RESEARCH ARTICLE

VOLCANICA

Geology of a Neogene caldera cluster in the Borgarfjörður eystri–Loðmundarfjörður area, Eastern Iceland

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Abstract

The Borgarfjörður eystri–Loðmundarfjörður area in Eastern Iceland hosts several volcanic centres in a relatively small area. Large volumes of silicic, as well as an unusual amount of intermediate rocks, occur in this area, alongside other volcanic and sub-volcanic features that formed in the Miocene between 14 and 12.2 Ma. We compiled the first comprehensive geological map of the area and summarise the geology based on more than 40 years of fieldwork. We identify regionally extensive marker horizons that comprise intermediate (icelandite) and mafic (olivine basalt and porphyritic basalt) lavas. These marker horizons, along with new paleomagnetic data and some previous radiogenic dating, allow us to bracket a phase of magmatic activity that is one of the oldest in Eastern Iceland. We describe the prominent features of the volcanic centres, including remnants of collapse calderas in Njarðvík, Dyrfjöll, Breiðuvík and other ignimbrite-producing vent structures in Kækjuskörð and Herfell. Notably, the area also contains extremely well exposed examples of volcanic vents, cone sheets, and unique caldera-lake sediments. We conclude with open questions to inspire future research on this understudied area.

Ágrip

Í Borgarfirði eystri og Loðmundarfirði er þyrping megineldstöðva með óvenjulega mikið af súrum og ísúrum bergtegundum, svo sem hraunum, innskotsbergi, og stórum flikrubergslögum sem urðu til á Míósentímabilinu (14 til 12.2 Má). Við birtum hér ítarlegt jarðfræðikort og yfirlit yfir jarðfræði svæðisins, sem er afrakstur meira en 40 ára rannsókna á svæðinu. Við lýsum merkum leiðarlögum úr ísúrum (íslandít) og basískum (aðallega ólivínbasalt og dílsabasalt) hraunum. Þessi leiðarlög ásamt segulmælingum og aldursgreiningum leiða í ljós eldvirkni sem er ein sú elsta á Austurlandi. Við lýsum megineldstöðvum í Njarðvík, Dyrfjöllum og Breiðuvík sem mynduðu öskjur og umfangsmikil flikrubergslög í gríðarlegum sprengigosum og gosstöðvum í Kækjuskörðum og Herfelli sem mynduðu stór flikrubergslög án öskjumyndunar. Svæðið hefur einnig að geyma vel varðveittar leifar af gosgígum, keilugöngum og öskjuseti. Frekari rannsókna er þörf til að setja myndun þessa svæðis í samhengi við jarðfræðilega uppbyggingu Austurlands og til að finna orsakir þessara óvenju umfangsmiklu sprengigosa. Í því skyni eru lagðar til ákveðnar rannsóknir til að skilja heildarmyndina betur.

Keywords: Borgarfjörður eystri; Loðmundarfjörður; Neogene volcanism; Iceland; collapse calderas

1 Introduction

The interaction between the mantle anomaly beneath Iceland (Iceland plume) and spreading at the Mid-Atlantic Ridge (MAR) has produced a variety of tectono-magmatic phenomena on the Iceland plateau that has developed into an unusually large landmass on a mid-ocean ridge. An anomalously thick crust, propagating rifts, flank zones and abundant silicic rocks give insight into this geodynamic growth during Iceland's geological past [Gibson 1963; Walker 1975; Pálmason 1980; Helgason 1984] with still much to learn. The glacially shaped landscapes of Eastern Iceland and the tilted strata towards active and extinct rift zones expose a continuous, 10 km-thick succession of volcanic rocks that formed since the Miocene and through the Plio-Pleistocene to the present [Walker 1974; Saemundsson 1979; Sigmundsson 2006]. The Miocene areas of Eastern Iceland have received comparatively little attention, despite their wealth of geological phenomena [Berg et al. 2014b]. Hence, there is a gap in our knowledge of the geological record preserved in Eastern Iceland.

To fill this gap, we mapped the area that comprises

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the inhabited fjord of Borgarfjörður eystri, the adjacent deserted coastal inlets, and the uninhabited fjord Loðmundarfjörður, known for their alpine landscapes and thick surficial debris cover in the valleys. The area hosts a cluster of Neogene volcanoes active between about 14 and 12.2 Ma [Gustafsson et al. 1989; Burchardt et al. 2011; Berg 2016]. These volcanoes comprise several collapse calderas, sub-volcanic intrusions, and substantial amounts of effusive silicic rocks, including large ignimbrite deposits that formed during large explosive eruptions. The rocks of these volcanoes are preceded by, and intercalated with, voluminous, regional flood basalts. These basalts have been suggested to reflect a more pronounced and wider-spread activity of the Iceland plume compared to its present-day extent [Óskarsson and Riishuus 2013; 2014].

Here, we summarise what is currently known about the geology of the Borgarfjörður eystri–Loðmundarfjörður (BEL) area, including the regional geological context and detailed maps that focus on the intermediate and silicic rocks, as well as marker horizons, and descriptions of key geological features. We present the first comprehensive geological map and volcanostratigraphy based on mapping of geological features, available radiogenic dating, and new magnetostratigraphic dating. Our study area provides a unique window into the tectono-magmatic activity during this volcanic phase in the Neogene. Despite our frequent visits to the area since the 1970s, much is left unstudied. Hence, we intend to inspire the reader to visit Eastern Iceland and explore more of this interesting area, which is why we conclude with open questions and suggestions for future work.

2 Geological setting

Iceland is the surface expression of the Iceland mantle plume superimposed on the MAR. The Iceland plume is generally viewed as a stationary mantle anomaly that impinged below Laurentia (current Greenland) in the Late Cretaceous and produced a Large Igneous Province, called the North Atlantic Igneous Province (NAIP). NAIP magmatism associated with continental break-up occurred in Greenland, the British Isles, and the Faeroe–Shetland basin in the Early Palaeogene [Saunders et al. 1997]. Due to the slight drift of the lithospheric plates relative to the Iceland plume, the plate boundary (i.e. the MAR) episodically "jumped" and re-established as a new rift zone [Helgason 1984; Lawver and Muller 1994]. In this way, the currently active Kolbeinsey Ridge (KR) took over from the Ægir Ridge as the main active segment of the MAR in the North Atlantic around 30 Ma, separating the Jan Mayen Microcontinent from the Greenland continental crust (Figure 1) [Blischke et al. 2016; Hjartarson et al. 2017; Blischke 2020; Foulger et al. 2022]. At around 30–25 Ma the Iceland plume likely started to intensify lava production on the rift segment that later became Iceland, thus creating an anomalously thick oceanic crust and elevating segments of the MAR above sea level [Torsvik et al. 2001; 2015; Steinberger et al. 2019]. Mapping the number of rifts and their configuration during the development of the Iceland Plateau has been a challenging task and is therefore an object of ongoing investigations (Figure 1).

At present, the MAR intersects Iceland through the Kolbeinsey Ridge in the north and the Reykjanes Ridge in the south. On land, Iceland hosts three main segments of the MAR, the western (WVZ), eastern (EVZ) and northern (NVZ) volcanic zones, where most of the present-day volcanism occurs. Active volcanism also occurs in two flank zones, the Snæfellsnes (SFZ) and the Öræfajökull (ÖFZ) flank zones (Figure 1C) [e.g. Sigmundsson 2006]. Two transform zones occur between the volcanic zones, (1) the South Iceland Seismic Zone (SISZ) that links the WVZ as the inland extension of the Reykjanes Ridge (RR) with the EVZ, and (2) the Tjörnes Fracture Zone (TFZ) that links the NVZ with the KR that extends offshore north of Iceland (Figure 1C). Rift-zone volcanism is characterised by tholeiitic composition, while volcanism in the EVZ and the SFZ and ÖFZ flank zones is transitional alkaline to alkaline in composition. The EVZ is thought to propagate into, and re-melt, older crust. Its rocks change character from tholeiitic to transitional alkaline to alkaline towards its tip in the Vestmann Islands south of mainland Iceland [Jakobsson 1972; Óskarsson et al. 1982; 1985; Thordarson and Larsen 2007].

Volcanism and rifting in the currently active volcanic zones are restricted to so-called volcanic systems that commonly consist of a fissure swarm with eruptive fissures and graben faults, and central volcanoes [Saemundsson 1979; Burchardt and Gudmundsson 2009]. Fissure eruptions in the volcanic systems are fed by (sub)vertical dykes that form dense dyke swarms at depth and contribute to accretion of new oceanic crust by intrusion and eruption of lava flows. Most volcanic systems also host a central volcano that may produce more evolved magmas in shallow crustal magma reservoirs through fractional crystallization and recycling of hydrothermally altered crust [Walker 1966; Saemundsson 1979]. Central volcanoes can thus be the site of explosive volcanism associated with caldera collapse and ignimbrite formation.

A number of fossil volcanic systems have been identified and documented in the Miocene areas of western and eastern Iceland [e.g. Walker 1958; 1963; Carmichael 1964; Burchardt and Gudmundsson 2009; Martin and Sigmarsson 2010]. These fossil systems have been interpreted to have formed either at the active rift zones and preserved through episodic jumps of the volcanic zones to the east following the west-ward drift of the plate boundary relative to the Iceland plume (Figure 1B) [Saemundsson 1979; Helgason 1984], or as flank volcanism that escaped burial at the axis of the

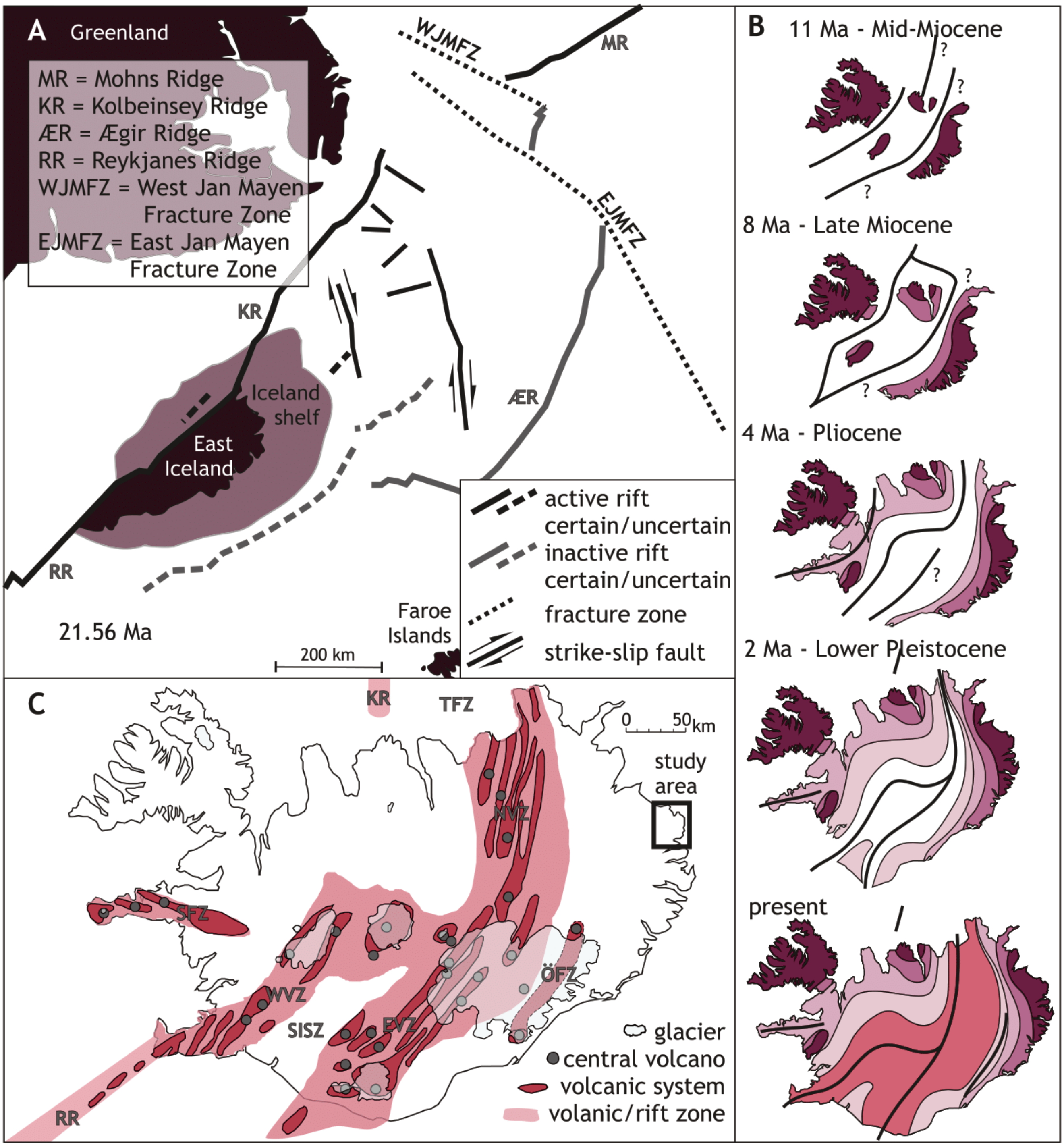

Figure 1: Geodynamic setting of Iceland through time. [A] Geodynamic setting of the North Atlantic 21.56 Ma following the transition from the Ægir to the Kolbeinsey Ridge. Modified from Blischke et al. [2016]. [B] Location of past rift zones and age of the surface rocks in Iceland. Note that little is known about the rift zone configuration in the geological past. Based on e.g. Walker [1975]. [C] Current arrangement of rift zones, flank zones, and volcanic systems in Iceland [see e.g. Sigmundsson et al. 2020].

volcanic zones [Pálmason 1980]. The British geologist G.P.L. Walker and his co-workers in the 1950s and 60s documented in detail fossil volcanic systems in Eastern Iceland. They comprise dyke swarms that extend tens of kilometres and represent the subterranean feeders of associated flood basalts, along with central volcanoes that rose above the surrounding palaeolandscape and fed local basaltic and intermediate lava flows, as well as rhyolitic effusive and explosive volcanism [e.g. Walker 1958; Gibson 1963; Walker 1963; 1974]. The central volcanoes often comprise swarms of magmatic sheets, centrally inclined towards the centre of the volcano, so-

