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A half-century of geologic and geothermic investigations in Iceland: The legacy of Kristján Sæmundsson

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ABSTRACT

One of the World's premier field geologists, Kristján Sæmundsson led immense geological mapping programs and authored or co-authored nearly all geological maps of Iceland during the past half century, including the first modern bedrock and tectonic maps of the whole country. These monumental achievements collectively yield the most inclusive view of an extensional plate boundary anywhere on Earth. When Kristján began his work in 1961, the relation of Iceland to sea-floor spreading was not clear, and plate tectonics had not yet been invented. Kristján resolved key obstacles by demonstrating that the active rifting zones in Iceland had shifted over time and were linked by complex transforms to the mid-ocean spreading ridge, thus making the concept of sea-floor spreading in Iceland acceptable to those previously skeptical. Further, his insights and vast geological and tectonic knowledge on both high- and low-temperature geothermal areas in Iceland yielded a major increase in knowledge of geothermal systems, and probably no one has contributed more than he to Icelandic energy development. Kristján's legacy is comprised by his numerous superb maps on a variety of scales, the high quality papers he produced, the impactful ideas generated that were internationally diffused, and the generations of colleagues and younger people he inspired, mentored, or otherwise positively influenced with his knowledge and generous attitude.

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1. Introduction

Gáð var af tindi	From the mountain peaks
glöggu auga	His eagle eye
yfir foldu	Scanned his country's
sem opna bók;	Open pages.
Ýmist jökla	-- Either glacial
eða elda fingrum	Or fiery fingers
letruð var í berg	Inscribed on rocks
landsins saga.	A wondrous story.

[by Þorsteinn Gislason; translator, Jacobina Johnson.]

This special issue aims at contributions about observations and modeling of mid-oceanic ridges, with a strong focus on Iceland. Topics include understanding the structure and magmatic processes at active tectonic plate boundaries, and the exploration and exploitation of hydrothermal systems along the ridge. With respect to these foci the name of Kristján Sæmundsson, jarðfræðingur, stands out as especially noteworthy, and a tribute to him in this journal issue is certainly fitting. Through detailed and accurate geologic field studies and mapping, coupled with innovative interpretive deliberation, Kristján revolutionized in Iceland the understanding of sea-floor spreading, tectonics, volcano history, and volcanic and geothermal processes. His deconvolution of the complex geologic processes shaping the largest subaerial part of the Mid-Oceanic Ridge system in Iceland forms the basis of our present-day understanding of this critical natural laboratory for spreading processes and its continued relevance to global mid-ocean-spreading research.

Kristján worked for over a half-Century with the geoscience division of the Iceland GeoSurvey (ÍSOR) and its predecessor, the National Energy Authority (NEA). He led immense geological mapping programs and studies of geothermal areas. Besides the monumental achievement of mapping the entire country, he and close colleagues produced detailed regional investigations and unexcelled maps and studies of the major central volcano systems such as Hengill, Krafla, and the massive rhyolite system Torfajökull. He extensively advanced both understanding of Iceland's evolution as a whole, as well as the details of individual volcanic systems in Iceland, directly relevant for our general understanding of how volcanoes work.

When the XXVI International Geological Congress was to be held in Paris in 1980 it was decided to arrange excursions in all countries of Western Europe. A review of the geology of each country was produced, and published together as *Geology of the European Countries* (Comité national francais de géologie, 1980). Kristján was the logical choice to serve as Editor for the groundbreaking *Geology of Iceland*, which was first released as a Special Issue of *Jökull* in 1979. In it he wrote several articles including the masterful benchmark paper, *Outline of the Geology of Iceland*, and another with Sigurdur Thorarinsson on *Volcanic activity in historical time*. He then led a major IGC field excursion.

Through these and similar efforts he inspired numerous geoscientists working in Iceland. He contributed to many international field excursions, summer schools and short courses in volcanology and geothermics, and stimulated researchers of all age around him. As his long-time colleague Páll Einarsson has said (Pers. Comm. to BV, 2016), "*It is hard to imagine where we would be in our work if Kristján had not been there before us*."

In this paper we highlight some of Kristján's achievements, beginning with an account of his development as a field geologist through university experiences and early geothermal-related research, in the context of contemporary Iceland geosciences of that period. In sections that follow we display his contributions to sea-floor spreading and plate tectonics in Iceland, extensive mapping programs, volcanology, magnetostratigraphy and geochronology, mineral alteration, geothermal investigations, and outreach with the United Nations University. We conclude with a consideration of his legacy.

Given the international audience of the journal, the Icelandic letters *ð* and *Þ* are written as *d* and *th* respectively in the text and references cited. Exceptions to this format include the place names on some of the maps, some captions, and the authorship list for the paper which is rendered in traditional Icelandic alphabetical order by Christian name.

2. The making of a field geologist

2.1. Schooldays and university life

The early career and influences of Kristján yield perspectives on his subsequent work and accomplishments. He was born in Hólmavík, a small fishing village in northwest Iceland. Kristján's father, who was a schoolteacher, got tuberculosis (died 1948), and difficulties which followed led Kristján to be sent in the early 1940s to a family in Vogar/Vatnsleysuströnd, a coastal town on the Reykjanes peninsula between Reykjavík and Keflavik. At that time in Iceland a dominant share of the transportation was horse drawn, or by sea – there were so few paved roads. He had only had his first orange as a teenager! But the world of Iceland had been changing rapidly. At the beginning of World War II with the German invasion of Denmark in April 1940, Iceland was a sovereign kingdom in personal union with Denmark, with King Christian X as head of state. Iceland officially remained neutral, but the German diplomatic presence in Iceland and the island's strategic importance alarmed the British faced with the Axis U-boat threat, and they invaded Iceland in May 1940. In July 1941, the defense of Iceland was transferred from Britain to the United States, at that time still a neutral country. Engineering projects initiated by the occupying forces – especially the building of Reykjavík Airport – brought employment to many Icelanders, and the Icelanders gained revenue also by exporting fish to the United Kingdom. On 17 June 1944, Iceland dissolved its union with Denmark and declared itself a republic. Even so it is hard to grasp the transformation of Iceland from an agrarian, third-world outpost to its current position as a world leader in science, technology, art and culture – so much of it born of the primal volcanic activity that envelopes everything there.

It was intended for Kristján to be there for a couple of weeks, but he stayed with this family more or less until he went to the boarding school *Menntaskólinn á Laugarvatni* for four years, similar to high school (Fig. 1a). In the holidays of this period he stayed at Laugarvatn and had a job as carpentry worker. He graduated from *Menntaskóli* in 1956 and in the same year began to study in the Medical Faculty at *Háskóli Íslands* (University of Iceland). The University yearbooks show him enrolled there through 1958, but Kristján had "*found out very soon that the medical studies were not for me*. *The smell in the hospital was enough*…" So after only a couple of months he left his studies at the university, pondered his options and sat down in the library to read and study all the books he could find about geology, including this: "*actually*, *there was one English book about continental drift*". *Just like that!!!* "*There was nobody who influenced me*, *no teacher*, *nobody at all; I was curious myself*…".[1]

But academic education in the earth sciences was a late starter in Iceland, and there was not yet such an option at Háskóli Íslands, the university.[2] Kristján considered his alternatives and decided to go to Germany and study geology. At this time many Icelandic students did study in post-war Germany, for the school-fees were not high and good students could get financial support to help to cover the student's living expenses. Kristján gained entry to the elite University of Freiburg in 1958 and got a stipend from DAAD (Deutscher Akademischer Austauschdienst).

[1] And yet, Amy Clifton recalls this*: "Kristján had told me about the time in his youth spend in Vogar*, *on the Reykjanes peninsula. The Vogar graben was a major part of my field research and I discussed it with Kristján at length. I remember that he told me that this very large tectonic feature was his boyhood playground. He said he spent many days wandering around the faults and fissures there. I can imagine that it sparked his imagination and curiosity about tectonics and geology. He didn't say this directly*, *but I suspect it made a lasting impression on him."*

[2] A three-year B.Sc. program in geology was formally initiated at the University of Iceland only in 1970, accepting students who were already on their way to B.A. degrees. In early stages of this program, and also later, Kristján was in charge of two-week field courses at locations in southwest Iceland, instructing in geological mapping techniques. For a while he also took part in giving a first-semester lecture course on General Geology, with Prof. Thorarinsson. Kristján has also supervised some B.Sc. thesis projects by these students, such as that of Haukur Jóhannesson in 1972, and provided advice on graduate research projects.

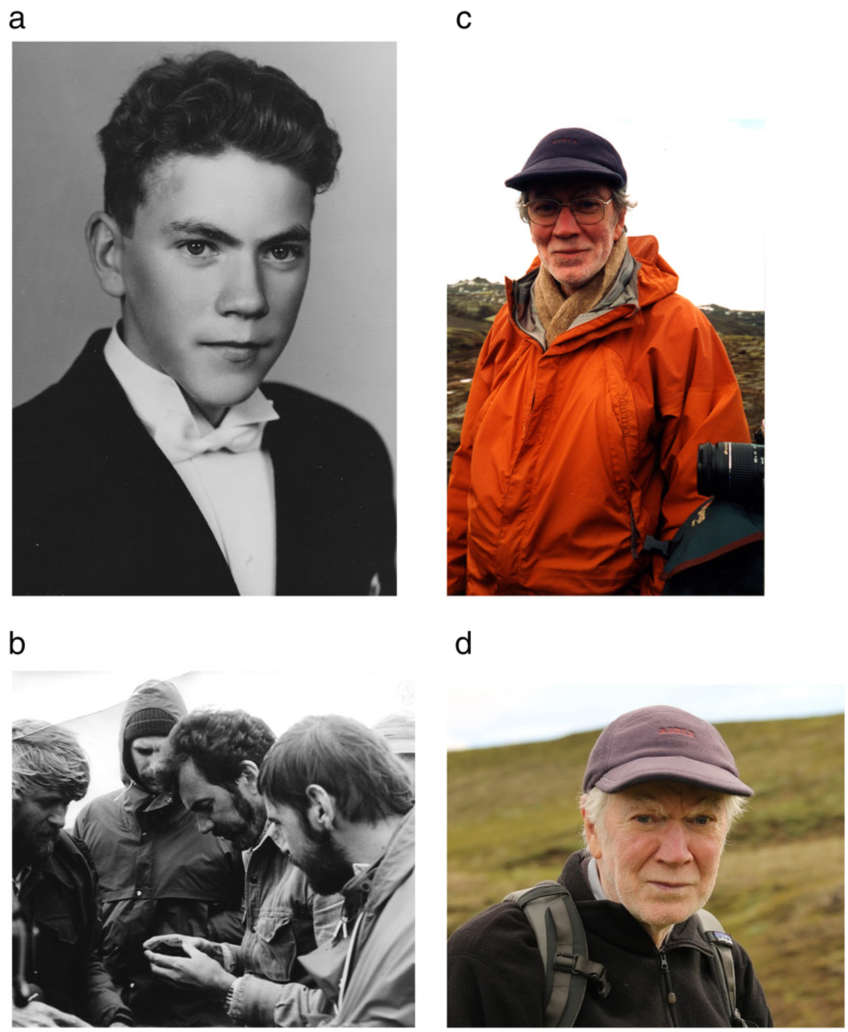


Fig. 1. Kristján through the decades. (a) 1950. A clear-eyed young man in impressive attire, taken at his confirmation, when he was about 14 years old. At that time most Icelanders were in the national church and confirmation was a big event, when one became an adult! (b) 1980, July. Kristján (in center) often joined B. Voight and the late Mark Jancin (two on left) in the Flateyjarskagi Peninsula (the peninsula name derives from their papers in 1985), for stratigraphic and tectonic work in their field area that often opened up only in late June. The 1980 IGC field workshop in north Iceland interrupted this work for a few days, and the photo was taken then. (c) 2001. Guiding a tour to Hrafntinnusker (Torfajökull area) for teams from Orkustofnun, and Landsvirkjun (National Power Company of Iceland). (d) 2015. At Laxárdalur, a farm in Gnúpverjahreppur in South-Iceland. Kristján was making a study for Landsvirkjun. (Photo credits, a,b,d: Sigga P; c: Inga K).

Freiburg had been founded in the 15th century and had a long tradition in the natural sciences. It was surely a good place to learn geologic facts and methods: *"There were lectures which separated me from nature, and field trips which led me to it,"* the sentiments expressed by the famed geologist and Freiburg graduate Hans Cloos in *Gespräch mit der Erde* shortly before Kristján arrived, and probably appreciated by him. Cloos (1947; cf. 1953) wrote about the crucial discovery at Freiburg of the boundary fault that defined the nature of the great Rhine rift valley. And not far away was the Kaiserstuhl, a deeply eroded alkali-carbonatite volcanic complex peering though a thick mantle of loess in which the mountain had been swathed during the Glacial Period.[3] Once Kristján was asked, "*Why Freiburg*?", and his answer was a short one: "*The geology of the surroundings – Kaiserstuhl, and the fold-mountains (fellingafjöllin)*." The Geologic Institute there had been founded by Gustav Steinmann, who had in the Alps and Apennines defined what later became known as "Steinmann Trinity" the occurrence of serpentine, pillow lava, and chert, the recognition of which served years later to build up the theory around sea-floor spreading and plate tectonics.[4]

Kristján received a *Vordiplom* (roughly equivalent to today's Bachelor's Degree) in Geology from Freiburg in 1960, and then moved northward down the Rhine valley to Köln, for students in Germany at that time could move easily between universities. Why there? Kristján recalled that one of the first books he read in German about the geology of Iceland was Martin Schwarzbach's (1956) little book, *Geologenfahrten in Ísland*, (Fig. 2a), and there was some magnetism to it that attracted him. In those days, as a leader of the Geological Institute of the Köln

[3] Jörg Keller, volcanologist and Professor at Freiburg who later studied alkali volcanism in the African Rift, was a fellow undergraduate with KS at Freiburg. Keller: *"You ask about the appearance of early plate tectonic concepts, ocean floor spreading etc during my first geology years (*i.e. *1958 to 1961) at Freiburg. Yes, Alfred Wegener's Kontinentalverschiebung, aside of other models such as Ampferer, Krauss and in particular Pascual Jordan's Expanding Earth were reported, and the presence of a mid-Atlantic 'Mountain Ridge' vaguely appeared at the horizon…..*" At the same time in the USA, continental drift and at some point expanding earth were mentioned, but were usually given short thrift and were basically cast aside as fantasy. Arthur Holmes in the UK, in 1930 and in widely applauded textbook editions (1944, 1965), had a better world-view plus a mantle-convection hypothesis that gave a plausible explanation for a continental drift mechanism, and was way ahead of them. Probably his work, plus awareness of the advances in geomagnetic research in UK in the 1950s, account for the better early reception drift ideas had received in the UK.

[4] During WW2 Freiburg had hardly any enterprises of military importance, but on 27 November 1944 the railway hub and adjacent built-up areas were subjected to incendiary and explosive carpet-bombing by 292 RAF Lancasters. The old town and suburbs were almost completely destroyed, including Steinmann's Geological Institute. Hans Cloos (1953, p. 315) reported, *"The Institute, which was erected to teach us how to decipher and interpret documents…was burst asunder and consumed in flame after an existence of only a few decades. With it were destroyed its paper records and its samples from the Earth's history book…All that is left is being trundled away in a wheelbarrow."* The town and university had been reconstructed after the war, when Kristján arrived.

University, Schwarzbach became a mentor for many German students who did studies in Iceland (Fig. 2b). Among them were Walter Friedrich and Horst Noll, who became Kristján's close friends (Fig. 2c).[5] Friedrich later became well known for his work at Santorini, and Noll researched maar volcanism and also co-authored some studies of Icelandic geology with Kristján. Horst recalls (Pers. Comm. to BV),

> *"Our institute was in a fortification in a semicircle of forts built about 1826 by the Prussian military at the western margin of Köln, in order to defend the town in case of a new French invasion….The working conditions inside this Prussian fort were bad…bombing attacks during World War II by the British air force had severely damaged the brick-edifice, and the upper floor could not be used. It had been considered urgent to plan and build a modern building with five floors for geology, geography, geophysical studies and meteorology, and these were the facilities that Kristján could use in his main years in Köln."*

2.2. The status of Icelandic geology when Kristján worked at Köln

The state of geology for Icelanders is revealed clearly in the booklet produced in 1960 for the International Geological Congress. It was edited by Sigurdur Thorarinsson, Iceland's leading geoscientist and the founder of the discipline of tephrochronology, with expertise particularly in glaciology and volcanology (Thorarinsson, 1960). In one chapter, palagonite (hyaloclastite) rocks (*móberg*; literally "brown rock") are treated by G. Kjartansson of the Museum of Natural History, Reykjavik, and in other chapters Thorarinsson discusses postglacial volcanism, tephra layers, and tephrochronology. The exploitation of natural heat resources is reviewed by Gunnar Bödvarsson from the State Electric Authority, and we find that a natural steam power plant is being planned, at that time expected for construction in 1963. No doubt Kristján pays attention to this news.

In his chapter on the plateau basalts, Trausti Einarsson (Faculty of Engineering at the University of Iceland), considers the basalts to be remnants of a thick plateau, with the lowest visible parts thought to be Eocene in age. Einarsson's geologic history is elaborated as a complicated one involving three separate periods of tectonic activity interspersed with complex erosion surfaces. Furthermore,

> "*The easternmost zone and the depression in Northern Iceland are connected to one zone as far as the young volcanic products are concerned. This has led to the assumption that also the depressions are connected, forming a subsidized* [probably intended: subsided] *rift zone cutting Iceland into two parts. The plateau basalts were said to fall on both sides towards this zone and indeed prove the existence of a great subsidence. Both points are wrong. The main tilting of the basalts is much older than the depressions, as we have stated, and towards the median zone the tilting decreases much. In the center of this zone the Tertiary plateau basalts are probably everywhere present at a shallow depth under the younger rocks.*"

Contemporary studies are exemplified by van Bemmelen and Rutten's (1955) broad reconnaissance study in 1950, and a progression of important work by G.P.L. Walker. Starting with van Bemmelen and Rutten, the Central Graben - which was the term they applied to the main rift zones in Iceland - was split by the Hreppar Horst into two adjacent parts. van Bemmelen and Rutten (1955, p. 160 and Fig. 37) claimed:

> "*Iceland can be considered as a great horst. This horst is situated on the northern end of the Mid-Atlantic Ridge, and the Central Icelandic Depression is the northeastward extension of the axis of the ridge. This indicates that this depression is an axial graben as is common on the top of geanticlinal crustal arches.*"

Furthermore, "*…it is generally assumed that in Tertiary time there was a continuous sialic layer, covered by Plateau Basalts, which extended from Scotland across the Faröer and Iceland to Greenland….The Iceland block was situated on the northern end of the mid-Atlantic Ridge – a belt with a tendency to rise in the youngest part of the Kenozoic…It stood out as a horst between newly formed oceanic basins of some thousands of meters depth. Such a structural high represented a strong accumulation of potential energy. In other words, a tensional stress field had come into being which tended to tear this horst apart.*"

They noted too the measurements by Bernauer (1943, p. 40) across lava fields dissected by cracks (*gjár*), yielding an estimate of postglacial extension of 0.36 cm per year, and thus, the Central Iceland Depression on the crest of the island could be considered as a major, primary result of this crustal tension. They conclude that there were two possibilities to explain the data:

> "*(a) …a phenomenon of great regionality, the hypothesis of continental drift, as advanced by Wegener or (b) …gravity pull as a phenomenon of restricted regionality….*" (see their Fig. 38).[6]

Nielsen (1930), Bernauer (1943), and Holtedahl (1953) were recognized as favoring the first interpretation.

Next we discuss G.P.L. Walker, who first visited Iceland in the summer of 1954 as a recently appointed lecturer at Imperial College (UK), and then devoted the first 12 summers of his career to geologic studies there (Walker, 1959, 1960, 1963, 1964, 1965; Self and Sparks, 2006; Sparks, 2009). He mapped huge areas of the eastern Iceland fjordland to define regional structure, and generated such significant contributions as a working classification of volcanic rocks and lava or tuff marker horizons to aid field mapping, recognizing the significance of dike swarms, and zeolite zonation, identifying central volcanoes and intrusive complexes, and identifying mixing of acid and basic magma that he thought might "tip the scales" so as to permit cold and viscous acid magma to erupt. He

[5] Walter Friedrich recalls this: *"It was about 1960 when Kristján Sæmundsson came from Freiburg to the group of doctoral students at the Köln Geological Institute. At that time, Professor Martin Schwarzbach was the leading scientist in Icelandic geology. He had written the book 'Climates of the Past', which attracted many scholars; Thorleifur Einarsson, later to become geology professor in Reykjavik, had just finished his studies in Köln, and Ulrich Jux [who] later became Professor of Paleontology in Köln, wrote his habilitation thesis on Iceland.*

Kristján joined the group of the Icelandic doctoral students, to which also Friedrich Strauch, who later became Professor in Münster, belonged. Fried, as he was called, wrote about Tjörnes in North Iceland; and there was Peter Everts, who studied an area (Skagi) in Northern Iceland. I was fortunate to receive one of the most interesting regions of Iceland for my dissertation: The fossil plants of the Northwest Peninsula. When the new institute building on Zülpicher Straße was finished, I shared a doctor's room with Kristján, to which I soon had a friendly, almost brotherly relationship. When, for some reason, he had lost his student room in Köln Sülz, he moved to my parents' home in Köln's old town.

Kristján spoke excellent German and many other languages. He was high-minded, and very modest. In addition, he had an ability that I envied him very much: Kristján could foresee exam questions! But perhaps it was only his knowledge of the human being that helped him. Kristján's mapping area in Iceland was near the Thingvellir Gorge, not far from Horst Noll's work area. The latter was to compare the Icelandic explosion craters (Maare) with those of Germany.

On a field trip with Kristján and Horst, I got to know their work in South Iceland. Kristján and I helped Horst in the surveying and measuring the depth of the craters. As we approached the Hvitá I had noticed that there were trout in the river, and from my scouting time I knew that you could catch trout without any tools with your hands if you could see their hiding place. This was difficult here, but we had a fishing hook, a plastic bag and a piece of string. I could blow up the bag and made a balloon which could hold the hook on the surface – only a plastic bag and a piece of cord and a hook. With that I tried my luck and caught a great trout.

