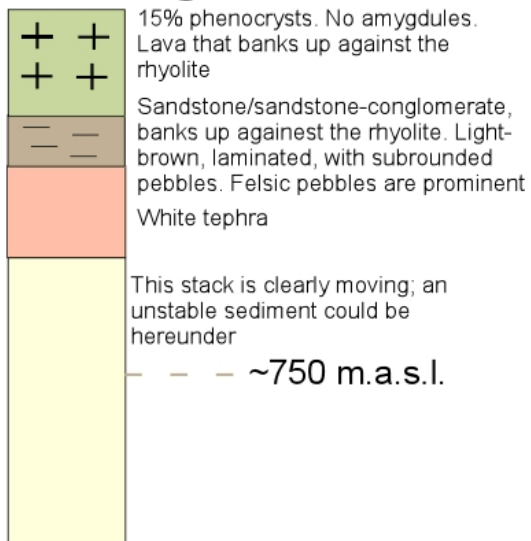
Hamragil



Hamragil and Between Hamragil and Fálkagil lower parts:

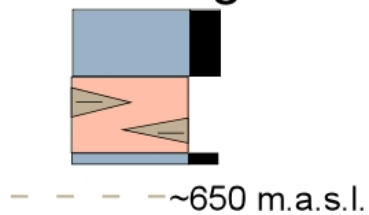


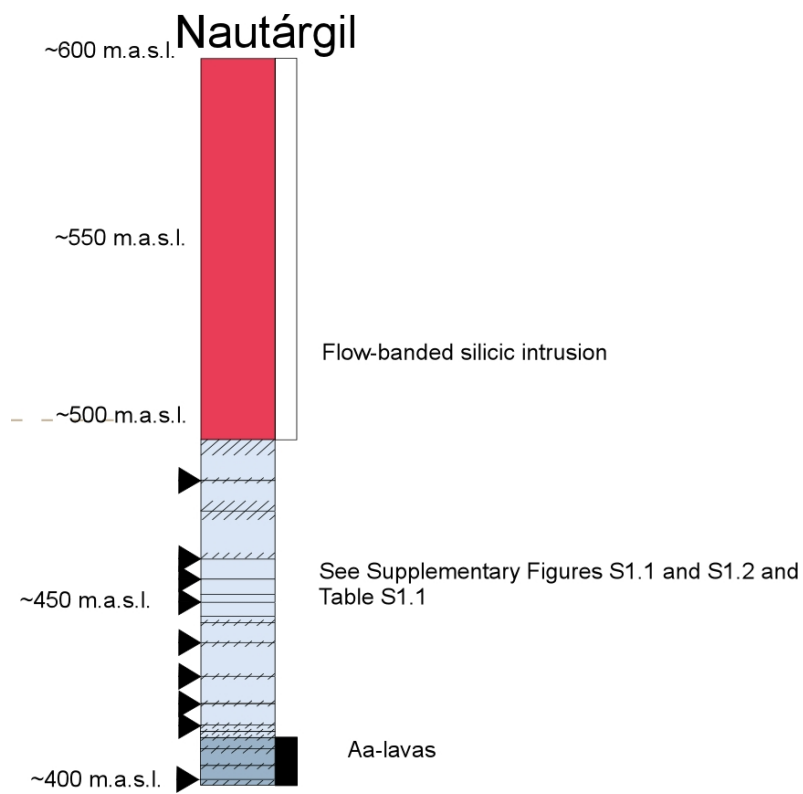
Fálkagil cont.



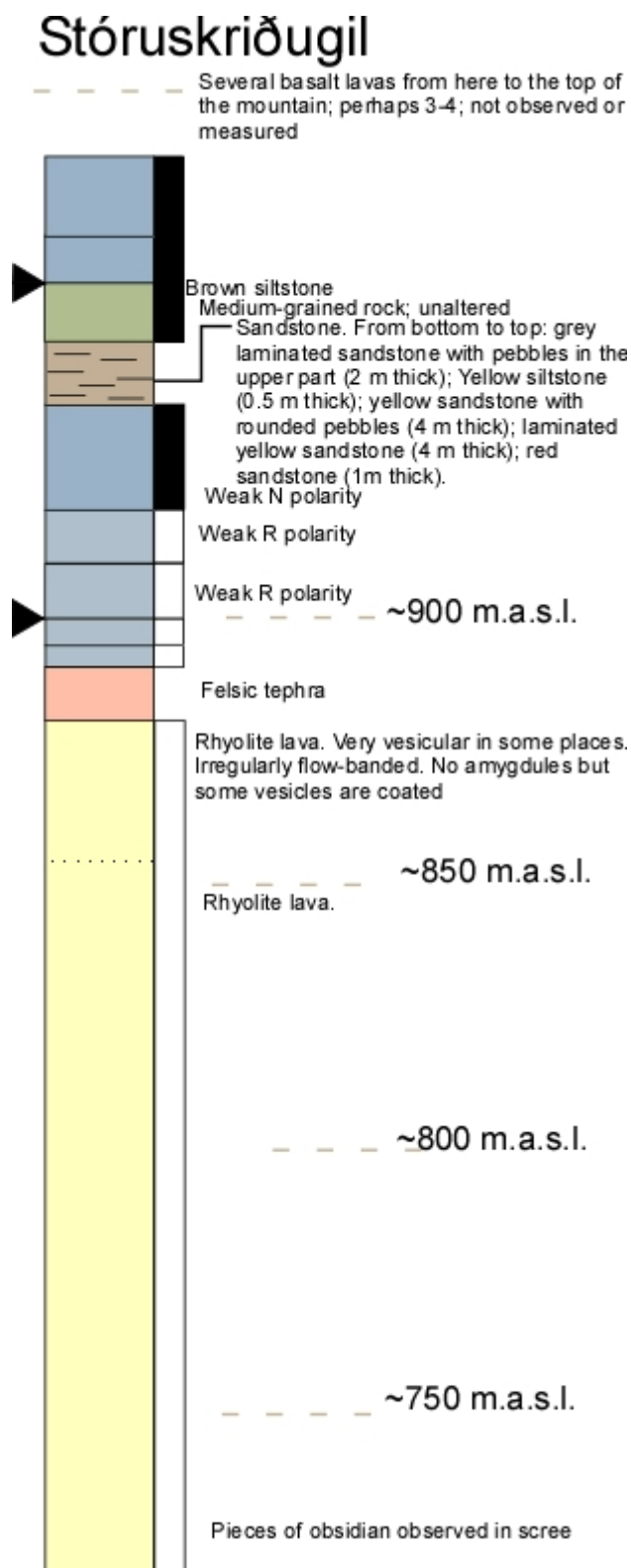
— — — ~700 m.a.s.l.