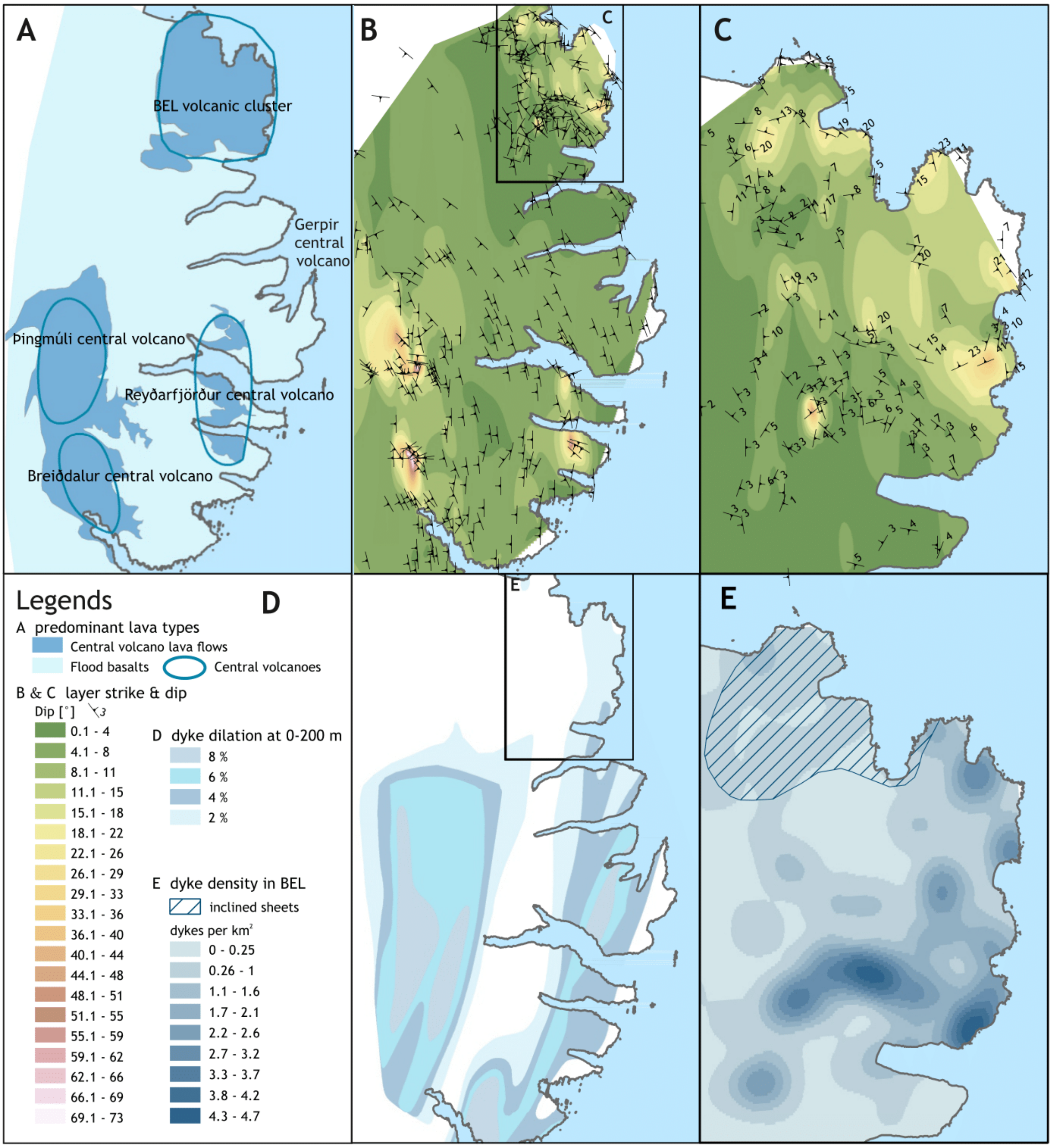

Figure 2: Overview maps of eastern Iceland including Borgarfjörður eystri and Loðmundarfjörður (BEL). [A] Distribution of lava flows by type morphology. [B] Strike and dip of the strata in eastern Iceland. Note the anomalies in dip directions that occur around the central volcanoes. [C] A close-up of the BEL area showing the distribution of strata attitude. [D] Map showing dyke dilation at 0–200 m, associated with the occurrence of dyke swarms. [E] A close-up of the dyke density in the BEL area.

called cone sheets or inclined sheets [e.g. Burchardt et al. 2011]. In the deeper eroded areas, such sheets occur in connection with plutons that are assumed to be the source magma chambers to the sheets [e.g. Walker 1974; Furman et al. 1992; Klausen 2004; 2006; Burchardt and Gudmundsson 2009]. The deeply eroded roots of central volcanoes often display localised contact metamorphism associated with the plutons. Remnants of associated geothermal activity are also common [e.g. Fridleifsson 1983; Liotta et al. 2020].

Early researchers were quick to recognise that the bulk of the lava flows of eastern Iceland represented eruptions of the so-called flood basalt type (Figure 2A) [Gibson 1963; Walker 1964]. One reason for this attribution was the great geographical distribution of the lavas that could be traced across the entire eastern fjords and interpreted to be the product of large fissure-eruptions. The other reason was based on architectural grounds, especially on the occurrence of extensive sheet flows of so-called simple flows (tabular flows) with plane-parallel stratification, which is suggestive of high effusion rate events [Walker 1971; Jerram and Widdowson 2005]. Simple flow architecture had been recognized previously in other flood basalt provinces, and their occurrence in Iceland impelled a genetic correlation between the flood basalts of eastern Greenland, the Faroe Islands and the northern British Isles that today form the NAIP. In recent studies, individual lava groups of Eastern Iceland have been mapped that include simple flows [Óskarsson and Riishuus 2013; 2014; Óskarsson et al. 2017] and suggest eruptions on a much larger scale than the largest lava eruptions in recent history, specifically the 1783–84 Skaftáreldar (Laki) eruption that formed a compound field of lavas with a volume of about 14 km^2 [Thordarson and Self 1993]. Thus, Miocene volcanism cannot be interpreted plainly through the lenses of modern volcanism, and the imagination needs to extend to processes on a larger scale than presently observed.

3 Previous research

One of the first publications to show a large silicic area within the northeast corner of Iceland was the geological map of Iceland in 1:600,000 of Thoroddsen in 1900, later republished in 1901 [Thoroddsen 1901] and 1906. Thoroddsen had visited the area in a reconnaissance fashion and based his mapping also on the findings of several visiting scientists in the 19th century. However, the true nature of this important rock series was not revealed until later during the 20th century. Thus the mountain Hvítserkur, a very prominent landmark mountain in this area and nearly completely composed of ignimbrite, was classified and mapped as liparite in Thoroddsen's time, liparite being the common Icelandic name for rhyolite. In the 20th century Dearnley [1954] was the first to produce a reconnaissance map of the Kækjuskörð area in Loðmundarfjörður, where he mapped most of the silicic rocks there as parts of a shallow intrusion. Walker, who worked extensively in Eastern Iceland, is not known to have gone to the BEL for concise mapping, but refers to silicic volcanism in the area in his notes and unpublished maps. In the 1970s, the northern part of Borgarfjörður eystri was mapped for the Sheet 7 (Eastern Iceland) of the 1:250.000 geological map of the Icelandic Institute for Natural History and the Icelandic Geodetical Survey. In this map, only the most basic rock series, like basaltic and silicic intrusive and extrusive rocks, are distinguished and no distinction between individual volcanic centres was made.

In the 1980s, Gustafsson [1992] mapped and distinguished the first volcanic centre of the area, the Dyrfjöll Central Volcano, as part of his PhD thesis. Gústafsson also defined the Njarðvík Volcanic centre as a part in the development of Dyrfjöll volcano. In the 1980s, the Kækjuskörð area was remapped by Gústafsson, Thomas, B. Lapp, and M. Lapp [Gustafsson et al. 1989]. They redefined Dearnley's intrusion as a silicic eruptive centre with subaerial silicic lava flows, mostly based on features typical of silicic lava flows, like ramp structures and the occurrence of basal ignimbrite layers. During this mapping campaign the existence of at least one other central volcano was inferred due to the occurrence of a massive ignimbrite sheet prominently exposed in and around the mountain Herfell to the southwest of Kækjuskörð. In the 21st century, Vogler mapped the southern part of Breiðuvík Central Volcano [Vogler 2014]. The Icelandic Institute of Natural History published a geological map in 1:100,000 of the mid-Eastfjords from Berufjörður to Loðmundarfjörður [Óskarsson and Riishuus 2019] and has recently mapped the BEL area in continuation of this map. The geological map presented as part of this study (see below) is partly the result of this mapping campaign combined with all the authors' observations.

Detailed investigations into structural and petrochemical problems have only begun in the last fifteen years. Martin and co-workers looked into the regional setting of the area during its formation, with emphasis on the formation of silicic rocks [Martin and Sigmarsson 2010; Martin et al. 2011], while Berg and coworkers studied the age and petrogenesis of the BEL area [Berg 2016; Berg et al. 2018]. The nature and age of zircon crystals from the area was also investigated by Carley and co-workers who concluded that Iceland is not an analogue for continental formation in the Hadean based on stable isotope data that indicates temperature conditions different to those in the Hadean [Carley et al. 2014; 2020], in contrast to what was proposed by Berg et al. [2014a]. Moreover, some of the subvolcanic intrusions have been studied by Burchardt and co-workers [Burchardt 2008; Burchardt et al. 2011], Saubin et al. [2019], and Kennedy et al. [2022].

4 Results

4.1 Regional geological context of the BEL area

Regional metamorphism registered in the zeolite facies is well documented in the Neogene parts of Iceland. [Walker 1960] discovered the facies and subsequently mapped the zones of zeolites in the lava pile. The distribution of zeolite zones reveals that the northern part of the Eastern fjords has undergone less burial and subsidence in comparison to areas in middle and Southeast Iceland. The uppermost Chabazite–Thomsonite zeolite zone that forms at temperatures of about 60 °C within the olivine basalts, appears at elevations of about 400 m a.s.l. in BEL, while this zone is found at 600–900 m a.s.l. in the flood basalt lava pile south of the Reyðarfjörður and Breiðdalur volcanic centres. As it is estimated that the top of the original land surface is found about 600 m above the base of the Chabazite–Thomsonite zone based on metamorphic conditions [cf. Walker 1960], the highest mountain peaks of BEL (e.g. Dyrfjöll reaching elevations of 1134 m a.s.l.) are today close to what would have been the original land surface [cf. Walker 1974]. This is corroborated by unaltered olivine crystals in the uppermost lava horizons of the Dyrfjöll mountains. Areas to the south have about 500 m eroded from the tops. However, locally the zeolite zones are sometimes raised a few hundred meters above the volcanic centres as a consequence of contact metamorphic aureoles formed by intrusions underlying the volcanic complexes. This applies both to the central volcano and the associated dyke swarm of a volcanic centre and is evident from the occurrences of minerals such as calcite and aragonite that form at higher temperatures around these centres in BEL and elsewhere.

Dyke density has been shown to increase with depth in the lava pile of Eastern Iceland [Walker 1960]. As each flood basalt had its own feeder channel, represented in the lava pile as a dyke, their number should indeed increase downward in a section through the lava pile. Dyke density is less than 4 % at sea level in BEL (Figure 2), indicating that only the upper part of the dyke swarm associated with the BEL volcanic systems is observed [cf. Walker 1974]. Conversely, dyke density in the dyke swarms to the south, in middle Eastern Iceland reaches >8 % at sea level and decreases to 2–4 % at elevations of 700–900 m a.s.l. (Figure 2D) [Walker 1974].

Generally, the lava pile in Eastern Iceland dips to the west and southwest towards the active rift zone (Figure 2B). In contrast, the inclination of the lava pile in the BEL area is multidirectional (Figure 2B and C). Deviations from the regional pattern south of BEL are local and occur where lavas would have been deposited on the flanks of extinct central volcanoes or as an uplift of lavas due to intrusive bodies like the Sandfell Laccolith in the fjord Fáskrúðsfjörður [Hawkes and Hawkes 1933], middle Eastern Iceland. In contrast, the areal extent of the BEL dip anomaly is about 600 km^2.

4.2 Geology of the volcanic centres of BEL

The BEL area hosts three volcanic centres, Njarðvík/Dyrfjöll, Breiðuvík, and Herfell, that have previously been distinguished based on geography, the location of collapse calderas, and the distribution of smaller eruptive centres like Kækjuskörð [Gustafsson et al. 1989]. Other sites of individual eruptions occur, but did not develop to form centres of repeated volcanic activity. Analysis of field relationships of rock units, e.g. the origin of the various ignimbrites, cross-cutting relationships of magmatic sheet swarms, and radiogenic dating and new paleomagnetic data (see description of each centre and Section 6.1) show that volcanism in the area was roughly contemporaneous [Burchardt et al. 2011; Berg 2016]. Hence, the established distinction of central volcanoes may have to be revised. To begin with, we will, however, describe the geological features according to the established volcanic centres (Section 4.1) before we re-evaluate the concept and distinction of individual central volcanoes in Section 6. All observations are included in the new geological map of the area (Figure 3).

4.2.1 *Njarðvík/Dyrfjöll*

The rocks exposed in the mountains around the cove of Njarðvík in the north of the area (Figures 4 and 5) document a multi-phase evolution. The oldest exposed rocks that can be ascribed to central-volcanic activity are thin (mostly 1–5 m thick) tholeiitic lavas [Lower and Upper Basalt Series of Gustafsson 1992]. These tholeiites are intercalated with regional flood basalt lavas on the eastern slopes of the Héraðsflói river valley, just below the mountain pass of Vatnsskarð. The lower sequence is of mostly normal magnetic polarity with one short reversal in between and can be traced to the west of Héraðsflói (beyond the study area) where a dacitic lava dome was dated to be 13.4 Ma [Martin et al. 2011]. This sequence includes the Naustá porphyritic group (NAUP in Figure 3) that is first identified in this area, the Knör olivine basalt group (KNOB), also first identified in this area, and a group of unusually dark/blackish tholeiites with chalcedony amygdales, which is widespread and extends to west of Héraðsflói. The absence of erosional surfaces and paleosols between the lavas indicate a high eruption frequency. Around the cove of Njarðvík, the basaltic lavas are tilted (Figures 4 and 5E), forming a depression or downsag caldera with a centre close to the back of the valley (Figures 3 and 4; see also Section 4.5).

Predominantly basaltic volcanism changed to bimodal, as evident from voluminous rhyolitic intrusions and associated extrusive rocks that frequently contain enclaves of mafic magma, and from composite dykes. Several rhyolitic sills and a larger subvolcanic intrusion with concordant and discordant contacts with the basaltic lavas are exposed in Njarðvík and the surrounding mountains (Figure 5; Njarðvík Silicic Complex of Gustafsson [1992]; see also Section 4.4). These rhyolitic intrusions in turn fed numerous inclined sheets, dykes and sills (Figure 5A, C, E; see Section 4.3), some of which are connected to vents, and were thus feeders of, effusive and explosive erup-