As we approached our tents [Fig. 2c], *I had the impression that Kristján stumbled over a stone, but then I saw that he picked up a stone and threw it immediately after an object. He had killed a Rjúpa, a field fowl." That was exactly the situation I had experienced in the dream," he said triumphant. Horst and I were deeply impressed by his ability to see future events for dinner, for there was trout, ptarmigan, and a smoked lamb, which Kristján's mother had packed with him."*

But a detail of his dream had been silenced by Kristján: on the way back to Reykjavik, he told us that he had also dreamed of a mountain of meat, and right when we passed a farm he fell back on the picture. Here, the farmer's wife with 27 lamb chops was waiting for us. She was very surprised when we were only three with her, because in the phone conversation with Kristján she had the impression that we would come with a large group of students.

Also, when we had both walked into our profession, I visited my old mapping area at Brjánslækur on the Northwest Peninsula. One day with my family on the way to Surtarbrandsgil gorge, I noticed that one person with fast steps had the same goal – this could only be Kristján! And in fact it was Kristján, who had learned from the peasants that I was in the area, and his almost supernatural ability to predict events had helped him find us.

[6] M. G. Rutten later changed his mind by the late 1960s, and then no longer considered the northern Iceland graben as possibly indicative of widespread crustal spreading. He now thought of it a shallow structure (Rutten, 1971) comparable to the Upper Rhine Graben, and produced by uplift, that is, stretching over a region of slight doming.

Fig. 2. Graduate studies and fieldwork while at Köln. (a) Kristján's copy of *Geologenfahrten in Island*, signed by him in 1957 when he was a student in Freiburg. One of the first books in German that Kristján had read on the geology of Iceland, it influenced Kristján to join Martin Schwarzbach's graduate student group in Köln. (b) An archaic photo from the early 1960s by fellow grad student Peter Everts using the large-scale camera of his father, during a feast in the Geological Institute of the Universität Köln. The institute was located in a massive vaulted fortification built by the Prussian military to defend the town from the French. Professor Schwarzbach, initiator of the Iceland research activities at Köln, has tapped a barrel of beer and is happy about the fact that he succeeded, not at all being a man of skilled practice at this. The filled glass in his hand appears to be excessively vesiculated. Kristján is the happy dark-haired young man with tie, to the right of the Professor, sitting at the end of the radiator. (c) Horst Noll and Kristján near Landmannalaugar in July 1963, where Kristján was mapping. Horst was studying Icelandic explosion craters (Maare) with phreatic phases to compare with those of Germany. Kristján and Walter Friedrich (who took the photo) helped Horst in surveying and measuring the depth of the craters in the river Tungnaá flood plain, with depth control in the craterlake Ljótipollur (the ugly pool). Here Horst and Kristján return from a survey, and Horst holds an arctic char intended for dinner. Friedrich expands on the story.[4] (d) Kristján's campsite in a gorge west of the Reykjanes-Langjökull rift zone near Húsafell, August 1966. From right to left: Professor Schwarzbach, Kristján, Dr. Ludwig Ahorner and Horst Noll. This work led to the Sæmundsson and Noll (1974) paper that presented the first dates obtained on a well-mapped continuous and geomagnetically-correlated section in western Iceland.

demonstrated that the geological history of Iceland was a continuous and indeed almost a steady-state process, rather than consisting of a few major episodes of different volcanic or tectonic upheavals as previously envisaged (Kristjánsson, 2005). Walker had "*combined systematic mapping, meticulous data collection, brilliant observations, boundless energy and hard work to spectacular effect*" (Sparks, 2009).

A major contribution was his argument that Iceland had been formed by processes of crustal spreading (Bödvarsson and Walker, 1964), in an article submitted in August 1963 before the Vine and Matthews (1963) paper had appeared in *Nature*. This idea had been raised before, as we had noted above (Nielsen, 1930; Bernauer, 1943; etc.), but Walker strengthened the argument with his data on dikes from the eastern fjordland. Most Icelandic geoscientists were skeptical then of the spreading concept, and many remained so. After the mid-1960s, inspired by work by Thorarinsson at Hekla and by the on-going Surtsey eruption, Walker shifted his field studies to places elsewhere over the globe, to study pyroclastic deposits that would lead eventually to a revolution in understanding of explosive volcanism. But he would return from time to time, and his work in Iceland had a profound and enduring impact. Walker was awarded the Icelandic *Order of the Falcon* in 1980, a rare distinction for a foreign scientist.

Kristján did not meet Walker during his university days, but as a student engaged in Icelandic field research he read his key papers, and Walker's work had an important and lasting influence. Martin Schwarzbach, Kristján's professor at Köln, often assigned the exemplary papers written by Walker to his Iceland team of graduate students. At one point he gave Kristján the task in a class to talk about the article which Walker had written with Bödvarsson. That was before the drift-theory or its mechanism was fully accepted, and the professors at Köln there didn't agree, but Kristján himself was convinced. Much later he went on a fieldtrip with Walker in the Landmannalaugar thermal area and Torfajökull central volcano, partly because an Icelandic student studying with Walker had begun work there. Kristján had earlier mapped Landmannalaugar in 1963 and 1964 during his university days (his map was published in Schwarzbach's 1964 edition of *Geologenfahrten in Ísland*, Fig. 48, p. 66), and he expanded the mapping subsequently in work with the NEA, in which he soon recognized and defined the caldera structure (Sæmundsson, 1972). He remembers that Walker was impressed by the rhyolites and ignimbrite he saw there.

Kristján received a Diplom-Geologe in 1964 (roughly equivalent to a Masters Degree). Kristján's doctoral thesis on the Hengill area in west Iceland was supervised by Schwarzbach, and as part of this work he published in 1965 a thorough report and detailed maps for part of this region, around Thingvallavatn (including the famous Almannagjá rift at Thingvellir) (Sæmundsson, 1965). In it he referenced the Bödvarsson and Walker, 1964 paper. He also found time to initiate mapping in the Borgarfjördur region (Sæmundsson, 1964). By 1966 his thesis work was completed (it was published in 1967, in the German language with English summary), and Kristján Sæmundsson became only the fifth Icelander to defend a doctoral dissertation on geological subjects, following Helgi Pjeturss (in 1905), Sigurdur Thorarinsson (in 1944), Gudmundur Sigvaldason (in 1959) and Thorleifur Einarsson (in 1960). (Thorvaldur Thoroddsen and Thorkell Thorkelsson had been awarded honorary doctorates).

2.3. Kristján's early work in geology and geothermal exploration

Already during his student period in Köln, Kristján started to work part-time at *Jarðhitadeild Raforkumálaskrifstofa* (a terrible title), or, the State Electricity Authority, which evolved later into *Orkustofnun* (National Energy Authority, NEA) and then into ÍSOR. For instance in August 1962 he produced two short geologic reports, one with geologist Jón Jónsson on water leakage in Skagafjördur, and another on a section in Ólafsfjördur (Jónsson and Sæmundsson, 1962; Sæmundsson, 1962). Kristján's thesis involved Hengill, which would become a major target for geothermal exploration, but even in 1964 he was able to produce a 28-page company report on a geological study he conducted between August and October 1964 on the SE-dipping lava pile between Borgarfjördur and the Reykjanes-Langjökull rift zone (Sæmundsson, 1964). The report included maps and sections, and consideration of paleomagnetic epochs. The study continued in 1966 (Fig. 2d) and afterward, supported by funding from both the energy authority and the German Science Foundation, and culminated in the important Sæmundsson and Noll (1974) paper.

In his PhD work Kristján had broken new ground in mapping and in understanding hyaloclastites, subglacial eruptive units of the Hengill volcano, raising the standard for those who followed. The morphology of volcanoes formed by subglacial volcanism in Iceland is comparable to that from submarine volcanism and would prove useful in interpreting features on the ocean floor. Upon his graduation in 1966 he returned to Iceland to take on practical and research work for the State Electricity Authority. At the start his main focus involved geological mapping of geothermal areas with emphasis on structure and volcanic stratigraphy, some of which also required further local regional studies, the siting of numerous boreholes in high- and low-temperature areas, and geological supervision during drilling and completion. In 1966 he conducted geothermal work in low-temperature sites at Ólafsfjördur and Reykholtsdalur (Sæmundsson, 1966a,b). In the following year he studied with Jens Tómasson borehole data at the high-temperature Nesjavellir site, and reported to NEA (Sæmundsson, 1967d) on a geothermal reconnaissance survey of Torfajökull made jointly in 1966 with Jens, Karl Grönvold and others. The study took advantage of Kristján's prior mapping around Landmannalaugar and was illustrated with Kristján's excellent photographs from 1963. In 1968 and 1969 he reported on geothermal work at Akranes, Ísafjord, Reykjadal, Reykholt, Laugaland, and Námafjall (Ragnars et al., 1970), and in late 1968 made a detailed interpretation of the airborne infrared scanning in August 1968 of Torfajökull. His NEA report was put out in January 1969 (Sæmundsson, 1969; cf. Pálmason et al., 1969, 1970). Torfajökull is the huge rhyolite massif in south-central Iceland, and in the western part of this area is located the largest and most intense high-temperature field in the country. Very incomplete information on geology, thermal springs and solfatara fields was available prior to 1966, so during the field seasons 1966–1968 the energy authority had organized data collecting trips there, and Kristján identified and mapped a likely 12 × 16 km caldera that enclosed large outcrops of volcanic tuffs and breccias and most of the hydrothermal features. The existence of the caldera was confirmed in his further studies (Fig. 3).

Systematic geothermal energy research by Icelandic government institutes had already begun in 1945 with the arrival of engineer/physicist Dr. Gunnar Bödvarsson at the State Electricity Authority, and he was the man in charge of the Geothermal Division when Kristján started working part-time with them in 1962. Bödvarsson remained director until 1964, the same year his paper on drift with George Walker was published, when he left to work in the USA. Then Guðmundur Pálmason, engineer/geophysicist, replaced him as head of the Geothermal Division when Kristján began full-time work in 1966. By the following year the Geothermal Division had evolved into Orkustofnun (NEA), and in 2003 it was reconstituted as Iceland GeoSurvey (ÍSOR).

2.4. Kristján and Icelandic geoscientists on drift and sea-floor spreading in 1960s

In 1960, the relation of Iceland to sea-floor spreading was unclear, and plate tectonics had not yet been invented. Arthur Holmes – who around 1930 had invented an idea of drifting by the mechanism of convective currents in the mantle, and had included the idea in his influential 1944 textbook – still thought in 1965 that Iceland was a raft of continental crust trapped over a convective oceanic rise. This view was also being considered by George Walker (1965). But the opinions of Holmes, and the geomagnetic studies of Blackett, Irving, and Runcorn, were major reasons why drift theories received a more favorable climate in Britain than in North America, and why many seminal advances in the 1960s came from scientists in the UK.

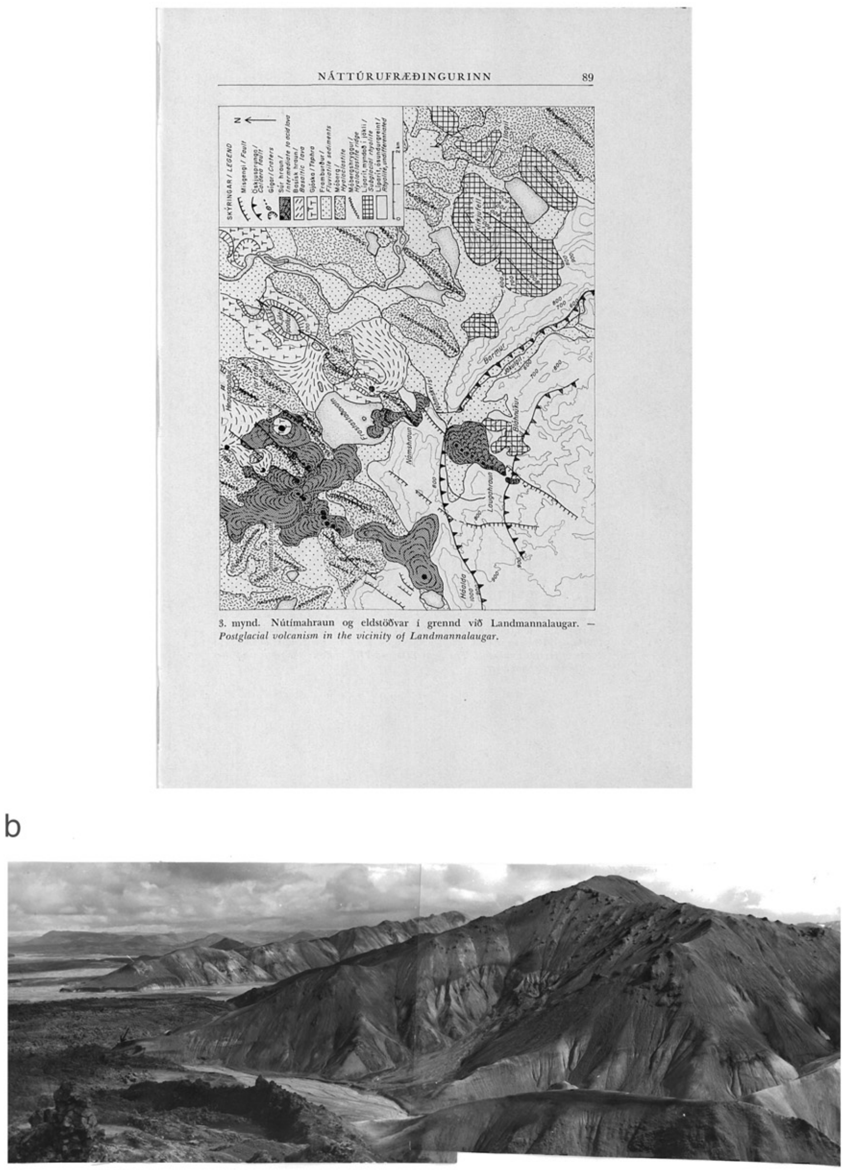
Even as Kristján was grappling with Iceland geology, the framework of mid-ocean geotectonics was evolving rapidly.[7] The Runcorn and Blackett approach of interpreting palaeomagnetic data in terms of *Drift* took on increasing support after 1956, and thereafter Drift was to

[7] While Kristján was gaining a toehold on Iceland geological experiences, ideas about mid-ocean geotectonics continued to advance. Already the palaeomagnetic research of the 1950s had given strong support to a concept of continental drift. But also throughout the 1950s marine scientists from several institutions were gathering reams of measurements on their voyages, although they had little time to digest them. At the Lamont Observatory of Columbia University, Maurice Ewing was mainly concerned about data collecting and seldom theorized, but when he did, supported by his close colleague Walter Bucher, he opposed Drift. He tolerated (sometimes barely) a few others with different views at Lamont such as Heezen (1959, 1960), who interpreted the mid-ocean ridges as extensional features and favored Expansionism, as did Carey (1958), who had come to a similar conclusion from continental data. For a time in the late 1950s-early 1960s it became a rival to Drift (LeGrand, 1988). Heezen changed his opinion in the mid-60s and died in the nuclear submarine *NR-1* collecting data offshore Iceland in 1977. Meanwhile Hess (1962), who had already since the 1930s with Vening-Meinesz explored the Holmes (1930) mantle convection current explanation (cf. Holmes, 1944), produced his view of the earth that soon was labeled seafloor spreading. It was published in 1962 but had been disseminated variously since 1960, prior to the Dietz (1961) publication of a very similar model. The model was similar to Holmes but naturally was more informed about seafloor data largely collected since World War II, and was soon supported by J.T. Wilson's (1963) observation of the increased age of volcanic islands with distance from a mid-ocean ridge. The Vine & Matthews proposal that the ocean floor recorded magnetic field reversals followed in 1963, but due to lack of hard evidence, generated little interest at the 1964 Royal Society meeting and indeed the idea was opposed by the Lamont scientists working in the mid-1960s on the Reykjanes Ridge (Heirtzler et al., 1966).

But Hess and J.T. Wilson admired the idea, and Wilson (1965), who not long before had been an ardent 'fixist' as regarding Drift, developed the concepts of the transform fault connecting offset portions of ridges, and of rigid plates. Then Vine & Wilson (1965; cf. Vine, 1966) examined the magnetic patterns off the Juan de Fuca Ridge, noting that ideally the magnetic patterns should be symmetrical about the ridge, and that for a uniform spreading rate, the ages of the magnetic stripes should match the time-scales based on dating of geomagnetic field reversals in continental rocks. The concept gave added significance to the age-dating and reversal studies being carried out at Berkeley (e.g., Cox et al., 1963, 1964) and Australian National University by Ian McDougall (who would later collaborate with Kristján) (McDougall & Tarling, 1963). Meanwhile, the Lamont group that had been working the Reykjanes Ridge were staunchly in opposition to the Vine-Matthews hypothesis, and to explain magnetic striping they offered self-reversals or differences in magnetic susceptibility. Neil Opdyke at Lamont was an outlier, and as a former Runcorn student was sensitive to data favoring Drift. In late 1965 he identified in Lamont sediment cores from the Pacific an event at 0.9 MYA, about the same time that Walter Pitman noted the similarity of magnetic data acquired by the research ship *Eltanin* in traverses of the East Pacific Rise. The bilateral symmetry of profile Eltanin 19 was "so nearly perfect that the two sides could be folded on top of one another across the ridge axis," (LeGrand, 1988). The profile was unveiled at the AGU meeting in Washington in 1966 and published in Science (Pitman & Heirzler, 1966).

The conversion for marine geoscientists occurred by 1966–68 (Frankel, 2012a,b), but not completed for the larger geoscience community until the early 1970s. The transformation from seafloor spreading to global tectonics was one from two-dimensional representations and debates from maps and charts to three-dimensional arguments based on the globe, and it may be said that McKenzie and Morgan independently discovered, developed, and tested versions of plate tectonics. Both had made essentially the same monumental discovery, a precisely formulated kinematic theory using Euler's Point Theorem that encompasses the kinematics of continental drift and seafloor spreading and its corollaries, the Vine-Matthew-Morley hypothesis and transform faulting (McKenzie & Parker, 1967; Morgan, 1968; McKenzie and Morgan, 1969). Morgan's (1971) mantle plume idea came soon after.

a


NÁTTÚRUFRÆÐINGURINN 89

3. mynd. Nútímahraun og eldstöðvar í grennd við Landmannalaugar. – *Postglacial volcanism in the vicinity of Landmannalaugar.*

b

Mynd 3

Laugahraun, Blá~~kollur~~ hnúkur – Barmur frá næstefsta uppvarpi Laugahrauns. Skilin milli Blákolls-líparíts og neðri líparítseríunnar sjást glöggt. Við hornið, sem örin bendir á, kemur tillít og basaltískt bólstraberg fram undir neðra, ljósa líparítinu.
(Ljósm. K.Sæm. 1963)

Fig. 3. (a) Post-glacial volcanism in the vicinity of Landmannalaugar (after Sæmundsson, 1972). This paper on the geology of the Torfajökull central volcano was published in Icelandic with an English summary. It describes an area 450 km^2 that is the site of copious rhyolite volcanism – unusual for a mid-ocean location. The oldest rocks are rhyolite flows, followed by a caldera collapse and formation of an ignimbrite contained within and near the caldera. The area had already been partly studied by Kristján, and an earlier map by him was published as Fig. 48 in Schwarzbach's (1964) edition of *Geologenfahrten in Island*. The 1972 study differs mainly in Kristján's recognition of a caldera complex, and fault structures, besides a larger areal coverage. (b) The landscape near Landmannalaugar, photographed by Kristján in 1963.

many a fact. Hess produced his model of seafloor spreading in 1960 and published it in 1962 and Dietz (1961) produced a very similar model. Then Vine and Matthews (1963) proposed that the ocean floor recorded magnetic field reversals, but this gained little acceptance until Vine and Wilson (1965) examined the magnetic patterns off the Juan de Fuca Ridge and noted that the ages of the magnetic stripes should match time-scales based on dating of geomagnetic field reversals in continental rocks. This idea gave impetus to age-dating and reversal studies already underway at Berkeley and Australian National University. The acceptance of sea-floor spreading for marine geoscientists occurred by 1966–68, but not completed for the larger geoscience community until the early 1970s (Frankel, 2012a, 2012b).

However in Iceland these ideas met with considerable resistance. In 1966 the Geoscience Society of Iceland was formed, with the purpose of promoting Icelandic research. Its first president was Sigurdur Thorarinsson, and in accordance with its statutes an Icelandic symposium on *Iceland and Mid-Ocean Ridges* was arranged in early 1967. It recognized the recent mid-ocean research being carried out, and that the median zone of Iceland, as an accessible supramarine part of this ridge-rift system, could play an increasing role in research on ridge scientific problems. The Icelanders saw value in synthesizing and debating their current knowledge and views on the geology and geophysics, to recognize the main present gaps in knowledge and to facilitate programs of future research with an eye on mid-ocean ridge issues.

Sveinbjörn Björnsson led the organization of the symposium, which was attended by 26 participants, all Icelanders.

Kristján's main symposium paper considered the structure of SW-Iceland, the young Langjökull-Reykjanes volcanic belt and bordering regions from Borgarfjördur to Thjórsárdalur, an older volcanic belt extending ESE from Skagi, plus five central volcanoes embedded in plateau basalts (Sæmundsson, 1967b). He showed that since the last interglacial the accumulation of volcanic rocks was not uniform over the length of the volcanic belt, the amount of fault downthrow was greatest in oldest rocks, and that faults repeated movements along the same fault planes within the graben structure. He identified the central Icelandic graben (i.e., the western rift) faults as dip-slip normal, with the open fissures indicating lateral tension. He quoted G.P.L. Walker's (1965) estimate of 0.5 cm/year of stretching over the Thingvellir lava plain. He concluded that in the Langjökull-Reykjanes volcanic belt, and probably also the eastern belt,

> "*there is no evidence definitely opposing a long history and a considerable crustal drift. On the contrary the evidence summarized here rather favors it. A value as high as 1 cm/year may be regarded as reasonable in the light of recent data (Vine, 1966). The rate of 2 cm/year of the Reykjanes Ridge postulated in this paper might be reached by both branches of the central graben of Iceland together. Assuming this rate the total horizontal displacement since the beginning of the N2-period* [i.e., Gauss normal epoch in more recent terminology] *would amount to 30 km in the Reykjanes-Langjökull belt alone. This brings the paleomagnetic N2-series on both sides of the Reykjanes-Langjökull belt very close together and a stationary volcanic belt (Bödvarsson and Walker, 1964), of similar width as today, becomes probable*."

