Catalogue of the Active Volcanoes of the World

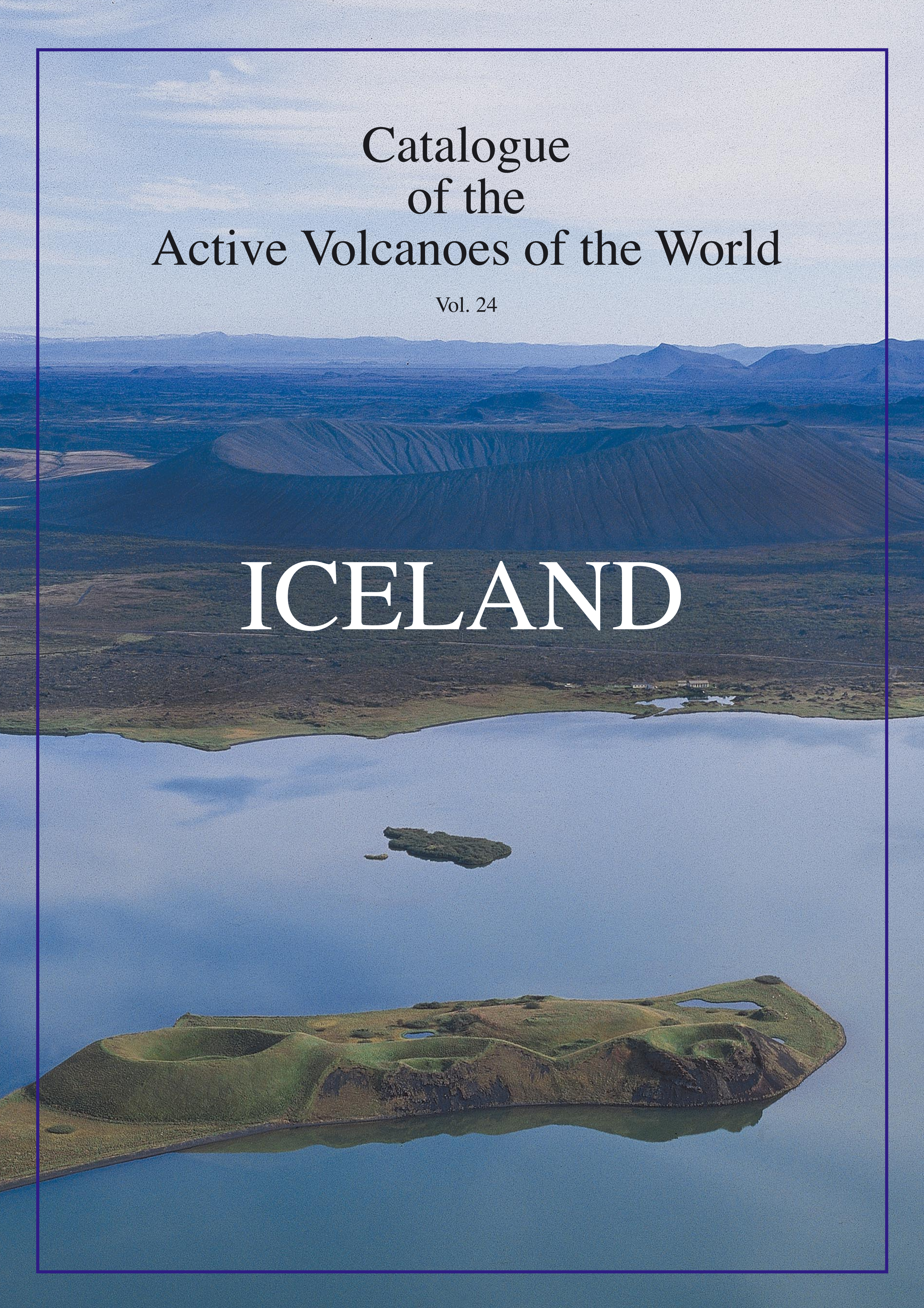
Vol. 24

ICELAND

Catalogue of the Active Volcanoes of the World

Vol. 24

ICELAND



INTRODUCTION

Iceland (Icel: Ísland) has been called a land of fire and ice, and despite the name it is better known for its volcanoes than for its glaciers — during the last 300 years, for which fairly reliable documents exist, Iceland has averaged about 30 eruptions per century. Some of these eruptions made the "world press" of the time, and even affected climate in the northern hemisphere.

Iceland is the third largest island in the Atlantic Ocean, with an area of 103,106 km^2 (39,758 sq. mi.), and average altitude around 500 m. The rate of volcanism in the country has been estimated 43,000-45,000 km^3/Myr, assuming Holocene volcanic productivity [1], at which rate the entire volume of Iceland above water (51,000 km^3 spanning 16 Myr in age) could have been produced in 1.2 Myr. This powerful source is balanced by equally powerful sinks, underscoring the extreme rapidity of geological processes in the island [2].

Iceland is situated almost entirely S of the Arctic Circle, its northernmost point, Rifstangi, lying at 66°33'N. Despite the northerly setting, the climate is temperate thanks to a branch of the Gulf stream circling the country and staving off the E-Greenland current that flows southwards from the Arctic Ocean. However, owing to the combination of high latitude and considerable precipitation, about 10% of the country are covered with glaciers, some of which are underlain by active volcanoes.

Iceland is entirely composed of igneous rocks and their erosion products. The Mid-Atlantic Ridge (MAR) crosses the country from SW to NE, and throughout Iceland's geological history (about 16 Myr) volcanic activity has been confined mostly to relatively narrow volcanic zones that are the subaerial expression of the MAR.

Fig. 1: Geological sketch-map of Iceland [10]

Geologically, Iceland can be divided into three formations that, although predominantly made of basalt, are distinguished by very different land forms: the Tertiary, Pleistocene, and Holocene.