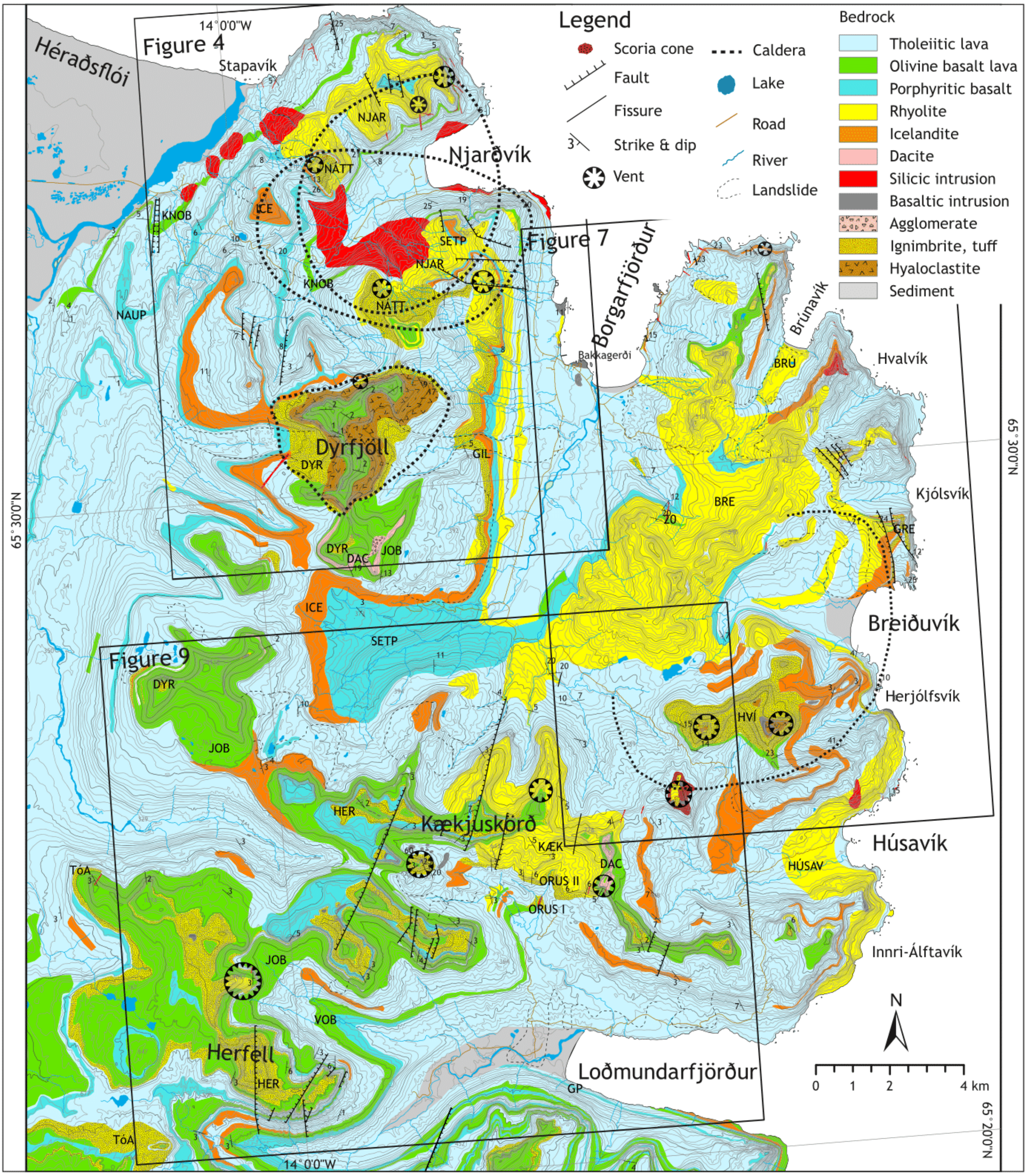

Figure 3: Geologial map of the Borgarfjörður–Loðmundarfjörður (BEL) area. Boxes indicate the locations of the detailed maps in Figures 4, 7 and 9. For names of stratigraphic formations, see text and Figure 15. The area includes numerous thick debris sheets of landslides and/or rock glaciers that have not been differentiated [based on Hjartarson et al. 1978]. Map issued by the Icelandic Institute of Natural History. Map prepared with ArcGIS software. Base map: The National Land Survey of Iceland (IS50V). Map projection: Lambert Conformal Conic (ISN93). Toponym: National Land Survey of Iceland. Cartography: Birgir Vilhelm Óskarsson.

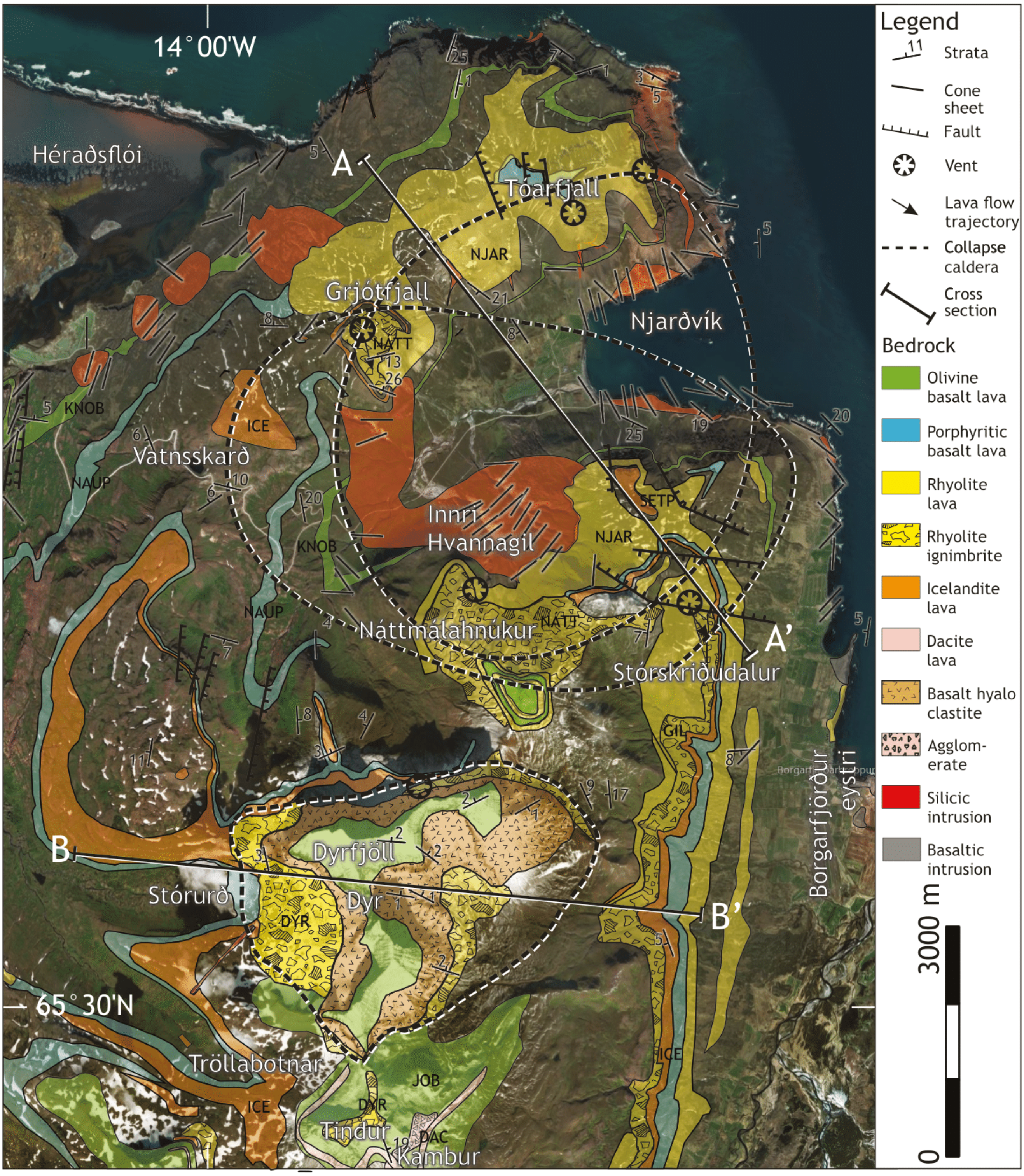

Figure 4: Geological map of Njarðvík and Dyrjöll. For location, see Figure 3. Satellite image from 2009 accessed through Bing Maps (`https://www.bing.com/maps`). For the cross sections A–A′ and B–B′, see Figure 13. For names of stratigraphic formations, see text and Figure 15.

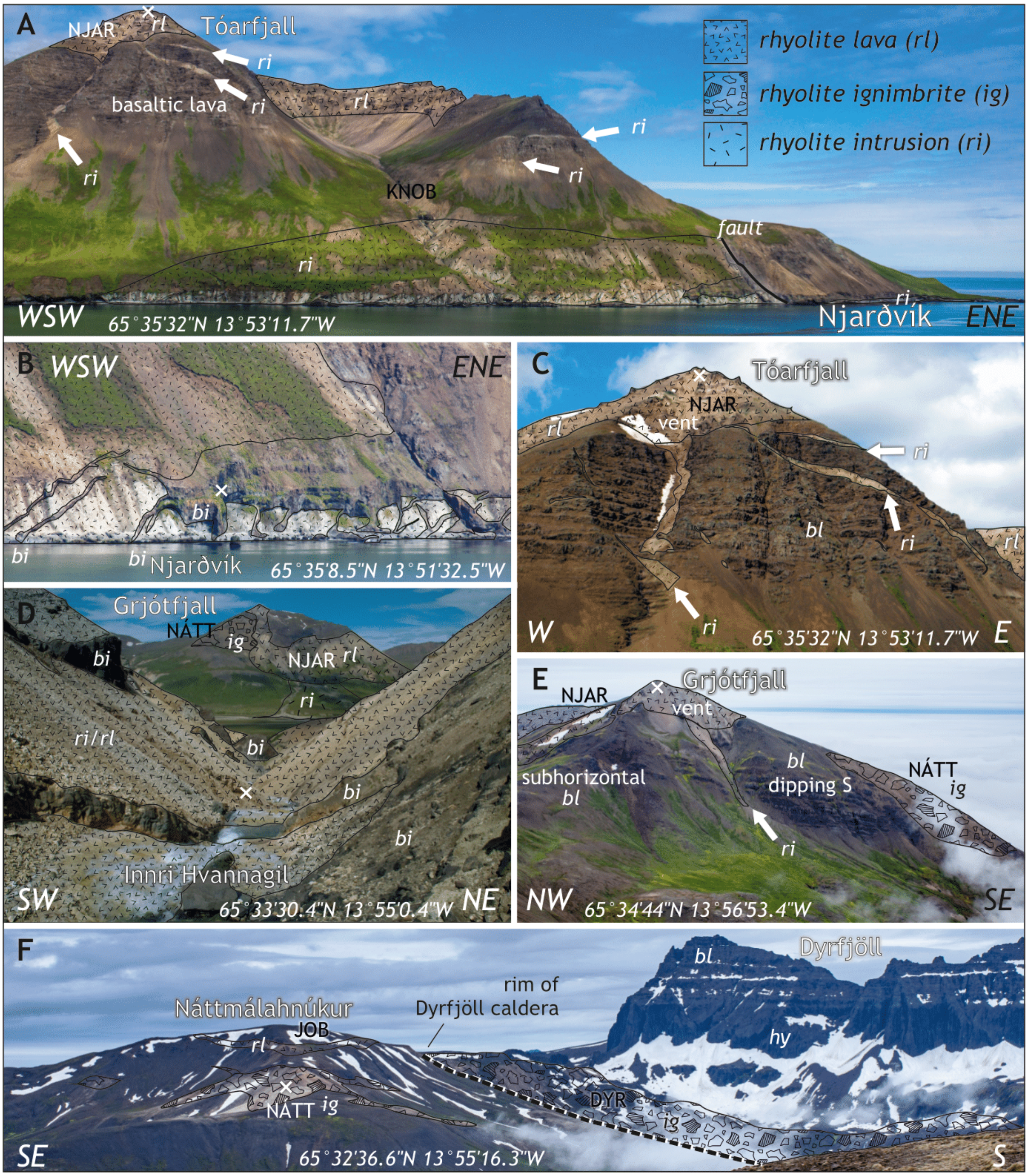

Figure 5: Annotated field photographs illustrating the geology of Njarðvík. For locations see Figure 4. Abbreviations: b = basalt, r = rhyolite, hy = hyaloclastite, l = lava, i = intrusion, ig = ignimbrite. × marks the location of the coordinates mentioned in each photograph. For names of stratigraphic formations, see text and Figure 15. [A] On the northern shore of Njarðvík, white coloured intrusive rhyolites are intruded by black basaltic cone sheets and overlain by grey-brown basaltic lava flows. The mountain peaks around the bay (e.g. Tóarfjall) are formed by rhyolitic lava. [B] The Njarðvík sill [Burchardt 2008] is formed by basaltic cone sheets intruding the white coloured intrusive rhyolite at the northern shore. [C] The peak of Tóarfjall is formed by rhyolitic lava fed by rhyolitic dykes cutting through basaltic lava flows. [D] The sub-volcanic rhyolite exposed in Innri Hvannagil is cut by basaltic dykes and cone sheets. [E] The peak of Grjótfjal is formed by an eruptive vent with rhyolitic pyroclastic rock. The underlying basaltic lavas dip towards the Njarðvík bay as a result of downsagging (see Section 4.5.1). [F] View towards Dyrfjöll and Náttmálahnjúkur with the two ignimbrites marked.

tions at the former land surface, which coincides with the present-day summits of the mountains surrounding Njarðvík (see below for more details). The main rhyolitic intrusion is exposed along the coast and the valleys in Njarðvík where it forms a mostly concordant dome-shaped intrusion with some faulted wall contacts (Figure 5A). The culmination of the dome was probably situated in the Njarðvík cove itself, based on the distribution of current outcrops. In the mountains along the northern shore, rhyolite magma intruded at a depth of approximately 300 m beneath the palaeosurface and reaches an exposed thickness of about 100 m (Figure 5A). While most of the intrusion is dense and lacks vesicles and is sometimes columnar jointed, its shallower parts exhibit features typical for extrusive rhyolite, such as lithophysae and flow folds. Hence, the intrusion likely pierced the surface of the volcano and partly extruded. A rhyolitic ring dyke extending from the main intrusion upwards into the mountains fed rhyolitic lava flows and pyroclastic rocks from vents (Figures 4 and 5A, C, D, E). Four of these vents are exposed at the peaks of the mountains around Njarðvík and exhibit remarkable exposures of rhyolitic feeder dykes, agglomerates, pyroclastics, and lava flows (Figure 5A, C, D, E; NJAR). In southern Njarðvík, a rhyolitic ignimbrite that likely originated at Grótfjall (Figure 5E) contains petrified wood occurs locally with a maximum thickness of 150 m and dips with up to 30° towards the valley at Náttmálahnúkur (NÁTT; Figure 5F). The caldera flanks of Dyrfjöll volcano are built by tholeiites, olivine basalt from the Jónsfjall Olivine Basalt Group (JOB), and one 50 m-thick dacite lava flow (DAC). The dacite flow was erupted from an agglomerate-filled vent at Kambur and is overlain by basaltic lavas and pyroclastic rocks at Tindur. Notably, the rocks of Tindur and Kambur immediately south of the Dyrfjöll caldera dip at up to 19° to the east.

The bimodal phase culminated in an ignimbrite-forming eruption forming the Dyrfjöll collapse caldera with a maximum diameter of 4 km. The Dyrfjöll caldera is bound by steeply inward-dipping ring faults in most locations and filled by at least 30 m of pink to green ignimbrite (DYR) that is welded at its base and overlain by up to 3.5 m of air-fall deposits (Figures 4 and 6; see also Section 4.5). While the bottom of the caldera is not exposed, an agglomerate-filled vent area with welded ignimbrite is exposed at the western and northern caldera margin.

Numerous basaltic, composite, and some silicic dykes and cone sheets intruded the rhyolitic intrusions and basaltic and rhyolitic lavas in Njarðvík and northern Borgarfjörður eystri (Figure 5B, D; see Section *4.4.2*) [Burchardt et al. 2011]. These sheet intrusions document the shift from bimodal to mostly basaltic magmatism. The lake within the Dyrfjöll caldera depression filled with at least 250 m of basaltic hyaloclastite, pillow breccia and pillow lava (Figure 6) of olivine basalt composition. Onlapping near the caldera margin and dips of the hyaloclastite towards the caldera centre indicate that the basalt erupted at or near the caldera margin and flowed into the lake. Due to the sharp contact between the underlying ignimbrite, no hiatus is evident, which implies that these flows could belong to the Jónsfjall olivine basalt group (see Section 4.3). However, a change to reverse polarity occurs in the subaerial lava flows above the hyaloclastites, as well as another change to normal polarity at the top of the lava sequence. This magnetostratigraphic sequence may correspond to the Hólmar olivine basalt group (dated 11.11 ± 0.12 Ma [Duncan and Helgason 1998]) that is laterally widespread in Eastern Iceland [Óskarsson and Riishuus 2013] and found at the mountains peaks south of Loðmundarfjörður overlying the ignimbrite of Tóahnjúkur (see Section *4.2.4*). Hence, part of the lava sequence at Dyrfjöll could belong to the Hólmar group, but no hiatus explaining the age gap between the Jónsfjall and Holmar groups has been found as of yet.