Anticline and syncline structures had already been noted by Tr. Einarsson (1962, 1965, 1967a, p. 23) and interpreted by him as reflecting tectonic deformation after the main pile of basalts had been deposited. Kristján recognized the structures as of major importance, but interpreted the synclines as indicators of earlier volcanic zones similar in structure to the current ones. Kristján's paper prompted objections from Tr. Einarsson (1967b, p. 160), who claimed:

> "*the blocks of the plateau basalts are separated by anticlines, synclines, and flexures, while within each block the dip is essentially constant. I cannot doubt this means tectonic disturbance of originally flatlying banks*."

Kristján's response was firm (p. 160–161):

> "*The dip within each block of plateau basalt is not essentially constant. In eastern Iceland it has been shown that the dip of an individual lava series increases from the highest outcrops on the mountain tops down to the valley floors. This is certainly not in agreement with a general disturbance of an originally flatlying block. It is difficult to understand how the lower part of the plateau could then suffer stronger tilt than the upper part. Also the flatlying zeolite zones speak to the same conclusion. If 6 km of rock had been eroded from the Borgarfjördur anticline we would expect to find correspondingly strong alteration there. This however is not the case*."

In addition Kristján actively participated in discussions of other papers. He strongly criticized Einarsson's (1967a) four-phases of geologic history (p. 29–30) and gave evidence why the concept was untenable. And he objected strongly to the arguments posed by Thorleifur Einarsson, a well-trained geologist who had studied under Schwarzbach at Köln prior to Kristján's arrival there. Th. Einarsson reported that it had often been stated that the Tertiary plateau basalts dip towards the central zone, the so-called "central graben", but that this was an incorrect generalization, and the main elements of the structure of Iceland comprise a series of anticlines and synclines (1967a, p. 177):

> *"The neovolcanic zone of Iceland, which has been active since late Quaternary time, seems mainly to be confined to synclinal structures. It is doubtful that there is any "central graben" existing at all in Iceland and the present grabens such as Thingvellir graben are rather small features…The structural pattern of Iceland seems to indicate that Iceland has suffered crustal compression, and that no dilatation or "drift" has taken place".*

Kristján's critique followed (1967c, p. 178):

> *"The circumstance that we observe dilatation in the synclines of the active volcanic belts probably indicates that they are not true synclines (with the inward dipping Tertiary basalts on both sides extending below them), but are the result of the huge accumulation of volcanic rocks within them, accompanied by a proportional amount of subsidence."*

Th. Einarsson's rejoinder on the same page:

> *"I don't think that any dilatation or drift has taken place in Iceland nor that the synclines are the result of sagging by piling up of young volcanics,"* led to Kristján's reply: *"If these synclines were the result of folding we would not expect dilatation in the core as displayed by the open fissures, normal faults, and intensive volcanism, but rather some compressional features, which are completely absent."*

In another paper, Guðmundur Guðmundsson discussed magnetic anomalies, and assumed the correctness of the Vine-Matthews hypothesis for the magnetic anomalies of the axial zones of mid-ocean ridges including the area surveyed on the Reykjanes Ridge. He had been convinced by the recent agreement of age-dated reversals in onshore lavas with the observed marine magnetic profiles (Vine, 1966; Pitman and Heirzler, 1966). Kristján offered some support to the concept, but Th. Einarsson (p.106–7) in a written comment argued for an alternative model, particularly one that assumed that the magnetic patterns reflected

> "*elongated ridges of pillow lavas piled on top of volcanic fissures, just in the same way as the subglacial móberg-ridges in Iceland…. According to this hypothesis it would be impossible to correlate the magnetic anomalies of the Reykjanes Ridge with the geomagnetic time scale, and… the regularity of the magnetic anomalies on the Reykjanes Ridge would then be a coincidence only and not a proof of spreading ocean floor*."

Tr. Einarsson (1967c, p. 135–138) proposed that the magnetic anomalies over the Reykjanes Ridge were caused by shear fractures, and that his interpretation refutes:

> "*the hypothesis (Pitman et al., 1966)* [actually, Pitman and Heirzler, 1966] *that the symmetric array of the anomalies is caused by drift away from the central axis*."

Also then among the anti-drifters, Guðmundur Pálmason (1967, p. 77) concluded that:

> *"The seismic results indicate that the Tertiary flood basalts form a continuous layer all over Iceland. In the volcanic zone they are overlain by younger volcanic rocks, which are usually less than one kilometer in thickness. This is in agreement with the opinion expressed by* [Trausti] *Einarsson (1965), that the neovolcanic zone of Iceland is a relatively young feature…. It is difficult to find in the upper crustal structure of Iceland a support for a hypothesis of crustal drift or sea-floor spreading, which had been going on since the beginning of the Tertiary."*

Pálmason's opinion opposed the interpretation of seismic data by his Geothermal Division predecessor in the Bödvarsson and Walker (1964) paper that favored drift. His views gave comfort to both Th. Einarsson (cf. 1967a, Fig. 2 and p. 174), and Tr. Einarsson (1967b, p. 179). And Sigurdsson (1967a, p. 169), who had mapped in western Iceland, cautiously suggested that the Tertiary tectonic pattern was more suggestive of compression than of E-W tension.

Thus of those expressing clear opinions at the conference, those strongly opposed to drift mechanisms within Iceland include Tr. and Th. Einarsson, and Guðmundur Pálmason. Others like Sigurdsson (1967a, 1967b) and S. Thorarinsson (p. 47) saw some problems with it but were less emphatic.

Those strongly in favor of it were Kristján, perhaps Kristján's colleague Jón Jónsson (1967, p. 145) who had mapped the Reykjanes peninsula and considered it to be "*truly part of the rift zone of the Mid-Atlantic Ridge*" with faults primarily of tensional origin, Guðmundur Gudmundsson (1967) (who had already left the NEA for a position at the General Bank of Iceland!), and Thorbjörn Sigurgeirsson (1967), who at the conference had summarized aeromagnetic surveys over Iceland and the Reykjanes Ridge. Sigurgeirsson, a physicist who had had contacts with P.M.S. Blackett and had participated in a recent geomagnetic polarity study in SW and eastern Iceland led by Roderic L. Wilson (Dagley et al., 1967), thought it difficult to account for the globally observed mid-ocean ridge patterns without using the universal reversals of the geomagnetic field as the basis for the explanation (p. 107–8). He further pointed out that the model of Th. Einarsson, using a few hundred meters of submarine volcanic rock to account for magnetic anomalies, was inadequate because it required magnetization of an order of magnitude greater than found in basalt.

Opposition to drifting mechanisms in Iceland continued after 1967. For example, M.G. Rutten, in a 1971 paper published after his death, changed some more open-minded views he had expressed earlier in his 1955 book with van Bemmelen, and now argued that "*the geology of Iceland does not favor the simple model of sea floor spreading as formulated by Vine and Matthews*." He supported the model proposed by Einarsson (1967b) in which elongate ridges of pillow lavas were thought to have piled up on top of parallel volcanic fissures, ignoring Sigurgeirsson's (1967, p. 107–8) critique of that paper. Further:

> "*…any statement on crustal spreading (Walker, 1964; Bödvarsson and Walker, 1965; Walker, 1965) based on an extrapolation from the eastern part over the whole of Iceland is unwarranted….It has always amazed me why this difference between the eastern part and the rest of Iceland has not been stressed before. Of course, one formerly took the boat from Reykjavik to the eastern fjords, and thus missed the opportunity for a comparison. But I must believe that Dr Walker, who travelled by car, raced across the island to reach his own area so fast that he failed to notice the distinction…*"

Rutten (1971) argued that *"the reason for these erroneous extrapolations lies, or course, in the fact that for central and western Iceland no modern detailed investigations are available, which can in any way compare with Walker's work*." It remained for Kristján to fill this gap, and to resolve the structural enigma by showing that the active rifting zones in Iceland had shifted over time and were linked by complex transforms to the mid-ocean spreading ridge.

3. Plate tectonics, mid-ocean ridges and contemporary impact

In evaluating Kristján's achievements on a broader scale it is important to put Iceland in its proper context. The global mid-ocean ridge system marks the birthplace of the oceanic crust that covers about 65% of the planet. Astride the boundary between the diverging North American and Eurasian plates, Iceland is the largest supra-marine exposure of mid-ocean rift system on Earth (Fig. 4; Sigmundsson and Sæmundsson, 2008). It represents the most accessible analog for oceanic crust and provides a critical window into sea-floor spreading processes. Thus Kristján's contributions to Icelandic geology have global significance. It has taken decades for studies of mid-ocean spreading centers to catch up to the perspective that Kristján and his colleagues developed in Iceland long ago. Kristján's work on fissure eruptions, faulting and hydrothermal systems, the three essential components of mid-ocean ridge processes, remain as templates for investigations on the deep seafloor, and Iceland became a required field experience for all marine geoscientists studying oceanic crust and spreading processes. More recently, Iceland has also been recognized as an excellent analog

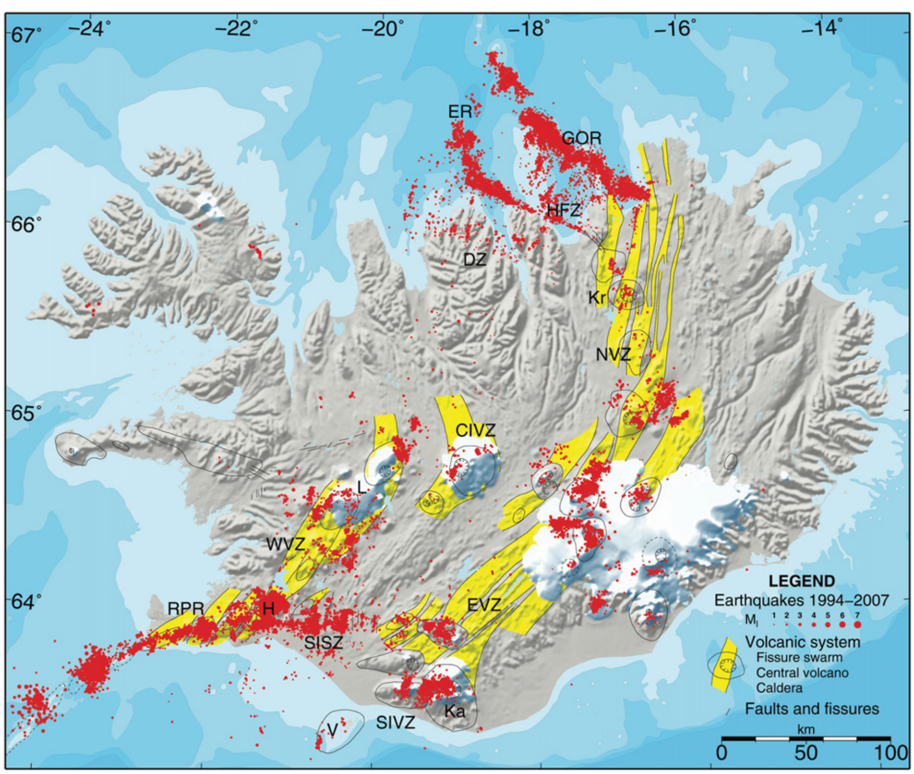


Fig. 4. Overview map of tectonic elements of Iceland showing various locations discussed in text. Volcanic systems with central volcanoes and fissure swarms after Einarsson and Sæmundsson (1987). Earthquake epicenters 1994–2007 and selected faults defining plate boundaries of Iceland are from Einarsson (2008). Transverse faults of RPR from Clifton and Kattenhorn (2007). Epicenters are from the Icelandic Meteorological Office. Individual plate boundary segments are indicated: RPR Reykjanes Peninsula Rift, WVZ Western Volcanic Zone, SISZ South Iceland Seismic Zone, EVZ Eastern Volcanic Zone, CIVZ Central Iceland Volcanic Zone, NVZ Northern Volcanic Zone, GOR Grímsey Oblique Rift, HFZ Húsavík-Flatey fault system, ER Eyjafjarðaráll Rift, DZ Dalvík Zone. SIVZ South Iceland Volcanic Zone. Kr, Ka, H, L, V mark the central volcanoes of Krafla, Katla, Hengill, Langjökull, and Vestmannaeyjar.

for the voluminous subaerial lava flows found along over 50% of continental rifted margins.

Kristjan and G.P.L. Walker were the pioneers in showing how Iceland despite its complexity could fit into the plate tectonic model (Fig. 5). As Steve Sparks of Bristol University notes (Pers. Comm. to BV, 2015):

> *"Over several decades Kristján has been the outstanding Iceland field geologist with remarkable achievements in a diversity of fields. During the 1960s and 1970s there were two outstanding researchers who together mapped out the geology of Iceland and related what they observed to the revolutionary ideas of plate tectonics and sea-floor spreading. George Walker worked mostly in eastern Iceland while Kristján worked in the west and north. In these early days of plate tectonics there was some skepticism about the application of plate tectonics as regional dips did not agree with simplified interpretations. Sæmundsson through his meticulous and careful mapping showed that the neovolcanic zone had shifted a number of times. In particular in a classic 1974 paper he showed how these shifts could be related to eastward migration of the mantle plume with respect to the neovolcanic zones, with development of transform faults and lateral rift zones. In this period he also demonstrated that transform faults linked the neovolcanic zones in Iceland with the ocean ridges in the North Atlantic."*

His 1974 *Geological Society of America* paper mentioned by Sparks was written in 1972 and released as an NEA report in January 1973 (Sæmundsson, 1973). "*Evolution of the axial rifting zone in northern Iceland and the Tjörnes Fracture Zone"* was indeed among the first to document the way mid-ocean ridges are broken into distinct segments and how such segments intersect transform fault zones (Fig. 6). More importantly that paper described the first incontrovertible evidence that spreading-centers periodically move to new positions. In this jam-packed paper he also advanced the idea that these 'ridge jumps' occur so that the spreading center can be over the actively upwelling mantle plume, a remarkable notion since the idea of plumes had only been published a year earlier.[8] Kristján's model is still the accepted process to explain ridge jumps on Iceland and also on submarine ridges; for instance, from Hardarson et al. (2010, cf. 2008):

> *"Eventually, a ridge-jump is expected whereupon the focus of extension in S Iceland will transfer from the WVZ to the EVZ* [see Fig. 4] *(e.g. Sæmundsson, 1980, Hardarson et al., 1997 and refs. therein). From the time when the Mid-Atlantic ridge system migrated WNW over the Iceland plume about 24 m.y. ago (Vink, 1984), the plume has repeatedly refocused the location of spreading with the necessary adjustments being accommodated by transform displacements of the ridge. Relocation of the spreading axis through ridge jumping is a prominent process in the evolution of Iceland and is the primary cause for the tectonic configuration as seen on the island and for the arrangement of high- and low-temperature geothermal areas (Sæmundsson, 1980)."*

Thus even his early work remains relevant to current mid-ocean ridge researchers,[9] *although they are now seen as so axiomatic that people commonly forget, or are unaware, that it was Kristján who made the fundamental discoveries.*

And in the same year that his "*axial rifting zone*" paper appeared, Guðmundur Pálmason and Kristján published their important comprehensive overview "*Iceland in relation to the Mid-Atlantic Ridge*" in an Annual Review of Earth and Planetary Sciences (Pálmason and Sæmundsson, 1974). It recognized that the location of Iceland gave it a unique role in the study of processes at the mid-ocean ridge crests. In 1967 Guðmundur had opposed the spreading concept, but with accumulating evidence and the influence of Kristján's seminal work at NEA and their collaborations (e.g., Pálmason et al., 1970), his opinion had reversed in polarity (Pálmason, 1973, 1980, 1981; Pálmason et al., 1979). Pálmason focused on the geophysical data for the paper, and Kristján posited arguments founded on his work on the shifting rift zones in northern and western Iceland. Thus the pattern of regional dips of the flood basalts was shown to reflect the position not only of the presently active zones of rifting and volcanism, but also of previously active zones (cf. Fig. 6). This concept invalidated the objections against drift in Iceland that the regional dips do not simply conform to the pattern of dip towards the active zone such as exhibited in eastern Iceland. Kristján and Guðmundur reported that correlation of the Reykjanes Ridge magnetic pattern with the pattern in Iceland neither proved nor disproved spreading in Iceland, but the crustal structure of Iceland did not appear to contradict spreading. And, geophysical and geochemical data point to a basaltic crust down to the upper mantle, whereas both Walker (1965) and Holmes (1965) had wondered about sial. Geothermal drillholes extending 1000–2000 m below sea level at the tip of the Reykjanes peninsula, and Heimaey, penetrated rocks which were typical of subaerial or shallow water eruptions. The central question to be answered concerning Iceland and its relationship to the Mid-Atlantic Ridge was answered – the available evidence strongly favored drift, but in a more complicated form than usually envisaged for the submarine parts of the Mid-Atlantic Ridge.

Also deserving mention here is Kristján's 1986 contribution to *The Geology of North America*, *volume M*, *Geological Society of America*, on subaerial volcanism and tectonics of the western North Atlantic (Sæmundsson, 1986). Three regions of subaerial volcanism occur near the eastern edge of the North America plate: Iceland, Jan Mayen and the Azores. In Iceland the ridge axis emerges above sea level, whereas the Azores lie on both sides of the oceanic ridge axis topping an extensive platform adjoining it. The platform was generated by excess volcanic production on the transecting ridge crest, similar to the ridge formation in Iceland, and the islands are stratovolcanoes formed off the ridge crest by flank volcanism. Kristján showed that the volcanism and tectonic settings of Jan Mayen and the Azores are analogous to the flank zones of Iceland.[10] The paper has implications on hotspot and hotspot track development and mantle plumes.

Likewise, work by Kristján on active and ancient dike intrusion events in Iceland had and continues to have broad impacts. The *Nature* paper with Axel Björnsson (1977) and others, "*Current rifting episode in North Iceland*" (cf. also Kristján's detailed 4D mapping in the brilliant 1991 *Náttúra Mývatns* book) described the first active dike intrusion events seen on a spreading center. In the following year, in "*Fissure swarms & central volcanoes of the neovolcanic zones of Iceland"*, *Geological Journal Special Issue 10*, he put the concepts of a central-volcano feeding ridge and rift segments into wider context. Starting in the 1980s a number of theoretical papers on lateral dike intrusion (e.g., Buck et al., 2006)

[8] An important point is that in that paper Kristján basically described what would later, in the mid-1980's, be recognized on the East Pacific Rise as overlapping spreading centers (OSCs) by Ken Macdonald and Jeff Fox in a Nature cover article. Also, even earlier, he had pointed out the nature of "volcanic systems" with their central volcanoes, calderas, and associated fissure swarms. It was not until the late 1980's that Ken Macdonald and his students produced a whole series of papers on "segmentation" of MORs—but based almost solely on multibeam bathymetric data—lacking all the geological detail of the volcanic systems that Kristján had described much earlier.

[9] The last decade or so of multichannel seismic reflection studies and seafloor mapping work on MORs has been focused on understanding along-axis variations in axial magma chambers, crustal structure, physical volcanology, and hydrothermal processes on the scale of spreading segments (i.e., volcanic systems).

[10] The mid-ocean ridge segment between the TFZ and Jan Mayen, known as the Kolbeinsey Ridge, is named after the islet Kolbeinsey 105 km north of the Icelandic mainland. The islet is subjected to heavy wave erosion and is likely to soon disappear, but its geology and tectonics have been studied by Kristján and Árni Hjartarson (Sæmundsson and Hjartarson, 1994). It is similar in shape to hyaloclastite mountains within the volcanic zones of Iceland, the so-called table mountains, which are formed in subglacial or subaquatic eruptions. The uppermost part is a relatively flat lava shield formed sub-aerially while the lower part consists of pillow lava and palagonite with scree slopes created by lava flowing into the sea. The form and size of the basement rock below the islet as well as the lava rocks composing it together with the surrounding skerries could indicate that both were formed in a single eruption piled up until reaching above sea level.

have their origin in Kristján's observations of these active and ancient dikes.

Similarly, the recent one cubic-kilometer eruption (2014–2015) from the Bárdarbunga central volcano, an effusive eruption north of the margin of Dyngjujökull, began as a dike intrusion under Bárdarbunga, and migrated north (Gudmundsson et al., 2016). It shows volcanic-tectonic relationships similar to those observed at Krafla, and Kristján and his team have demonstrated this further in remapping of the Northern Volcanic Zone. This is the best documented dike intrusion event anywhere to date, and we know so much more about this area because of detailed mapping by Kristjan et al. of the Holuhraun area before the most recent eruption (Sigurgeirsson et al., 2015). Likewise, the well-studied series of fourteen dike intrusion events that occurred from 2005 to 2011 along the Dabbahu spreading segment in the Main Ethiopian Rift, the only other place of substantial sub-aerial plate spreading, showed a pattern first informed by the Iceland research (Grandin et al., 2010). It is accepted now that dikes propagate laterally away from magma chambers on mid-ocean ridges[11] much like the central volcanoes of Iceland.

4. The maps that changed the world… of Iceland

During the last five decades of field research in Iceland, major advances in understanding the geology of Iceland have been achieved. During that period of time, Kristján has played a pivotal role, individually and collaboratively with Icelandic and non-Icelandic scientists, because of his considerable skill in mapping, interpreting, and and synthesizing the geology of Iceland. Some of these outstanding achievements are noted in this section.