Tertiary flood basalts (16-3 Myr) occupy the northwestern, northern and eastern parts of the country (Fig.1). The successions of flat-lying basalt, that generally dip towards the respective centers of origin, bear witness to rather flat and uneventful landscape in the Tertiary. Towards the coasts the basalt plateaux have been deeply dissected by the Pleistocene glaciers, and subsequent isostatic uplift resulted in the mountainous landscape characterizing these regions. The monotonous basalt successions are interspersed with extinct central volcanoes, but in general the individual layers of basalt represent large flows that reached far outside the volcanic zone of origin, as evidenced by the observation that the mean difference in age between two adjacent flows varies between regions from 4000 up to 10,000 yrs [3] — that of the entire Holocene.

In the Pleistocene, alternating glacial and interglacial periods resulted in the formation of mountains made up of palagonitic tuffs occasionally capped by subaerial lavas, on the one hand, and thick valley-filling basaltic flows on the other. The palagonitic mountains now exposed at the surface derive especially from the last two glaciations (~0,2 Myr). One effect of the Pleistocene was to transform Iceland from the gentle landforms of the Tertiary to the mountainous and rugged landscape of the present: Glacial erosion gouged out deep valleys and fjords towards the coasts while subglacial volcanoes created lofty palagonite hills and ridges along the volcanic zones.

Volcanic products in the Holocene are predominantly lava flows, although special circumstances (such as silicic composition, high groundwater table, or overlying glacier ice) may locally lead to explosive volcanism. Certain distinctive volcanic formations appear to be confined to the uppermost Pleistocene and early Holocene, tuyas (table mountains) and lava shields of primitive composition. These formations represent in all probability rapid and extensive magma production associated with the isostatic rebound at the end of the glaciation [4], and since then the rate of volcanism appears to have decreased exponentially, the present productivity being but

1/30th of that 10,000 yrs ago [5].

Plate tectonic setting

Iceland owes its existence in the middle of the North Atlantic to a mantle plume that, due to its high "potential temperature" has given rise to an excessively thick basaltic layer and, at the same time, buoys up that thick basaltic crust. In terms of global tectonics, it is a hot spot located at or near an accreting plate boundary. It is the largest mass of land found on the Mid-Atlantic Ridge, and the transverse ridge crossing Iceland from Greenland to Scotland is one of the most substantial aseismic ridges of the oceans (Fig. 2).

Until the mid-1960s, the extensive topographic high of which Iceland is the emergent peak, and the deep Bouguer gravity low over it, found their explanation in a light sialic base beneath the basaltic crust, a continental fragment left by the opening of the N Atlantic. This hypothesis, first promulgated by Alfred Wegener for reasons of isostasy, found added support in the abundance of silicic rocks in Iceland, which were assumed to be remelted sial [6]. Furthermore, the transverse ridge encompassing the plateau basalts of Greenland, Iceland, the Faeroes and Britain, were all thought to be early Tertiary in age, the "Hebridean," "Brito-Arctic" or "Thulean" Province. Both ideas were shown by isotope geochemistry to be wrong: the silicic and basaltic rocks of Iceland have oceanic Sr-isotope ratios, and radiometric dating showed that the oldest rocks of E and W Iceland are about 16 Ma old. All these circumstances — the topographic high, the silicic rocks, the transverse ridge, and the progression in age from the active central rift of Iceland to the Tertiary basalts of E Greenland (65 Ma) and Britain (45-50 Ma) — now find their explanation in the high productivity of the Iceland mantle plume and its position near the plate boundary. The transverse ridge, over 20-km thickness of basaltic crust, is the passive trail of the hotspot which has been active since before the opening of the N Atlantic. The Iceland Plateau, with its negative Bouguer anomaly, reflects the buoyancy of a more than 400-km deep plume of ascending hot upper mantle presently centered below SE Iceland [7]. The high proportion of silicic rocks in Iceland results from the continuous recycling of rock in a slow-spreading rift zone over a highly productive mantle plume [8] (see Petrology and chemistry, below).

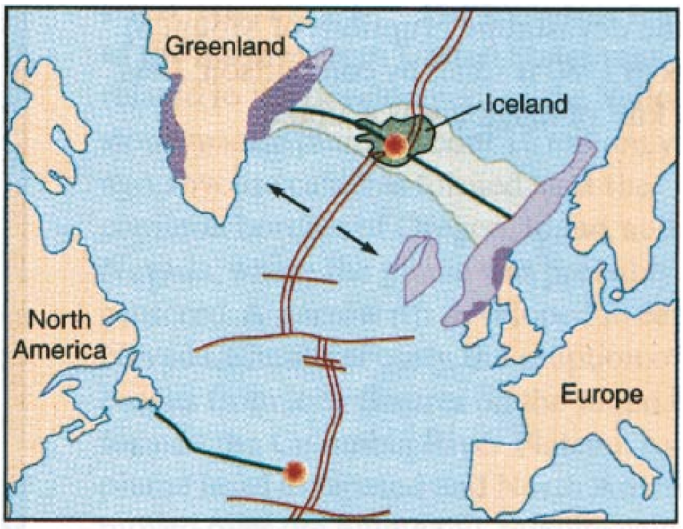


Fig. 2: Plate-tectonic setting of Iceland “at the junction of two oceanic ridges”, the Mid-Atlantic spreading ridge and the aseismic Greenland-Faroe ridge. From [45].