Fálkagil

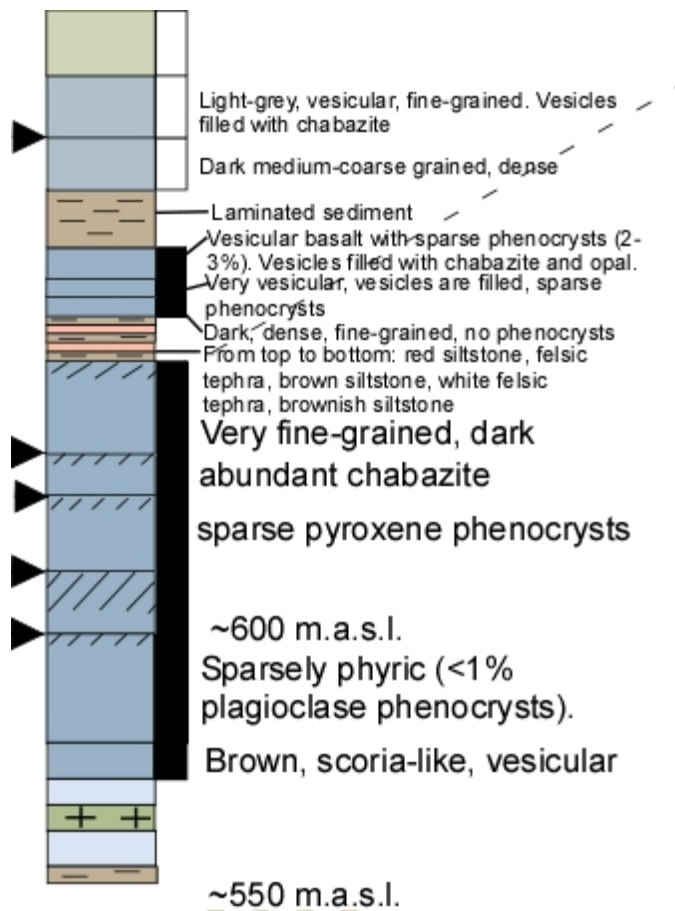


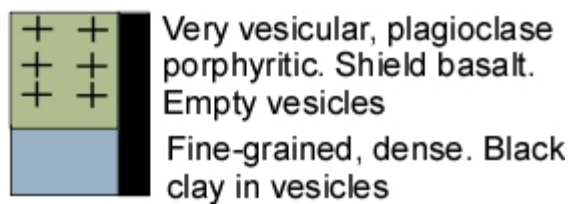
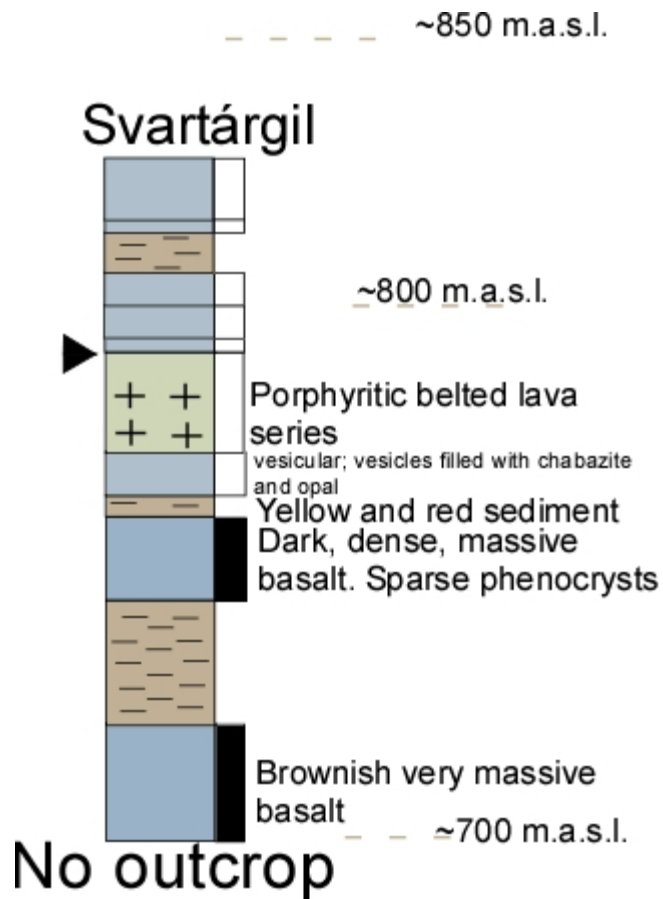


Stóruskriðugil upper part:

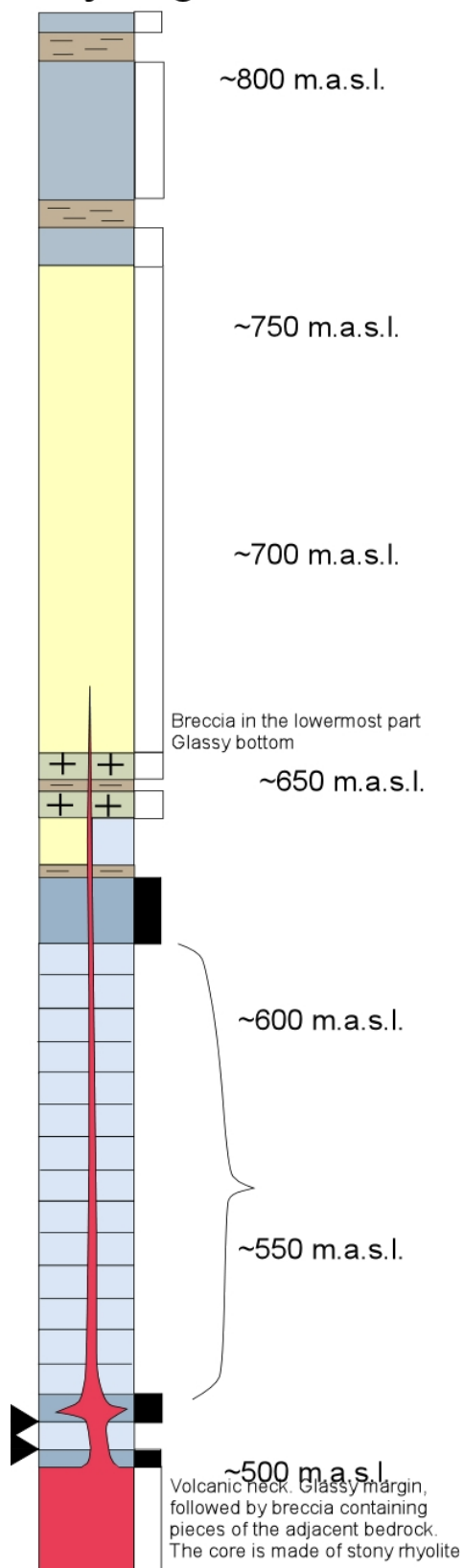


Stóruskriðugil lower part:

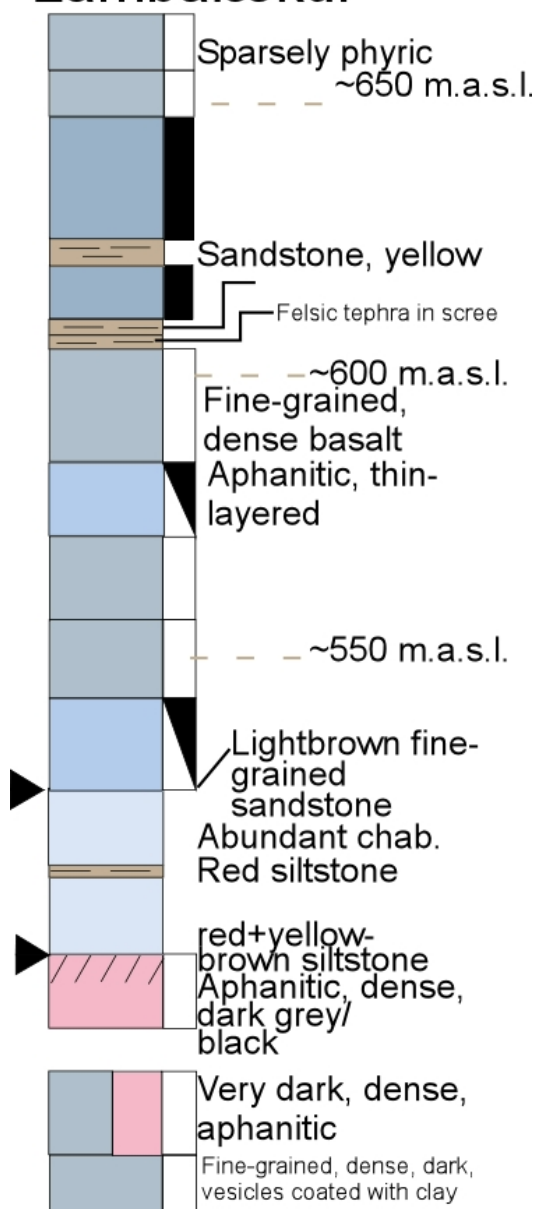




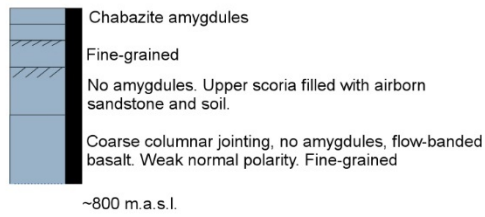
Leyningsdalur



Lambalækur



Torfufells-
dalur
(Torf2)



~750 m.a.s.l.

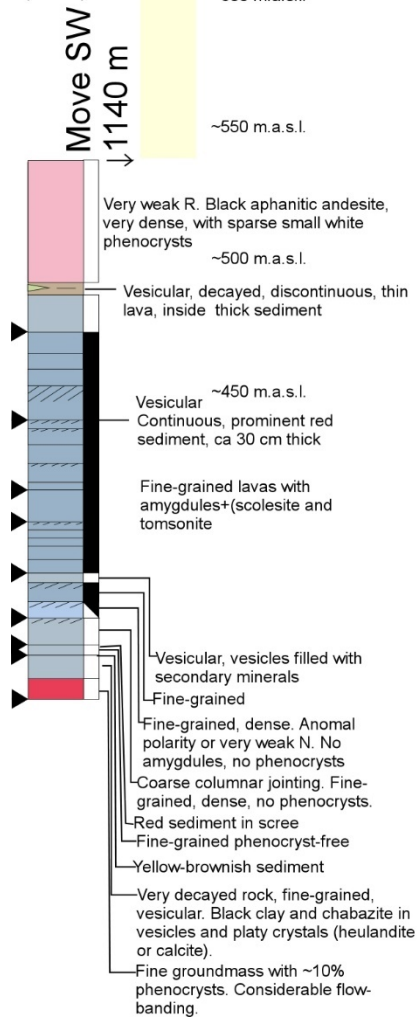
~700 m.a.s.l.