The country is covered by nine 1:250.000-scale regional geologic maps, of which seven have been published. Kristján has published three of these 1:250.000-scale maps, either alone (sheet 7, Nordausturland (Sæmundsson, 1977), or in collaboration with other geologists (sheet 6, Midsudurland, in multiple editions (Sæmundsson et al., 1982; Jóhannesson et al., 1990); and sheet 3, Sudvesturland, also multiple editions (Sæmundsson and Einarsson, 1980). With his superb collaborator in field mapping, Haukur Jóhannesson, or more recently with Árni Hjartarson, Kristján has also coauthored six bedrock and tectonic maps (1:500.000- and 1:600.000- scale) of Iceland (Jóhannesson and Sæmundsson, 1989, 1998a,b, 2009a,b; Hjartarson and Sæmundsson, 2014), plus another on geothermics (Jóhannesson and Sæmundsson, 2006). And in 2012 and 2015, as senior author and coauthor, two 1:100,000-scale Geological Maps of the Northern Volcanic Zone of Iceland (northern part, and southern part) were published (Sæmundsson et al., 2012a; Sigurgeirsson et al., 2015) (Fig. 7), and another soon followed for Reykjanes by Sæmundsson et al. (2016) (Fig. 8). The 1:100.000 maps are partly the product of many previous maps but included much additional fieldwork involving Kristján and a strong project team (Fig. 9). It is difficult to convey to the reader how much effort has been required for such achievements in fieldwork, but Árni Hjartarson offers discerning insight:

> *"Mapping is not an easy task in Iceland. The landscape is mountainous, the vast central highlands are remote and barren, without roads and bridges, the climate is cold and the summer season short. It is better to be fit and fearless. In the field Kristján is passionate. He starts work early in the morning and quits late in the evening, his assistants or coworkers must take care of mealtimes, otherwise they might be forgotten. His lunch box is tiny and unappetising, he eats fast and then starts*

[11] The only documented examples are on the EPR and Juan de Fuca ridges – fast to intermediate growth – but this certainly applies on slow-spreading ridges too where magma bodies are less commonly present and only documented in a few places. And this is also very relevant to dike intrusion events documented in Hawaii. It shows that lateral dike intrusion is a serious volcanic hazard that can reach 10s of km from a volcanic center along a rift zone. Also, as in the Buck et al. 2006 paper, valuable information about stress in the lithosphere is given by dike intrusion events.

a
b

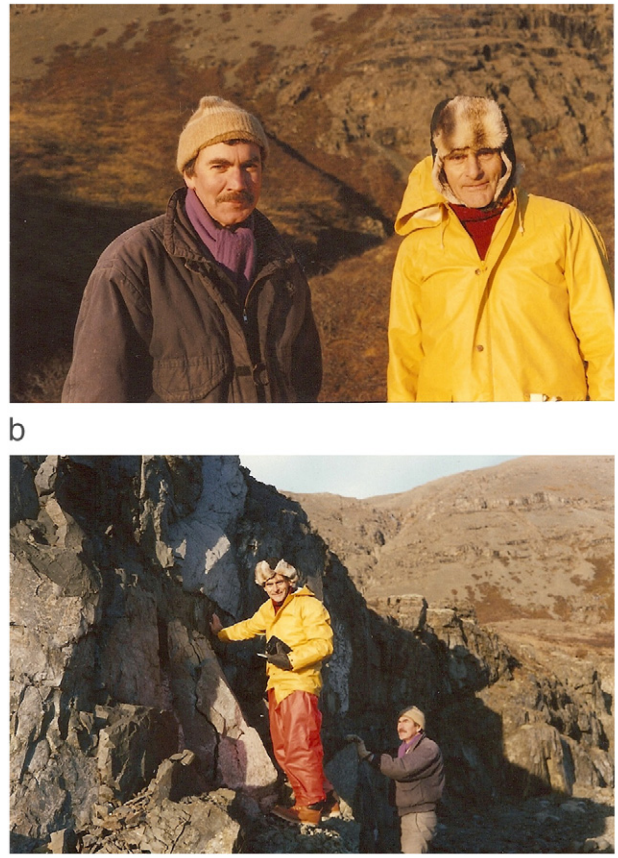


Fig. 5. The Pioneers – George P. L. Walker and Kristján Sæmundsson. (a) In 1988, George was awarded an honorary doctorate and he and Kristján flew to Hornafjörður. Guðmundur Ómar Friðleifsson met them and they drove back to Reykjavik, looking at outcrops along the way[12]. (b) It was cold so Walker borrowed GÓF's Kasmirian wolfskin hat. Afterward, Guðmundur's wolfskin hat was called by Kristján "*the 'thinking hat*" – *after the 'grand master' – which Kristján recommended I put up "whenever in case of serious debate on some outcrop"*.

[12] Kristján and G.P.L. Walker did not meet in the field often, but some stories of meetings of these two soft-spoken individuals are memorable. Here is one from Gretar Ívarsson, a PhD student of Walker: *"I got Kristján and George into the field together only once, in 1982. Both had a lot of respect for each other but neither was able to communicate that feeling, and they did not appear to interact a great deal. I remember when we went into Illagil (evil gully) on the northern perimeter of Torfajökull Central Volcano. George and Kristján were sitting in the back of the Bronco and when we stopped and stepped out, I walked in front of the car and made a one-minute summary of my work in that region, not looking back, just forward. What followed was total silence. I waited a bit and then turned around and there was no one. Looking around I saw George walking up the western slope of the gully and Kristján walking up the eastern slope. I did not see them again till a few hours later. I do not actually remember what I did or how I dealt with this, but this was very typical of both George and Kristján. I am a closed person with limited personal communication skills, but both Kristján and George are miles behind me in that respect.*
Kristján was able to change his mind. In the tent in the evening he tended to talk a little about the day in the field and gave me an overview. The day after in the tent he did this again, and said, remember what I said last night? That was all wrong, I think I see the light now. That's progress, always something new happening every day.
Even George broke down once and confided in me, and I discovered he was human like the rest of us. Both George and Kristján had stashes of raisins in their pockets to keep up the energy. Once in the field George ran out of raisins, and we had to hike back, go to a store, get raisins, and return to the field. Both had one-track minds…."
Another meeting of the two occurred in 1988 when Walker was awarded the Honorary Doctorate at the University of Iceland. As recalled by Guðmundur Ómar Friðleifsson:
"He and Kristján took a flight to Hornafjörður – and I was there with a car and we drove back to Reykjavik – looking at a lot of outcrops on the way from the southeast. It was autumn and cold, and Walker borrowed my Kasmirian wolfskin hat and a red sweater I had used in the field for years - and the rest of the field costume he got from UNU, if I remember correctly. For the following years my wolfskin hat was called by Kristján the "thinking hat" – after the "grand master" – which Kristján recommended I put on, whenever in case of serious debate on some outcrop."

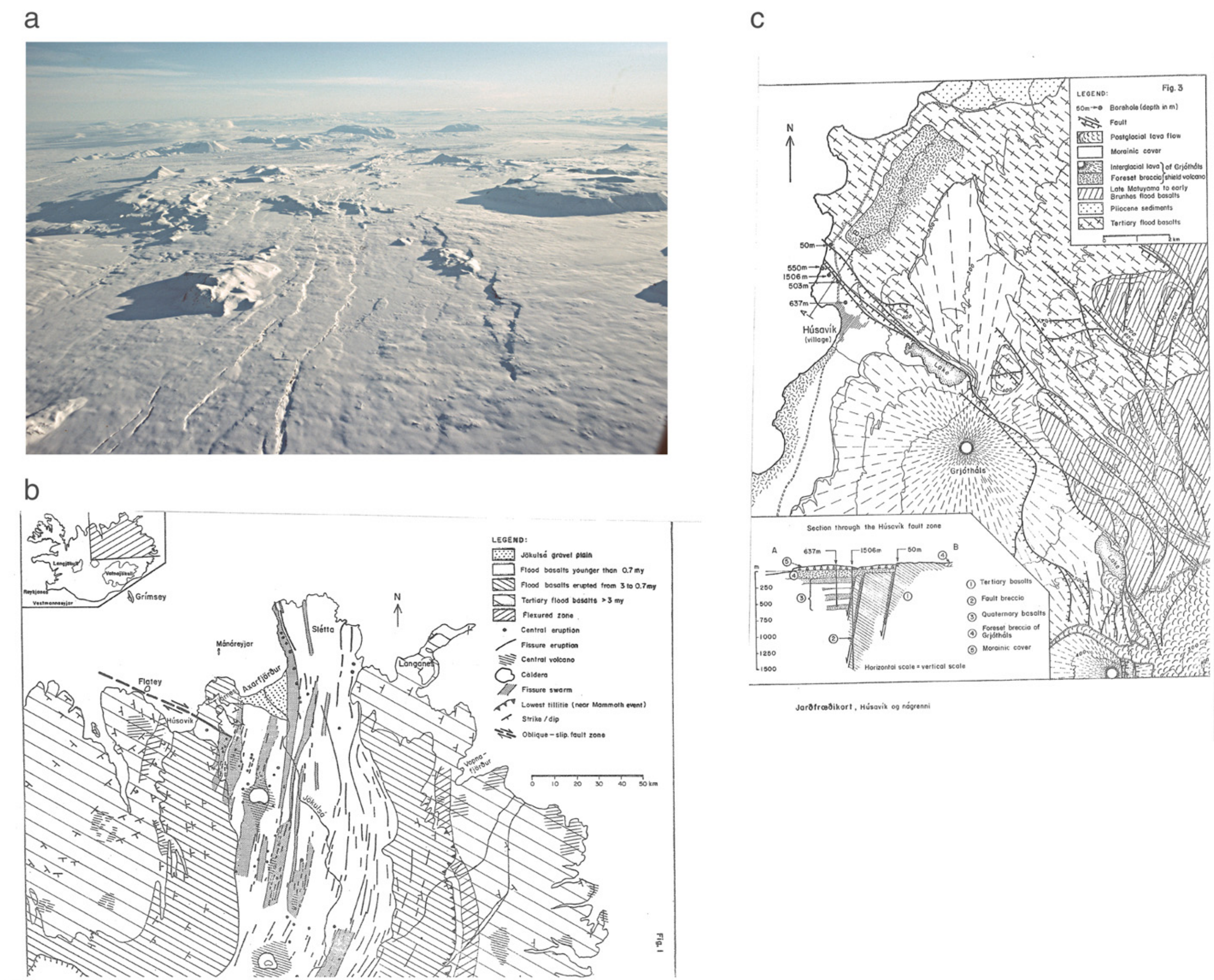


Fig. 6. (a) Fissure swarm of the Krafla volcanic system, northeast Iceland. Viewed to south from Gjástykki (March 1977 photo by Oddur Sigurðsson). At left foreground, Hrútafjall subglacial hyaloclastite ridge. The Gæsafjöll table mountain is at middle right, and to left of it is the 10-km broad Krafla caldera, which is crossed by the fissure swarm and some hyaloclastite ridges or mounds of basalt or rhyolite composition. Geology of the region is mapped in Fig. 11a. A plate-boundary rifting episode with its Krafla Fire eruptions occurred here in 1975–1984, also in 1724–1729 and earlier times (Sæmundsson, 1991). (b) Structural map of northeastern Iceland, as drawn in 1972 and filed in an NEA report (1973). The same map appears later in his 1974 *Geological Society of America* paper with the addition of strike-dip symbols to the eastern region. Kristján proposed the specific term "axial rifting zone" to designate the continuation of the axis of the Mid-Atlantic Ridge through Iceland along stretches between fracture zones. His map shows trends in the axial rifting zone and its continuation across the land portion of the Tjörnes Fracture Zone (TFZ), with the TFZ then extending west-northwest offshore towards the mid-ocean Kolbeinsey Ridge. The southern part of the TFZ is identified by transform faulting passing south of Flatey through Húsavík village, displaying right-lateral slip, and passing into an active northerly-trending fissure swarm. Two central volcanoes with calderas and fissure swarms are also shown, at Krafla, and Askjá (in the south). (c) The right-lateral oblique-slip fault zone near Húsavík, drawn in 1972 and used also in the 1974 paper. The foreset breccia forming the base of the Grjothals shield volcano represents a submarine facies of the lava flow; the boundary altitudes of 200-m elev north of the faults and 100-m elev south of them represent sea level at time of eruption, providing Kristján an absolute measure of fault displacement since the eruption. On entering the volcanically active fissure swarm of the axial rifting zone, displacements are transformed into extensional faults.

writing in the notebook or colouring his field map waiting for the others to finish their meal. He is susceptive to the small things in the surroundings, to a tiny tephra layer, a small amygdale, or a faint fracture but at the same time he also recognises the broad strokes of the geology, the regional patterns and formations and the fingerprints of the global tectonics."

The various new maps are refinements founded on decades of earlier work by Kristján and his cohorts in mapping and in tephrochronologic studies, and although formally retired '*the Grand Old Man of Icelandic Geology*' is clearly quite active in the mapping developments, and stories about his passion and character are the stuff of legend.[13,14] The superb regional geologic and tectonic maps representing the Reykjanes Peninsula (Sæmundsson et al., 2016) and the Northern Volcanic Zone (Sæmundsson et al., 2012a; Sigurgeirsson et al., 2015) document key structures that connect directly to mid-ocean ridges (Figs. 7, 8), and it is to a significant extent Kristján's contributions that make Iceland a 'natural laboratory' for seafloor spreading and related lithospheric processes, gaining global attention from marine geologists studying oceanic crust and tectonic spreading.

Kristján contributions of the regional geology of Iceland include the identification of the 30 Volcanic Systems within the seven Volcanic Zones and Belts (e.g., Sæmundsson, 1974, 1978; Jóhannesson and Sæmundsson, 1998a, 1998b), all of which, with the exception of the Reykjanes Volcanic Belt, have one or more central volcanoes and associated fissure swarms. The tectonic overview map of Fig. 4 illustrates these zones as currently understood (cf. Einarsson and Sæmundsson, 1987), in the context of plate boundaries and seismicity. With the exception of four Volcanic Zones, all have had volcanic eruptions during the Holocene Epoch, and seven systems erupted after 870 CE (Larsen and Eiríksson, 2008).

Kristján produced stellar detailed maps of the central volcanoes, and also the calderas associated with a third of them (e.g., Sæmundsson 1967a, 1972, 1982, 1991, 2008, 2013). His research often pioneered use of the latest available technology, such as after 23 July 1972, when ERTS 1 (Landsat 1) was launched by the U.S. Geological Survey. Six months later, on 31 January 1973, a remarkable low-Sun-angle image of the Vatnajökull ice cap was acquired. This image revealed several "new" volcanic, tectonic, and glaciological features of what was concealed beneath the ice cap, including the Bárdarbunga central volcano and caldera, two elliptical calderas in the Kverkfjöll central volcano, ice cauldrons, and other features. Working with Sigurdur Thorarinsson and Richie Williams, Kristján published a comprehensive analysis of the features revealed on the image (Thorarinsson et al., 1973; cf. Williams Jr. et al., 1973).

Examples of detailed work include the maps in his 1966 doctoral thesis, *Vulkanismus und Tektonik des Hengill-Gebietes in Südwest-Island* (Sæmundsson, 1967a), and his critical ensuing work (cf. Sæmundsson et al., 1990; Sæmundsson, 1995a, 1995b; Franzson et al., 2010) – the Hengill central volcano and its high temperature geothermal fields in Nesjavellir and Hellisheidi warm up the majority of all houses in the capital city and its suburbs and supply the biggest proportion of geothermal energy, and Kristjan's mapping holds the key to the flow systems.

And then there is the Torfajökull silicic central volcano complex, with a large caldera discovered by Kristján (Sæmundsson, 1972). The system is comparable in area to the adjacent Katla volcanic system's central volcano and caldera, fissure swarms, and high-temperature geothermal system within the caldera (Sæmundsson, 1972, 1988). However it is remote with limited road access, and fieldwork there has an extremely short working season. Guðmundur Ómar Friðleifsson worked there with Kristján for a decade and reveals the difficult work involved,[12,15] but they produced wonderful geologic and geothermal maps, mapping at scale 1:20,000 with overview maps presented at 1:40.000 (Fig. 10) (Sæmundsson and Friðleifsson, 2001a,b; Sæmundsson, 2007, 2013). Dave McGarvie offers further observations

[13] Árni Hjartarson, ÍSOR jarðfræðingur, worked on mapping projects with Kristján for decades:

"Many stories have been told about Kristján and his habits in the field. On the way home, after two weeks of research in the Central Highlands, he has sometimes suggested an extra day or a half to check on a few interesting things or to dig some additional holes for tephrochronology. These ideas are unpopular and are usually totally rejected by the companions. However, he has not changed through the years, his enthusiasm for geology always seems the same."

[14] Ingibjörg Kaldal has been working with Kristján since 1997, first as his deputy as Head of the Geology Department at ÍSOR and later as a project manager for the 1:100.000 geological maps ÍSOR has been making since 2008: *"Due to very different geological background, Kristján and me always worked in different departments with different projects – he is the main guru in Iceland on geothermal research and geological mapping of Iceland. I, on the other hand, have mostly been mapping superficial deposits and glacial features for the hydropower sector. Unfortunately we therefore never worked together in the field, but luckily he was my teacher in geological mapping at the University of Iceland where he taught us facts and tricks we never forget!*

Since our teamwork started with the geological maps in scale 1:100,000 for the volcanic zones in Iceland, we have been working closely together. The maps are the products of many older maps in larger scales which have been revised and new data added. Because Kristján is the main author of so many of the older maps he has been very much involved in this work along with a group of younger geologists, although he retired on pension early in 2006.

The first map, 'Geological Map of Southwest Iceland', was compiled in the first years after the financial crisis in Iceland, when the finances of ÍSOR were very bad and so it was decided that no new field work was allowed. Just before the map was ready to print, Kristján came frequently with his GPS tool and a sketch with the words: 'I took a walk yesterday evening and found out that we have to change this – is it possible?'. He was so enthusiastic and told me he had to take a walk every day because of health problems and his face told me how much fun he had. And because of all the enjoyment, he took these walks in his spare time and often accompanied with his wife!

Kristján still turns up in the office almost every day although he is now 81 years old. His mind is always fresh and enthusiastic and he always willingly spreads his knowledge to his coworkers. He is also always ready to change his mind about his mapping if we give good arguments. If I ask him about some geological feature on the maps we are making, he usually gives, on the spot, a detailed description about his field research, even many decades before. To be absolutely certain he often goes home and brings back his field diary, an old, torn field map, aerial photo or some photographs to show me. Kristján Sæmundsson is indeed 'The grand old man' in Icelandic geology."

[15] From Guðmundur Ómar Friðleifsson, Chief Geologist at the geothermal company HS Orka:

"Kristján was my field class teacher at the University of Iceland during my BSc study – during which time it became clear to me what an eminent geologist Kristján was. I continued for several years into subsurface geological studies using drill cuttings in high-temperature geothermal fields, and then mapped and studied the geological and hydrothermal history of a deeply eroded Miocene central volcano in SE Iceland during my PhD study. In his long career Kristján had encouraged a number of young geologists in Iceland to deal with similar research on Iceland's central volcanoes. After my PhD study I continued using my skill to study the subsurface of the Icelandic high temperature systems for several years, until Kristján recruited me to work with him on detailed mapping of the Hengill and the Hveragerdi volcanic centres, which lasted several years, followed by a decade in detailed mapping of the Torfajökull Central Volcano. The Torfajökull system is by far the largest silicic centre in Iceland, estimated to have a potential of some 1000 MWe or more, while located in a natural reserve, and now a part of a national park. At the time we began, in the early 1990s, the complex was considered to span some 200,000 years llfetime, but when we finished a decade later, we were running after geomagnetic outcrops to convince ourselves it was not dating all the way back to Matuyama, but clearly beginning some 700,000 years ago.

The Torfajökull field is very remote and mostly above 600 m.a.s.l., and road access is very limited to the centre of the system. Our maps covered some 600 km^2, and most of the years we could only begin the field season in August and rarely past September, occasionally snowing in. Most commonly we stayed in tents or primitive huts, and were more or less out of telephone reach or other contact with civilization. Making maps of this sort, both geological and hydrothermal, demanded us to cover every single hectare (or acre) of the system. The mapping itself brought up a series of geological questions on the age and field relations of the different rock formations. Evidently, the simplest of all were the Holocene obsidian lava flows, which we hardly needed to touch as many researchers had done so before. But the details of the subglacially formed rhyolitic eruptives and the contacts between units was a painstaking ordeal to sort out. I often felt that Kristjan had an extraordinary insight in how to sort out the details – resulting in the first proper geological map of the Torfajökull Central Volcano. In his prime days Kristján had mapped the Hengill Central Volcano, which mostly is composed of endless heaps of subglacial basaltic fissure eruptive hyaloclastites, exceptionally difficult to separate in detail. Working with him for years on revising his earlier maps was an exceptional experience as well. So Kristján is one of a kind."

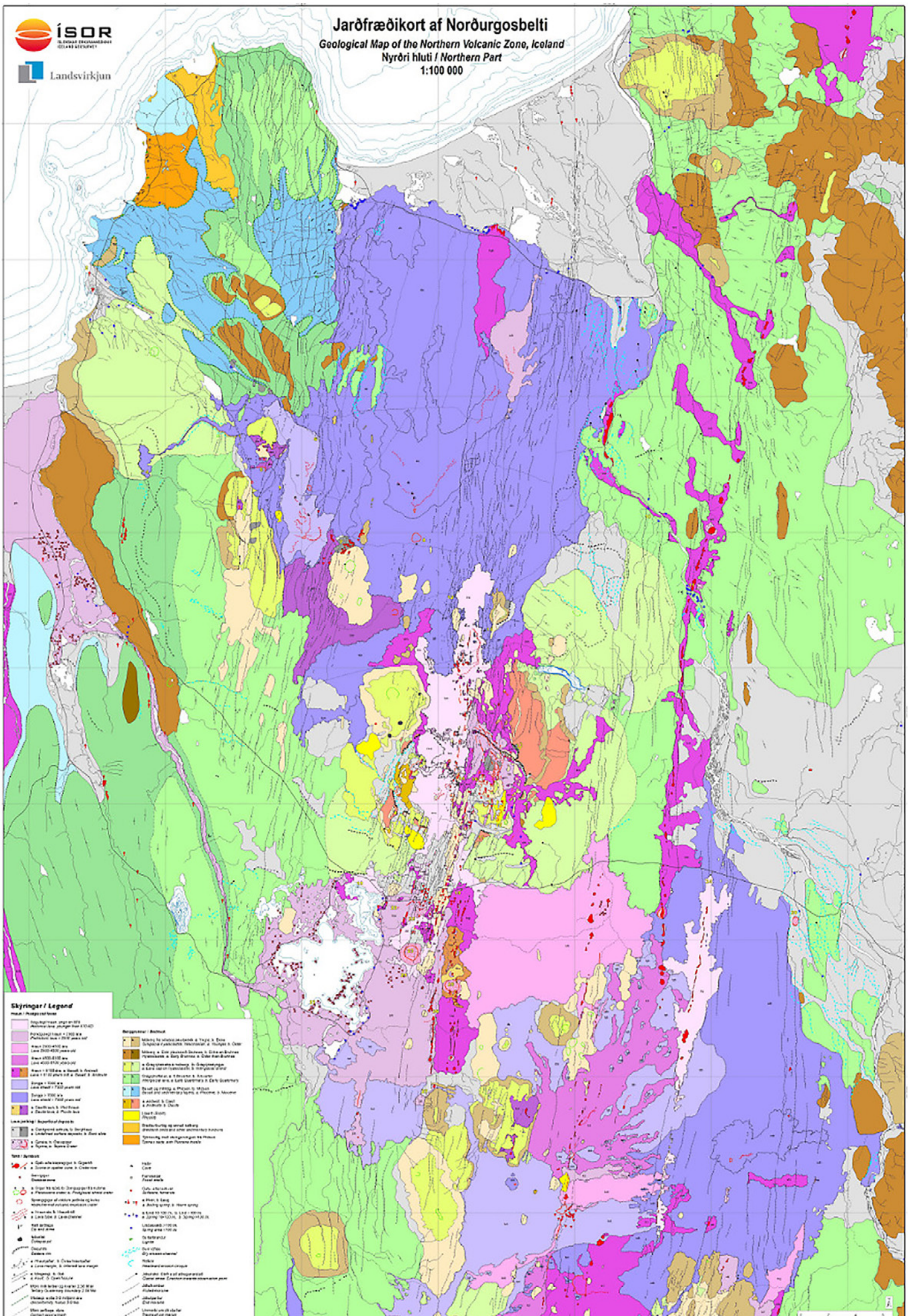


Fig. 7. Geological map of Northern Volcanic Zone, Northern Part, original at 1:100,000 (Sæmundsson et al., 2012a), covering the area from Tjörnes Peninsula and Öxarfjörður in the north, to table mountains 20 km south of Lake Mývatn. The map shows the main geological features of the onshore region in north Iceland connected to the mid-ocean ridge system. The oldest rocks are of Miocene age and the youngest from the Krafla Fires eruption in 1975–1984. The latter eruption was focused on the Krafla caldera (17 km NNE of Lake Mývatn) and its associated fissure swarm (Fig. 6a), extending as far north as Öxarfjörður. Key tectonic features are shown along with the main deglaciation structures. Transform faulting through Húsavík to the fissure swarms are shown at upper left. The map includes 61 lava flows, divided into 7 age groups with the aid of tephrochronology. This map is the product of several previous maps in larger scales created by Kristján and his team of colleagues at ÍSOR and the NEA.

of Kristján there, and his approaches to field mapping.[16] A recent major book, *Náttúruvá á Íslandi. Eldgos og Jardskjálftar* (Natural Hazards in Iceland: Volcanic Eruptions and Earthquakes), contains sections on Kristján's work at Torfajökull, and also Askja Central Volcano, the Northern Volcanic Zone, and Reykjanes peninsula (2013a,b,c).