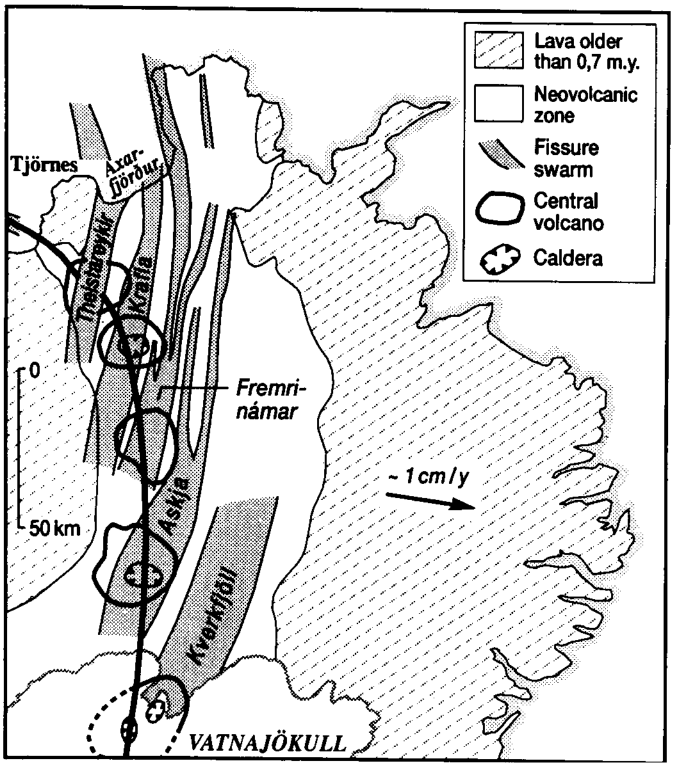


Fig. 3: At depth the plate boundary in N-Iceland underlies the central parts of the volcanic fissure swarms. From [44], modified after [46].

Kinematics and crustal structure

Present-day crustal movements in Iceland are monitored by a range of measurements, including seismics [9], satellite radar interferometry (SAR) [10], measurements of ground tilt and of strain in boreholes. A network of seismometers [11] has delineated the plate boundary (Fig. 3), relative movement on active faults, and the fact that spreading is sporadic (episodic) along the plate boundary. Tilt measurements (and, more recently, SAR) show that the Icelandic crust is extremely labile, responding almost instantaneously to changes in glacial loading [12]. Recently, the monitoring effort has shown some success in short-term prediction of earthquakes and volcanic eruptions.

The Icelandic crust, or basalt layer, is 25-35 km thick owing to the extreme productivity of the Iceland plume [13]. The upper crust (corresponding to oceanic layers 1 and 2) is characterized by rapid linear increase in P-wave velocity with depth. At V_P about 6.5 km s^{-1} the top of the lower crust (layer 3) is reached and the velocity gradient levels off sharply and may even inverse locally. The Moho beneath Iceland is very indistinct, signifying perhaps an increase in V_P from 7.2-7.4 to about 7.7 km s^{-1}. This relatively low upper-mantle velocity reflects probably the high temperature of the Iceland mantle plume compared to normal upper mantle; beneath the adjacent aseismic ridges the upper-mantle velocity is about 8.0 km s^{-1}.

Perhaps the most exceptional feature of Iceland's geology, as compared with "classical geology," is embodied in Palmason's kinematic model of crustal accretion [14] (Fig. 4). In contrast with the customary idea of horizontal layers accumulating one upon the other — in the fashion of a layer cake — the accumulation of Iceland's basalt succession takes place more in the fashion of a conveyor belt: the source is almost exclusively in the rift zone, from where the formations drift away as new rocks are formed. Both the tilt of the succession towards the rift zone, and the seismic layering of the crust, are formed in the rift zone as an integral part of the accreting process. Regional synclines in Iceland, therefore, dip towards the rift zone whence they originated, whereas regional anticlines result from rift-jumps.

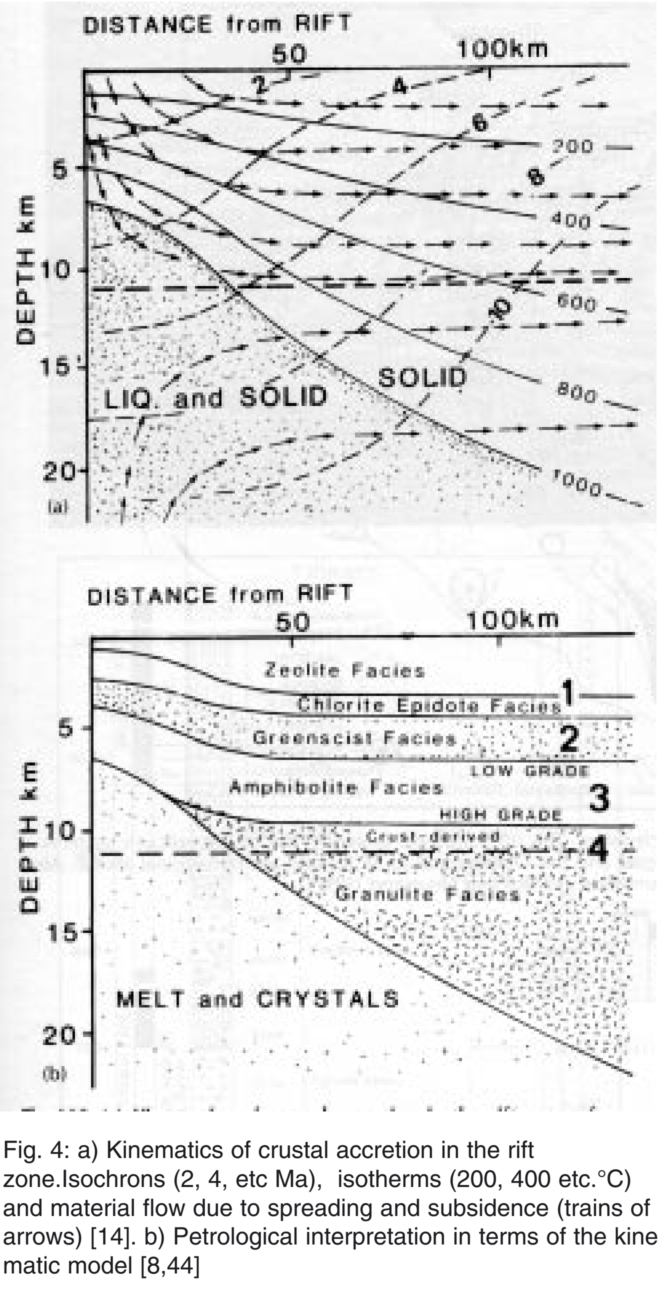


Fig. 4: a) Kinematics of crustal accretion in the rift zone.Isochrons (2, 4, etc Ma), isotherms (200, 400 etc.°C) and material flow due to spreading and subsidence (trains of arrows) [14]. b) Petrological interpretation in terms of the kinematic model [8,44]