4.2.2 *Breiðuvík*

The volcanic stratigraphy of the area between Borgarfjörður eystri and Loðmundarfjörður (Breiðuvík volcano; Figure 7) resembles that of Njarðvík and Dyrfjöll to the north. The stratigraphically oldest silicic rocks can be found in and around Brúnavík (BRU) and were potentially erupted from a feeder dyke at the coast of Brúnavík. This sequence has not been dated but correlates with the lower sequence in Njarðvík (Chron C5ACn; see Supplementary Material). A rhyolitic ignimbrite at the shore south of Húsavík was dated at 13.10 ± 0.20 Ma [HÚSAV; Martin et al. 2011] and may relate to a now-eroded volcanic centre to the east. These silicic rocks are overlain by central-type tholeiitic lava flows intercalated with several flat-lying icelandite lavas. The sequence correlates with lava flows of reverse polarity in Borgarfjörður and Loðmundarfjörður of Chron C5Ar.3r and C5Ar.2r. Icelandite is a type of andesite characterised by low amounts of Al and high amounts of Fe that Carmichael coined in his petrographic study of the Thingmúli volcano south of the BEL area [Carmichael 1964]. Rhyolitic ignimbrite sheets occur between tholeiitic lavas east of Grenmór (GRE) and in Kerlingarfjall [Vogler 2014]. This bimodal volcanic succession is overlain by at least one olivine basalt flow that can be found in Herjólfsvíkurvarp, Húsavíkurheiði, and Víknaheiði underlying the Hvítserkur ignimbrite.

Voluminous rhyolitic rocks including mostly lavas, but also at least two lava domes, dominate the mountains between Borgarfjörður and Breiðuvík (BRE; Figure 8). These rhyolites overlie the olivine basalt flow and the porphyritic basalt lava we call the Setberg Group (SETP).

The Hvítserkur ignimbrite (HVÍ) is the infill of a pronounced collapse caldera that is described in detail in

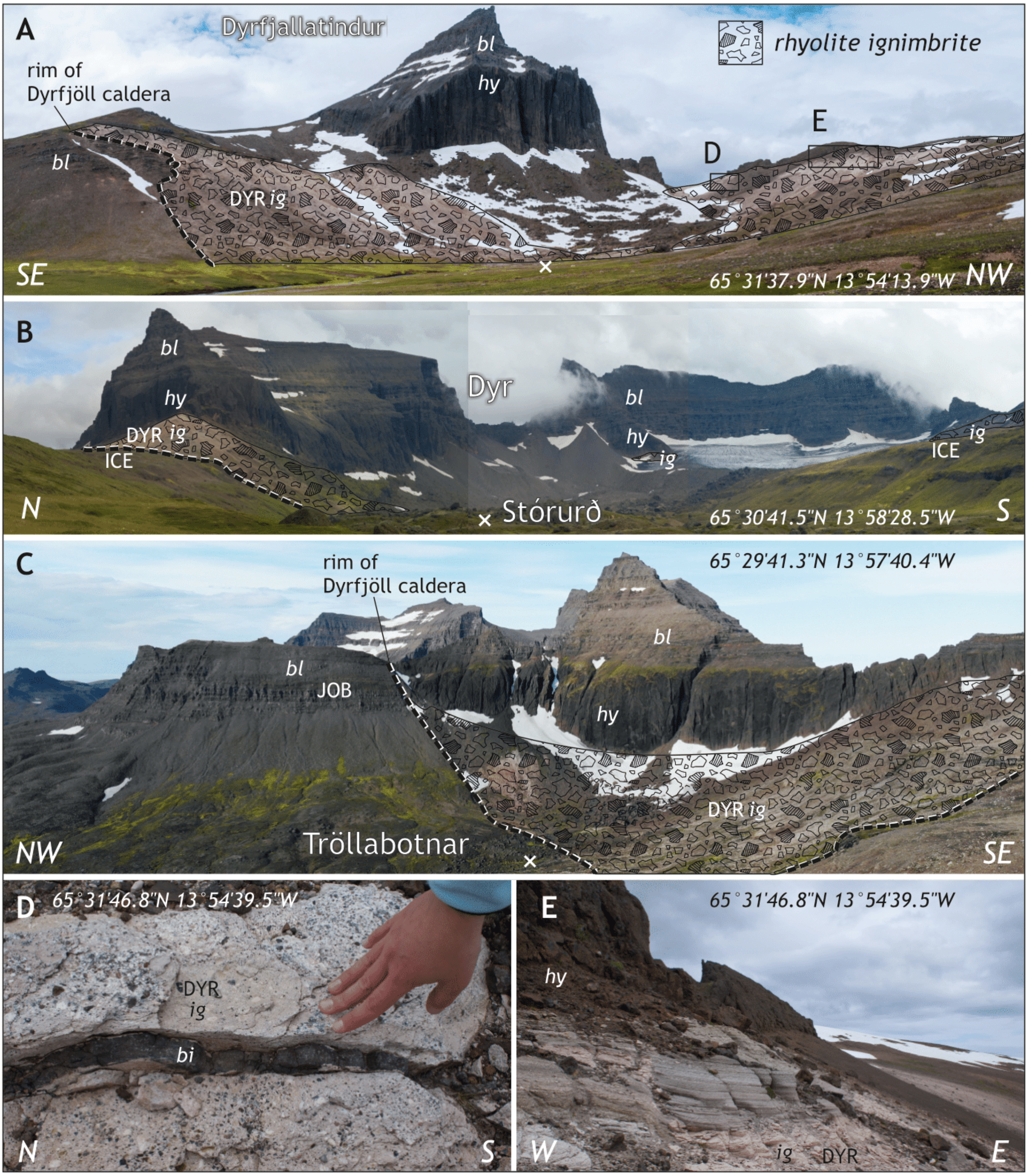

Figure 6: Annotated field photographs illustrating the geology of Dyrfjöll. For locations see Figure 4. Abbreviations: b = basalt, r = rhyolite, hy = hyaloclastite, l = lava, i = intrusion, ig = ignimbrite. × marks the location of the coordinates mentioned in each photograph. For names of stratigraphic formations, see text and Figure 15. [A] to [C] Views of the Dyrfjöll caldera rocks, including the caldera margin (dashed line), the caldera-filling rhyolitic ignimbrite, the hyaloclastite (massive brown rock unit) erupted in the caldera lake, and the flat-lying olivine basalt lava flows that covered the entire volcanic complex, forming the mountain peaks. [D] thin basaltic dyke cutting through the Dyrfjöll ignimbrite that contains white pumice and dark basaltic lithics. See hand for scale. [E] Layered airfall deposits at the top of the Dyrfjöll ignimbrite. Thickness here approximately 2 m. The brown rocks overlying the airfall deposits are the base of the basaltic hyaloclastite erupted in the caldera lake. Locations of [D] and [E] marked in [A].

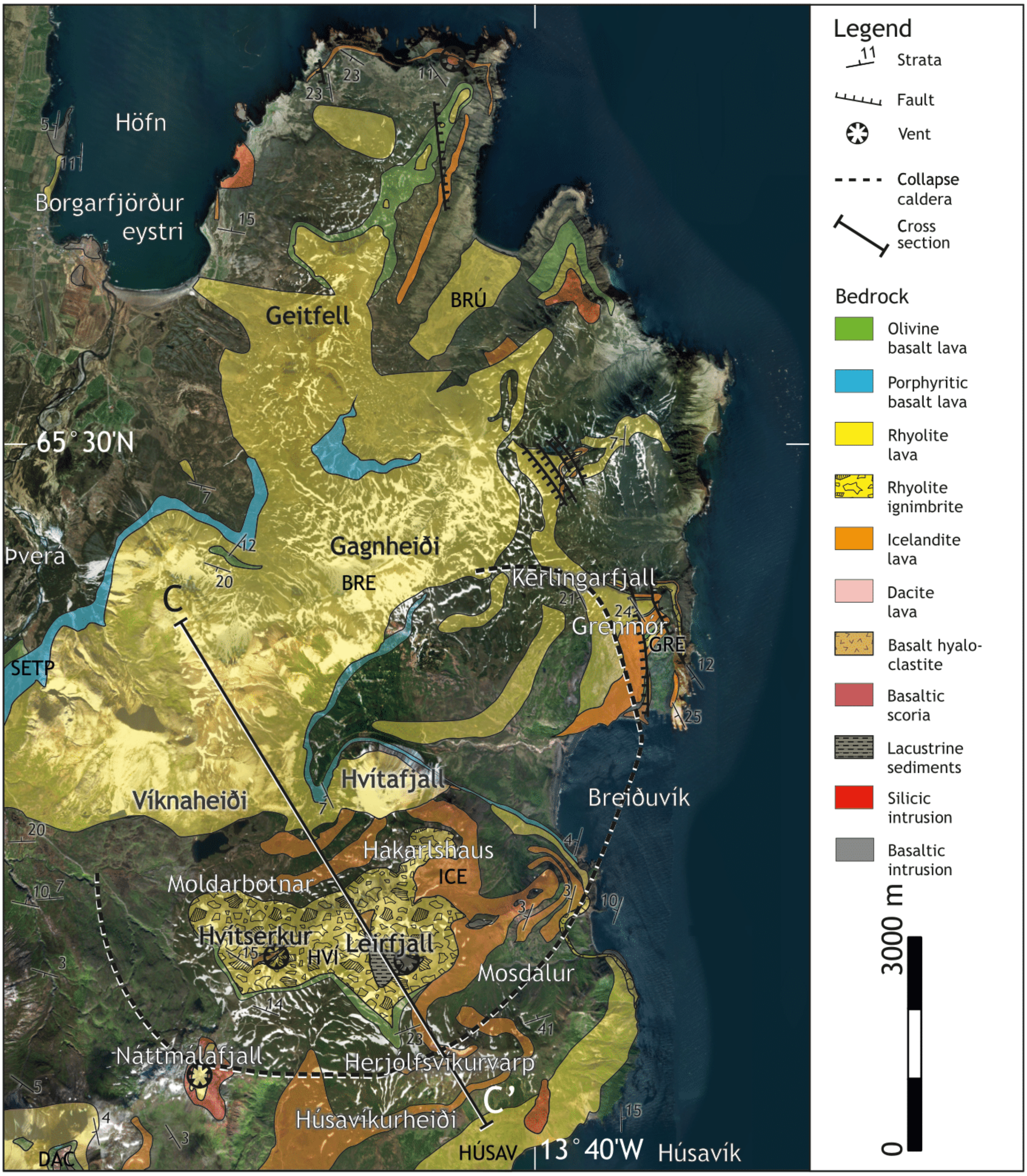

Figure 7: Geological map of the Breiðuvík volcano. For location, see Figure 3. Satellite image from 2009 accessed through Bing Maps (`https://www.bing.com/maps`). For the cross section C–C′, see Figure 13. For names of stratigraphic formations, see text and Figure 13.

Figure 8: Annotated field photographs illustrating the geology of Breiðuvík. For locations see Figure 7. Abbreviations: b = basalt, r = rhyolite, hy = hyaloclastite, l = lava, i = intrusion, ig = ignimbrite. × marks the location of the coordinates mentioned in each photograph. For names of stratigraphic formations, see text and Figure 13. [A] Panoramic view of the Breiðuvík caldera with the caldera-infill Hvítserkur ignimbrite and the overlying caldera lake sediments marked. [B] Southern flank of Hvítserkur showing the landmark ignimbrite crosscut by dark basaltic dykes. The top of the mountain is formed by basaltic hyaloclastite erupted in the caldera lake overlain by subaerial lavas. [C] southern flank of Leirfjall. The Hvítserkur ignimbrite is overlain by clastic lacustrine sediments intruded by basaltic dykes and sills. [D] The colourful mountains near Gagnheiði consist of rhyolitic lava flows. [E] Thick rhyolitic lava flow forming the top of Svartafell. the layered appearance is a result of different jointing directions in the rhyolite lava. [F] View from the top of Hvítserkur. The mountains between Breiðuvík and Borgarfjörður eystri consist of rhyolitic lavas and lava domes. Hvítafjall is the remnant of a lava dome.

Section 4.5 (Figure 8A, B, C). The ignimbrite is overlain by at least 70 m of fine-grained lake sediments that contain a 5 m-thick distal rhyolitic ignimbrite (see description of the caldera; Figure 8C). Numerous dykes and some sills crosscut the ignimbrite and the lake sediments (Figure 8B, C), most of them are composed of olivine basalt (see also Section 4.3). Some of the dykes are connected to vents feeding the pillow lavas and hyaloclastite forming the summit of Hvítserkur. The very summit of Hvítserkur is formed by subaerial basaltic lava (Figure 8B).

In the upper Breiðuvík valley, a conspicuous light-coloured hill called Hvítafjall occurs in what was probably the central part of the caldera (Figure 8F). Hvítafall consists of strongly altered rhyolite breccias that cut the gently-dipping lavas of the caldera floor at steep angles. Hvítafjall is therefore most likely the remnant of an intra-caldera dome, although the timing of its formation relative to the ignimbrite is unclear.

Downfaulting of the cliff east of Grenmór [Vogler 2014] postdating caldera formation and a succession of thin basalt lavas dipping steeply towards the sea north of Húsavík indicate that the Breiðuvík volcano had steep flanks during its lifetime.

4.2.3 *Kækjuskörð*

The area west of the Breiðuvík volcano and south of Dyrfjöll is characterised by a bimodal volcanic suite ascribed to Kækjuskörð volcano (Figure 9) [Gustafsson et al. 1989]. Kækjuskörð comprises a series of rhyolitic and intermediate extrusive rocks and contemporaneous central-volcano type and intercalated with regional flood basalt as described by Gustafsson et al. [1989]. The oldest exposed rocks in the area are central-type tholeiite flows that dip at low angles (<10°) towards Skumhöttur (Figure 9). Within these tholeiites, a few icelandite lavas occur, one particularly prominent icelandite flow can be traced from a small eruption site in Náttmálafjall all around Húsavík and to the north flanks of Loðmundarfjörður and from there into Norðdalur. The basaltic lavas directly underlie the olivine basalt lava at the base of the Breiðuvík caldera. Tholeiitic and olivine basalt lavas are intercalated with a number of rhyolitic ignimbrites, several rhyolitic lava flows, and a dacite flow that occur locally and originate from eruption sites that progress in age from north to south (Figure 10).

Rhyolitic volcanism overlying the tholeiites and icelandites in the area started with an up to 40 m-thick flow at Kollutungur. Two rhyolitic ignimbrites are exposed locally in the vicinity of Skumhöttur (Figure 10B), Orustukambur ignimbrites I and II [Gustafsson et al. 1989]. The older ignimbrite is about 30 m thick and contains up to 2 m-long, silicified tree fragments. The younger Orustukambur II ignimbrite can be found as a thick (ca. 80 m) sheet in Kerlingardalur and is suggested to be the product of a dome-collapse at Skúmhöttur [Gustafsson et al. 1989]. The overlying Kækjuskörð rhyolite is connected to and emanates from an eruption site at Skúmhöttur, covers an area of 15 km^2, and reaches a maximum thickness of 300 m (cf. Figure 10B) [Lapp 1990]. The Kækjuskörð rhyolite is covered by two younger rhyolite flows, Þriggjahnjúkafjall rhyolites I and II (Figure 10A). These flowed downhill for a distance of 1 km from Þriggjahnjúkafjall and reach thicknesses of 50 m and 30 m, respectively. The eruption site of Þriggjahnjúkafjall rhyolite II is exposed at the mountain with the same name (Figure 9). Some distal pyroclastic deposits characterised by small grain sizes and a scarcity of lithics cover the Þriggjahnjúkafjall rhyolite II.