5. Contributions to volcanology

Volcanism in Iceland is diverse for an oceanic island and has featured nearly all volcano types and eruption styles known on Earth. In 1979, Sigurdur Thorarinsson and Kristján published a comprehensive paper that summarized "*Volcanic activity [in Iceland] in historical time [post-870 CE]*," presenting also a table on volcanic landforms and the various environments and eruptive processes in which they form (Thorarinsson and Sæmundsson, 1979). Their paper built on Niels Nielsen's work in the 1930s and provided a benchmark reference for a quarter century, until new information led to an updated review by Thordarson and Larsen (2007).

The volcanic system is the fundamental building block of Icelandic crust, one that features a fissure (dike) swarm or a central volcano or both, and has a typical lifetime of 0.5–1.5 million years (Figs. 4, 6; cf. Sæmundsson, 1974, 1978, 1979). The fissure swarms of each system are elongate structures aligned more or less sub-parallel to the axis of the hosting volcanic zone. The central volcano, when present, is the focal point of eruptive activity and is typically the largest edifice within each system. Besides journal publications, these are all described in the useful online *Catalogue of Icelandic Volcanoes* (http://icelandicvolcanoes.is), which was initiated in 2012 by the Iceland Meteorological Office and collaborators.[17] Kristján wrote the chapter on Krafla and seven other volcanic systems (Fremrinámar, Heiðarsporðar, Hengill, Hrómundartindur, Prestahnjúkur, Torfajökull), or eight of the 32 chapters in the Catalogue.

[16] From Dave McGarvie, at the Open University in Edinburgh: *"One of Kristján's great passions was mapping the geology of Torfajökull volcano, one of the most complex areas to map in Iceland. He was rather pleased that he managed to get some funding for his mapping via a 'back door' route, and this enabled him and Guðmundur Omar Friðleifsson to construct what is a genuine masterpiece of mapping. Although, being Kristján, he did also spend a lot of his vacation time mapping the volcano. In fact, he is well known amongst Icelanders as a father and husband who frequently took his family on vacation to areas of geological interest to him. At Torfajökull, his modest tales of driving in two vehicles (one for him and one for Guðmundur) into areas never before explored by vehicles is the stuff of legend, with the lead vehicle often getting into trouble when crossing rivers, sand plains, and quicksand – and having to be rescued by the second vehicle. During this mapping, Kristján and Guðmundur gave names to many unnamed features in and around Torfajökull, some of which were decidedly mischievous. His insight into this volcano is truly remarkable.*

A recent and unexpected (and memorable) encounter with Kristján was in north Iceland in the fissure swarm north of Krafla. I was with a group of Earthwatch volunteers doing a gravity survey and we were on a rough and narrow unmarked track through lava, when a jeep appeared on the crest ahead of us and managed to pull over. On getting closer I saw it was Kristján, and pulled over for a chat. He was putting together a map of the northern part of the active rift zone, and despite having a period of ill health a few years back, he was still very active in the field. One of the volunteers was awestruck at meeting Kristján (having read many of his papers), and Kristján was very gracious at putting her at ease and just talking about his work and answering her questions in his typical unassuming and quiet manner. One of the volunteers asked Kristján if he drove back to Mývatn every night to sleep, to which he replied that at the end of a day's mapping he would have a meal, and then park his jeep with the front elevated and simply sleep underneath it. We met up the next day near a 'secret' track on the road to Askja, as he wanted to show me some subglacial basalts he'd just been mapping and wanted my views. At one point there was an open and deep fissure bridged by a few fallen lava blocks, and Kristján demonstrated his 4 × 4 skills by simply driving up it with no fuss. Being in a rented 4 × 4 and not on a marked mountain road, I backed off. The combination of Kristján's driving skills and his rough camping while doing fieldwork left a strong impression on the volunteers, and gave them an interesting insight into the dedication that Kristján still had at such a grand age, as well as his ability to endure hardship to get as much done as possible in the time available."

[17] The Catalogue of Icelandic Volcanoes is a collaboration of the Icelandic Meteorological Office (the state volcano observatory), the Institute of Earth Sciences at the University of Iceland, and the Civil Protection Department of the National Commissioner of the Iceland Police, with contributions from a large number of specialists in Iceland and elsewhere. The Catalogue is an official publication intended to serve as an accurate and up to date source of information about active volcanoes in Iceland and their characteristics.

Twenty of the 30 volcanic systems defined by Sæmundsson (1978) and Jóhannesson and Sæmundsson (1998a, 1998b) feature a fissure swarm, and of those, 12 are relatively mature and 4 are regarded as embryonic. The mature and moderately mature fissure swarms are distinct narrow and elongated strips (5–20 km wide and 50–200 km long) with high density of tension cracks, normal faults and volcanic fissures, whereas embryonic swarms feature one or a few discrete volcanic fissures. Nineteen systems have central volcanoes, with four systems, Hofsjökull, Tungnafellsjökull, Bárdarbunga–Veidivötn and Grımsvötn, having two central volcanoes (Fig. 4; Table 1). The maps by Jóhannesson and Sæmundsson (1998a,b, 2009a,b) and Hjartarson and Sæmundsson (2014), and decades of previous work by Kristján and others, show the remaining systems contain high-temperature geothermal fields. These suggest the presence of a shallow crustal magma holding-chamber and may represent central volcanoes at their earliest growth stage (Thordarson and Larsen, 2007).

All of the central volcanoes and high-temperature fields have been subjected to study by Kristján, most in substantial detail. His unexcelled maps and studies of the major central volcano systems like Hengill (Sæmundsson, 1965, 1967a, 1995a,b) and Krafla (Sæmundsson, 1991, 2008; cf. Mortensen et al., 2009) led to fundamentally improved understanding of the magmatic systems, as well as the interplay between magmatic and geothermal processes. Kristján also pioneered the recognition of calderas in the rift zone central volcanoes (Sæmundsson, 1972, 1978, 1982), studied shield volcanoes of the Reykjanes peninsula (Sæmundsson, 1995c), the Askja central volcano and caldera (Sæmundsson and Sigmundsson, 2013b), and was a key member of teams investigating the Hekla eruptions in 1980–81 and 1991 (Grönvold et al., 1984; Gudmundsson et al., 1992). Thus besides Kristján's extensive contributions to understanding Iceland's evolution as a whole, he has provided the details of a number of individual volcanic systems that improve our understanding of how volcanoes work.

Certainly a key site for Kristján was the Krafla volcano. His work there began in detailed mapping of the central volcano and geothermal areas before the Krafla Fires volcano-tectonic episode commenced in December 1975, which lasted until September 1984 (Einarsson, 1991; Sæmundsson, 1991). The first eruption broke out from a short fissure inside the caldera at Leirhnjúkur (Fig. 11a), producing a small lava flow and a few explosions, and was followed by an immediate subsidence within the caldera floor and subsequent gradual inflation of the caldera floor over the next months. This pattern of gradual inflation at 7–10 mm/day and sudden deflation recurred throughout the episode (Ewart et al., 1990, 1991). Rifting began by rock failure beneath the caldera and then migrated along the fissure swarm as indicated by outward-propagating earthquake swarms (Brandsdóttir and Einarsson, 1979). Magma flowed into open fissures and sometimes erupted as surface flows, each of which Kristján mapped (Fig. 11). In total 21 rifting events occurred during the 1975–1984 Krafla volcano-tectonic episode. The total widening of the Krafla fissure swarm during the 9-year volcano-tectonic episode was about 9 m or almost three orders of magnitude greater than the long-term average spreading rate of the plate boundary in Iceland, which is 1.8 cm/year (Tryggvason, 1984; Sigmundsson, 2006). The Krafla Fires and the preceding Mývatn Fires (1724–1729) episodes showed that spreading along the plate boundary is not continuous, but is periodic and confined to short volcano-tectonic episodes that make up for longer periods of tectonic quiescence.

Much of Kristján's stellar work on Krafla, and other places too, is not as well known as it might be, because of publications written mostly in the Icelandic language and/or in company reports (e.g., Sæmundsson, 1991; Mortensen et al., 2009). An example is his study of Krafla in the book *Náttúra Mývatns* (1991), in which his series of maps reveals the step-by-step complex history of historical and pre-historical eruptive events and geothermal features of various styles (Fig. 11). These components also contributed to his 1:25.000 map of 2008, and the 1:100.000 Northern Volcanic zone map of 2014 (Fig. 7).

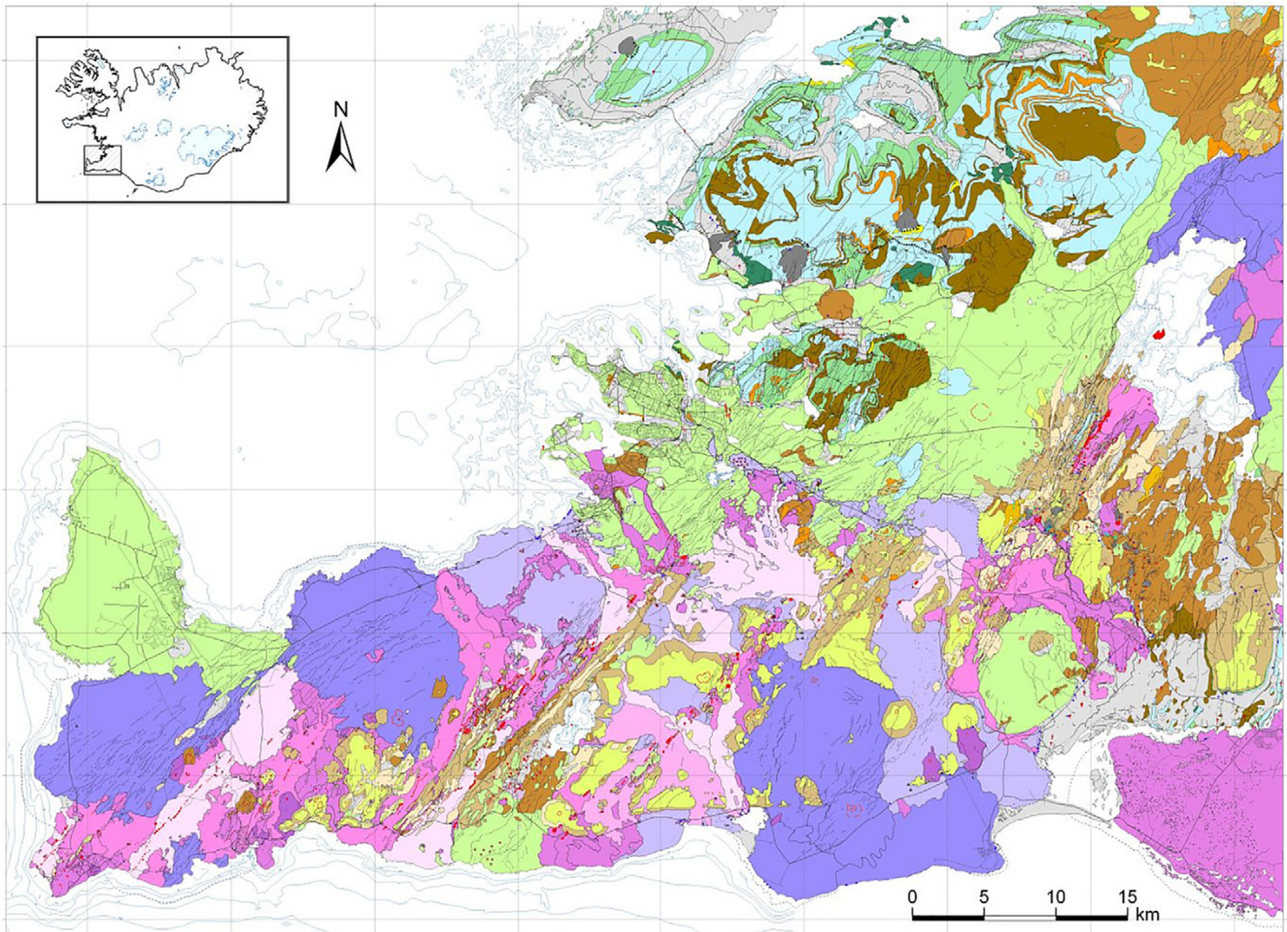


Fig. 8. Geological map of Southwest Iceland, original at 1:100,000 (Sæmundsson et al., 2016). The map shows the main geological features of the onshore region in southwest Iceland connected to the mid-ocean ridge system, including tectonic features and 160 different lava flows. The oldest units shown are 4 m.y. old and the youngest are lavas from an eruption on Reykjanes peninsula in 1211–1240 CE. The map is based on mapping at scales 1:20,000–1:50000, by Kristján and several others at ÍSOR and NEA, revised with new geological mapping (cf. Sæmundsson et al., 2010; Sæmundsson and Einarsson, 2014).

This paper is notable too for its demonstration of skilled use of detailed tephrochronogy to discern localized events (Sæmundsson, 1991, Figs. 10, 11, 15, 18, 25). Guðrún Larsen comments on this aspect of Kristján's work (Fig. 12b):

"The way Kristján used tephra layers to identify individual eruptions of the Krafla volcanic system and their products – and to date the eruptions – is an excellent example of how to apply tephrochronology as a tool in volcanology, and is indeed an outstanding achievement.[18] *Kristján has dated most of the basaltic Krafla lava flows using soil sections with tephra layers of known age, either on top of or below the lava, or both. To do this he dug out and logged well over 100 sections (probably closer to 200 sections), and over 60 such sections have been published. Based on tephrochronology Kristján divided the activity at Krafla into three eruptive periods: the Lúdent period ~12,000–-8000 years ago, the Hvannstóð period ~8000–2800 years ago and the current one, the Hverfell period. This last eruptive period is subdivided into six volcano-tectonic episodes or Fires (as such episodes are called in Iceland), the last being the Krafla fires, 1975–1984. He defined the largest fissure eruption on the system, the Hverfell fires, about 2700 years ago, erupting about 1 km^3 of lava, creating the tuff ring Hverfell and surrounding tephra deposit of at least 0.17 km^3 of tephra. The lava shield Gjástykkisbunga, erupted about 12,000 years ago is, however, the largest basaltic eruption of the Krafla volcanic system with estimated volume of 2–3 km^3."*

Tephrochronology was hugely important for the recent 1:100.000 scale map projects (Fig. 9). The work in the Northern Volcanic Zone is intriguing, as it defined the postglacial eruptive history of the Northern Volcanic Zone divided between the volcanic systems (Fig. 12c, from Sæmundsson and Sigmundsson, 2013a, in Sólnes et al., 2013 (eds.), *Natural Hazards in Iceland*). The study expanded on Kristján's earlier work at Krafla (1991, Fig. 10) and demonstrated the very different histories for the individual volcanic systems. In one particular, the Fremrinámar Volcanic System is shown to be active in the period from 3000 to 8000 years ago, when Krafla was quiet with only one known eruption. The result is an important contribution to the understanding of

[18] From Guðrún Larsen: *"Kristján Sæmundsson is, in my opinion, our best field geologist with superior knowledge of the Icelandic geology. I recall particularly some work with Kristján in 2006 at the Dimmugljúfur (Dark Canyon), the canyon of Jökulsá á Brú, during the construction of the Kárahnjúkar dam in East Iceland. We were dating the down-cutting of Jökulsá in this part of the canyon by digging out soil sections with tephra layers on ledges in the canyon. The ledges are several metres wide and easily accessible. We wanted to know when the river stopped flowing on the ledges and when floods reached up to a certain level for the last time – therefore some sections had to be close to the edges.*

This was quite an adventure. Kristján dug out the soil section closest to the edge and left a narrow "wall" of soil between the section and the precipitous canyon wall to safeguard me while I was logging the section (Fig. 12b). *From the ledge down to the water was near vertical drop of 80–90 m. The opposite canyon wall is about 100 m and fully vertical.*

*I am not afraid of height (but very careful in such circumstances watching my steps) and I logged this section and other similar sections in the canyon. However, looking at Kristján working enthusiastically at the edge was a bit too much and I had to look in the other direction for a while. I am not saying he was too daring but he was, as always, very enthusiastic. On this particular ledge the Jökulsá river had stopped flowing some 1200–1400 years ago but floods (*e.g. *spring-floods) may have disturbed the soil sometime later."*

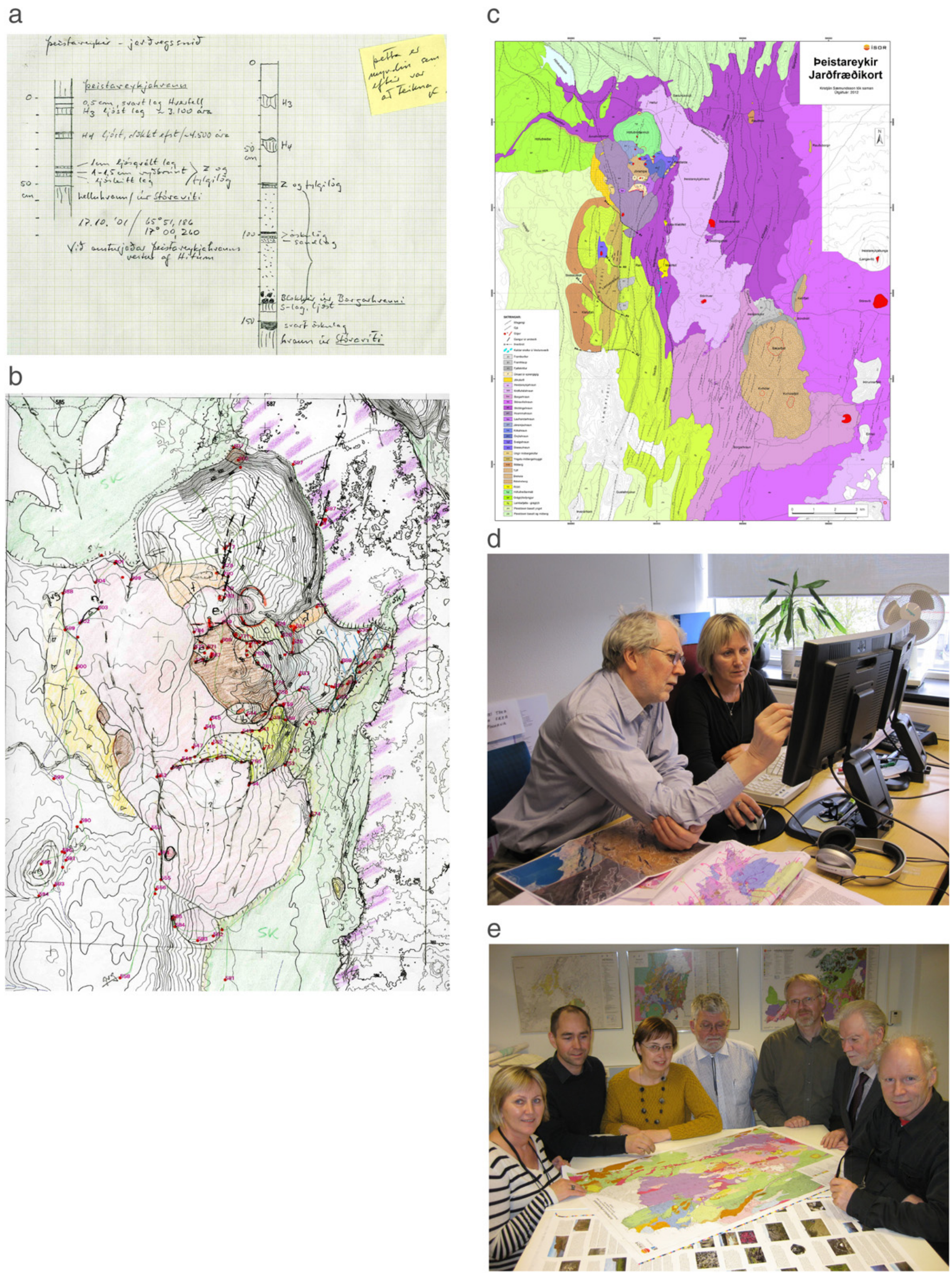


Fig. 9. Production of a geologic map is a big process that starts with field investigations and concludes with a finished product. (a) Typical handscripted notes by Kristján from his investigations near Theistareykir volcanic system, describing the tephra sequence from hand-dug pits, Oct 17, 2001. *Theistareykjahraun* at the top of one log is lava from the volcano, and H3 and H4 are the largest and most important marker tephras from Hekla in Holocene time (cf. Larsen and Eiríksson, 2008). (b) Hand-colored field map of a 5 km-wide region at Theistareykir. Red marks indicated GPS waypoints, and units are shown in the following completed map. (c) Kristján's Geological Map of Theistareykir (Sæmundsson et al., 2012b). The map has special mid-ocean tectonic significance because it is the place where the right-lateral Flatey-Húsavík transform connects from the Kolbeinsey Ridge to extensional faults of the Northern Volcanic Zone. It is also a site of important geothermal development. (d) This field study and mapping formed an integral part of the mapping project for the Geological Map of the Northern Volcanic Zone (Fig. 7; Sæmundsson et al., 2012a). Here the quintessential field man sits in front of a computer screen, working with ÍSOR cartographer Guðrún Sigríður Jónsdóttir to prepare the finalized first map of scale 1:100,000 for public distribution. (e) The NVZ map is completed, and the team deserves to be proud of their accomplishment: from the left, Guðrún Sigríður Jónsdóttir, Sigurður Garðar Kristinsson, Ingibjörg Kaldal, Skúli Víkingsson, Magnús Á. Sigurgeirsson, Kristján, Árni Hjartarson.