Evolution with time

The Mid-Atlantic Ridge crosses Iceland from SW to NE, at which latitude the spreading rate is 1.95 cm/y, and the direction of spreading N103°E [15]. Relative to the adjacent oceanic Reykjanes and Kolbeinsey Ridges, the plate boundary in Iceland is displaced some 100 km to the E by a set of transform faults or fracture zones, the Tjörnes Fracture Zone (TFZ) in the N, and in the S by the Reykjanes Transform Fault and S Iceland Seismic Zone (SISZ). The Central Iceland Transverse Zone, previously the site of a transform, seems to be all but extinct, with the activity taken up by the SISZ. Focal mechanism studies show that movement on the TFZ is dextral strike-slip, and on the SISZ sinistral strike-slip. During the geological history of Iceland, the present configuration of volcanic zones has come about in a series of ridge jumps and rift propagations, caused by the gradual WNW drift of the North Atlantic Plate system relative to the Iceland mantle plume (Fig. 5). The three flank zones termed, respectively, the Snaefellsnes, Southern, and Öræfajökull volcanic zones, are all distinguished by volcanics of alkalic tendency resting unconformably upon much older basement, as opposed to the tholeiitic rocks of the rift zones. Each of the three has its own distinct tectonic origin: the Snaefellsnes zone is a volcanic outlier in the W plate, representing a dying remnant of an earlier configuration — prior to the eastward relocation of the rift system some 6 Myr ago, it corresponded to the Central Transverse Zone. Conversely, in S Iceland the rift zone is propagating southwestwards into a 10 Myr old plate; the Surtsey eruption 1963-67 represents the southernmost site of volcanic activity yet. Finally, the Öræfajökull zone in SE Iceland may represent the opening up of old crust above the mantle plume.

Volcanic systems

Crustal spreading and volcanism on the median rift zones takes place on discrete fissure swarms strad-

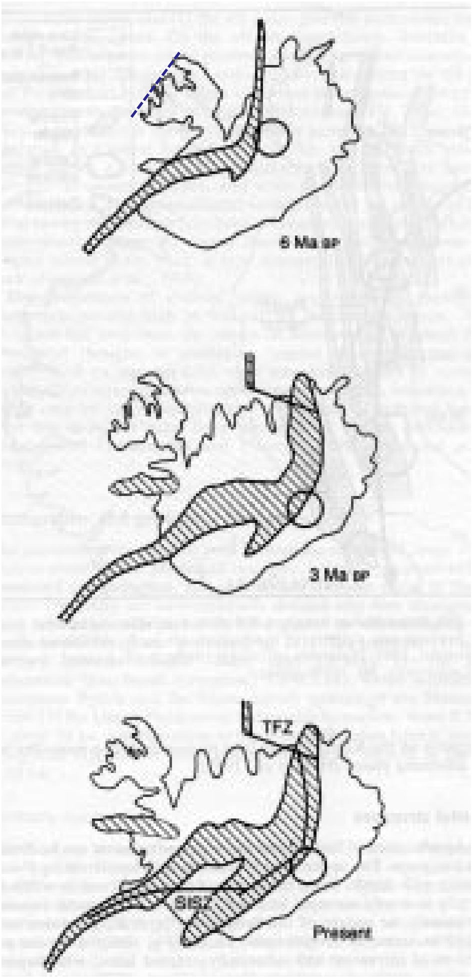


Fig. 5: Summary of the tectonic evolution of Iceland, with reference to the Iceland mantle pllume (circle). TFZ: Tjörnes Fracture Zone; SISZ: South Iceland Seismic Zone [44]. The broken line in the uppermost Figure indicates the position of the rift 15 m.y. ago [43]

dling the plate boundary in an en echelon array (Figs. 3 and 6). The swarms may be 10 km wide and 100 km long. They are characterized by extensional tectonic features such as open fissures, graben structures and crater rows at the surface, and dikes and normal faults at deeper levels. The central, most active part of each system, overlying the plate boundary, is frequently the site of a central volcano, characterized by a range of compositions from basaltic to rhyolitic, and a high-temperature geothermal system. The central volcano together with the fissure swarm transecting it form a comagmatic entity termed a volcanic system. In the Reykjanes Peninsula (SW Iceland) the relationship between the plate boundary and the volcanic systems has been elucidated by seismics [16]: epicenters defining the plate boundary below about 3 km depth cluster along a narrow vertical plane striking N80°E, whereas shallower epicenters fall along the strike of the fissure swarms, about N40°E. Historical accounts and seismic monitoring over the last 20 yrs has revealed that rifting in individual fissure swarms is episodic, with activity moving from one system to the next. In the years 1975-1985 such event took place in the Krafla system in N Iceland where, after 250 years of quiescence, the 80 km long fissure swarm underwent about 5 m extension, accompanied by nine lava eruptions and lateral dike injection at depth.