In Kerlingardalur, a proximal rhyolitic ignimbrite occurs locally and discordantly (Figure 10C; previously described as tuff ring by Thomas [1988]), which we interpret as the product of a caldera collapse (see Section 4.5). The ignimbrite was subsequently intruded by basaltic sills and dykes. The age relationship between the Kerlingardalur and other ignimbrites remains unclear, but it is possible that the Kerlingardalur ignimbrite and Orustukambur ignimbrite II are in fact the same ignimbrite (see Section 4.5).

The rhyolites in the area are covered by olivine basalts from the Jónsfjall group (see Section 4.3). This group is covered by a local group of porphyritic flows, the lowest most flow with conspicuous plagioclase macrocrysts (<10 %) reaching 6 cm in diameter. Southwest of Norðdalshnjúkur, this sequence is replaced with another peculiar porphyritic flows of plagioclase and pyroxene rich basalt, with segregation of the pyroxenes in vesicle cylinders and the upper vesicular zone. The remnants of a basaltic fissure eruption are exposed in Kækjuskörð, and the area is cut by an up to 200 m-wide and 1 km-long basaltic dyke swarm (see Section *4.4.1*). Following the eruption of these basalts, a dacite flow was erupted from a feeder dyke exposed in Skúmhattardalsbrik. From there, the dacite lava flowed to the south for a distance of 1.5 km and was subsequently covered by the Herfell ignimbrite.

4.2.4 *Herfell*

The geology around Loðmundarfjörður (Figure 9) resembles the basic stratigraphy of the areas described above. At the base of the stratigraphy, local central volcano and flood basalt lava flows are intercalated with at least one (locally two) icelandite flows (ICE). One of the flows appears to be the same that occurs further north (see Section 4.3). In Norðdalur, this prominent icelandite flow locally thickens towards the closure of the valley.

Up sequence, two rhyolitic ignimbrites are exposed as concordant sheets in between basaltic lavas, testifying to a flat landscape covered by basaltic lavas at the time of deposition. The ignimbrite sheet at Tóarhnjúkur (TóA) mountain about 750 m above sea level

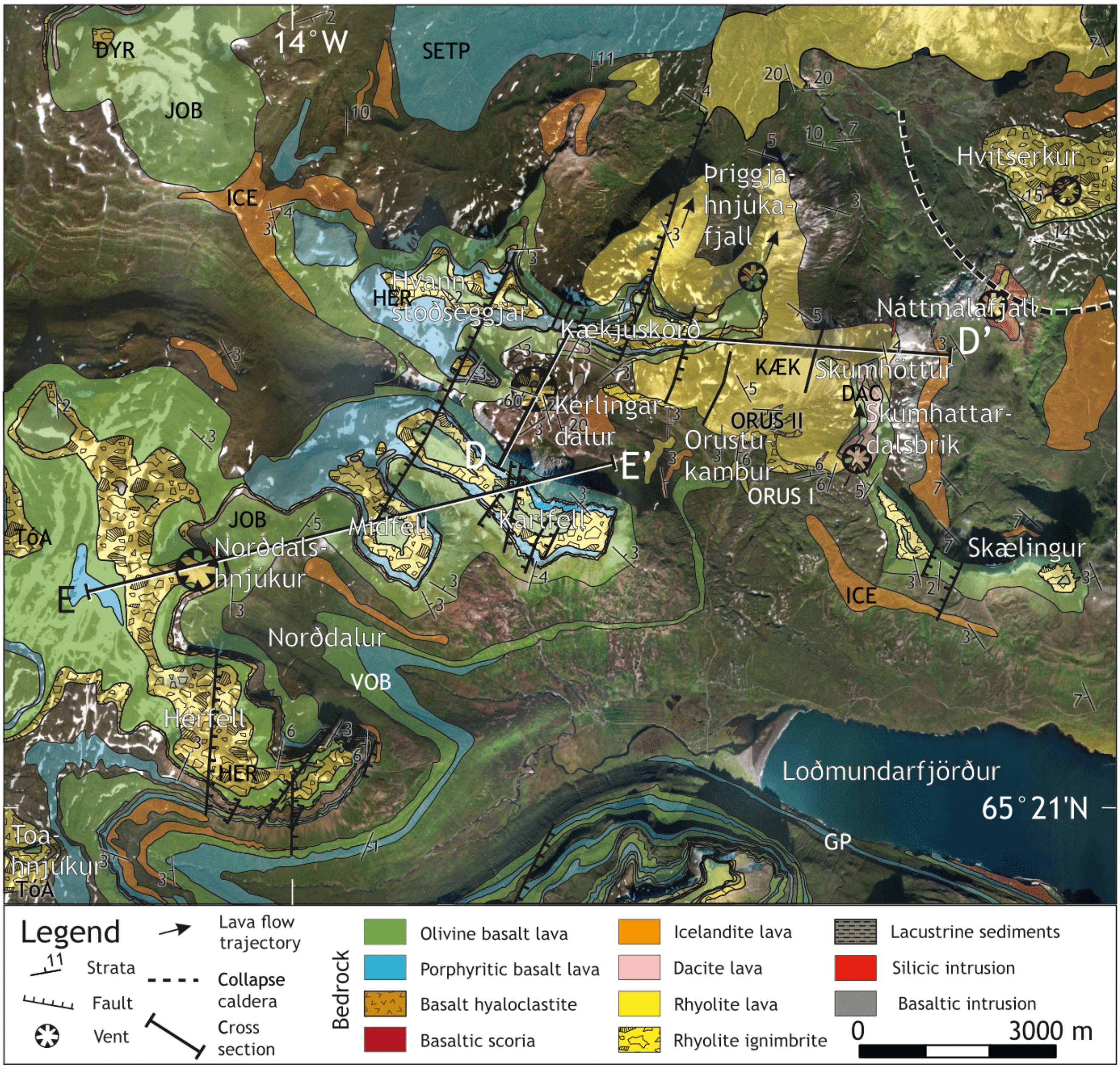

Figure 9: Geological map of the area west and north of Loðmundarfjörður. For location, see Figure 3. Satellite image from 2009 accessed through Bing Maps (https://www.bing.com/maps). For the cross sections D–D′ and E–E′, see Figure 13. For names of stratigraphic formations, see text and Figure 13.

likely originated from near Tóarhnjúkur, where air fall deposits with large pumice clasts (up to 6 cm) and basaltic lithics (up to 3 cm) are exposed (see also Section 4.5). This ignimbrite can be traced from Tóarhnjúkur towards the north and northeast at least to Kerlingardalur (Figure 9). At elevations of 900 m a.s.l., the Herfell ignimbrite (HER) is exposed in the western and northern parts of Loðmundarfjörður. The Herfell ignimbrite was first described by [Dearnley 1954] and erupted at 12.40 ± 0.12 Ma (U–Pb age of zircons) [Berg 2016]. In Norðdalshnjúkur, a vent related to the Herfell ignimbrite is exposed with a base at about 700 m a.s.l., (Figure 10D; see also Section 4.5). At Norðdalshnjúkur and Herfell, the Herfell ignimbrite is partly welded and reaches its maximum thickness of 120 m. From west to the east, the ignimbrite occurs as a concordant sheet on the mountains of Herfell, Norðdalshnjúkur, Miðfell, Kallfell/Karlfell, Hvannstoðseggjar, Bungufell and Skælingur (Figure 9). The thickness of this ignimbrite sheet is at a maximum of about 120 m around the mountain Norðdalshnjúkur and decreases to the east, still having a thickness of about 60 m at the easternmost outcrop in Skælingur. No prominent outcrops of this ignimbrite are found in the mountains to the south of Loðmundarfjörður. There, only relatively thin, distal ignimbrite deposits are intercalated

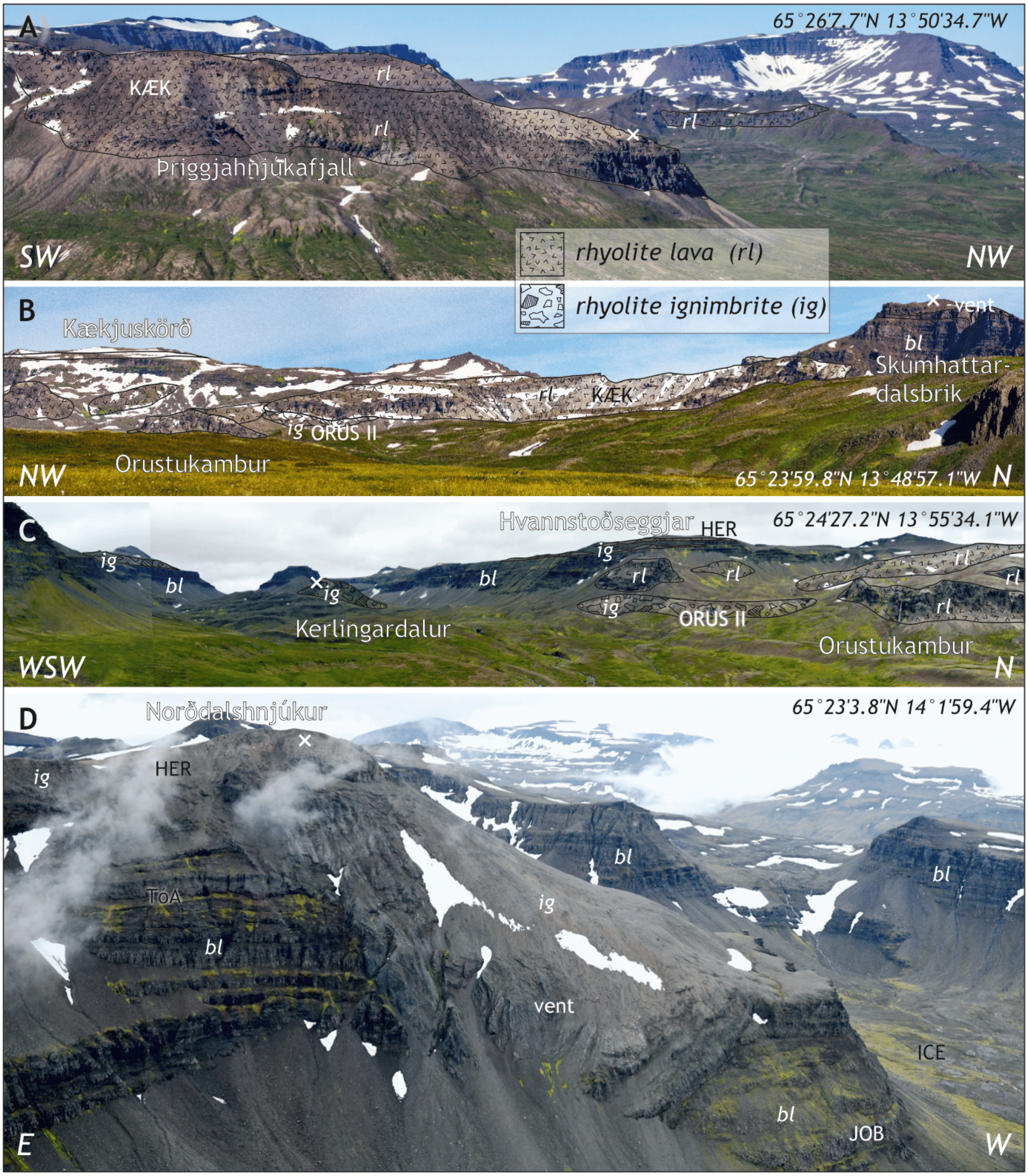

Figure 10: Annotated field photographs illustrating the geology of the area in Figure 9. Abbreviations: b = basalt, r = rhyolite, hy = hyaloclastite, l = lava, i = intrusion, ig = ignimbrite. × marks the location of the coordinates mentioned in each photograph. For names of stratigraphic formations, see text and Figure 13. [A] the Þriggjahnjúkafjall rhyolites I and II were erupted north of Skúmhattardalsbrik and flowed northward. [B] Panoramic view of the rhyolite lavas and ignimbrites around Orustukambur. Also note the feeder dyke and lava flow of dacite in Skúmhattardalsbrik. [C] Continuation of the panoramic view in [B], looking into Kerlingardalur. [D] Unmanned Aerial vehicle (drone) photograph of a large vent structure in Norðdalshnjúkur that is connected to the Herfell ignimbite.

between basaltic lava flows. Hence, the bulk of the Herfell ignimbrite was deposited towards the northeast. Olivine basalt dykes cut through the ignimbrite and fed lava flows (see Section 4.3).

4.3 Local lava groups and regional flood basalts

Unlike the areas to the south and west where flood basalt groups can be traced long distances, the BEL area is predominantly built up by local groups confined to the BEL intercalated with a few regional flood basalts. The most prominent local group that is a stratigraphic marker extending from Njarðvík to Breiðuvík is the Setberg porphyritic Group (SETP), a peculiar group of relatively thin flows of darkbrown/blackish basalt with acicular and lamellated plagioclase phenocrysts and macrocrysts (up to 2 cm) with varying degree of crystal cargo, reaching up to modal 40 vol.% in some flows. The group is thickest with over 20 flows in Hvannstóðsdalur but thins to 5–6 flows east and north (Figure 3). On top of this group is another marker, a group of icelandite flows (ICE). The group is thickest west of Hvannstóðsdalur, some flows reaching over 30 m in thickness and the total volume of the group is about 2–3 km^3. The third local group is the JOB described by Óskarsson and Riishuus [2013]. The Jónsfjall olivine basalt group is found at high elevations and extends from Loðmundarfjörður to Borgarfjörður eystri. The group is thickest west of Loðmundarfjörður with over 30 flows of thin darkbrown/blackish olivine basalts.

The widespread and regional flood basalts interdigitating with the central volcano basalts in the study area correlate with the lower stratigraphy of Reyðarfjörður, mapped by Walker [1958], beginning below the Gerpir porphyritic group (GP; Figure 9) and extending up to the Hólmar olivine basalt group. The Herfell ignimbrite (HER) is covered by olivine basalts that correlate both stratigraphically and paleomagnetically with the Hólmar olivine basalt group [Óskarsson and Riishuus 2013].

This stratigraphy indicates that volcanism seems to have largely ceased in the area after the Hólmar event, while it continued extensively to the south, forming a stack over 2000 m thick in the Thingmuli and Breiðdalur volcanic systems [Óskarsson and Riishuus 2019].

4.4 Sub-volcanic intrusions

Post-volcanic glacial erosion of the area has exposed sections as deep as 1100 m into the flanks and upper volcanic plumbing system of the volcanic centres and their surroundings. In this section we give an overview of the wealth of sub-volcanic features we have encountered in the area.

4.4.1 *Dyke swarms*

Although the BEL area is less deeply eroded than Southeast Iceland where erosion levels reach up to 2 km at the present-day sea level [Walker 1974], dykes do frequently occur at all elevations in our study area, and we estimate the density of subvertical dykes to reach 3–4 % at sea level (Figure 2) [cf. Lapp 1990]. The orientation of dykes in BEL shows a NNE strike (Figure 11A), with a slightly more northerly strike towards the east in BEL and a slightly more north easterly strike reported for the Kækjuskörð area (Figure 11; this study) [Lapp 1988; Thomas 1988; Lapp 1990; Burchardt et al. 2011, Gudmundsson, A. I., pers. comm.].