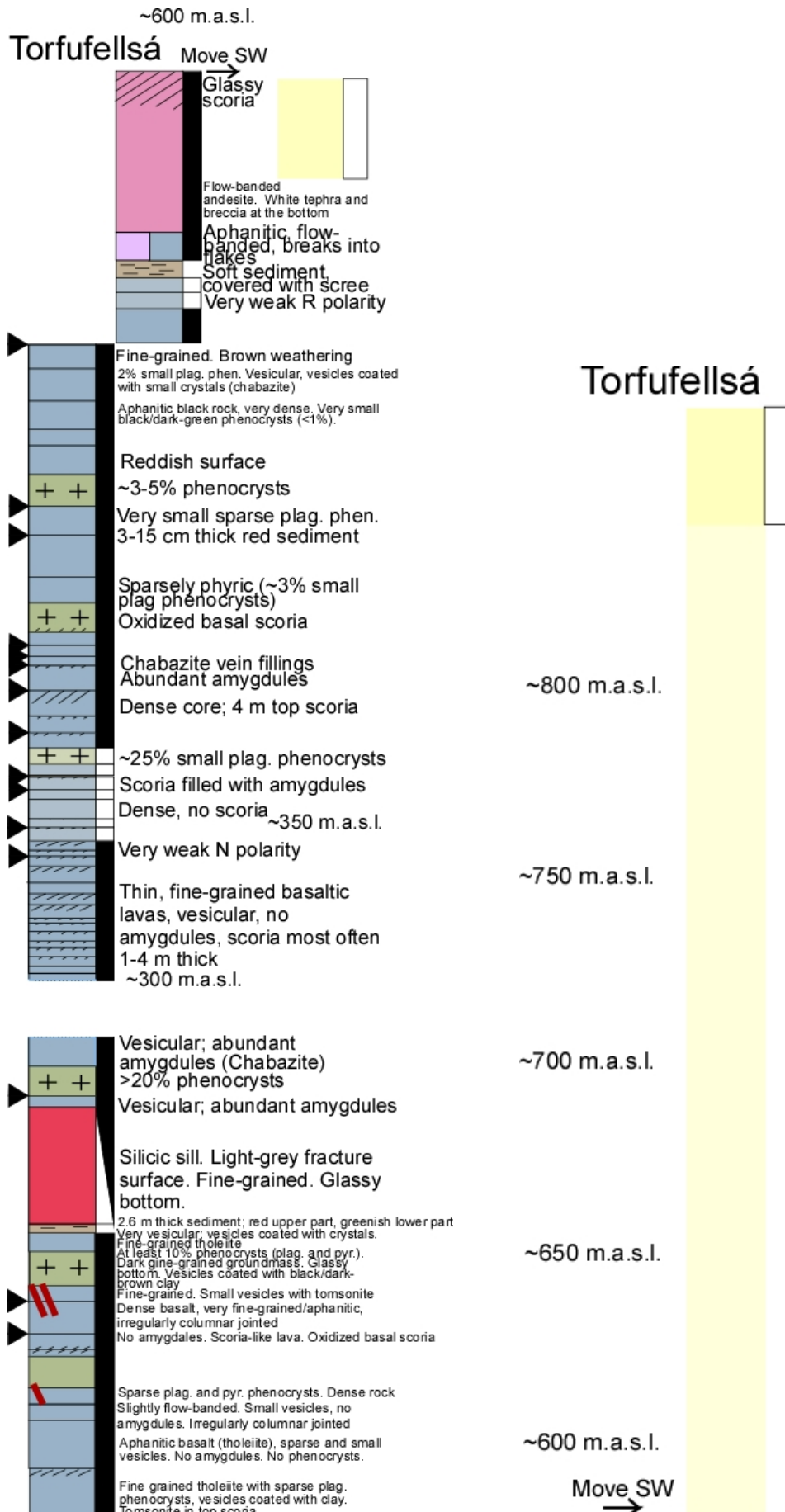
~650 m.a.s.l.

~600 m.a.s.l.

~550 m.a.s.l.

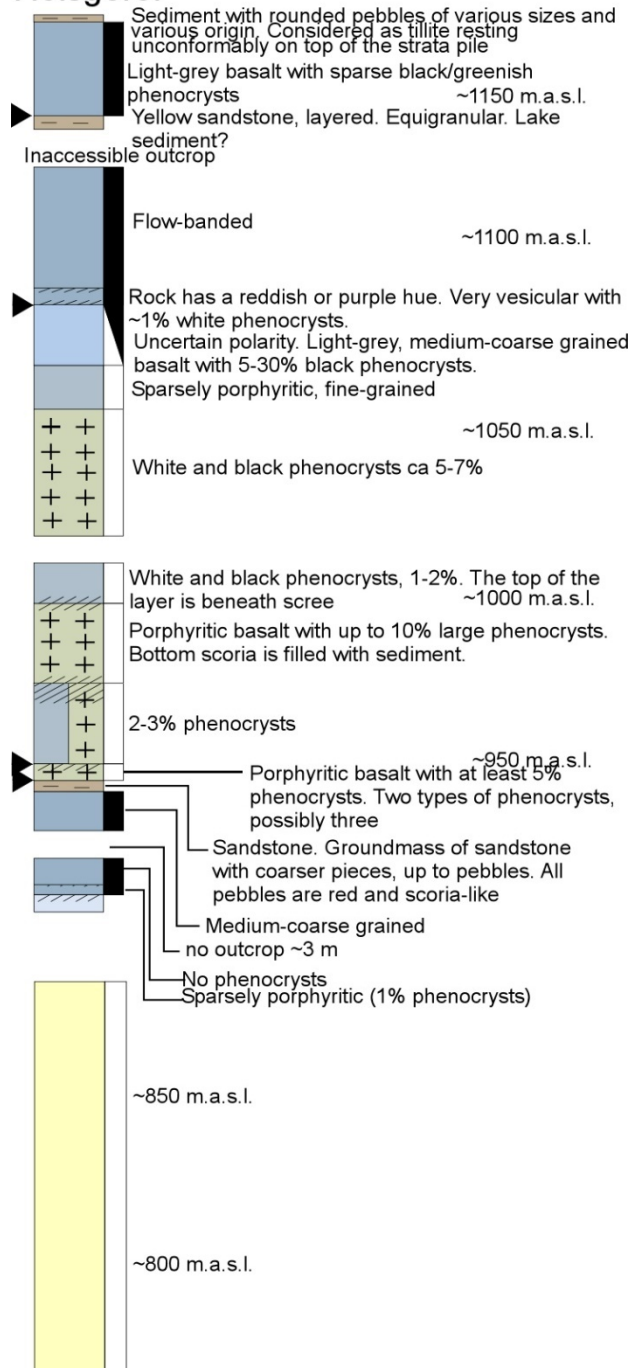
Torfufells-
dalur
(Torf1)