Evolution of volcanic systems

Based on geological mapping of extinct volcanic centers, it is estimated that their lifespan may be 0.3 to more than 1 m.y. [18]. The various stages of their evolution can be seen in Iceland, from the "primitive" fissure swarms in the westernmost Reykjanes peninsula, to "mature" centers like Krafla or Askja [19]. The relationship seen in Figs. 3 and 6 indicates that magma enters the upper crust at the intersections between the fissure swarms and the plate boundary. At the depth where isostatic equilibrium is reached, magma pools to gradually form a magma chamber. During spreading episodes, magma empties from the magma chamber into the adjoining fissure swarm, as seen in the Krafla Fires 1974-85.

As the volcanic center develops, silicic magma starts forming by remelting of hydrated basalt. The magma chamber, as it evolves chemically, rises in the crust and finally the roof caves in, forming a caldera (e.g. Askja). When the crust is relatively thin, as in the rift zones, it is unable to support lofty edifices and consequently the volcanic centers never take the form of classical central volcanoes, unlike for example Snæfellsjökull and Öræfajökull which stand on thick off-rift crust.

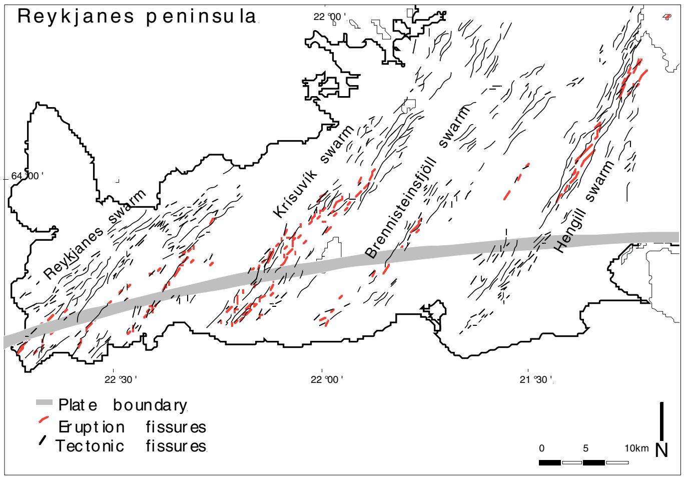


Fig. 6: Below 3 km depth the plate boundary, as shown by seismics, forms a vertical plane striking E-W. The fissure swarms strike NE-SW. Volcanic centers form at the intersections of the two. [17]

External factors in volcanism

A great variety of volcanoes and volcanic formations exist in Iceland. Single eruptions range in volume from a few cubic meters to 50 cubic kilometers, compositions range from picrite to rhyolite, the eruptive environment ranges from subaquatic to subglacial to subaerial, and so on. Thorarinsson classified basaltic subaerial volcanoes in Iceland according to shape of eruption vent, on the one hand, and explosivity on the other (Fig. 7).

External factors affecting the volcanic products are, of course, primarily water and its various forms of occurrence — ground water, surface water, or glacier ice.

The palagonitic tuyas and ridges, so characteristic for the Upper-Pleistocene formation in Iceland, are now known to be the products of subaquatic—mostly subglacial—volcanism. When fully developed, these formations are composed of three main divisions: pillow lava at the base, followed upwards by pillow breccia grading into tuff, and finally capped by lava flows (Fig. 8). This sequence is associated with the interaction between magma and the overlying water and ice during the eruption: Pillow lava forms as long as the external water pressure is sufficient to contain the volatiles dissolved in the magma. As the vent builds up towards lower water pressures, the magma starts foaming in the crater to explode into glassy shards; finally, once the vent reaches out of the water, normal lava flows are formed. This entire scenario was played out during the Surtsey eruption 1963-67, when also it was found that the palagonitization of the hyaloclastite tuff is in reality an integral part of the eruption, taking place during the cooling of the volcanic pile [21].

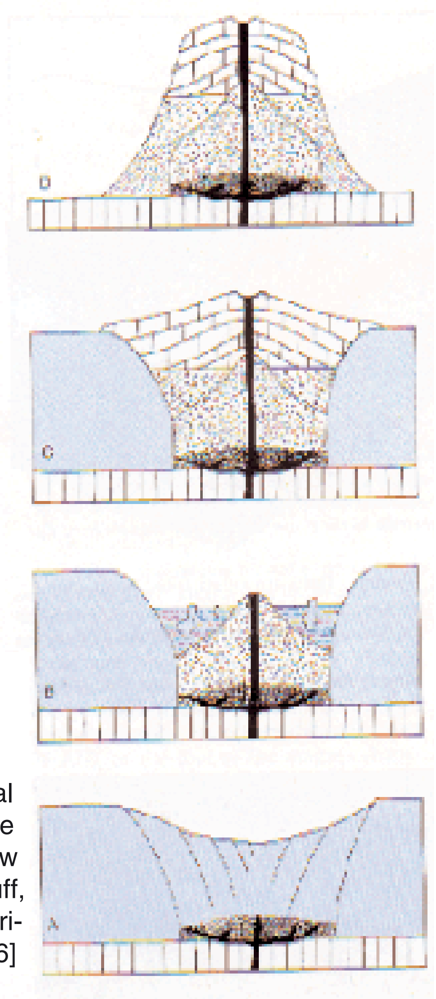


Fig. 8: The evolution of a subglacial volcano, “tuya” (Icel. stapi). As the external water pressure on the vent decreases, pillow lava is followed by tuff, and in turn by subaerial lava flow. From [16]

Only a minority of subglacial/subaquatic volcanoes have developed all three facies: many mountains lack the lava cap, some are entirely built up of hyaloclastite, and a few only of pillow lavas [22].

Interaction at shallow levels between ground water and basaltic magma results in hydromagmatic volcanism and the formation of tuff craters. Many such formations exist in Iceland, both single craters (Fig. 9) and crater rows (see e.g. Vatnaöldur, 1703-02B). When fluid lava flows over marshy ground, the lava causes the underlying water-logged sediment to compact and squeeze water into the lava, resulting in explosions which give rise to rootless craters (pseudocraters) which in some instances make extensive fields in Iceland (Fig. 10). These crater fields were formerly attributed by some volcanologists to "areal eruptions" [23].