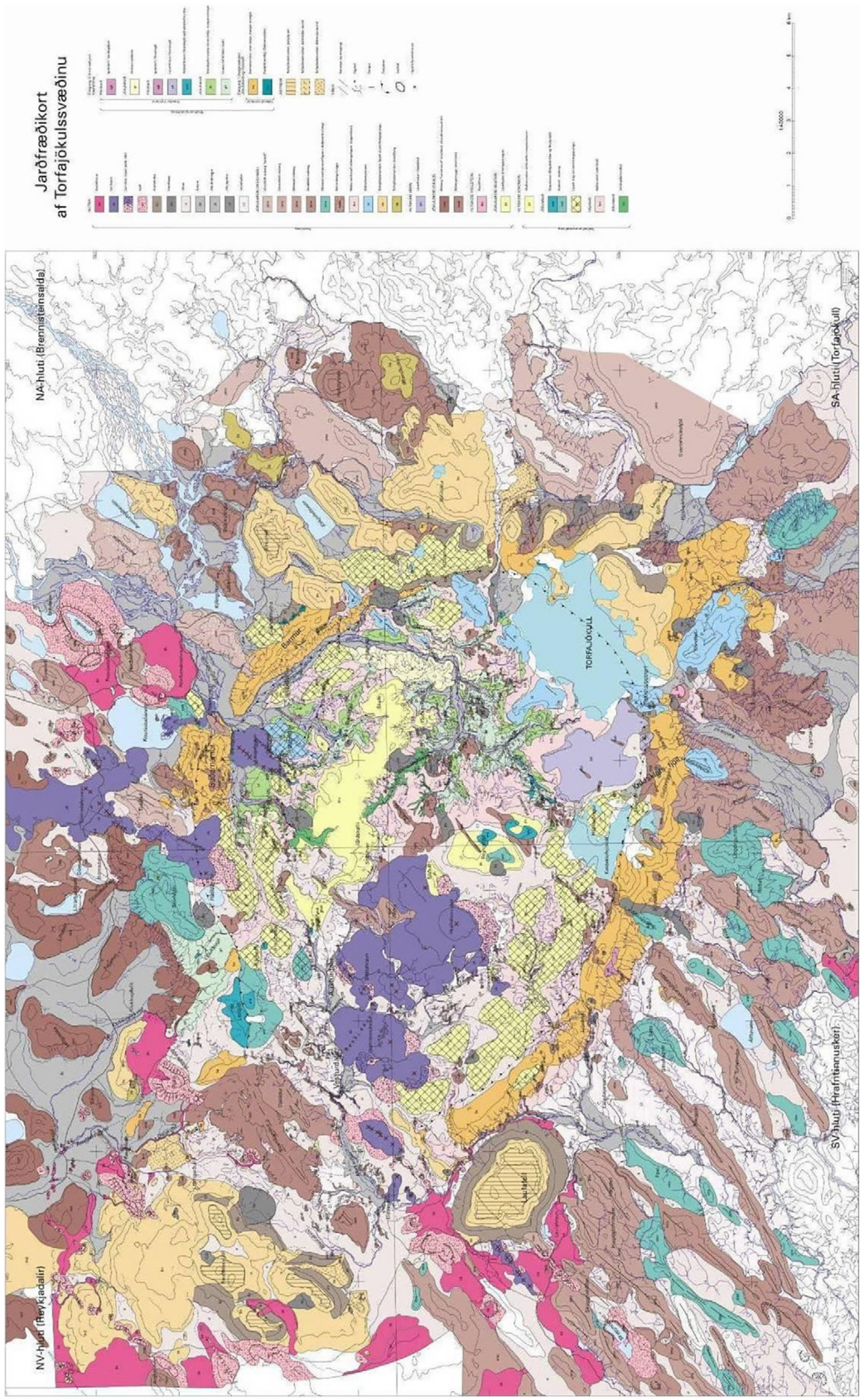


Fig. 10. Geology of the Torfajökull Volcano – a masterpiece. The oldest unit crops out in an elliptical narrow zone which encloses the caldera. In Holocene time, rhyolite lavas were erupted in the center of the caldera, and mixed lavas near its periphery. The ring fracture rhyolites are shown in pale yellow. Holocene rhyolite lavas, mixed with tholeiite to some degree, erupted on a NE-SW fissure swarm. The tholeiitic component of the lavas indicates that the eruptions were triggered by lateral injection via dikes from a rift zone volcano 80 km distant to the NE (Bárdarbunga, in Vatnajökull Glacier). Three Holocene basaltic eruption fissures transected the western part of the volcano without intersecting the magma chamber. Intense thermal manifestations are related to faults and eruption foci of the active NE-SW fissure swarm. Map based on mapping at 1:20.000 by Kristján and Guðmundur Ómar Friðleifsson.

interaction of overlapping volcanic systems, and also has plate tectonic implications. For example, the Krafla Fires episode of 1975–1984 exhibited faulting in and near the Krafla volcanic system, affecting the caldera and (particularly) the associated fault swarm north to Axarfjördur, with displacement then transformed to the Grímsey Oblique Rift (GOR, on Fig. 4). The GOR is commonly considered to comprise the northern limits of the Tjörnes Fracture Zone. However, the activity of the Fremrinámar system (east of the Krafla system, and extending along the western edge of the Slétta Peninsula), suggests that the effective northern TFZ boundary of 3000–8000 years ago was further north than the GOR, and positioned north and offshore of the Slétta Peninsula -– much as already proposed by Sæmundsson (1974, p. 497 and Fig. 3).

Finally, another topic where Kristján, with colleagues John Sinton and Karl Grönvold, made observations that have stimulated new thinking relates to the time variation of volcanism on Iceland. One of the important contributions in their *Postglacial eruptive history of the Western Volcanic Zone*, *Iceland* (2005) is the accurate timing *plus* constrained volumes of lava flows; the combination of these data are rare and difficult to obtain. Their data show that huge outpourings of volcanic output occurred at an early stage as the ice sheet on Iceland was melting. Jull and McKenzie (1996) had built a basic quantitative model to account for this, and it was refined by Maclennan et al. (2002). But the Sinton et al. 2005 paper with fundamental, quantitative mapping and dating of young lavas of the Western Rift Zone provided the essential geological details needed to evaluate theory. It was also the Iceland work that inspired more recent suggestions that sea level changes might trigger MOR eruptions.

6. Contributions to magnetostratigraphy and age dating

In the 1950s and early 1960s, pioneering work was done in Iceland by Dutch and Icelandic scientists on measuring the directions of natural remanent magnetization in lava flows (Hospers, 1951, 1953; Einarsson, 1962; cf. Kristjánsson, 1983). It was found that in the lava pile the polarity of this remanence alternated at irregular intervals, which could be used for stratigraphic purposes. These results suggested that radiometric dating of long series of well-exposed unaltered Icelandic lavas emplaced in known order might aid in establishing a global time scale for the geomagnetic reversals. A British-Icelandic field project in 1964–65 collected oriented drill-core samples from some 1100 lava flows in a 9-km composite section through eastern Iceland for laboratory studies. The detailed mapping and correlation techniques introduced by G.P.L. Walker were used by him to tie together 21 individual mountainside profiles. The paper by Dagley et al. (1967) on this exceptional effort showed among other things that the rate of reversals was considerably greater than that derived from magnetic anomaly lineations over ocean ridges, published in the following year. This inference was confirmed by the extensive 1970s work described below.

Late in the 1960s, portable fluxgate magnetometers were becoming available to geologists. With these, the magnetic polarity of up-down oriented hand samples could be found quickly, for use in stratigraphic correlation and relative age estimation (Fig. 13a). It was advisable to make careful measurements on 3 to 5 samples preferably from the bottom (oxidized) parts of a flow when possible, in order to minimize interference from so-called viscous and induced magnetization components and to recognize flows with transitional directions. Kristján was among the first to employ the fluxgate method extensively, for instance in the volcanic sequences of the Húsafell sequences in the Borgarfjörður region of western Iceland (Sæmundsson and Noll, 1974). Their fieldwork was carried out in 1966 and 1969, and in Kristján's earlier study and report for the *Raforkumálastjóri* (Sæmundsson 1964), and extended further by Kristján and students after 1970. Their polarity results generally were confirmed in subsequent laboratory measurements on oriented and magnetically cleaned drill cores. Seven K-Ar age determinations made by Teledyne Isotopes for the Sæmundsson and Noll paper, funded by the German Science Foundation, were the first dates obtained on a well-mapped continuous section in western Iceland. The results agreed reasonably with the stratigraphy, and enabled estimates of the rate of magma production, the onset and frequency of glaciations, the life span of the central volcano, and the time span of unconformities.

Then in 1973, N.D. Watkins who had participated in the above eastern Iceland project, initiated a large magnetostratigraphic study in Borgarfjörður with Kristján (Fig. 13b). For this, Kristján's section NT of 113 numbered lava units was extended downwards by the section NP of 320 units based on Haukur Jóhannesson's B.Sc. thesis (supervised by Kristján). Their mapping in 24 profiles partially overlapping in ages involved measurements of flow thicknesses (3.5 km in total, including sediment interbeds), petrographic types, magnetic polarity, alteration state (zeolite zoning), tectonic tilts which average about 5° towards the Reykjanes-Langjökull rift zone, faults and intrusions. With some later sampling, laboratory paleomagnetic direction measurements were eventually made on 393 flows. An essential part of the project was the acquisition of new K-Ar dates from 24 flows by Ian McDougall, chosen after thorough inspection of their mineralogy. The dates showed a remarkably uniform rate of buildup of the lava pile, at 730 m/m.y. in the period between ~7 and 2 m.y. ago. This nearly complete record of the geomagnetic polarity history extended the time scale of reversals based on subaerial volcanics from 4.5 to about 6.5 m.y. ago (Fig. 13b). Extension of the polarity time scale by direct measurement was of course important to check on extrapolations based on marine magnetic anomaly data or paleomagnetic measurements of deep-sea sediment cores. Limits were obtained on the age of epoch 9 (marine magnetic anomaly 5), and among other results the ages of two short events (Sidufjall and Thvera) in the Gilbert epoch were established, and the durations of the two preceding geomagnetic epochs provided a constraint on the age of the Miocene-Pliocene boundary (McDougall et al., 1977; cf. Watkins et al., 1975).

The successful collaboration in Borgarfjördur was soon followed by two other projects of the same kind. In the previously uncharted mountainous Tröllaskagi peninsula in central northern Iceland, Kristján and his student assistants mapped 14 profiles of up to 1000 m thickness. 455 flows were sampled for paleomagnetism in 10 of these profiles in 1974–78, making up a composite section of almost 5 km. 34 K-Ar ages were obtained by McDougall, but due to alteration they were not as consistent as those in Borgarfjördur. A buildup rate of 1 km/m.y. was indicated in the lower part of ca. 9.5–11 m.y. age, and a rate of 4 km/m.y. for the upper part of 9–9.5 m.y. age (Sæmundsson et al., 1980).

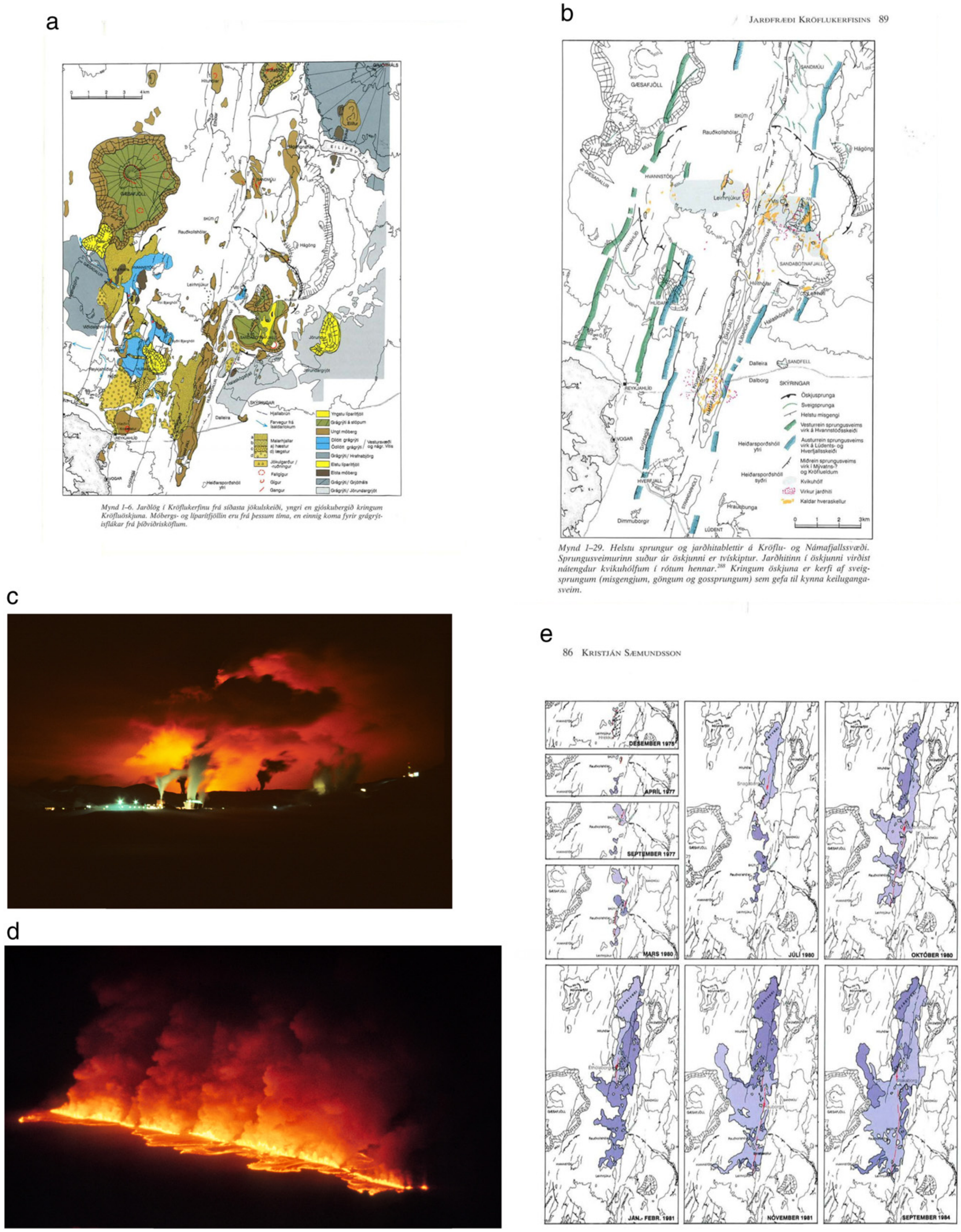
The final magnetostratigraphic survey of Kristján's collaboration with I. McDougall and N.D. Watkins took place in the Northwest peninsula, with new mapping in composite sections of over 4 km and over 3 km cumulative thicknesses, respectively through its western and eastern coastal areas. The project suffered great loss by Watkins' untimely death from cancer in 1977. His role in that survey was completed by Leo Kristjánsson who had also taken part in the Borgarfjörður and Tröllaskagi projects. Altogether 1261 lava flows were sampled for paleomagnetic laboratory studies in some 40 profiles, a world record which probably still stands. 71 flows were K-Ar dated, yielding a rate of buildup of 1.8 km/m.y. in the western section (12–14 m.y.) and 0.7 km/m.y. in the eastern one (8–12 m.y). The rate may have varied on a more local scale, as the ages obtained for a thick normal-polarity zone in the Northwest peninsula expected to date from Epoch 9 (marine Anomaly 5) did not agree well with ages of such thick zones in Tröllaskagi or in eastern Iceland (McDougall et al., 1984).

The pioneer geophysicist Ian McDougall, ANU, recalled his work with Kristján (Pers. comm. to BV, 2015):

> *"I got to know Kristján well when I was working in Iceland with Norman Watkins and Leo Kristjánsson. Kristján was critical in our aim to sample the lavas of Iceland in regard to magnetostratigraphy and age of the sequences. In collaborations Kristján was inevitably the person who understood the geologic framework better than anyone else and who was thus able to facilitate use of technology and give proper context to the interpretations. Thus our efforts were successfully accomplished. We were able in several studies to extend the geomagnetic time scale,*

which could be applied to the calibration of age of magnetic 'stripes' bounding the mid-ocean ridges, and hence rates of seafloor spreading."

The number of K-Ar dates published in the three projects alone far exceeded the total from all other studies on the Iceland lava pile to 1985. These projects encouraged new magnetostratigraphic mapping which has been ongoing in other parts of Iceland ever since, although most of the country remains virgin territory in that respect. The mapping has given rise to a data base of over 5000 stable remanence directions and intensities. From that homogeneous collection, it has been possible to obtain robust information on various fundamental properties of the geomagnetic field behavior in the last 15 m.y., not available from any other sources. These surveys have also generated much



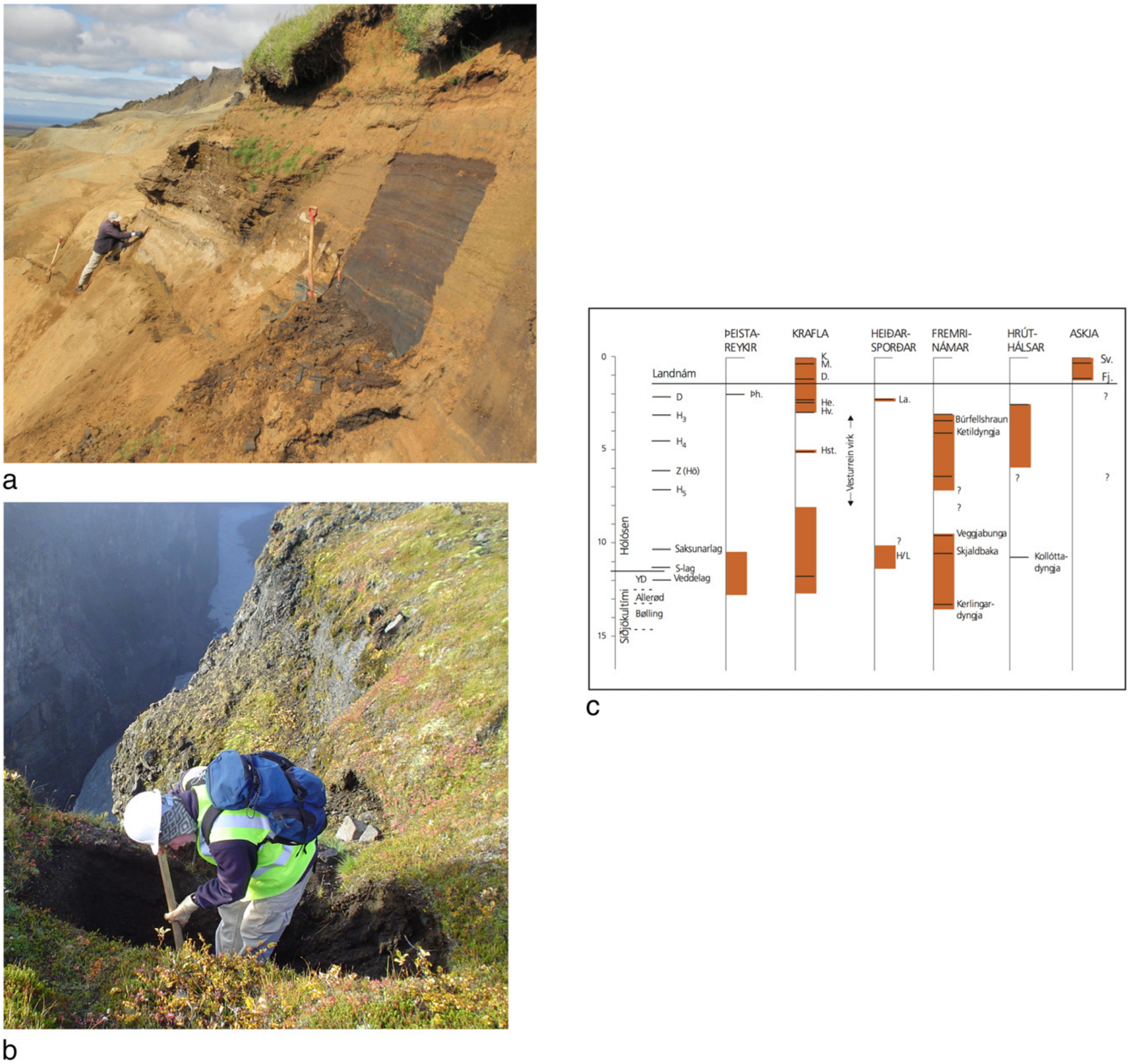
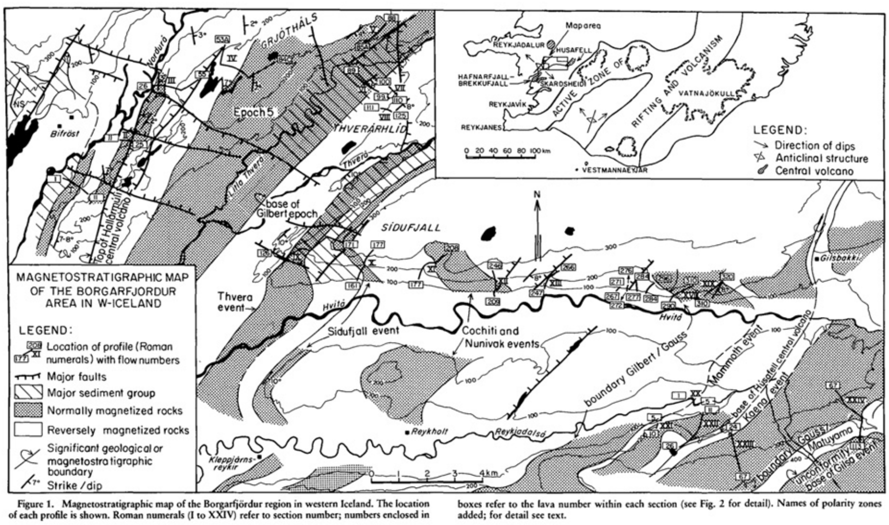


Fig. 12. Tephra studies. (a) August 2010. Kristján hard at work, scraping clean and logging tephra layers in a thick soil and sediment deposit at Sog, south of Grænadyngja on the Reykjanes Peninsula. (Magnús Á. Sigurgeirsson photo). (b) September 2006, at the edge of Dimmugljúfur (Dark canyon), the canyon of Jökulsá á Brú. Kristján and Guðrún Larsen were dating down-cutting of Jökulsá using soil sections with tephra layers on ledges in the canyon. They wanted to know when floods reached up to this level for the last time. Here Kristján is digging a pit, with a narrow "wall" of soil between the section and the precipitous canyon wall 80–90 m high to safeguard Guðrún, who says: "*I am not saying he was too daring but he was very enthusiastic*".[18] (G. Larsen photo). (c) The huge effort in tephrochronology by Kristján and his team in the Northern Volcanic Zone is intriguing, as shown by this overview figure of the postglacial eruptive history of the Northern Volcanic Zone, divided between the volcanic systems (from Sólnes et al., 2013 (eds), *Natural Hazards in Iceland*). Timeline in thousands of years shown on left axis. The last few thousands years of the preceding glacial time include the Bølling and Allured warm periods and the Younger Dryas cold period (YD). The second column shows the timing of the main tephra marker layers. Shading shows eruptive periods for the various volcanic systems. Acronyms show some known eruptions in the volcanic systems: Þh: Þeistareykir lava, K: Krafla Fires, M: Mývatn Fires, D: Dal Fires, He: Hóls Fires, Hv: Overfill Fires, Hst: Hvannstóð, La: Younger Laxár lava, H/L: Lúdent and Hraunbunga, Sv: Askja-Sveinagjá, Fj: Fjallsendi lava. Note in particular that the Fremrinámar Volcanic System was active in the period from 3000 to 8000 years ago, when Krafla was quiet with only one known eruption. Immense geologic field exploration stands behind this image, and the result is an important contribution to the understanding of interaction of overlapping volcanic systems and defining the shifts in the Tjörnes Transform Zone boundaries.