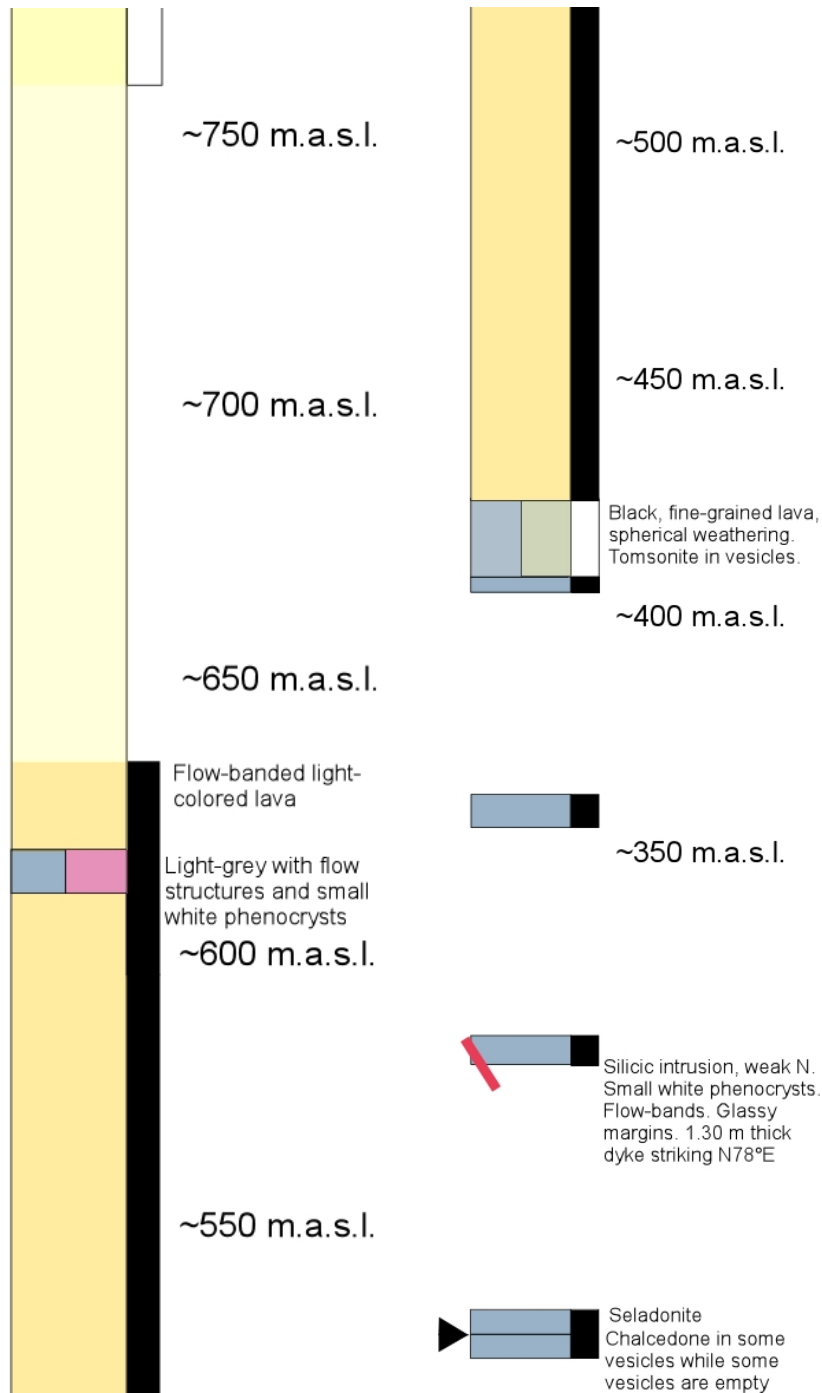


Hólsgærði upper part:

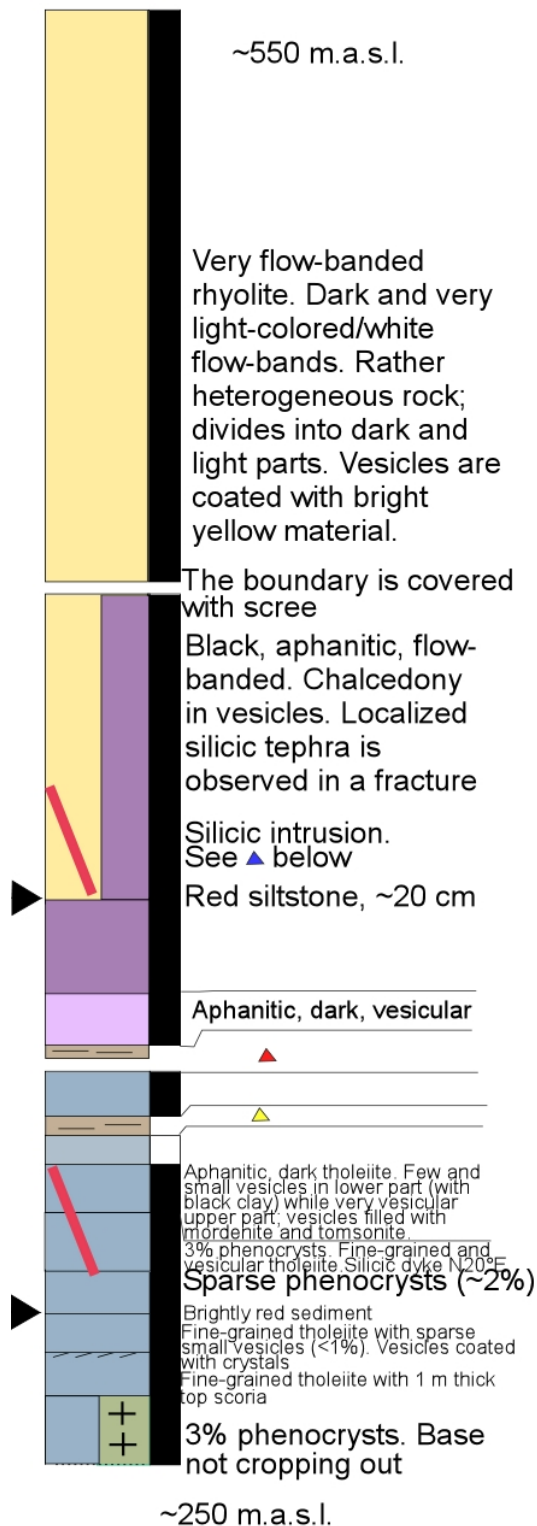
Hólsgærði



Hólsgærði middle and lower part:



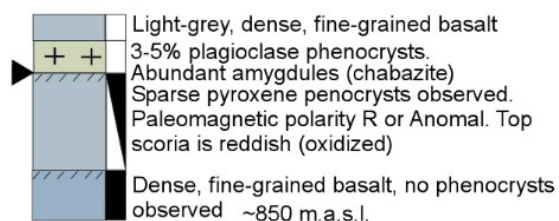
Úlfá



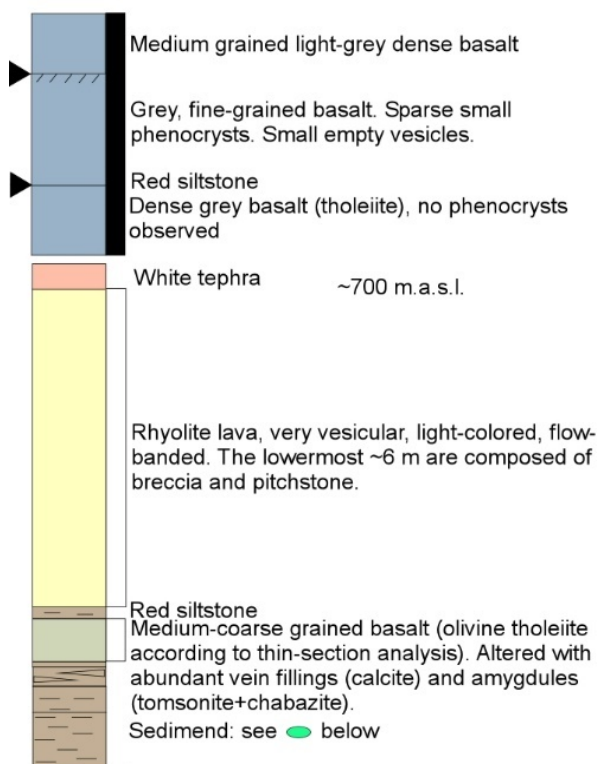
- ▲ Upper part: light-red sediment covered with scree. Lower part: Black sediment with black, spongy glass fragments
- ▲ Sediment covered with scree. Upper part: red and laminated; breaks into flakes. Lower part: light-grey to white fine-grained flakes with coarser grains of black rock fragments. Laminated; breaks into flakes
- ▲ At least ~15 m thick intrusion; shape is not obvious, but appears to align approximately N100°E. Adjacent with the bedrock is breccia with light-colored tephra in the groundmass and larger fragments of dacite, while the center is composed of crystalline silicic rock

Nóngil upper part:

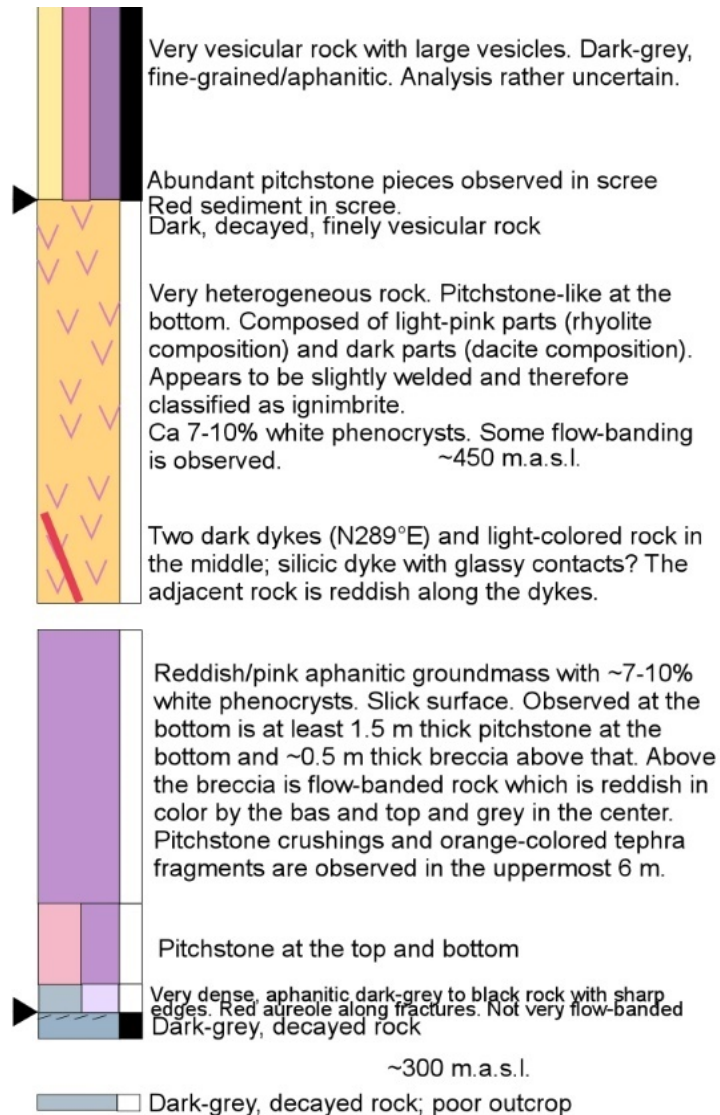
Nóngil



~800 m.a.s.l.

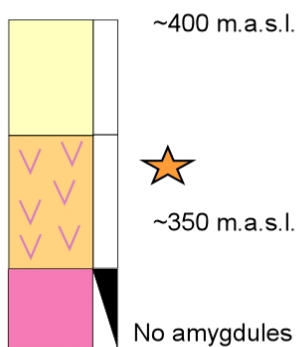
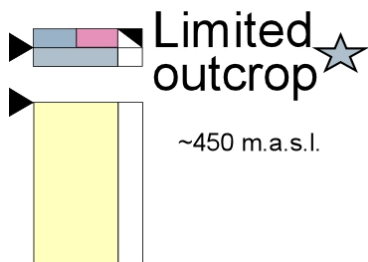
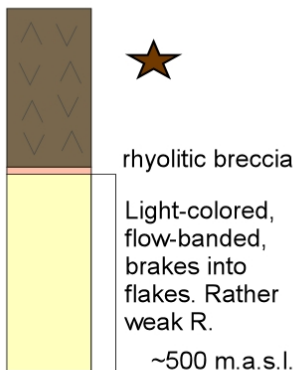


Nóngil lower part:



- The lower half is composed of yellow-brownish sandstone. At the bottom, the sandstone appears to be stirred/mixed with the underlying dark lava. On top of the sandstone are 2 cm of dark/black silt-claystone. Then 5 cm thick light-yellowish sandstone, then 2 cm light-colored siltstone. At the top is ~2 m thick light-colored siltstone with coarser black grains (sandsize to fine gravel size)