4.4.2 *Inclined sheet swarms*

Inclined (cone) sheets, i.e. moderately dipping sheet intrusions with a sub-circular shape in map view and converging to a common subsurface location that has been interpreted to correspond to the source magma chamber are prevalent in Njarðvík and Borgarfjörður eystri (Figures 4, 5, 11 and 12B, C) [Burchardt et al. 2011]. They are mostly basaltic in composition and crosscut the silicic and basaltic rocks. The best exposures of cone sheets can be found along the shores of Njarðvík where they can be seen to connect from one side of the shore to the other in arcuate outcrops. However, exposures of cone sheets can be found in all river beds, coastal outcrops, cliffs, and steep mountain flanks around Njarðvík, Stapavík, and Borgarfjörður eystri.

The cone sheets belong to several swarms that were fed from different locations in the area. Based on 3D structural modelling and convergence areas, the most pronounced cone-sheet swarm has been shown to originate from about 1–2 km depth beneath the Njarðvík valley [Burchardt et al. 2011]. Based on cross-cutting relationships, another, contemporaneous cone-sheet swarm has been shown to converge towards a source beneath the Borgarfjörður valley [Burchardt et al. 2011]. Additional, overlapping inclined sheet swarms to the north and east of Njarðvík indicate the widespread distribution of magmatism. Hence, volcanism likely occurred in overlapping centres or a larger volcanic cluster that is now dissected by the Borgarfjörður eystri fjord.

4.4.3 *Other sub-volcanic intrusions*

Sub-volcanic intrusions of different types occur frequently in the study area (Figure 11). Here, we will name just a few examples, as these intrusions are subject to ongoing research.

Sills are the most common form of intrusion apart from dykes and cone sheets. The best studied sills in the area are the Njarðvík sill that are fed by basaltic inclined sheets emplaced close to sea level in Njarðvík (Figure 12C) [Burchardt 2008] and the rhyolitic Land-

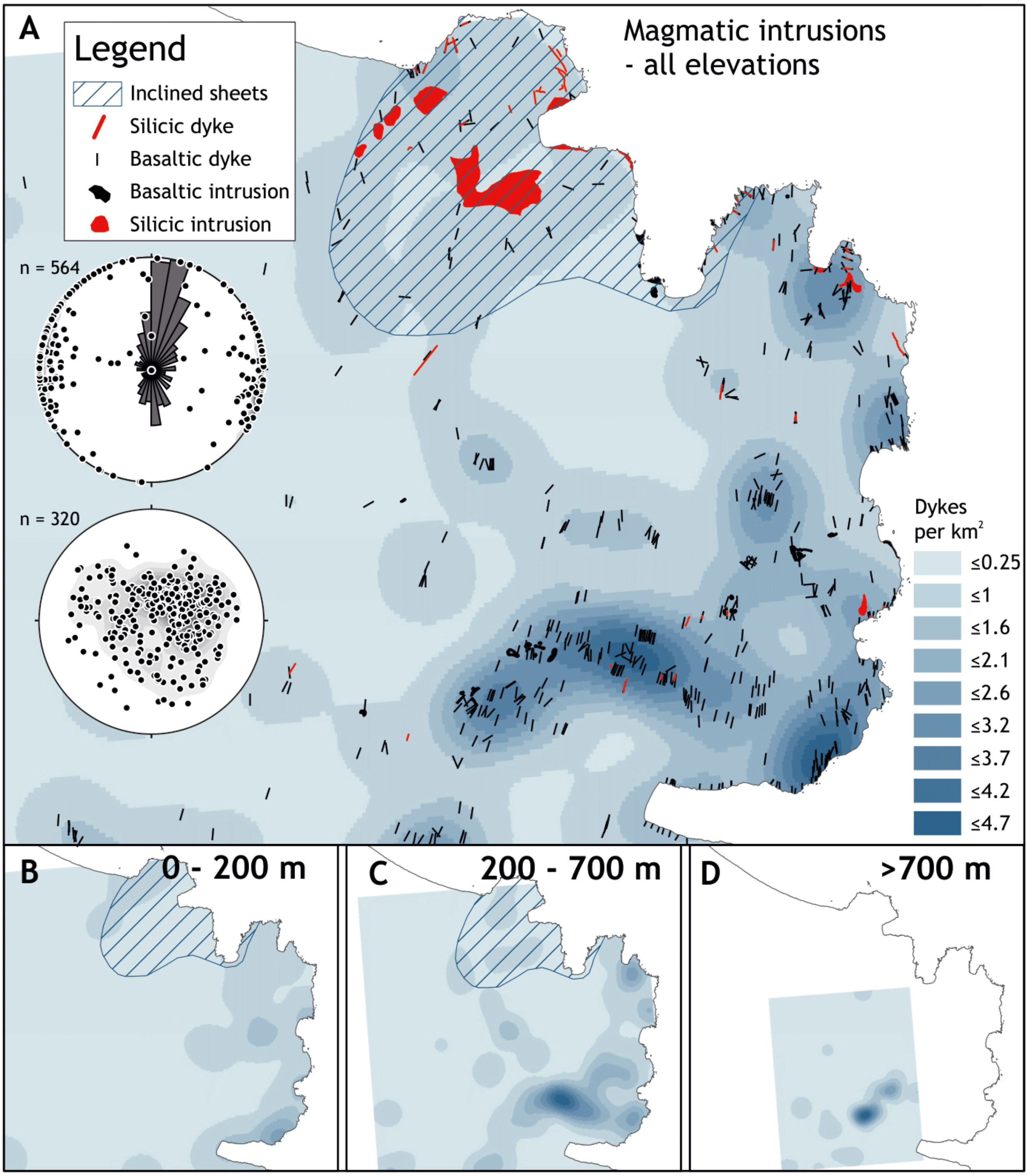

Figure 11: Density and distribution of magmatic intrusions in BEL at [A] all elevations, [B] 0–200 m, [C] 200–700 m, and [D] above 700 m above sea level. [A] Stereographic projections of sheet intrusion orientations in equal area lower hemisphere plots: Upper plot: poles to planes of the 564 sheet intrusions displayed in the map in [A]. The rose plot and Kamb contour plot show a clear preference of sheet intrusions to strike NNE. Maximum density in Kamb contour plot = 90. Maximum bin of Rose plot contains 23 % of all measurements. Data: this study. Lower plot: poles to planes of 320 inclined sheets measured in the shaded area in [A]. The Kamb contours indicate a small circle distribution of inclined sheet orientations with a slight preference for sheets to dip towards the SE. Maximum density in Kamb contour plot = 28. Data from Burchardt et al. [2011].

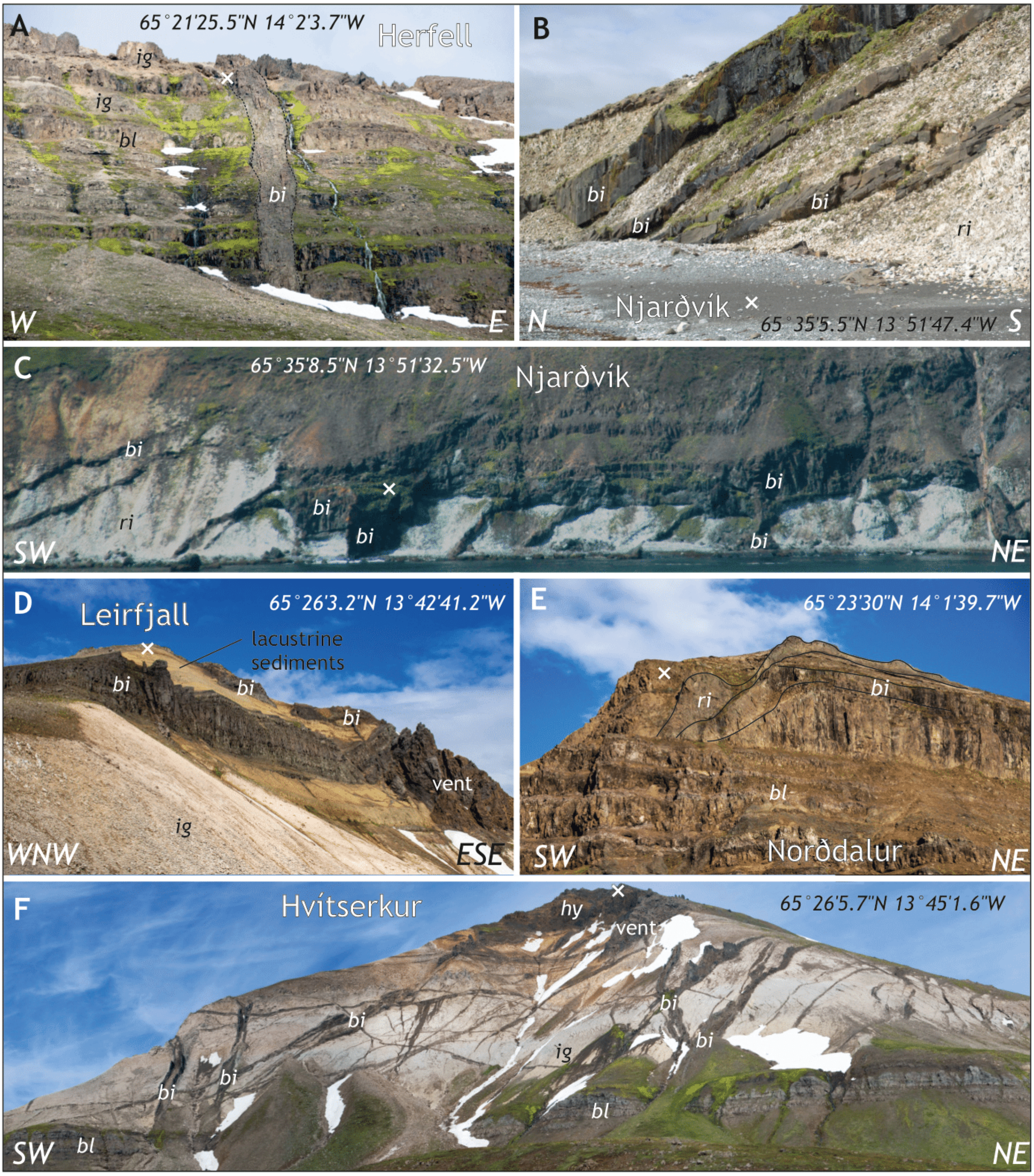

Figure 12: Annotated field photographs of magmatic intrusions in BEL. Abbreviations: b = basalt, r = rhyolite, hy = hyaloclastite, l = lava, i = intrusion, ig = ignimbrite. × marks the location of the coordinates mentioned in each photograph. [A] Regional dyke crosscutting basaltic lavas and rhyolitic ignimbrites on the south flank of Herfell. Thickness of the dyke is approximately 5 m. [B] Basaltic inclined sheets crosscutting the white subvolcanic rhyolite of the Njarðvík intrusive complex at the shore of Njarðvík. Middle sheet is about 0.5 m thick. [C] The Njarðvík sill fed by inclined sheets crosscutting the white subvolcanic rhyolite of the Njarðvík intrusive complex at the shore of Njarðvík. See Burchardt [2008] for details. [D] Basaltic sills, dykes and vent in the yellow-brown lake sediments of the Breiðuvík caldera. See Section *4.5.3* for a detailed description of the caldera. [E] Dyke and sill in the basaltic lavas on the northern end of Norðdalur. [F] Basaltic dykes cutting the Hvítserkur ignimbrite of the Breiðuvík caldera. See Section *4.5.3* for a detailed description of the caldera.

sendi sill exposed between Njarðvík and Borgarfjörður eystri [Saubin et al. 2019]. Both sills are examples of concordant sheet intrusions emplaced between and/or into lava flows and sub-volcanic intrusions of their associated volcanoes. Other sills that are currently investigated can be found in the Hvítserkur ignimbrite and the overlying lake sediments of the Breiðuvík caldera (Figure 12D, F). In addition, there are a multitude of unstudied sills, e.g. near the western shore of Borgarfjörður eystri, by the cliffs east of Mosdalur, in Kerlingardalur, south of Herjólfsvík, by Náttmálafjall and north of Norðdalshnjúkur (Figure 12E).

Other sub-volcanic intrusions of the area are the dome-shaped, rhyolitic Njarðvík sub-volcanic complex (Figure 5) [Gustafsson 1992; Burchardt 2008], as well as rhyolitic intrusions at the coast near Höfn in Borgarfjörður eystri. Generally, rhyolitic intrusions appear to be more frequent in the north of BEL (Figure 11).

Sub-volcanic vent or feeder structures frequently occur higher up in the stratigraphy of the volcanic structures in the BEL area. Gustafsson [1992] described some of the vents in the Njarðvík-Dyrfjöll area, for example the rhyolitic vent structures associated with the ring dykes on the peaks surrounding Njarðvík, the vent associated with the Dyrfjöll caldera, and the agglomerates of the vent producing the dacitic Kambur lava (see Figure 4 for locations). In the Breiðuvík caldera, several basaltic vents cut through the Hvítserkur ignimbrite and the overlying lake sediments and are in some cases connected to the hyaloclastites and pillow breccias at the summit of Hvítserkur (Figure 8). In the southern part of the study area (see Figure 9 for locations), a basaltic vent with red scoria deposits forms the summit of Náttmálafjall and a dacitic vent is connected to the dacite lava near the summit of Skúmhattadalsbrik (Figure 10B) [Lapp 1990]. Moreover, the vent to the Þriggjahnjúkafjall rhyolite II lava is exposed in the mountain with the same name [Lapp 1990].

4.5 Collapse calderas and eruptive vents of ignimbrites

The study area hosts a number of rhyolitic ignimbrites, some of them associated with collapse calderas and some apparently originating from vents. In this section, we describe their occurrence and eruption features. Their comparative size and distribution are discussed. Most of the ignimbrites are located in the upper half of the exposed stratigraphy, underlain and overlain by olivine basalt lavas. The oldest ignimbrite in the area is found by the coast in Brúnavík and has not been dated but the oldest dated ignimbrites in the stratigraphy is found in Húsavík and dated by [Martin and Sigmarsson 2010] at 13.10±0.20 Ma. Other ignimbrites so far undated, occur in the lake sediments of the Breiðuvík caldera (see description below), the Kækjuskörð area, namely Orustukambur I and II, as well as in Kerlingardalur and in Tóarhnjúkur.

4.5.1 *Njarðvík collapse calderas*

In the northern part of the study area, the cove of Njarðvík contains evidence for successive caldera collapse in two, partly overlapping calderas. The older of the two is evident from the concentric inward tilt of the otherwise subhorizontal basaltic lavas (Figures 4 and 5E, Figure 13 A–A′), forming a depression or downsag caldera with a centre close to the back of the valley. The outline of this downsag caldera in the map in Figure 4 encircles the area with anomalous inward dips. No eruptive deposits are associated with this caldera structure, and crosscutting relationships with the local intrusions indicates that it predates the Njarðvík silicic complex.

Renewed caldera formation occurred in connection to a rhyolitic ring dyke that extended from the subvolcanic silicic intrusion in the bay upwards into the mountains surrounding Njarðvík and fed rhyolitic lava flows and pyroclastic rocks (Figure 5A, C, D, E). Remnants of what was likely a circumferential fissure and associated vents connected to the dyke can be found on four of the mountain tops surrounding Njarðvík and exhibit remarkable exposures of rhyolitic feeder dykes, agglomerates, pyroclastics, and lava flows (Figures 4 and 5A, C, E). The rhyolitic Náttmálahnúkur ignimbrite (NÁTT) and an associated vent in southern Njarðvík may be associated with this caldera collapse. The ignimbrite contains petrified wood, has a maximum thickness of 150 m and formed at 12.61±0.16 Ma [Berg 2016] (Figure 5F). Post-deposition tilting of up to 30° towards the centre of the caldera may either indicate that the ignimbrite is unrelated to the second Njarðvík caldera, or that subsidence occurred subsequent to the eruption. The outline of this caldera in the map in Figure 4 follows the rhyolitic ring dyke exposed in the northern and western mountains surrounding the cove and even encompasses the two rhyolitic vents south of the bay/valley.