Fig. 7. Subaerial basalt volcanoes in Iceland [20].

Eruption products		Form of feeder channel		Addenda
		Short fissure or tubular channel	Long fissure	
Decreasing temperature Increasing explosivity and production rate ↓	Lava Effusive activity	Lava ring Type: Eldborg near Krýsuvík		Lava lake usual in crater
		Lava shield Type: Skjaldbreidur		The lava flows are mainly pahoehoe (Icel. *helluhraun*)
	Lava and tephra Mixed activity	Agglutinate cone Type: Búrfell near Hafnarfjördur	Crater row Type: Threngslaborgir	The crater rows of mixed eruptions often develop craters of both types, The lava flows are mainly aa (Icel. *apalhraun*)
		Scoria cone Type: Búdaklettur	Crater row Type: Vikraborgir	
	Tephra Phreato-magmatic activity	Tephra cone Type: Raudaskál	Tephra cone row Type: Vatnaöldur	The volcanic activity is influenced by contact of magma with water
		Tephra ring Type: Hverfjall		
		Maar Type: Grænavatn	Explosion chasm Type: Valagjá	

Fig. 9: The tephra ring Hverfjall by Lake Myvatn . Photo KPS

Tephras and tephrochronology

All soils in Iceland are Holocene in age, having accumulated on ice-polished bedrock and debris left by the Pleistocene glaciers. For centuries it was understood that the "sand bands" in the soils, well known by diggers of peat, are layers of volcanic ash, and in the 1930s Sigurdur Thorarinsson began studying and mapping them systematically with the aim of using them to date soil profiles, archeological remains, etc. Tephras [24] from Icelandic volcanoes are found over most of Iceland, the surrounding sea floor and adjacent countries on both sides of the Atlantic, including the Greenland ice sheet. Through tephrochronology the volcanic history of Iceland and its individual volcanic systems is being traced 12,000 years back in soils and lacustrine sediment, and on the sea floor and in distant lands much farther back. It is one of the most powerful tools in Icelandic volcanology.

Fig. 10: Pseudocraters north of the Laki-1783 fissure

Petrology and chemistry

The exposed volcanic pile of Iceland is built up predominantly of basaltic lava flows (80-85%), with silicic and intermediate rocks constituting about 10%. [25] (In the Holocene, the proportion of evolved rocks may be as small as 3% [26]). In a typical Tertiary section, volcanogenic sediments amount to some 5-10%; in the Quaternary areas, however, they form a much greater part of the succession owing to the influence of the glaciation on both volcanism and denudation [27]. The silicic rocks are confined to volcanic centers of which about 65 are known in the Tertiary formation, and around 30 in the Quaternary and Holocene areas, respectively (Fig. 13). Recent investigations have shown that (1) the rift zones give rise to tholeiitic basalts and their derivatives and (2) the off-rift Snaefellsnes, Southern, and Öraefajökull volcanic zones produce alkaline to transitional-alkaline rocks (Fig. 14); (3) there is a systematic variation along the rift zone and

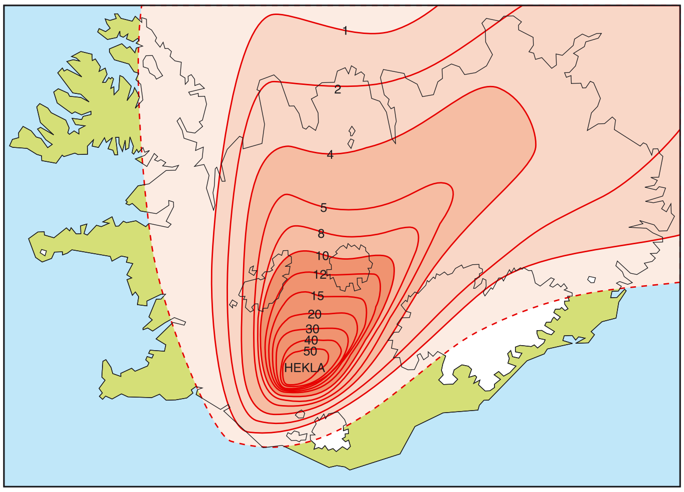


Fig. 11: Isopach map of the Hekla tephra H_3, about 2800 BP (From [16], redrawn after Thorarinsson, 1961)

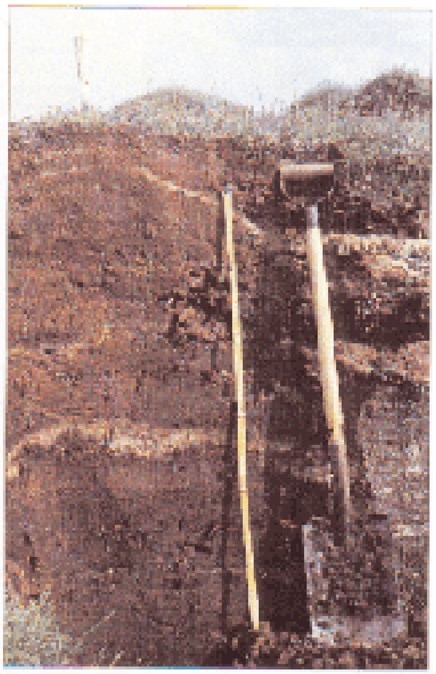


Fig. 12: Section in N Iceland showing three Hekla tephra layers, H1 (1104 AD), H3 (2800 BP) and H4 (4000 BP). From [16].