Ytra Mógil

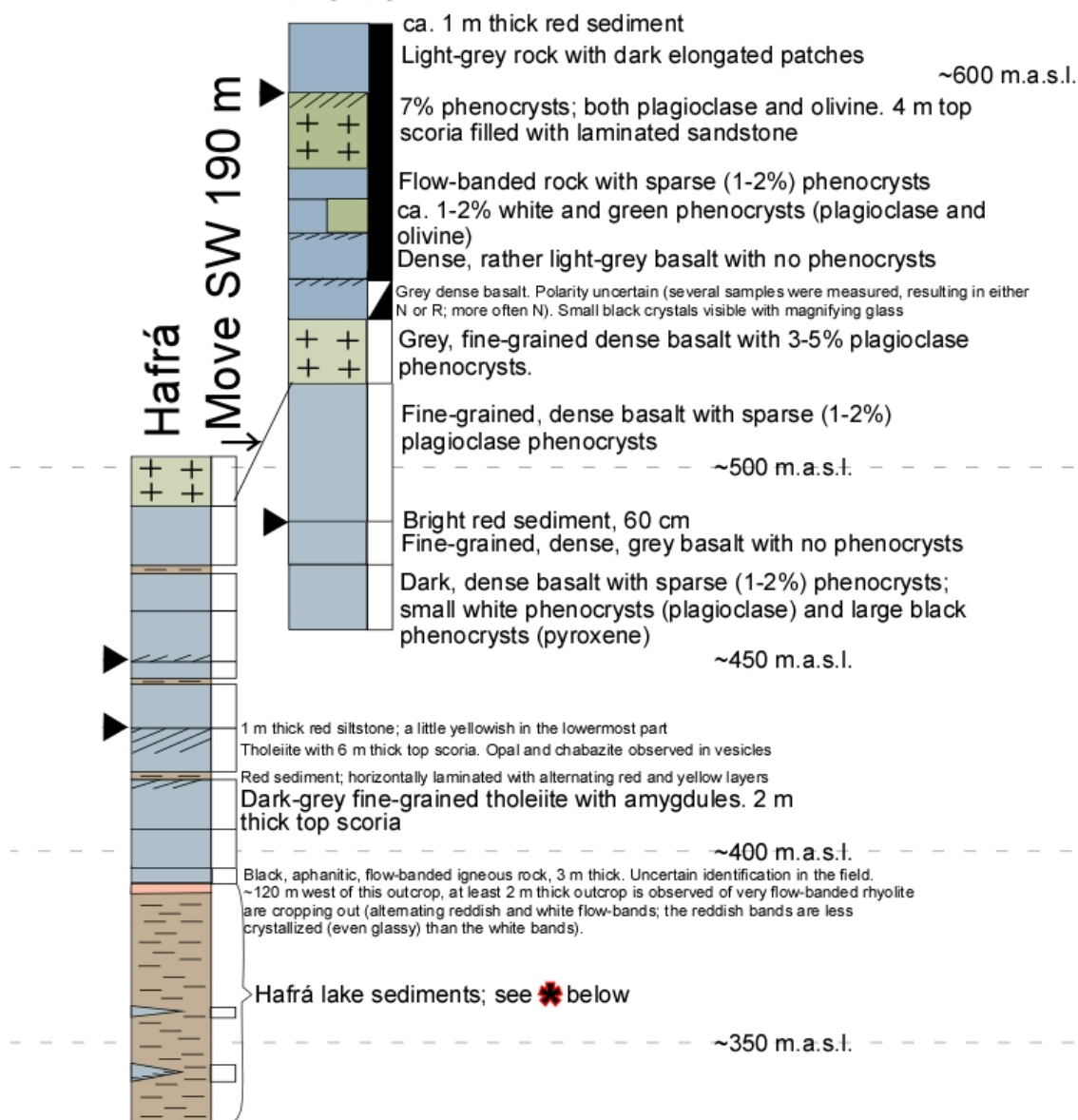


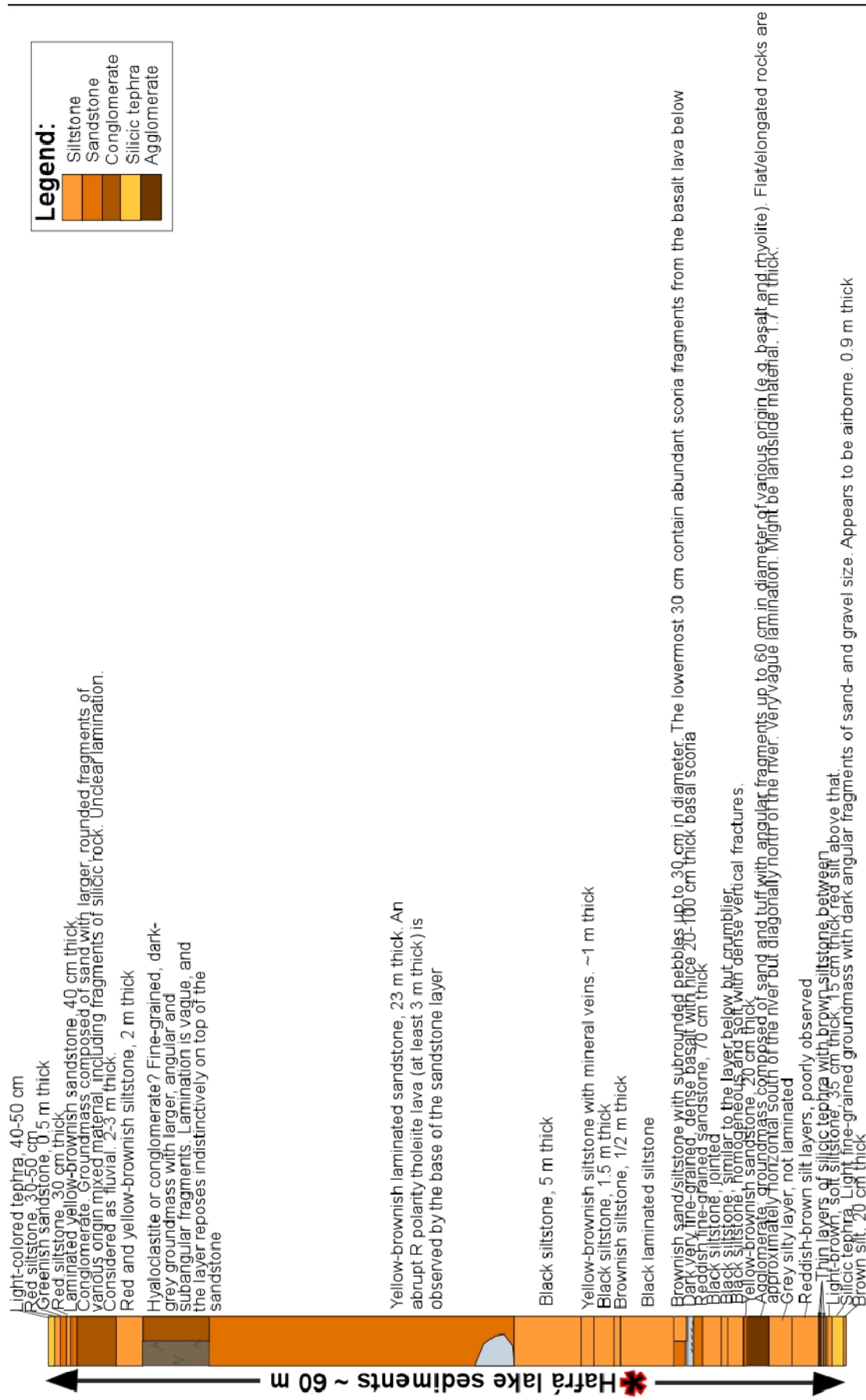
★ Strong R polarity. Red tephra-like groundmass with black elongated and horizontal fiamme (e.g. 10x2cm, 8x1cm, 7x1.5cm, 11x2cm, 9x3cm, 14x3cm). Some vesicles are observed; also elongated and horizontal.

★ Fine-grained, dense

★ brown tuff, fine-grained. Unclear lamination. Rhyolite fragments and pebbles are visible in several places (rhyolite fragments are particularly prominent in the lowermost part). Groundmass is made of silt- to fine sand.

Hafrá





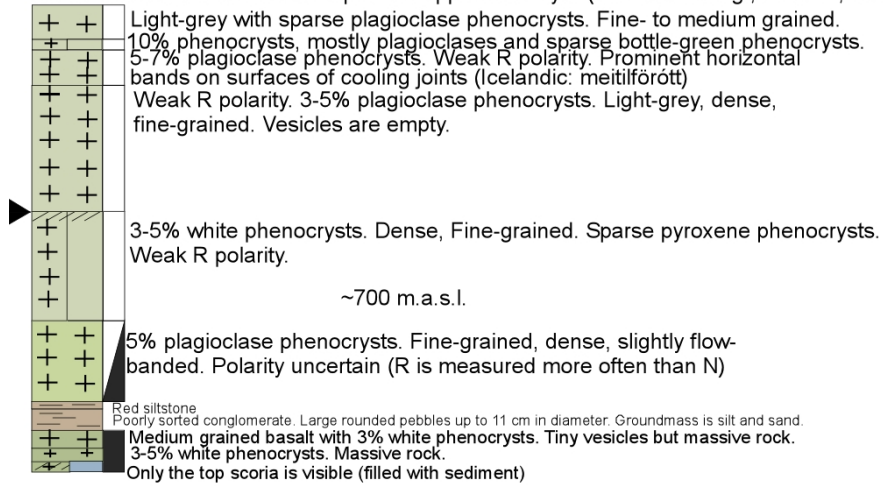
Skriðugil cont.

~850 m.a.s.l.



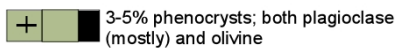
~800 m.a.s.l.

Glacial striations observed on top of the uppermost layer (orientations e.g., N177°E, N200°E, N165°E)



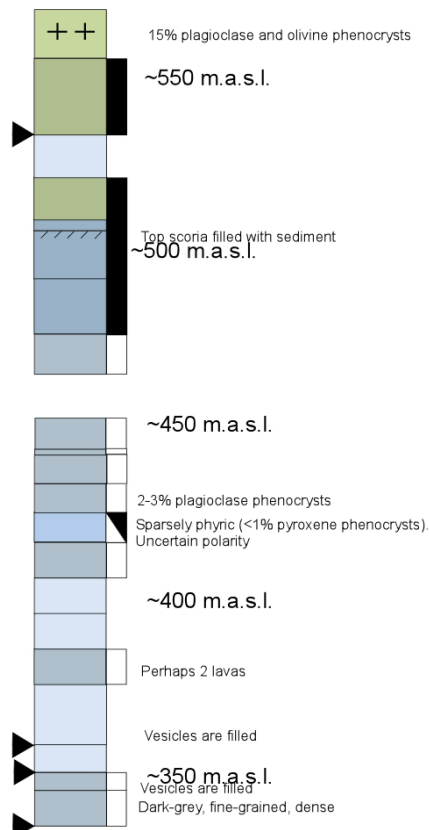
~700 m.a.s.l.

No outcrop

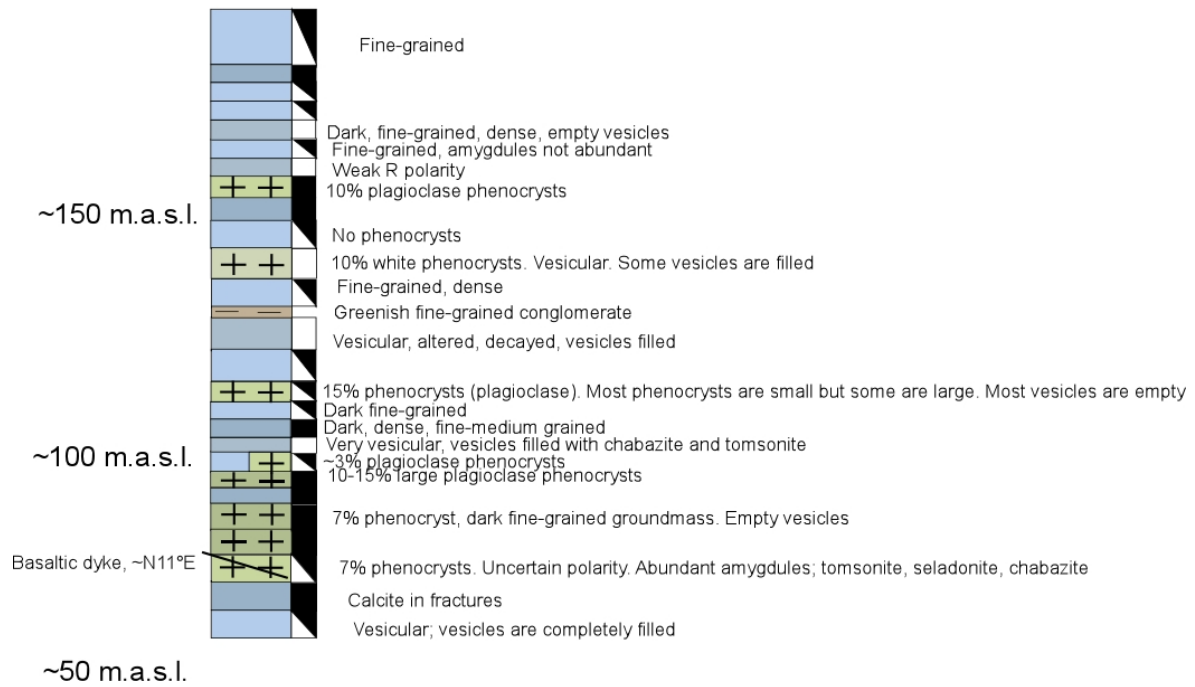


~600 m.a.s.l.