4.5.2 *Dyrfjöll collapse caldera*

Approximately 5 km SSW of Njarðvík, an ignimbrite-forming eruption produced the Dyrfjöll collapse caldera with a maximum diameter of 4 km (Figures 4 and 6). The Dyrfjöll caldera is for the most part bound by steeply inward-dipping, well-exposed ring faults (Figures 6 and 13 B–B′). While the bottom of the caldera is not exposed, an agglomerate-filled vent with welded ignimbrite is exposed at the northern caldera margin. The caldera is filled by at least 30 m of pink to green ignimbrite that is welded at its base and overlain by up to 3.5 m of air-fall deposits (Figure 6F). Berg [2016] dated the Dyrfjöll ignimbrite (DYR) at 12.40 ± 0.19 Ma.

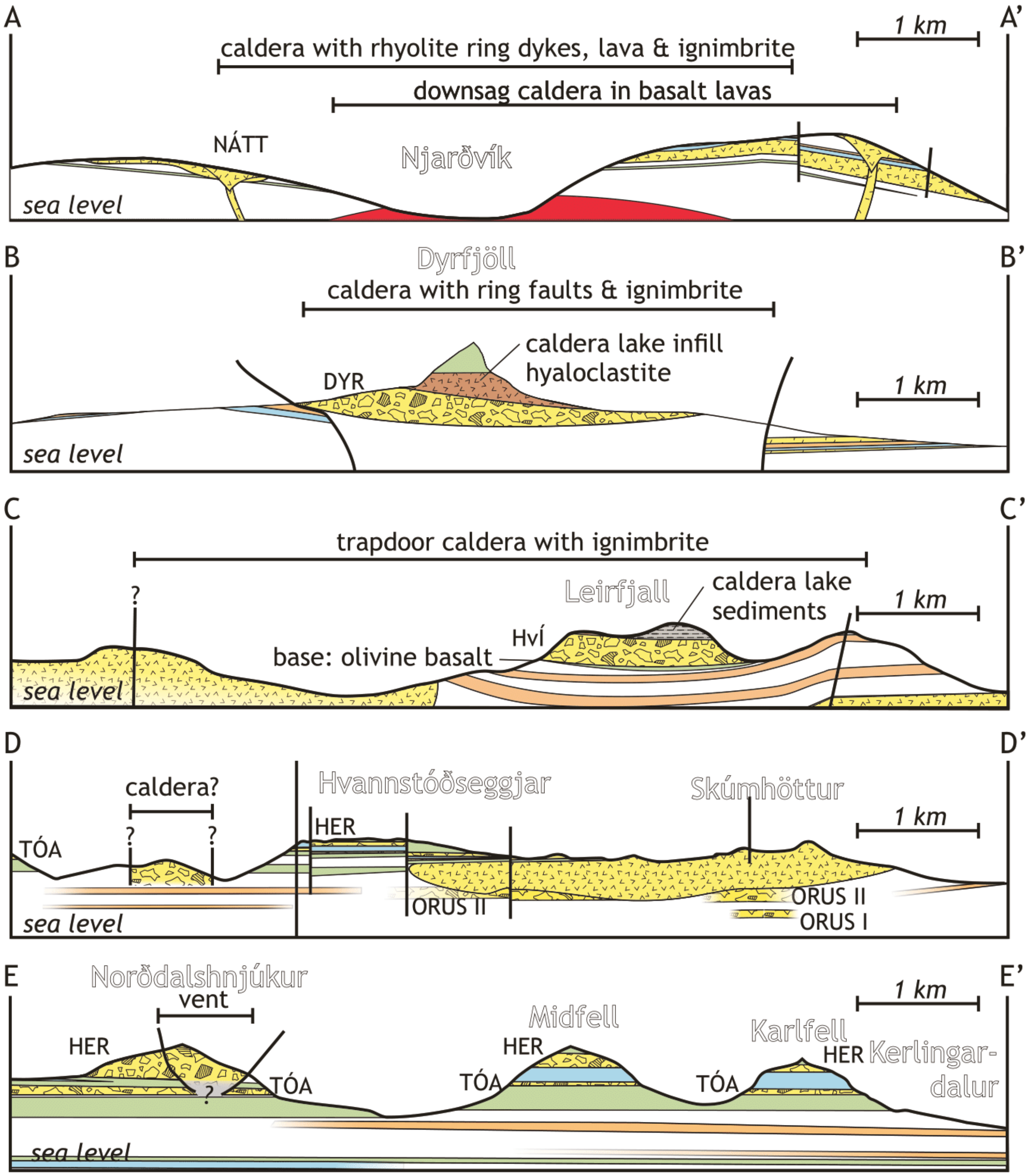

Figure 13: Cross sections through the collapse calderas and volcanic features associated with rhyolitic ignimbrites in the BEL area. For locations of cross sections and legend, see Figures 4, 7 and 9. Stratigraphic abbreviations from stratigraphic oldest to youngest: *ORUS I* = Orustukambur ignimbrite 1, *ORUS II* = Orustukambur ignimbrite 2, *TÒA* = Tóarhnjukur ignimbrite, *HER* = Herfell ignimbrite, *HVÌ* = Hvítserkur ignimbrite, *DYR* = Dyrfjöll ignimbrite. *HER, HVÌ*, and *DYR* have approximately the same age (ca. 12.4 Ma) [Berg 2016], the other ignimbrites are not dated.

4.5.3 *Breiðuvík collapse caldera*

In the Breiðuvík area, parts of the mountains Hvítserkur, Hákarlshaus, and Leirfjall consist of the so-called Hvítserkur ignimbrite (HVÍ) that is the infill of a ca. 7.5 × 4.5 km collapse caldera (Figures 7, 8 and 13 C–C′) with an age of 12.50±0.60 Ma [Martin and Sigmarsson 2010] or 12.41 ± 0.28 Ma [Berg 2016]. At the southern caldera rim, the flat-lying lavas of the caldera floor abruptly change dip to 55° to the north at Herjólfsvíkurvarp. This abrupt change of dip of the lavas towards the caldera is also observed in Náttmálafjall south of Hvítserkur and in Grenmór at the northern shore of Breiðuvík, where basaltic and rhyolitic lavas dip with up to 25° to the southwest [Vogler 2014]. To the northwest, the extent of the caldera is obscured by erosion within altered rhyolitic lavas.

The caldera floor is bowl-shaped with decreasing dips towards the caldera interior and filled by the Hvítserkur ignimbrite. The ignimbrite reaches a current exposed thickness of 180 m at the southern flank of Hvítserkur, 277 m on its western flank, and 410 m on its northern flank. The ignimbrite itself is mostly unwelded and beige, topped by a 2–3 m thick, flat-lying pink airfall deposit on the south side of Hvítserkur. On the north side of Hvítserkur, Leirfjall, and in Hákarlshaus, the ignimbrite is locally welded and dark brown in colour. Petrified wood and plant remains have been found in the ignimbrite [Vogler 2014]. Although the caldera-filling ignimbrite is eroded in the northern part of the caldera in Breiðuvík, we could use the dip of the caldera-floor lavas and the top contact of the ignimbrite to reconstruct the three-dimensional shape of the caldera (Figure 14). Assuming that the caldera depression was filled by the ignimbrite as seen in the south, the total volume of the ignimbrite before erosion may have been around 4.07 km^3.

Unusually high oxygen isotope values in the Hvítserkur and Dyrfjöll ignimbrites have been interpreted to result from prolonged hydrothermal alteration in the caldera lakes [Berg et al. 2018]. The ignimbrite is overlain by a succession of lake sediments that range in thickness from less than 2 m in Hvítserkur to up to 70 m in Leirfjall. At their base, the lake sediments comprise interbedded sandstones and siltstones with reworked pumice and basalt grains. Cross-bedding and ripple marks in some of the beds indicate a shallow lake depth and water movement. The overlying mudstones to sandstones contain pumice fragments on top of beds, which indicates that the sediment was likely sourced from the erosion of the Hvítserkur ignimbrite beyond the caldera. Moreover, desiccation cracks in several of the mudstones demonstrate that the lake dried out episodically. Up-sequence, the sandstones contain reworked pumice and basaltic grains. Towards the top, the sequence contains an up to 5 m-thick distal ignimbrite with fiamme. This ignimbrite is overlain by a succession of brown to black, partly silicified mud- and siltstones. Numerous dykes and some sills crosscut the ignimbrite and the lake sediments, most of them are composed of olivine basalt (see also Section 4.3). In Leirfjall, shallow intrusions with pepperites and a large vent indicate magma-water interaction at very shallow depths. In Hvítserkur, some dykes are connected to conduits feeding the pillow lavas and hyaloclastite at the summit. The occurrence of pillow lavas and hyaloclastite demonstrates that the Hvítserkur caldera lake still existed at the time of their eruption. However, the subaerial olivine basalt lava at the very summit of Hvítserkur testifies either to the end of the caldera lake or that phreatomagmatic volcanism changed to effusive volcanism as the eruption reached above the level of the lake.

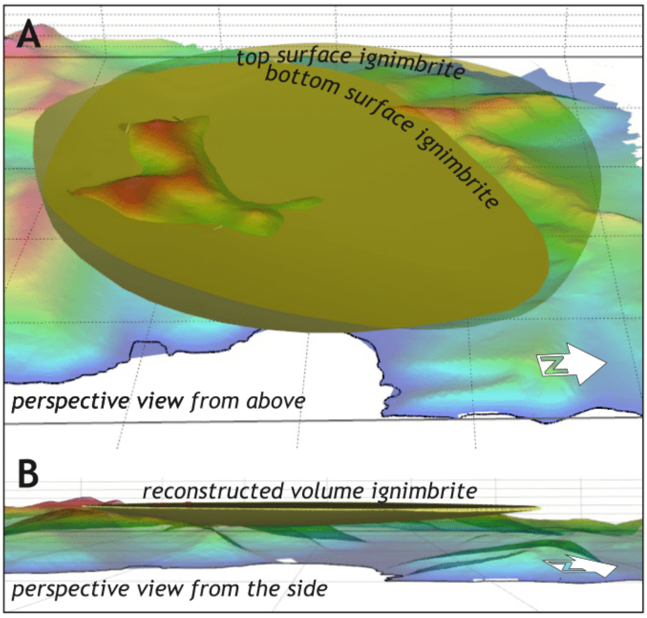

Figure 14: [A] Perspective view and [B] side view of the three-dimensional reconstruction of the Breiðuvík caldera-infill (Hvítserkur) ignimbrite from mapping of the bottom and top surface of the ignimbrite. The reconstruction and volume calculation were done in Move 2018 (Petroleum Experts). The caldera bottom is bowl-shaped (see also Cross section C–C′ in Figure 13). Note that the caldera depression was not entirely filled by the ignimbrite. A caldera lake formed after the eruption, as evident from lacustrine sediments and basaltic hyaloclastites erupted in the lake.

4.5.4 *Norðdalshnjúkur/Herfell eruptive vent and origin of other ignimbrites*

The southern part of our study area (Loðmundarfjörður) contains several rhyolitic ignimbrite sheets throughout the stratigraphic sequence (Figures 9 and 13 D–D′ and E–E′). Moreover, ignimbrites are locally exposed in numerous locations around the study area, where they can often not be linked to any of the

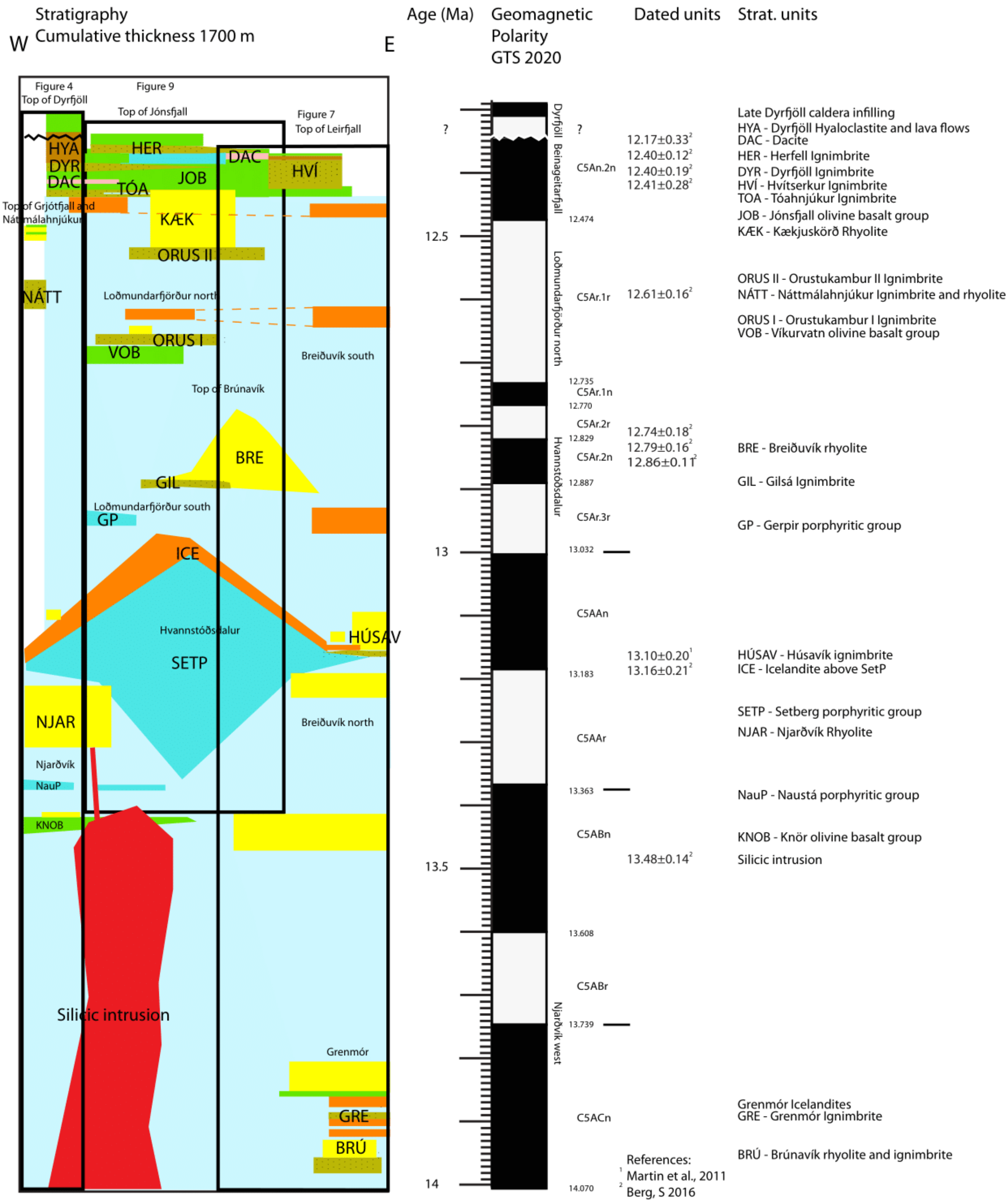

Figure 15: Composite stratigraphic section showing the order of the geological formations described in the text as correlated with the magnetostratigraphy (this study) and the available radiometric ages.

identified collapse calderas. In general, we use the size of lithics and the degree of welding to identify proximity to the source locations of ignimbrites.