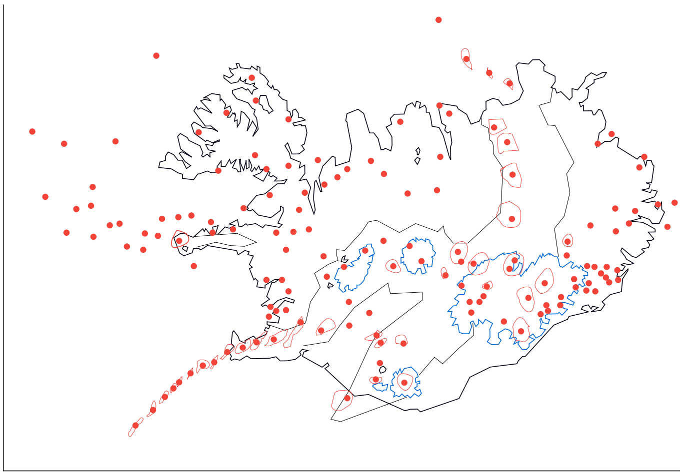


Fig. 13: Volcanic centers (red dots) and active volcanic systems (red curves). Major glaciers (blue) and the neovolcanic zones (black) are indicated. Redrawn afters [28].

the adjacent oceanic ridges in various petrochemical properties (predominantly the range of basalt compositions (Fig. 15); the volcanic productivity varies systematically along the rift zone, with a maximum in Central Iceland (Fig. 16); and (5) each volcanic system shows a range in compositions, from 'primitive oceanic tholeiite' to quartz tholeiite, and even to silicic and minor intermediate rocks [32]. The compositional variation along the rift zones (Fig 17) has by different authors been ascribed to heterogeneities in the upper-mantle source [33], to crystal fractionation, or to anatexis and magma mixing in the crust [34]. It now appears that all processes are at work [35].

The proportion of evolved rocks, predominantly rhyolites and dacites, is surprisingly high in Iceland considering its tectonic setting at the junction of two oceanic plates. In this respect Iceland is entirely different from, for instance, the Hawaiian islands, where such rocks hardly occur at all [36]. Intermediate rocks are much less common than either basalt or rhyolite, and a Daly gap is frequently present in individual volcanoes. Indeed, the evolution of the silicic rocks, and the 'Daly gap', has in Iceland long been the object of controversy. Ever since Robert Bunsen's suggestion 150 years ago that beneath Iceland there exist two magma sources, basaltic and rhyolitic [37], three schools of thought, in particular, have argued their respective case: Remelting of an ancient sialic crust was disproved in 1965 by Sr isotopes [38]; crystal differentiation still has vociferous proponents, whereas a very strong case for the dominating role of anatexis of hydrated basaltic crust has in recent years been provided by isotope geochemistry [39].

Geothermics

At present, over 40% of Iceland's energy consumption is geothermal, mostly in the form of space heating (homes and greenhouses), but also for industry and the production of electricity. The regional heat flow in Iceland falls within the heat flow anomaly of the Mid-Atlantic Ridge crest and varies between about 80 and 300 mWm^{-2} [40]. Low- and high-temperature thermal areas are distinguished empirically by the geothermal gradient in the uppermost 1km of the crust. The low-temperature areas are characterized by a gradient of less than 150°C km^{-1}, by a relatively low degree of thermal metamorphism, and by hot springs and geysers. The water is exclusively percolating groundwater, usually mildly alkaline.

Hot springs are found in more than 300 localities spread all over the country, although there are very few in the E and SE. The largest spring,

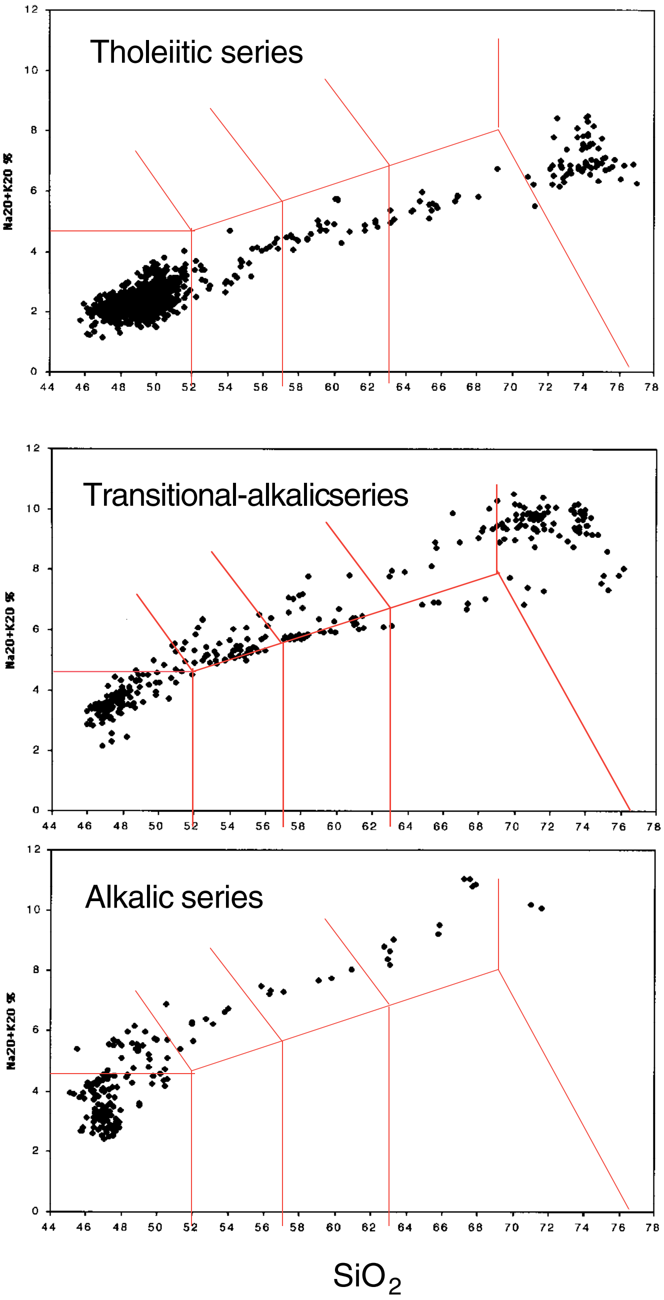


Fig. 14: Total alkalis vs. silica for the three petrochemical series in Iceland — whole-rock analyses of Upper Pleistocene and Holocene rocks. Data from [29].