Skriðugil



Núpá in Sölvadalur

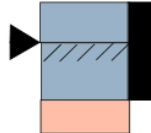


Draflastaðir



Massive porphyritic basalt, ca. 7% phenocrysts, mostly plagioclases but also olivines.

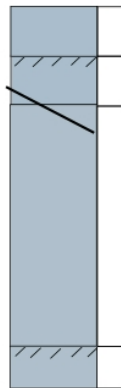
~900 m.a.s.l.



Dense, fine-grained, black clay in vesicles and fractures. Flow structures.
Dense, medium grained basalt., possibly with altered olivine. Thick top scoria, red-oxidized
Felsic tephra in scree

~850 m.a.s.l.

Fault, downthrow towards south. Strike N34°E



Light, dense medium-grained basalt with slight flow-structures (vesicles are elongated and horizontal). Vesicles are empty.
Fine-grained basalt with sparse large phenocrysts. Small vesicles. Dark-grey with slight flow-structures. Top scoria is filled with sediment.

~800 m.a.s.l.

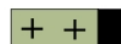
Strong R polarity. Dark-grey basalt with sparse olivine phenocrysts. Fine-grained. Vesicles coated with light-brown material.

Reddish coarse-grained rock, very dense. Top scoria is filled with secondary minerals.

~750 m.a.s.l.



~700 m.a.s.l.

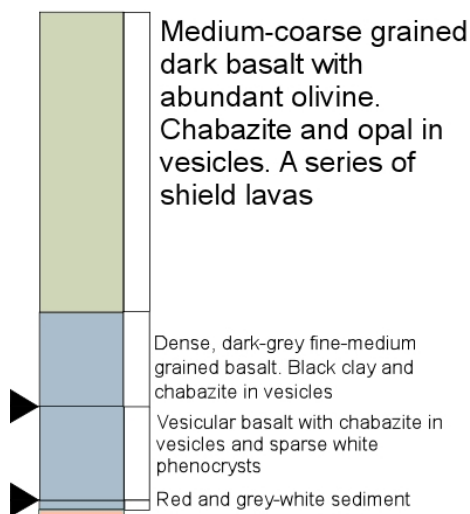
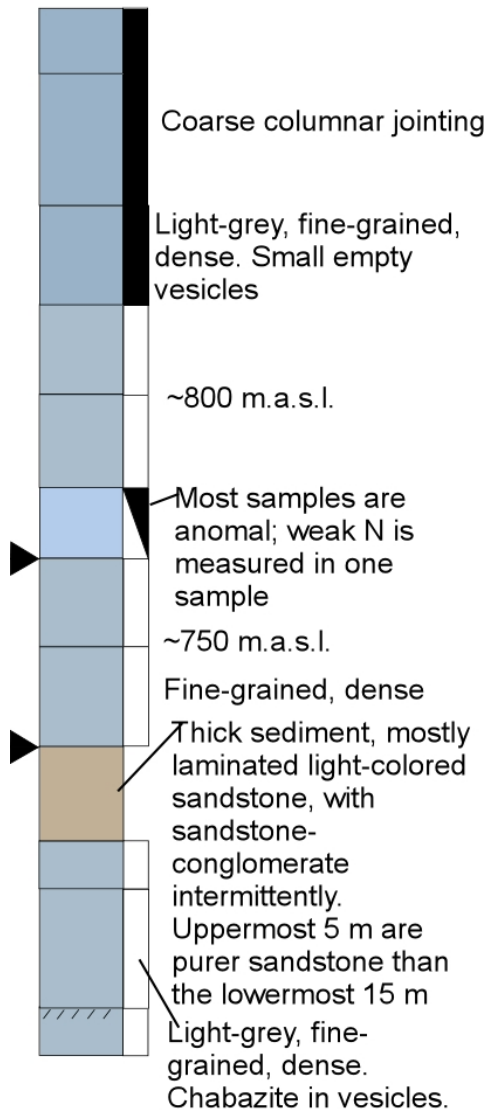


Light-grey basalt with 3-5% plagioclase phenocrysts, both small and large. Spherical weathering.



Very vesicular, weathered basalt. Vesicles sometimes empty. Fine-grained.

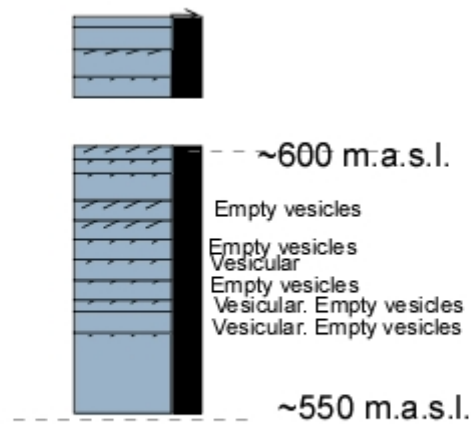
Þormóðsstaðadalur



~500 m.a.s.l.

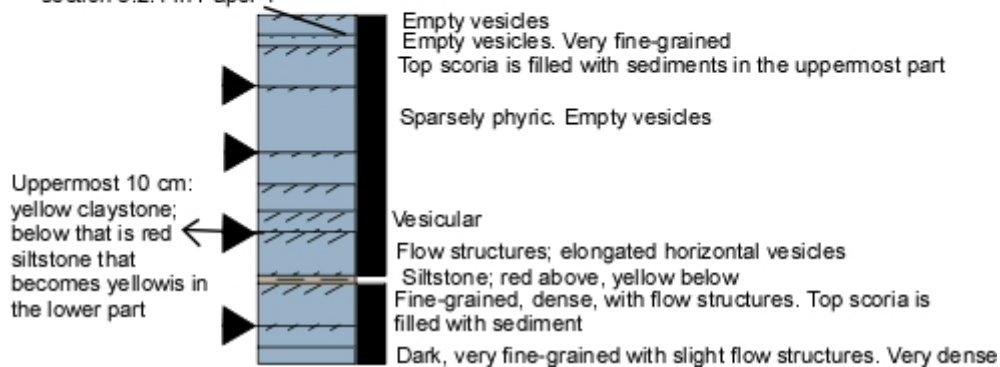
Nýibær upper part:

Nýibær

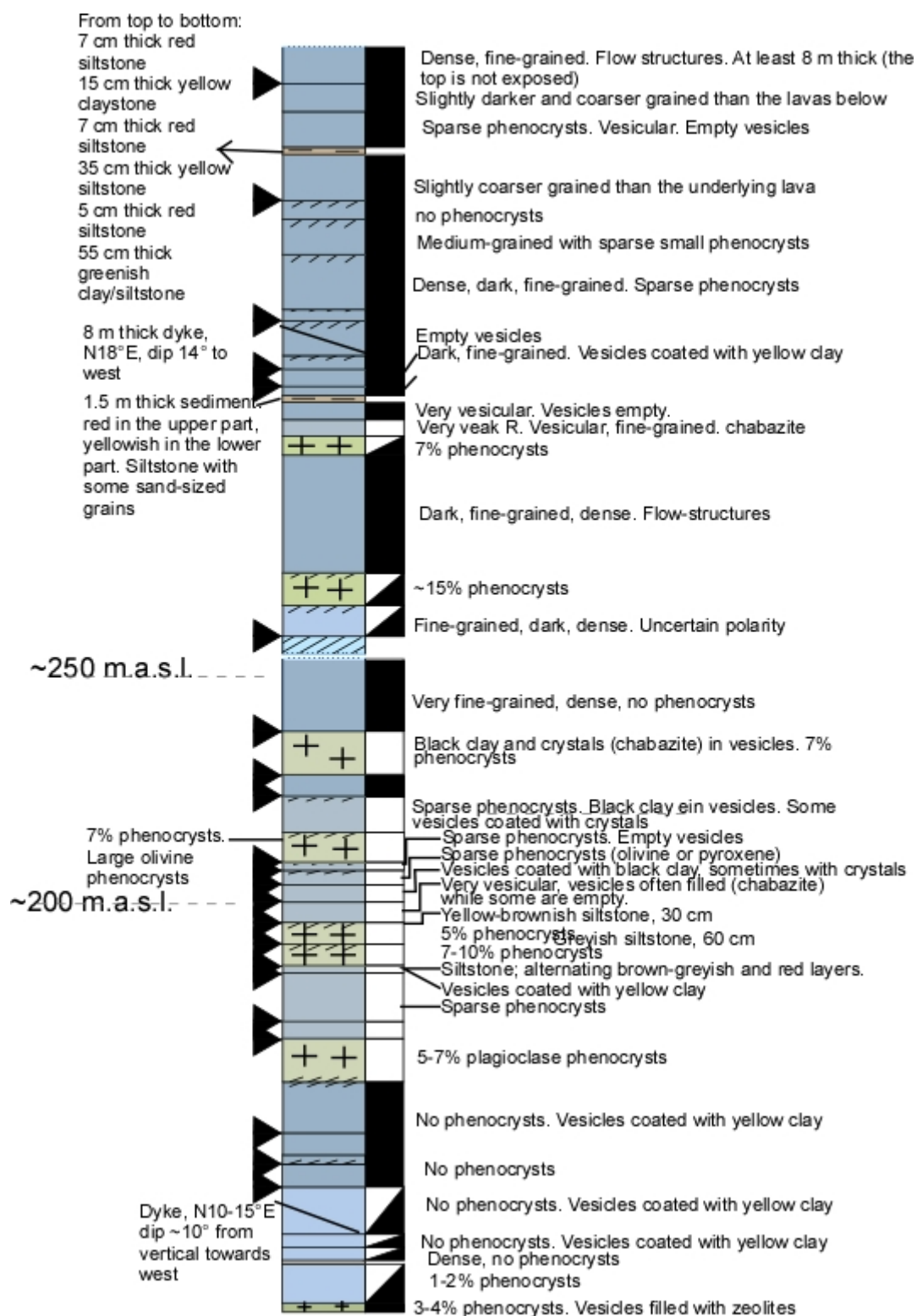


~500 m.a.s.l. - - - - -

The Vothamrar dyke, ~N344°E. Porphyritic; up to 40% phenocrysts, both plagioclase and olivine. See Figure 10 and section 3.2.1 in Paper 1

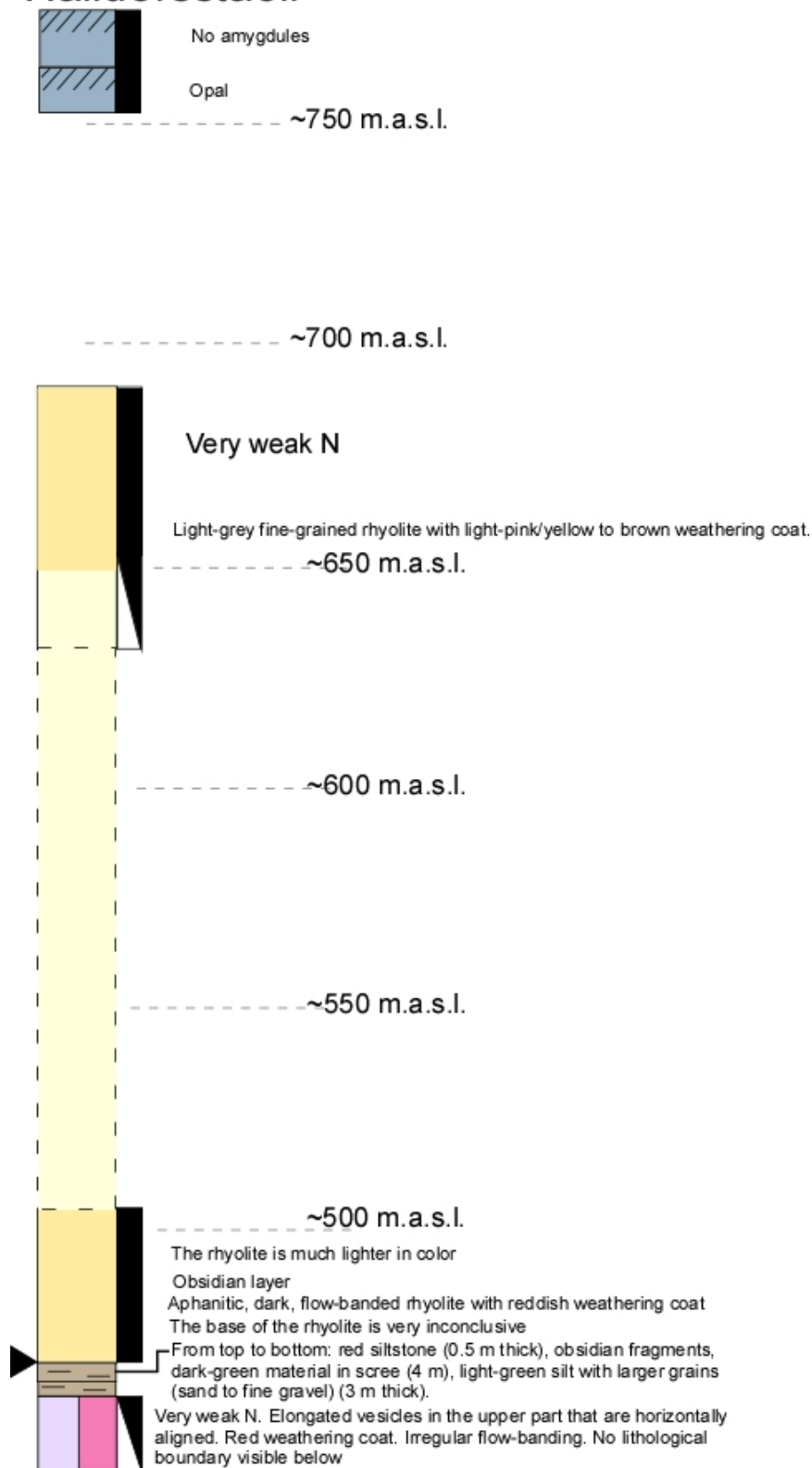


Nýibær lower part:



Halldórsstaðir upper part:

Halldórsstaðir



Silicic dyke, N320°E, dips 22° from vertical towards West. The dyke is made of flow-banded rock, with glassy margins and greenish altered core. Flow-banding is parallel to the dyke. Small white phenocrysts ca. 1%



Tjarnir

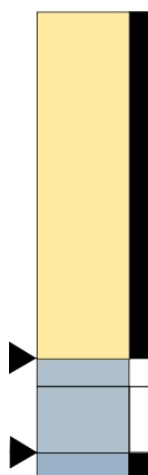


Dark, medium-grained rock
~500 m.a.s.l.
Red and vesicular

~400 m.a.s.l.



~350 m.a.s.l.



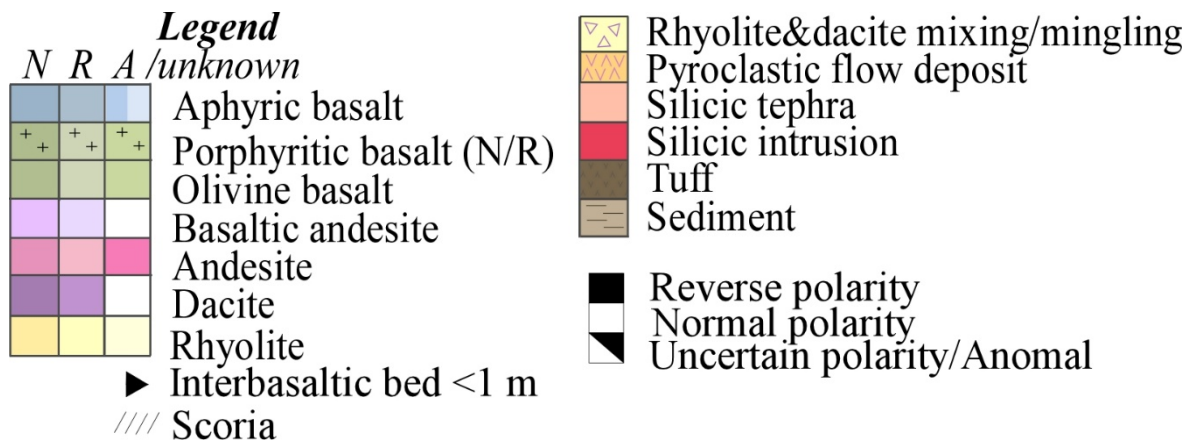
Light-grey rock, fine-grained, flow-banded

Dark/grey-black, spherical weathering is prominent.
Vesicles and fractures are completely filled

Glerá

~700 m.a.s.l.





B3 Torfufell central volcano geological map