Fig. 11. Krafla Volcanic System. (a) Geological formations of the 20-km-diameter Krafla central volcano, caldera, and fissure swarm during the last glacial period (from Sæmundsson, 1991). Hyaloclastite and rhyolite mountains are formed during this time, but interglacial basaltic lavas also appear. This is just one of 13 overlay maps for Krafla produced by Kristján, each representing a specific time period. Ice interaction with eruptions resulted in hyaloclastite mountains and ridges, or table mountains of pillow lava and hyaloclastite capped with basalt. Hyaloclastites are of basalt (*móberg*, brown) or rhyolite (*liparite*, yellow) composition; basalt lava (blue, olive). The 8 × 10 km caldera fault is indicated by the heavy black line with triangular ticks. An oblique airphoto of the region is shown in Fig. 6a. (b) A simplified structural map from the 1991 paper shows the presently active fissure swarm for the last ~3000 years; fissures more than 8000 years old (outlined in blue), and a fissure swarm further west, active during mid-Holocene ~5000 years ago (outlined in green). 1- The caldera fracture (heavy black dash), 2- chief faults and fractures (lighter dashes), 3- axial zone of the Mývatn and Krafla Fires (double marked dash), 4- outlines of S-wave attenuation in the magma chamber (grey hatch, after Einarsson, 1978), 5- active fumaroles (red symbols), 6- hydrothermal surface manifestations (yellow symbols). (c) Bright gas plume illuminated on 19 October 1980 over the basalt eruption 7-km north in the Krafla fissure swarm. The people operating the 60 MWe Krafla geothermal plant are getting nervous, and that's a fact! (Oddur Sigurðsson photo). (d). Fire fountains and flowing lava from the Krafla fissure swarm, 4 September 1984 (Páll Einarsson photo). The 1984 lava extended 15 km along the swarm, from Leirhnjúkur (inside the caldera) to Gjástykki. (e) Kristján's maps of the individual Krafla Fires eruption events, 1975–1984 (Sæmundsson, 1991). Light purple are lava flows for the specifically indicated event, and the associated active eruptive fissures are shown in red. Dark purple indicates previously erupted Krafla Fire lavas.

a



b

Fig. 13. (a). There is no place on earth where a portable fluxgate magnetometer is a more useful "hand-lens" for peering into rocks than in Iceland, for keeping track of a fairly indistinctive stratigraphy directly in the field. The dominating flood basalts have strong thermal remnant magnetism, and at 65°N latitude the rock's north-pole points nearly directly down (today); or up, if the paleo-field was reversed. At the outcrop, the geologist's complex task of orienting the declination of a hand specimen is not necessary. Kristján only has to mark and keep track of the top of the sample in introducing the rock to the magnetometer's calibrated sensor. It looks like a microphone and Kristján is interviewing the rock, which, when you think about it, is what great field geologists do, asking it incisive questions (J. Aronson photo). (b). Magnetostratigraphic map of the Borgarfjörður region in western Iceland (after McDougall et al., 1977), with named polarity zones. Kristján was among the first to employ the fluxgate method extensively in the volcanic sequences of western Iceland. His field work here began in 1964, continued with Horst Noll in the late 1960s, and extended further by Kristján and students after 1970. Then, work with Norman Watkins and Ian McDougall began in 1973 on a large magnetostratigraphic study in Borgarfjörður, founded on the geologic work by Kristján and Haukur Jóhannesson. K-Ar dates from 24 flows were provided by Ian McDougall, and this nearly complete record of the geomagnetic polarity history extended the time scale of reversals based on subaerial volcanics from 4.5 to about 6.5 m.y. ago. The ages of two short events (Sidufjall and Thvera) in the Gilbert epoch were also established.

potential for new research on the mapped lava sequences, but it has only been exploited to a limited extent so far.

Besides these projects should be mentioned the important work of James Aronson and Kristján, based on sampling conducted in 1970, in which K/Ar ages for basalts were reported from older levels of the lava pile (Aronson and Sæmundsson, 1975).[19] Of importance at that time was the question of the origin of the Tertiary basalts, keyed to the geographic distribution of their age. The oldest rocks dated so far were not Eocene or even Paleocene (as had been thought up to 1968), but 16 m.y. at the northwest edge of Iceland, and 13 m.y. at the eastern edge (Moorbath et al., 1968). These ages at the extremities of Iceland were consistent with a sea-floor spreading origin for the Tertiary basalts, but there was a distinct gap in data for the central part of Iceland, and the reported age of 13 ± 2 m.y. at Borgarnes in southwest Iceland by Moorbath et al. (1968) was inconsistent with simple sea-floor spreading origin of the older rocks of Iceland. It had been argued further that old rocks occurring in the cores of structural anticlines, some of them near the Neo-volcanic zone, opposed the sea-floor spreading model for Iceland and that Tertiary lavas could underlie the entire Neo-volcanic zone (cf. Th. Einarsson, 1967a,b; Tr. Einarsson, 1965, 1967a,b,c). The four areas studied by Aronson and Sæmundsson included the Borgarnes and Hreppar regional anticlines in south Iceland, a regional anticline near Eyjafjördur, and the Tjörnes peninsula horst in north

[19] From Jim Aronson: "*Kristján has been crafting his whole career into one 'Michelangelo' major piece of art that reveals how Iceland works and did so in the past. He crafted his work-of-art career out of his character and his dedicated hard work, which he enjoyed immensely. His scholarship went in two directions, towards understanding the stratigraphy and structure of the flood basalts across the vast dissected Iceland Plateau, and through his applied work with NEA, toward understanding the geothermics and volcanology of the several central volcanoes along Iceland's present-day Axial Rift Zones, which are Iceland's best prospects for geothermal energy… we in this volume are all blessed to have learned so much from you in the field – it was more than the geology….we hope all of your precious notebooks will be preserved, protected and archived. They will inform and inspire students and scholars of Iceland forever.*

Iceland. The Tjörnes data confirmed the major role played by the Húsavík faults in the transform displacement of the Tjörnes Fracture Zone, and the other results gave firm evidence that spreading axes through Iceland had a history of shifting location, and that the regional anticlines of Iceland, a seeming structural anomaly in a spreading regime, resulted from shifting spreading axes which transitionally coexist and create regional anticlines in between.

Kristján then followed this work by directing attention to the region between Eyjafjörður and Skjálfandi in north central Iceland in a collaborative project organized with Barry Voight (Fig. 1b). No detailed geologic studies of the bedrock had been conducted in Flateyjarskagi (the name soon given to this previously un-named peninsula), but reconnaissance work by Kristján had recognized the significance of this poorly accessible region to the reorganization of crustal accretion in north Iceland, and to the evolution of the Tjörnes Fracture Zone. Their detailed work started in 1979 and included mapping, lithostratigraphy, magnetostratigraphy, and new K/Ar ages aided by James Aronson (Jancin et al., 1985, 1995; Young et al., 1985; Voight et al., 1983; Voight & Ewart, 2016).[20] Two flood basalt piles are in unconformable contact along the western flank of the Northern Volcanic Zone (NVZ, Figs. 4, 6). The older ranges in age from ~9.5 to 13 Ma, and its upper portions define a 15°–35° SE-dipping monoclinal flexure developed during early development of the present NVZ. Lavas of a flood basalt group younger than about 6.5 Ma were deposited unconformably on the flexured basalt pile. An important discovery and unique for Iceland is the 11-km broad zone of severe crustal distortion by rotational shear, associated with the active Húsavík-Flatey transform fault in the southern part of the TFZ (Young et al., 1985). Interpretation of this deformation has been debated, but paleomagnetic analyses have confirmed the huge clockwise tectonic rotation (Orkan et al., 1984; Young et al., 2018, this volume). Kristján thought this an important contribution (Pers. Comm. to BV, 2017):

> *"The time of rotation occurring early in TFZ development makes sense, with the Húsavík-Flatey fault taking up the transform movement as a narrower transform fault after the first 2 million years of rotating the borders…In discussions about the position of Tjörnes, I have maintained that it has moved some 100 km (even 120 km) east relative to its original position north of eastern Skagafjördur. I am going to keep to that."*

7. Mineral alteration in lavas and a unique book

In Iceland, buried lavas have been partly dissolved and new alteration minerals have been deposited in fissures and cavities (amygdules), in accord with the local thermal environment. Let Kristján describe it (Sæmundsson and Gunnlaugsson, 2002):

> "*The formation of amygdules depends on temperature, the type of rock and the composition of water it contains. Olivine basalts begin to alter at lower temperatures than tholeiite and rocks richer in silica. Zeolite zones are most easily identified in olivine basalts. In tholeiites, quartz minerals and silica-rich zeolites, such as mordenite, stilbite, heulandite, and epistilbite are more common. Below the zeolite zones greenschist zone minerals occur with chlorite, epidote, and finally actinolite. In central volcanoes, high temperature zones occur at shallow depth. There the deeper alteration zones of ordinary lava pile reach highest.*"

Common amygdules such as most zeolites and silica minerals form at temperatures below 200 °C. At higher temperatures, only quartz and two species of zeolites form, along with various high-temperature minerals like chlorite and epidote. The crust cools as it moves away from the rift zone where it was generated. Amygdules corresponding to the highest temperatures reached in the alteration stage remain in the rock, but at lower temperatures different mineral species may form successively on top of existing ones. Thus Iceland had long become famous to mineral collectors, for mineral-bearing outcrops near sea-level. However more significant to geologists was G.P.L. Walker's classic study of zeolites in the east of Iceland, which he discovered to be zoned more or less horizontally, with each zone having its characteristic minerals. Since Walker's (1960) study, others have added to the existing knowledge in this field, and sought to define the temperature limits of formation of individual secondary minerals. Such knowledge is very useful when boreholes are drilled in geothermal systems, especially high-temperature systems, as it reveals their temperature history (Pálmason, 1980; Arnórsson et al., 2008; Franzson et al., 2010).

In his fieldwork in western and northern Iceland, Kristján studied rock alteration and demonstrated similar patterns of secondary mineral zoning as had been found in eastern Iceland (Sæmundsson et al., 1980; McDougall et al., 1977; Jancin et al. 1985). A good example is his study at Húsavík village, where 10-my basalts are cut off by NW-SE trending Húsavík-Flatey transform faults (Sæmundsson, 1974; Aronson and Sæmundsson, 1975). Many secondary minerals in lavas were identified by Kristján, but laumontite occurs sporadically, suggesting the proximity near sea level of the laumontite zeolite facies (Sæmundsson and Karson, 2006). This implies a temperature near 120 °C at time of mineralization, which is expected at a depth of about 1500 m of rock. Exhumation of the basalts required erosion of 1500 m, with corresponding isostatic uplift. Buildup of a 1500 m thick lava pile may have taken some 2 m.y., leaving about 3 m.y. left for uplift, erosion, and intense faulting, as an age gap of 5 m.y. separates these basalts from an overlying, less faulted unit.

In earlier work, Kristján had used zeolite data to help explain the anomaly of how the regional anticlines, usually interpreted as compressional features, had developed in an environment like Iceland of evident

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[20] Kirby Young worked along with Mark Jancin in Flateyjarskagi, and got guidance from Kristján: *"The first time I met Kristján was in the first couple of days after our arrival in Reykjavík in early July 1980 for eventual fieldwork up North. Possibly that first meeting was at Kristján's flat in the early evening, while he was hosting one of the pre-eminent volcanologists of the 20th century, George P.L. Walker. Both of these scientists were soft-spoken, but nevertheless a lot was said with us added to the mix. Combined, they probably were authors or co-authors of 80% or more of the journal articles I relied on to finish my Masters paper, though I expect I didn't fully appreciate that at the time.*

Kristján supported us in every way he could regarding our field efforts up in North Iceland. He loaned us portable fluxgate magnetometers to help with our volcano stratigraphy mapping, stored our blue jeeps over the winter, and in later years with a larger flat, was able to host our stay in Reykjavík rather than us having to rely on the Salvation Army Hotel. Staying at his place was a welcome beginning to the coming two months dominated by rustic camping in our remote field locales, now and then suffering the harsh "summer" weather coastal North Iceland could bring.

I recall my first day in the field with Kristján. Being myself quiet by nature, combined with Kristján's soft spoken approach and some discomfort at speaking English, I am sure it was not the most rousing and raucous atmosphere. I selected a mountain for us to ascend where I would be able to see him in action recording lava stratigraphy. I found he indeed quickly dispatched rock samples into lithologic descriptions, paleomagnetic polarity results, and zeolite mineral identifications. But this of course turned out to be the hottest day of my four summers, easily 27C or more, and since I was carrying little water, I got sick with the heat and the day was cut short, to my great personal embarrassment. I could only surmise that he must be thinking "this is Barry's choice for his second grad student on this peninsula?" What I do recall was the speed and efficiency with which he worked at collecting observations, probably 3× or 4× faster than me, but maybe he was only 2× faster by the time I finished my four summers of field work.

My first summer of fieldwork in North Iceland included a holiday of sorts later on when we joined with an International Geological Congress field trip to Iceland during its visit in the North. Kristján was the leader for all of this segment, dealing with excursion stops ranging from Tertiary volcano stratigraphy, transform faults, Holocene volcanism, and geothermal resources. Needless to say, these were all his specialties. He was truly a renaissance scientist. That first field season for me also included by some luck a visit to a volcanic eruption at Krafla volcano. We arrived on our own, but Kristján was of course already there as I recall. It was nice to be near to him as we watched this most memorable of life experiences.

My fellow grad student Mark Jancin recounted to me that the previous summer to my first visit there, he, Professor Barry Voight, and Kristján were visiting the water-filled fissure Stóragjá near Lake Mývatn. Barry, always one to goad a self-confident personality such as Mark in a friendly if competitive way to push the envelope, wound up exploring some of the totally underwater openings to be found in the fissure. As things got more extreme in Mark's explorations (influenced not least by Mark's world-class caving experiences) Kristján blurted, 'Barry, you need to stop it, you are going to lose him!' No one was lost that day."

extensional tectonics. Kristján had noted that the relatively weak zeolite alteration in the core basalts at the Borgarnes anticline argued against the formation of the regional anticline by tectonic uplift (Sæmundsson, 1967c), and at Eyjafjördur, the highest elevations along the anticlinal axis preserve rocks that have never undergone zeolitization (Aronson and Sæmundsson, 1975). Thus these anticlines could not have formed by active compressional uplift from deeply buried levels.

Finally, Kristján's strong interest in alteration mineralogy led him to produce with Einar Gunnlaugsson an immensely useful and beautifully illustrated book on rocks and minerals found in Iceland (Fig. 14; Sæmundsson and Gunnlaugsson, 1999, 2002, 2014). It is an unusual book in the special attention given to the diverse crystalline zeolite minerals that contrast starkly with the ubiquitous grey to black basaltic rocks of Iceland, for as indicated above, these minerals are the key to understanding the past thermal structure of the Icelandic crust, glacial denudation processes, and geothermal prospecting. And noteworthy is Kristján's selection of the cover photo, showing the fairly rare zeolite *garronite*, which occurs in olivine basalt in the chabazite-thomsonite zone. This mineral was named by G.P.L. Walker (1962), after the place where it was first found, on the Garron Plateau in Northern Ireland. No doubt its selection here by Kristján was not accidental, but heralded 'a tip of his hat' toward George Walker.

8. Geothermal investigations

Iceland is rich in geothermal resources due to the volcanic activity. Although hot water from warm springs had been used locally, large-scale utilization of geothermal resources in Iceland only began in 1930 when a district heating system started operation in Reykjavik, supplying hot water to a hospital, a school, a swimming pool and some 70 homes. The utilization grew and by 1966 about 40% of Icelandic houses (mostly in Reykjavík) were heated by geothermal water, the rest mainly by oil, but production of geothermal electricity had not yet started.

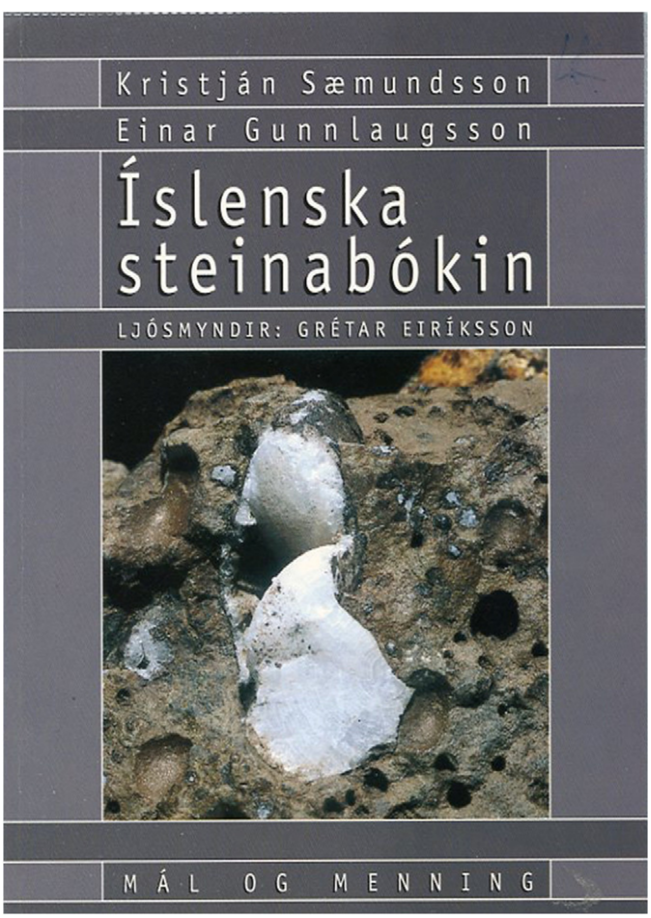

Fig. 14. The brilliant, superbly illustrated rock and mineral book produced by Kristján and Einar Gunnlaugsson is aimed at both the layman and professional. It is virtually unique for its clear exposition of the numerous zeolite minerals found in Iceland. It was produced in Icelandic, and English, editions.

Kristján officially started his professional career in 1966, and shortly afterward a huge development started in the Icelandic energy industry, in both hydropower and geothermal sectors. A political decision was made to remove fossil fuels from the house-heating sector, and harnessing of the high temperature fields for electricity and heat was vigorously initiated in the 1970s. Today 90% of houses in Iceland are heated by geothermal energy. Geothermal electric generation has also increased rapidly since 1970 with development in the Reykjanes peninsula (Svartsengi and Reykjanes), in the Hengill area in the Western Volcanic Rift Zone (Nesjavellir and Hellisheidi) and in the Northern Rift Zone (Krafla, Námafjall and Theistareykir (cf. Sæmundsson et al., 2012b)).

Sound knowledge of the geology of Iceland and related geological processes remain the basis for the successful development (cf. Pálmason, 1980; Flóvenz and Sæmundsson, 1993; Sæmundsson, 2005; Arnórsson et al., 1987, 2008; Sæmundsson et al., 2012b,c; Flóvenz et al., 2012; Georgsson et al., 2005). This was understood already by Guðmundur Pálmason in the 1960s, and young scientists were hired almost directly from the universities to build up the knowledge base for the geothermal industry. Kristján played a vital role in this development (Fig. 15) and soon became the Head of the Geological Department. Kristján organized and directed geological and geothermal surveys in active geothermal areas all over the country, often with co-workers, many of whom he had earlier trained during their university studies. In his first decade alone he had studied and written or co-written 85 reports that were archived at NEA, and hundreds more followed. Building on his extensive work within the realm of basic geological sciences, he has had a magnificent career in geothermal exploration for more than a half century. His insights and vast geological and tectonic knowledge on both high- and low-temperature geothermal areas in Iceland yielded major increases in knowledge of geothermal systems and still make him a highly sought advisor for geothermal exploration and utilization (Fig. 15c). He has mapped *all* the high temperature fields in Iceland to some extent, and *all* the developed fields in detail prior to and during the subsurface exploration. He studied the volcanic timelines of each area and unraveled the volcanic history, dated the various volcanic events, studied faults and fractures that commonly guide the flow of geothermal fluids, lava flows and hyaloclastite surface formations influencing permeability, and related the volcanic history to the geothermal activity. In addition risk assessments are needed for modern geothermal developments because most high-temperature fields are located in or near geologically active areas, and environmental studies are also required. Kristján has engaged in all of these topics (Sæmundsson, 2006; Gudmundsson and Sæmundsson, 1980; Sæmundsson and Jóhannesson, 2006; Sæmundsson and Hafstað, 2007; Thorbjörnsson et al., 2009; Friðriksson et al., 2010; Sæmundsson and Sigmundsson, 2013a,b; Sæmundsson and Sigurgeirsson, 2013).