From bottom to top, the following ignimbrite sheets have been identified: Orustukambur I (ca. 200–230 m a.s.l.) and II (300–380 m a.s.l.), Tóarhnjúkur (ca. 700 m a.s.l.), and Herfell (ca. 900–1020 m a.s.l.). These ignimbrites can be traced south to Seyðisfjörður and west to Fljótsdalur [Óskarsson and Riishuus 2019]. The Orustukambur II ignimbrite has been suggested to originate from Skumhöttur [Thomas 1988] where there is evidence for an eruptive centre. Alternatively, the Orustukambur II ignimbrite may originate from the ignimbrite outcrop in nearby Kerlingardalur (Figure 9), which we interpret as a possible caldera infill ignimbrite, mainly based on the proximal nature of the ignimbrite. We suggest that the Tóarhnjúkur ignimbrite sheet originates from somewhere close to the mountain with that name west of Loðmundarfjörður (Figure 9). Regarding the source of the Herfell ignimbrite, Gustafsson et al. [1989] used thickness isopachs to suggest a source west of Miðfell. Our mapping of this area identified a funnel-shaped vent in Norðdalshnjúkur (Figures 10D and 13 E–E′). The vent exposure is about 200 m deep and contains several, inward-dipping rhyolite flows with tuff breccia holding angular fragments of basalt at the base and grading into rhyolitic ignimbrite upwards. On the northeast side of Norðdalshnjúkur, a rhyolitic dyke cuts the underlying basalt and connects to the rhyolite lavas in the caldera. The ignimbrite is the same as the one covering the mountain Herfell (HER), which is welded in western Herfell and unwelded further east, where its thickness decreases from 120 m in Herfell to 60 m in Skælingur. The Herfell ignimbrite has been dated by Berg [2016] to 12.40 ± 0.12 Ma.

In summary, our observations of the distribution of rhyolitic ignimbrites and collapse calderas shows various styles of collapse caldera structures [cf. Cole et al. 2005], such as a downsag caldera (Njarðvík, older caldera), a caldera bound by ring dykes (Njarðvík, younger caldera), a piston caldera (Dyrfjöll), and a trapdoor caldera (Breiðuvík). These calderas range in size from ca. 4.5 km (Dyrfjöll) to ca. 7.5 km (Breiðuvík) in diameter and were up to ca. 450 m deep (Breiðuvík).

5 Paleomagnetism

The paleomagnetic properties of lava flows within stratigraphic sections west of BEL were assessed with a fluxgate magnetometer (Figure 13, and profiles in Supplementary Material Figure 1). The composite section shows thirteen reversals, and the cumulative thickness of the pile amounts to 1700 m (Figure 13). The lowermost sequence comprises three Chrons, two normal polarity Chrons that make the bulk of the lower stratigraphy, the reverse Chron in between only recorded in 2–3 flows. As the silicic intrusions in Njarðvík are dated 13.48 ± 0.14 Ma [Berg 2016], we infer that the host rock sequence corresponds to Chron C5ACn, and the normal Chron above C5ABn correlates with the dacitic dome dated 13.4 Ma west of the BEL area [Martin et al. 2011]. The sequence above includes numerous reversals, and interestingly, the SETP captures four of these reversals despite showing morphological and petrographic homogeneity and little evidence of any hiatus in between flows. The reversals indicate a dynamic and complex build-up of the group where different localities record different stages of the eruptive period and hence different magnetic polarities. The icelandites above the porphyritic flows and an ignimbrite in Húsavík have dates of 13.10 ± 0.20 Ma [Martin et al. 2011] and 13.16 ± 0.21 Ma [Berg 2016], respectively, and correlate with Chron C5AAn. The sequence above the icelandites with the Breiðuvík (BRE) and Kækjuskörð rhyolites (KÆK) and the Orustukambur ignimbrites (ORUS I and II) up to the Jónsfjall olivine basalts (JOB) includes five reversals, and most of the flows exposed record reverse polarity. The sequence including the Jónsfjall olivine basalts and the upper ignimbrites is entirely normal polarity, and the age of the ignimbrites (all about 12.4 Ma) [Berg 2016] correlates with the subsequent Chron C5An.2n. The Dyrfjöll sequence above the hyaloclastites is reverse, turning normal at the very top of the mountain. The regional Hólmar olivine basalt group which is mostly reverse polarity overlies the ignimbrites in the Seyðisfjörður area, yet a hiatus is needed spanning four reversals in order to correlate the reverse sequence above the hyaloclastites of Dyrfjöll with the Hólmar group. No evident hiatus can be seen in the sequence in Dyrfjöll, apart from a few redbeds that include plant remains. Thus, it remains unclear to what Chron the upper Dyrfjöll sequence correlates (Figure 13), a question that can only be resolved by improved dating.

6 Discussion and conclusions

6.1 Summary of the observations and general volcanostratigraphy

The Borgarfjörður eystri and Loðmundarfjörður area north of Seyðisfjörður and on the eastern flank of Héraðsflói formed during Neogene silicic volcanism and is characterised by a wealth of volcanic and subvolcanic structures and extraordinary natural beauty. Here, we summarise the general observations of previous workers and our own observations to come to some conclusions on the geological history of the area.

Generally, the rocks in the BEL area belong to a phase of silicic, central-type volcanism that is bracketed by regional flood basalts, both at the base and the top. The lowest silicic volcanic rocks that occur around Brúnavík and Húsavík testify to the existence of still older, now-eroded volcanoes. Their deposits are overlain by flat-lying basaltic lavas, intercalated with a few marker horizons, such as at least two extensive icelandite lava fields, in the lower part of the stratigraphic sequence. The Jónsfjall olivine basalts, the Setberg porphyritic basalts and the icelandites had centres of accumulation south of mid-Borgarfjörður, near Hvannstóðsdalur (cf. Figure 2; see Figure 3 for locations). Away from these centres, the topography was flat at the onset of central-type volcanism.

Mapping of the regional olivine basalt groups and intrusive and extrusive rocks of the central volcanoes, and dating the rocks in the study area, show that the volcanic centres described above represent the progressive, seemingly simultaneous, evolution of volcanic activity in the entire BEL area. The formation of central volcanoes started with tholeiitic lava fields. These were partly covered by olivine flood basalts of Jónsfjall Group, that accumulated in the Loðmundarfjörður area. At the same time, voluminous rhyolitic magmatism occurred in the entire area, comprising sub-volcanic intrusions at depth, and rhyolitic lava flows and lava dome eruptions at the surface, e.g. in Njarðvík and Kækjuskörð. Several near-contemporaneous caldera-forming ignimbrite eruptions occurred in Njarðvík, Dyrfjöll, Breiðuvík, and probably other locations and marked the violent culmination of silicic volcanism [cf. Berg 2016]. Lake sediments in the Breiðuvík caldera document erosion of the Hvítserkur ignimbrite deposited outside the caldera, but also catches distal deposits of another silicic ignimbrite. Olivine basalt volcanism then became dominant, intruding the caldera-infill ignimbrites and lake sediments, erupting within, and filling, the caldera lakes at Dyrfjöll and Breiðuvík. Towards the end of the volcanic sequence in BEL, voluminous olivine basalts from large regional fissure eruptions extending far south of the study area continued to bury the sequence, the remains of which are found on the mountain peaks of Loðmundarfjörður.

6.2 Central volcanoes or a volcanic cluster?

Previously, the volcanic structures in the BEL area have been sub-divided into several central volcanoes [Gustafsson et al. 1989]. This subdivision was based on the spatial distribution of caldera structures, vents, and silicic rocks, as well as topographic features, such as fjords. Moreover, Gustafsson et al. [1989] applied the concept of volcanic systems with a discrete central volcano as the site of silicic magma eruption, as observed in the present-day rift zone. However, Burchardt et al. [2011] proposed that the volcanic centres were in fact overlapping in space and time, based on the arrangement of intrusive sheet swarms in Njarðvík and Borgarfjörður eystri. Indeed, subsequent radiogenic dating of silicic rocks across the entire study area by Berg [2016] demonstrated that extrusive units and collapse calderas formed roughly contemporaneously. Our compiled maps, including the volcano-stratigraphy summarised above (Section 6.1), confirm this picture of wide-spread silicic volcanism with multiple and dispersed eruption sites forming a large volcanic cluster.

In fact, the varied flow directions of the rhyolite lavas indicate that there was no central summit. Instead, the relief of individual rhyolite flows formed temporary elevation highs that were often subsequently straightened out and covered by basaltic and intermediate lava flows. Collapse calderas formed both within areas with a high density of rhyolitic vents, such as Njarðvík and Breiðuvík, and at the edges of the rhyolitic areas, such as in Dyrfjöll, Herfell, and Tóarhnjúkur. The calderas exhibit a variety of collapse styles, ranging from downsag in Njarðvík to trapdoor in Breiðuvík to ring faulting in Dyrfjöll (Figure 13). The near-contemporaneous formation of four voluminous ignimbrites of similar composition in the area, the largest of them without clear associated caldera depression, may indicate that there was a common source.

6.3 Implications for the geodynamic setting of the BEL area

To sum up, BEL magmatism is characterised by the following features:

- The occurrence of low-temperature zeolite belts at low elevations indicate that the BEL area escaped deep burial and alteration in contrast to the fossil volcanic centres in the south.
- The multidirectional dip of the lava pile in the BEL area deviates from the regional westward dip and forms a much larger dip anomaly than other eroded central volcanoes further to the south in Eastern Iceland.
- The volume and spatial extent of the icelandite lavas is remarkable for Icelandic volcanic centres.
- The overall volume of silicic rocks, as well as the volume of individual silicic units, is high for Icelandic centres.
- The distribution of regional dykes does not indicate the existence of distinguishable, elongated dyke swarms.
- The distribution of silicic volcanism in numerous eruptive centres, and several calderas with contemporaneous explosive activity, is unlike other exposed volcanic systems that usually have one central volcano.

These peculiarities call for answers about the geodynamic setting of the BEL area during the Neogene that might explain the difference compared to other exposed volcanic systems further south. However, the detailed arrangements of Icelandic rift/volcanic zones in the geological past are still unclear, although a number of models exist that attempt to explain the distribution of extinct volcanoes and the high crustal thickness (cf. Figure 1A, B) [e.g. Walker 1974; 1975; Pálmason 1980; Helgason 1984; Smallwood et al. 1998; Blischke 2020]. The composition of the rocks in the BEL area and within the volcanic zones to the south is tholeiitic to mildly alkaline [Gustafsson 1992; Óskarsson and Riishuus 2013; Berg 2016], and along with evidence for low burial and alteration may indicate that volcanism occurred in a flank setting or propagating rift zone, similar to the Snæfell-Öræfajökull zone or southern part of the recent Eastern Volcanic Zone [Jakobsson 1972; Óskarsson et al. 1982]. Generally, flank zone volcanism is assumed to lack signs of extension expressed as tectonic thinning through graben formation or magmatic extension in the form of eruptive fissure swarms at the surface and regional dyke swarms at depth [cf. Maccaferri et al. 2014], which is largely the case for this area. Alternatively, Martin et al. [2011] proposed that the area formed at the juncture of a Neogene oceanic transform fault (equivalent to the recent Tjörnes Fracture Zone) and the Neogene rift zone. Unfortunately, our current knowledge based on our mapping and observations so far cannot fully resolve the uncertainty regarding these scenarios as yet. However, we note the absence of any structures indicating faulting in a transform zone. Regarding the off-rift or propagating rift setting, we note the occurrence of normal faulting and regional dykes indicating NNE-SSW extension but the exquisite preservation and low alteration of the centres indicating little burial which would suggest distance from the main rift and/or the centre of the mantle anomaly.

6.4 Open questions and suggestions for future research

We conclude our report on the geology of the BEL area with a number of suggestions for future research that are based on our current state of knowledge.

On the scale of Eastern Iceland as a whole, we highlight the need for a reconstruction of the geodynamic setting following the North Atlantic rift zone relocation from the Ægir Ridge to the Kolbeinsey Ridge after about 30 Ma. Systematic age dating of the extinct volcanic systems in Eastern Iceland and the Westfjords could provide the currently missing puzzle piece to reconstruct the arrangements of rift zones in the past.

On the scale of the entire study area, we highlight the need for more detailed mapping and additional radiogenic dating and petrological work to unravel open questions, such as:

1. the nature, structure, and origin of the older silicic rocks (e.g. in Brúnavík) underlying the volcanic sequence we describe here;

2. age determination and paleomagnetic assessment of the eastern part of Borgarfjörður eystri which includes the oldest silicic volcanic rocks within the BEL area;

3. improvement of the stratigraphic connection of the study area with the areas to the south (Seyðisfjördur) and west (Héraðsflói and Vopnafjörður);

4. the relationship between silicic and mafic magmatism, in particular the relationship between central-type silicic and local and regional olivine basalt magmatism;

5. the origin and context of unstudied rhyolitic ignimbrites, as well as a more detailed investigation of all ignimbrites in order to assess the relationship between contemporaneous ignimbrites to shed light on a potential common source;

6. the detailed structure of the regional dyke swarms, including the distribution and density of dykes;

7. petrological studies of the peculiar porphyritic groups in the area (e.g. Setberg Group, pyroxene-rich flows southwest of Norðdalshnjúkur);

8. although not the focus of this study, the BEL area displays many thick quaternary surficial debris sheets that are referred as landslides or rock glaciers but that have not been properly mapped and classified.

Moreover, on a smaller scale, we encourage further investigations of individual features such as (1) the stratigraphy of individual ignimbrites; (2) vent structures; (3) the structure of individual intrusions; (4) the structure of the different collapse calderas; (5) the nature, structure, and origin of the regionally extensive icelandite lavas.

Despite more than 40 years of geological investigations into the Borgarfjörður eystri/Loðmundarfjörður area between Héraðsflói in the northwest and Seyðisfjördur in the south, we realise that we are just at the beginning of unravelling the geology of this northeastern part of Eastern Iceland, which certainly has the potential for new and exciting research. We would therefore like to invite the scientific community to use this publication as a stepping stone for their own research in the area.

Author contributions

SB initiated the effort to write up a summary of the known geology of the BEL area. The bulk of the content was created during LEG's PhD mapping of the area and his supervision of B. Lapp, M. Lapp, and L. Thomas during the 1980s and 1990s, as well as various field campaigns by SB for her own PhD, supervision of SEB, and other campaigns, and several mapping campaigns by BVO for the Icelandic Institute of Natural History. MSR supervised SEB and BVO during their PhD. SEB did fieldwork, sampling, and analysis. SB, BVO, and LEG wrote the manuscript, and SB and BVO created the figures. All authors commented on the manuscript.

Acknowledgements

This study is the summary of more than 40 years of field work in the BEL area, partly related to the authors' PhD theses, partly to systematic mapping by the Icelandic Institute of Natural History, and partly as a homage to the beauty of this area. Geological investigations in the area were furthermore supported by funding from the Royal Swedish Academy of Sciences, the Swedish Research Council, and the Knut and Alice Wallenberg Foundation to SB, a PhD stipend from Nordvulk, a Liljewalch stipend and research funding from Uppsala University to SEB.

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Data availability

The ArcGIS shape files of the geological map in Figure 3 are available at https://zenodo.org/record/6337621#.YidTCpYo-Uk and are published under a creative commons license with doi 10.5281/zenodo.6337621. Paleomagnetic profiles are available as Supplementary Material alongside the online version of this article.

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