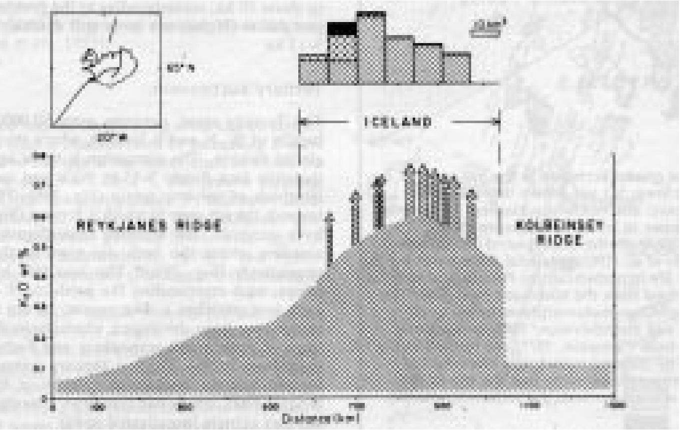


Fig. 15. Volume (upper) and LIL-element (K_2O) variation along the rift zone and adjoining ridges. From [44].

Deildartunguhver in W Iceland, has a discharge of 180 l s^{-1} of 100°C water (Fig. 18).

The 22 known high-temperature areas are part of active volcanic systems in the rift zones. The geothermal gradient in the uppermost 1km exceeds 200°C km^{-1}. Steam vents in the high-temperature areas discharge carbon dioxide, hydrogen sulfide and hydrogen. Their fluid is derived almost exclusively from percolating groundwater, whereas the heat and the volcanic volatiles are probably derived from cooling intrusions at relatively shallow depths. The mineral content of the high-temperature water depends systematically on the temperature [41]. Large deposits of silica sinter have formed in two high-temperature areas, including that of the Great Geysir in S Iceland. In the Reykjanes Peninsula some of the geothermal systems are characterized by highly saline brines due to the infiltration of sea water.

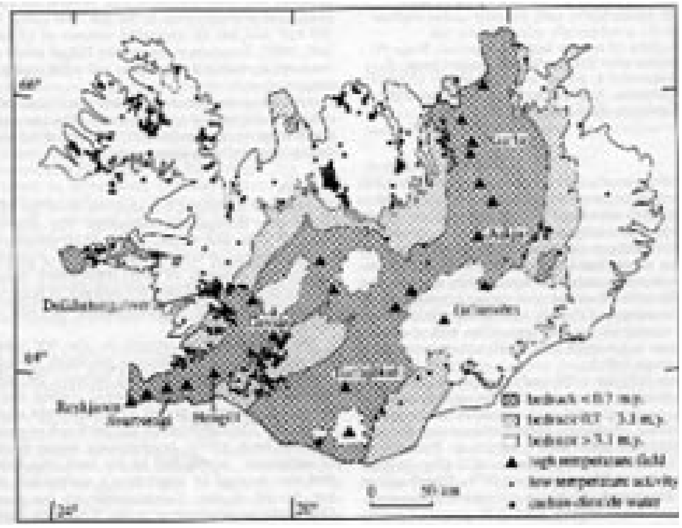


Fig. 18: Distribution of geothermal activity in Iceland. High-temperature activity is confined to the neovolcanic zones, and carbonated water typically to the off-rift Snaefellsnes Zone. From [44]

References

1 Jakobsson 1979; Sæmundsson 1979
2 Steinthorsson 1987
3 e.g. Watkins & Walker 1977; McDougall et al. 1977, 1984; Saemundsson et al. 1980
4 Sigvaldason et al. 1992; Hardarson & Fitton 1991; Jull & McKenzie 1996
5 Sigvaldason et al. 1992
6 Walker 1966
7 Tryggvason et al. 1980, Wolfe et al. 1997
8 Óskarsson et al. 1982
9 www.vedur.is
10 www.norvol.hi.is
11 www.raunvis.hi.is
12 Tryggvason 2000, Sigmundsson 1990
13 McKenzie & O'Nions 1991; Bjarnason et al 1993; Staples et al. 1997
14 Palmason 1973, 1986
15 DeMets et al. 1990
16 Einarsson 1991
17 after Jakobsson et al. 1979 and Einarsson 1991
18 Saemundsson 1979
19 Steinthorsson et al. 1987
20 Thorarinsson & Saemundsson 1979
21 Jakobsson & Moore 1986
22 Jakobsson 2000 (Abstract)
23 e.g. Hans Reck, see Rittmann 1960
24 Thorarinsson's term for all types of pyroclastics, from Aristoteles' Meteorologica
25 Jakobsson 1979
26 Sveinn Jakobsson, pers. comm.
27 Saemundsson 1979
28 Kristjansson & Helgason 1988
29 Jakobsson 1972
30 Schilling 1973; Brooks & Jakobsson 1974; Sigvaldason & Steinthorsson 1974
31 Jakobsson 1979
32 e.g. Carmichael 1964
33 Schilling 1973
34 Oskarsson et al. 1982
35 Hémond et al. 1993
36 e.g. Marsh et al. 1991
37 Bunsen 1851
38 Moorbath & Walker 1965
39 Sigmarsson et al. 1992; Hémond et al. 1993
40 Freidleifsson 1979
41 Gislason & Arnorsson 1990
42 Steinthorsson et al. 1987
43 Hardarson et al. 1997
44 Steinthorsson & Thorarinsson 1997
45 Hamblin & Christiansen 2001, Fig. 22.18
46 Björnsson 1985