For instance, the Hengill region is one of the most extensive geothermal areas in Iceland (110 km) and a huge geothermal resource, located at a triple junction where two active rift zones meet a seismically active transform zone (Figs. 4, 7; Clifton et al., 2002; Einarsson, 2008; Sæmundsson et al., 2016; cf. Arnason et al., 1969). Kristján showed that postglacial volcanism of the Hengill region includes three fissure eruptions of ~9, ~5 and ~2 thousand years (Sæmundsson 1995a,b; Franzson et al., 2010; Sæmundsson et al., 1990). The volcanic fissures of the latter two can be traced to the north, through the Nesjavellir geothermal field and into Lake Thingvallavatn (Sæmundsson, 1965, 1967a, 1992, 1995a). At Nesjavellir these volcanic fissures define the main outflow channel of the geothermal system, and the fissures are also believed to act as major outflow zones in the Hellisheidi field to the

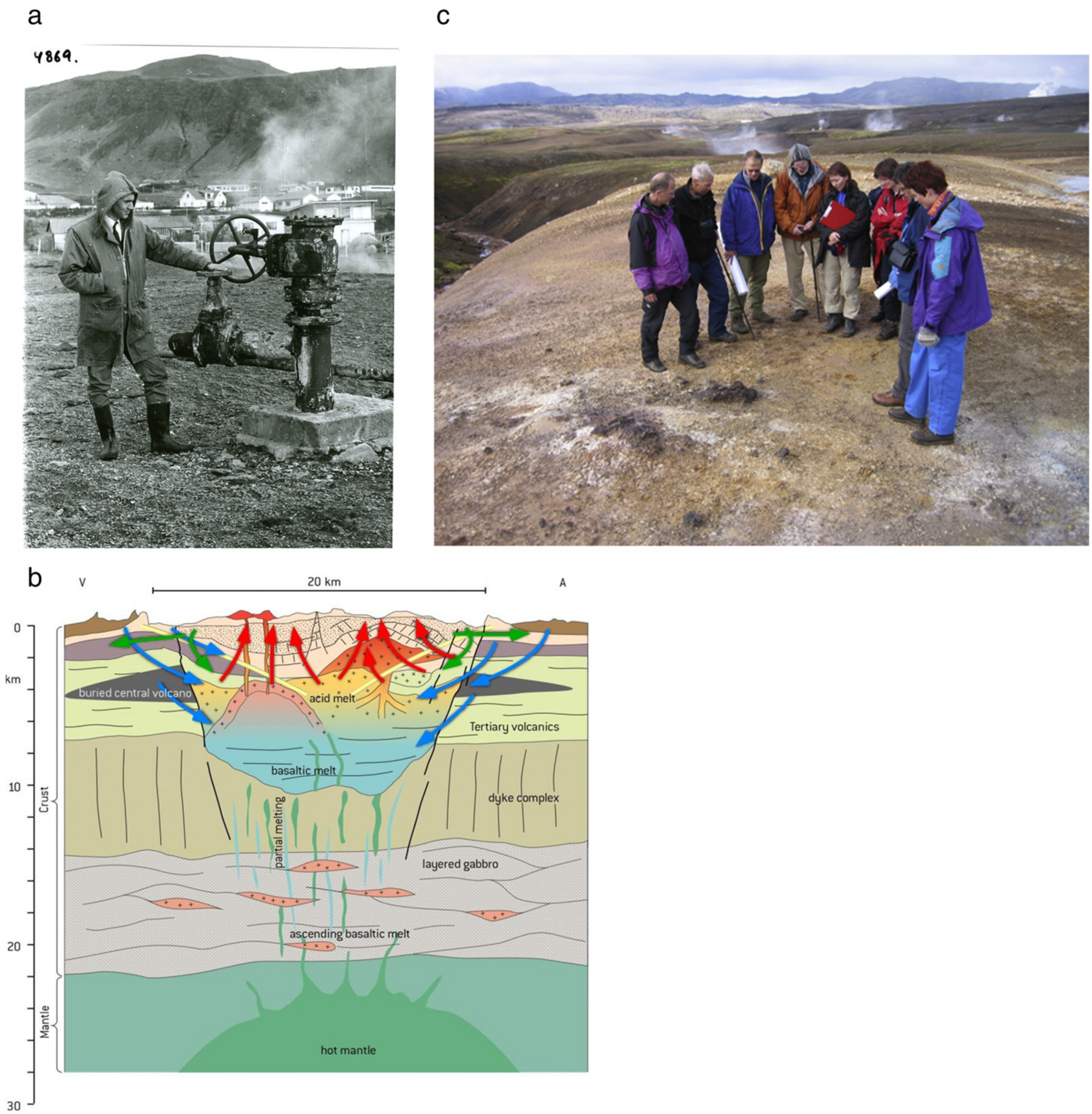

Fig. 15. Geothermal investigations. (a) A young Kristján at well no. HS-00 in Hveragerdi in 1968. A greenhouse industry grew from development at this low-temperature (c. 100 °C) geothermal field, and Kristján is immediately welcomed when he visits this community. He was on hand when the National Energy Authority began in 1967, and the first Icelandic power plant (3 MWe) came soon after in 1969. He was the lead geologist in site exploration and geothermal well drilling for virtually every geothermal project, and Ólafur G. Flóvenz has said: "*It is hardly possible to find a single successful geothermal project in Iceland without detecting Kristján's footprints*." (b) The Torfajökull system is by far the largest silicic center in Iceland, with a potential of 1000 MWe or more. KS created this schematic cross section and used it in a UNU-GTP Short Course report he gave in Kenya. Red arrows indicate hydrothermal upflow, blue arrows downflow and green arrows outflow. Stem-like conduits feed the shallow magma chamber. (c) Kristján at Hrafntinnusker, within Torfajökull central volcano. He is fourth from left, guiding specialists from the Icelandic power companies, Landsvirkjun Power and Orkuveita Reykjavíkur. The site is under consideration for new developments (ÍSOR photo).

south (Franzson et al., 2010; Hardarson et al., 2010), where they have been one of the two main drilling targets. Also, reinjection of waste geothermal fluid into geothermal systems plays an important role in present-day reservoir management and is most often environmentally necessary, and for this it was vital to define tectonic structure and geology in relation to the location of injection wells (Hardarson et al., 2010).

In one well at Nesjavellir, superheated conditions prevail at about 2100 m depth (Franzson et al., 2010). Supercritical fluids have higher enthalpy than steam produced from two-phase systems and large changes in physical properties near the critical point can lead to extremely high flow rates. The Iceland Deep Drilling Project (IDDP) was initiated to investigate this matter, and Kristján's studies provided a cornerstone to these investigations, which have been carried out also at Krafla and Reykjanes Peninsula (Friðleifsson et al., 2003, 2006, 2018; Elders and Friðleifsson, 2010; Elders et al., 2011).

Kristján's achievements are summed up by Ingvar Birgir Fridleifsson:

> *"In the high-temperature fields he has been the main geologist in detailed structural and geothermal mapping of many active central*

volcanoes, preceding the exploration drilling and later commissioning of geothermal power plants. [And] *during most of his career, he has used his distinguished skill, commonly alone, to unravel hidden treasures in the form of low-temperature water for domestic heating. This includes villages and farming communities all over Iceland, as well as individual farmhouses in more remote settings. Drilling geothermal wells is a very expensive business, and therefore Kristján's almost magic skill to site the wells for correct depth and temperature has been extremely valuable for individual farms as well as larger communities.*"

9. Outreach with United Nations University

Through Kristján's pioneering work on the geology and geothermal research in Iceland he became soon a world-class expert in geothermal development. And besides this, he was willing to aid other countries to develop their geothermal resources and skills. The Government of Iceland and the United Nations University (UNU) decided in 1978 to establish the UNU Geothermal Training Programme (UNU-GTP), with the National Energy Authority as the host institution. Ingvar Birgir Friðleifsson, who earlier had been guided by Kristján in his university work, was appointed Director of the UNU-GTP during 1979–2013. Kristján was put in charge of the geological training in exploration mapping and structural geology 1986–2006, and still remains involved in advisory missions and workshops and preparation of short-course literature. He took on many field missions to do this, and disseminated his knowledge over three decades to many hundreds of specialists in dozens of countries via the UNU-GTP. By this he contributed substantially to international science and to benefit societies in many countries.

He instructed his students in reconnaissance studies and structural mapping leading to the siting of geothermal wells, with training for both high- and low-temperature fields. Many of his students later became the leading geologists in geothermal exploration and development in their home countries. Now in places like Kenya, in addition to vital large energy production, geothermal-heated greenhouse products aid local communities just as they do in Iceland. In Fig. 16a Kristján is shown in the African Rift Valley of Kenya, instructing geothermal trainees on convecting geothermal water circulation. As the caption notes, no doubt his fingers are speaking louder than his soft-spoken words. Over the decades in the African Rift he has become a living legend (Fig. 16b) – "*the fearless geologist, never missing the opportunity to inspect good outcrops, irrespective whether lions or snakes could be lurking around*." The photograph shows Kristján with some Masai friends, who know a thing or two about lions, and clearly more than Kristján; when they enter bush country they carry spears.

Fig. 16. United Nations University geothermal training missions. (a) In Kenya in 2014, Kristján instructed geothermal trainees on convecting circulation processes of geothermal waters. Probably his fingers are speaking louder than his soft-spoken words. (b) With Masai tribesmen in the African Rift Valley. Kristján first assisted Kenya in 1979 at Olkaria Geothermal field, and returned many times since, becoming known as the "*Fearless Geologist*" in searching for outcrops in lion country and snake-infested bush. Sometimes too much passion can get a geologist into trouble, but it didn't happen to Kristján (UNU photos).

10. Honors

Kristján is widely recognized as the thoughtful, soft-spoken, modest, patriarch of Icelandic geosciences. He has never sought the limelight, for it is not in his nature to do this, and anyway he actually doesn't consider that he personally has achieved anything of such value as to deserve high honor. But few who really know him would agree with his modest self-assessment. For Árni Hjartarson,

"*Kristján is a humble and silent character and never injects himself. He is not among those who sit in the canteen telling jokes and stories, in meetings his talks are low-key, short and never preaching, at parties he never dominates with poetry and songs as so many Icelandic geologists do. He doesn't care to be the center of attention. However, everyone falls silent when he talks, and cocks his ears not to miss out on what he has to say. The voice is soft and he seldom speaks up. Despite that tranquil way his opinions and thinking, along with his writings and maps have had a resounding influence on the theoretical and practical ideas of geologists for more than half a century.*"

Yet he so exemplifies the unselfish ideals of science that it is easy to understand why Icelanders regard Kristján as a national treasure and why he was awarded the *Order of the Falcon (Knight's Cross)* by Iceland's President (Fig. 17a). One of the most prestigious national awards, it has been presented to only a handful of the most eminent scientists working in Iceland. The great geologist George Walker, a guiding light to Kristján from the 1960s, had got one and proudly wore it, and it was only fitting that Kristján should have one too – not only for his contributions to the documentation of geology and crustal processes that are relevant to both oceanic and continental terranes, but also because it is difficult to recognize any geologist worldwide that has been so consequential to improving the standard of living of a nation.

His papers from the 1960s through the millennium gave testimony of pioneering work that contributed hugely to our understanding of rifting and divergent plate tectonics and associations with geothermal activity. In recognition of this work he was elected in 1995 as *Honorary (Foreign) Fellow* of the Geological Society of America, a major award of that society with only one or two persons honored annually. And to follow this up, in 2018 the Geological Society of America awarded him the *Florence Bascom Geologic Mapping Award*, another major and coveted honor, that recognizes his superb geologic mapping that led to significant discoveries and

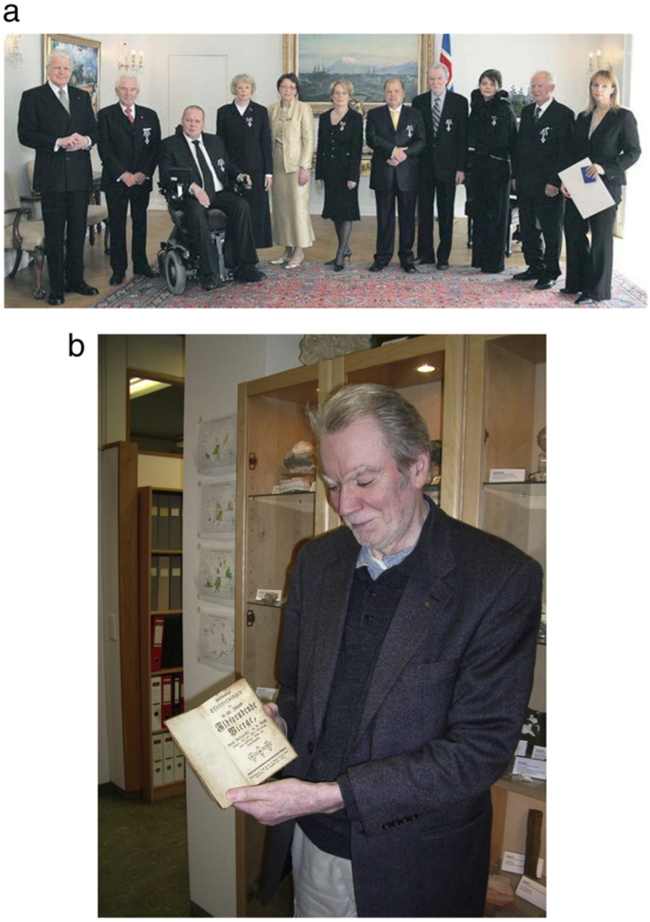

Fig. 17. Honors well deserved. (a) Kristján (4th from right) receiving the Order of Falcon *riddarakross* from the President of Iceland (in white), for his contributions in science and in advancing Icelandic geothermal developments to benefit society. 2007. (b) Kristján is an eager collector of books so when he had his 70-year birthday the staff of ÍSOR honored him with a rare, very old book (from 1757). He was very pleased, as anyone can tell. The gesture likely gave him as much pleasure as any society award he had received (I. Kaldal photo).

greater understanding of fundamental geologic processes. He was recipient also of the *Ása Gudmundsdottir Wright Award* in 2003, from the Science Academy of Iceland *(Societas Scientiarum Islandica)*, given to an Icelander for major contributions to the advancement of science.

Meanwhile Kristján had also educated several generations of Icelandic and foreign geoscientists, both as an adjunct at the University of Iceland in 1971–1980, and frequently advised on undergraduate and graduate projects and theses at the University of Iceland. In recognition of such contributions, as *"a major contributor to our advancement of understanding the geoscientific and natural potential of Iceland, and as a confirmation of our joint respect for his work, he has been unanimously elected by the Faculty of Science to receive an Honorary Doctorate at the University of Iceland."*

And as much as Kristján might respect such recognition, he no doubt appreciated more the affectionate consideration of colleagues who had nominated him. So when he had his 70-year birthday, the staff of ÍSOR collected some money and bought him a very old book – from 1757! Kristján is an eager collector of books and was very pleased as you can see from Ingibjörg's photograph (Fig. 17b). Probably he prized this gift from his good friends as much as any institutional honor he had received.

11. Legacy

Kristján's extraordinary productivity during the past half century can be partly explained by his passion and innate curiosity about Iceland's unique geologic setting, his relative comfort and pleasure in conducting strenuous fieldwork irrespective of frequently arduous conditions, and his remarkable ability to make the key observations. He has a ceaselessly enquiring mind. His forté has always been fieldwork with hammer or shovel in hand, but still he was ready to use such newly developed instruments as the fluxgate magnetometer, or airborne and satellite imagery, and was comfortable too in collaborations with both Icelandic and non-Icelandic scientists, young and old, exchanging insights with willing collaborators. Although in fact he has broad interests, he can appear as *"a geology addict. He thinks about geology and reads about geology day and night. He is a book collector, his home is packed with geological and geographical publications, paintings of volcanoes and lava fields hang on the walls*…." (ÁH).

His legacy uniquely includes a vast quantity of superb scientific maps and papers of the highest quality, impactful ideas and models generated that were internationally diffused, and the several generations of colleagues and younger people he mentored, taught, or otherwise influenced.[21,22,23] His helpful and enabling attitude towards his colleagues and students have encouraged others to adopt and propagate his open approach to science, and this certainly is part of the legacy. His monumental and enduring achievements have painted the clearest view of an extensional plate boundary anywhere on Earth. And of course it adds perspective to recall that when he began his work in

[21] One of these scientists he influenced was Amy Clifton, who began research in Iceland in the 1990s and then became a Research Associate at the Nordic Volcanological Institute. One of her research papers (Clifton et al., 2002) concerned plate movements at the Hengill triple junction. Not coincidentally, Hengill was the site of Kristján's first major investigation in Iceland, conducted years before the notion of a triple junction entered the mind of man. Amy recalls:

"He was my main contact person when I started doing field work in Iceland…. He was very generous with information and guidance and gave me copies of his unfinished map of Reykjanes…. After I moved to Iceland in 1999, I consulted Kristján many times. He was always willing to spend time with me, giving me Orkustofnun publications, unpublished maps and always good advice. Several times, he gently chastised me for not bringing a rock hammer into the field so I would know which lava flow I was in. I told him that I relied on his maps for that. He was very modest about his own work and reminded me that I should not take everything on his map as truth. He was interested in what I had to say, especially with regard to details I had noticed in the field….I always learned something new from him and I valued his support and advice".

[22] Dave McGarvie, Edinburgh: *"I have known Kristján since 1982, when I first embarked upon my PhD studying the Torfajökull volcano in Iceland. When I arrived in Iceland I was instructed to meet a senior geologist to discuss my research permit, and was unexpectedly told that there were to be constraints placed on what I was permitted to do in case it overlapped with other Icelandic workers. There was also a lack of openness and explanation. And then I met Kristján. What a breath of fresh air! Kristján's encouragement and openness were most refreshing, and what was most inspiring was his willingness to discuss what he'd seen and not yet published – "in case it might be of help to you". I learned that this was grounded in Kristján's philosophy that seeking better understanding and knowledge is what is of greatest importance. Kristján was also both humble and open, and for example when I went back to him to discuss my findings – some of which ran counter to his interpretations – he was genuinely pleased to hear that someone had spent more time there and had arrived at a different conclusion. As a mere PhD student, this was a very supportive and enabling approach, and it was much appreciated by me. It gave me confidence.*

Kristján's helpful and enabling attitude towards me (and others), naturally led to me adopting his open approach to science. And throughout my career I have openly shared field data, observations, and analytical data in the interests of furthering our science. At times to the detriment of my career, but these minor irritations are overwhelmed by the greater satisfaction of seeing good science being done by more people and on topics in which I have a great interest. Kristján is a thoroughly decent human being, and his humility and generosity of spirit are two attributes that I found particularly inspiring and influenced my further work.

[23] Yet another of many international scientists with admiration for Kristján is Carolina Rodríguez, a Chilean geothermal geologist from Santiago:

"I had the honor to meet Kristján Sæmundsson in 2008 with occasion of the IAVCEI General Assembly hosted in Reykjavík that year. Kristján generously offered his house to accommodate a group of geologists from Chile, Argentina, Colombia, Canada, Russia and USA. He knew just one person of the group, but he did not hesitate to welcome the entire group at the expense of his family's comfort. Not only did we crowd his place for seven days, he also invited all of us to join his delicious family dinner every night. Kristján also introduced us to the geology of Iceland taking us in his own car to the classic localities close to Reykjavík (Thingvellir, Reykjanes peninsula, Hekla volcano). As if that wasn't enough, he also helped us organize a post-conference field trip to visit Iceland's main volcanic centers and several important geothermal operational sites, providing us with maps, papers, and valuable advice for the travel. Little did I know that the generous person that received us was a living legend in Iceland's geology and geothermal development. He is an example as professional but also he is a notable human being, capable to transmit his knowledge with great passion and generosity, but keeping always a very humble attitude."

1960s, the relation of Iceland to sea-floor spreading was unclear and in fact vigorously opposed in Iceland, and plate tectonics had not yet been invented. It took Kristján to resolve the key tectonic obstacles by showing that the active rifting zones in Iceland had shifted over time and were linked by complex transforms to the mid-ocean spreading ridge.

Earlier we had inquired, "*It is hard to imagine where we would be in our work if Kristján had not been there before us*." So much of what we understand about processes stems from his detailed work in Iceland that could be put in a logical geological context, that could then be related to the global mid-ocean ridge system, volcanic rifted margins or volcanic rifts.

Finally, in considering Kristján's formidable scientific production it is easy to neglect the fact that his main job was simply to find and assist production of geothermal resources, and not to focus on pure science and journal publications. Thus his research achievements must be considered even more remarkable. Geophysicist Ólafur Flóvenz, a long-time colleague of Kristján and now chief of ÍSOR, thinks of him as "*a great scientist*" and has expressed his legacy concisely:

"*Kristján Sæmundsson is in my mind the main author of the modern understanding of the geology of Iceland and has contributed more to it than any other. Same applies to the geothermal sector, no single person in Iceland has contributed more to the successful geothermal development of Iceland than Kristján*."

Kristján has been an inspiration to all of us who have had the good fortune and immense pleasure to work with him. We stand in awe of his lifetime achievements in interpreting the geology of Iceland, and with profound affection for his personal qualities and humanity.

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The complete and enthusiastic support to this paper by the staffs of ÍSOR and Haskolí Íslands, among others, is most greatly appreciated. Most co-authors had the pleasure of working with Kristján, and the author list includes several classmates of the Ísland research group assembled at Köln University by Professor Martin Schwarzbach around 1960, who are happy to share memories of Kristján's adventures as a student. Fortunately during the last years of World War 2 the Royal Air Force had enabled just enough of the foundations of Freiburg and Köln to survive and facilitate reconstruction, and Kristján had taken advantage of this situation a decade after the war ended. Jörg Keller kindly provided a perspective of Kristján's days at Freiburg in the 1950s. The 1970s are also represented here by several colleagues, and many more reflect the decades since then up to the present.

Kristján did not participate in providing information for this paper; the project was an undercover operation and kept as a surprise for him. Brynja Jónsdóttir once reminded BV that "*Kristján is not that kind of a person who likes the spot light!*" BV recognizes this as an understatement, and that it's more accurate to say that he expressly takes pains to avoid it!

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