Mineral Resources in Iceland Volume II

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Ores

By

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»HÉR ER NÓG UM BJÖRG OG BRAUÐ,
BERIRÐU TÖFRASPROTANN;
ÞETTA LAND Á ÆRINN AUÐ,
EF MENN KUNNA' AÐ NOTA' HANN«

»If you have the magic touch,
we are rich in food and such.
Those who are both smart and wise
The land will reward with a prize«

Jón Ólafsson (1850-1916)

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PREFACE

Mineral resources and mines are in many ways a basic need of any society and will always be a driving force in exploration for such matters. Such exploration in Iceland has been done in three main phases. A few of the early Icelandic settlers to America and Australia got hooked on gold exploration at the onset of the nineteenth century, and brought the knowledge back on return home. This caused the first enthusiastic search which continued for more than two decades. The second one is centred on an ambitious effort of the Yugoslav geologist Slobodan Janković in the early seventies, who travelled around the country with a number of geology students exploring for economic resources, particularly metals around large intrusions. The third phase started in the early nineties with the new knowledge of a close relation between geothermal systems and deposition of gold and other metals. A good example of this is the metal rich scales found at well heads in the high-temperature geothermal area in the Reykjanes peninsula, which is similar to conditions in black smokers. Exploration phase of such type of resources is still ongoing with new locations found.

This book that the reader is now getting into his hands, is an independent continuation of the book "*Mineral Resources in Iceland - Coal Mining*" written by Pokorný et al. 2021. Second volume, entitled "*Mineral Resources in Iceland - II. Ores*" summarises the history from the first prospector (Gísli Magnússon "the wise" (1621-1696) who initiated considerations of possible occurrence of economic deposits of base metals and gold, silver, and other precious metals. The book is an interesting mixture of historical accounts, newspaper stories and scientific results, the last being based on the best results available at the time. It is divided into two main chapters; the first one describes the main ore deposits in old eroded volcanic centres and silicic bodies in the east and then younger systems in the south as well as still active systems on the Reykjanes peninsula. Other types of deposits were explored such as black sands and sediment ores. The second section includes four story-cases about gold, followed by silver, copper, zinc, titanium, iron, aluminium, and radium. The final chapter focuses on ores in Faeroe Islands which has a similar basic geology as Iceland.

Vigdís Harðardóttir (GRÓ – The Geothermal Training Programme)
Hjalti Franzson (ÍSOR – Iceland Geosurvey)

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The first author, Richard Pokorný, extend sincere gratitude to his family, especially his wife Gizela and children Jakub, Jáchym, and Emma. Their unwavering support was instrumental in bringing this book to fruition. Without them, this endeavour would not have been possible.

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INTRODUCTION

Iceland is not a place boasting of rich and plentiful mineral deposits. This fact, however, did not leave the island aside in various attempts at mineral prospection – ranging from amateur ventures to thoroughly planned scientific expeditions.

One of the first prospectors who initiated considerations of possible occurrence of economic deposits of base metals, or even precious metals, in Iceland was Gísli Magnússon (1621–1696), also known as Vísi Gísli (loosely translated as “Gísli the wise”). Being the son of a renowned Icelandic lawyer Magnús Björnsson and Guðrún Gísladóttir, he received education at various schools in Iceland and abroad. After graduation, he was holding the position of a sheriff (sýslumaður) at Rangárþing County in SW Iceland.

In addition to his official duties, Gísli Magnússon was involved in a number of scientific projects; among others, he has been documented to experiment with the growing cereals, vegetables and potatoes around the year 1670. Moreover, he was thinking of metal mining and smelting, extraction of salt from seawater and the mining of sulphur and processing. He even sent his essays about his ideas and experiments to the Royal Court in Copenhagen. In these documents he mentioned the presence of gold, silver, copper, mercury and iron deposits in Iceland and asked for a consent to their exploitation, offering to deduct a one-tenth share of all extracted metals to the king. Gísli Magnússon also proposed that, if the mining licence was agreed upon by the king, he would send experts to Iceland at his own expense. These would include metallurgists and mint masters responsible for the mintage of Icelandic gold and silver coins produced from metals from the local mines.

These proposals by Gísli Magnússon were realised to a limited extent only: he was mercifully granted permission for exclusive rights to extract and sell sulphur from Icelandic deposits by the king Christian V (1646–1699) for an annual fee of 100 gold rigsdalers. His other plans, however, got no positive response.

A certain impact of Magnússon’s letters on the proceedings at the Royal Court in Copenhagen can be, however, still perceived. Þorkell Arngrímsson Vídalín (1629–1677) was sent out to Iceland by a royal decree several years later to search for ore deposits. Vídalín was an educated man from Iceland who studied medicine in Copenhagen and possessed wide knowledge also in other scientific disciplines: he got closely acquainted with the operation of ore mines during a trip to Norway, and received geological expertise from the Danish physician and naturalist Ole Worm (Springborg 1991). During his trip across Iceland, Vídalín was guided by a Norwegian miner called Pétur bergmaður (Pétur "rockman", Anonymus 1988b).

The first note related to a systematic description of the inanimate nature of Iceland dates to the 18th century. This text, named "*Um steina, mineralia og málma*", was written by scholar Jón Ólafsson (1705–1779). It stated that "...minerals are rare in Iceland…" The same comment was made by the author in relation to metals, starting the chapter "*Um málmana – De metallis*" with the following words: "…Neither metals can be commented much. In my opinion, the story of Mr. Þorkell Arngrímsson[1], who was sent out to Iceland to study ore deposits as a chemical engineer, is correct. After his return, he reportedly informed Christian V, the King of Denmark and Norway (1670–1699), that metals were present in such low amounts in Iceland that their mining was not worth the effort …"

In the next paragraph, however, Ólafsson complemented this sceptical statement with a more optimistic view that "…a variety of good metals, possibly even gold and silver, could be retrieved from areas of hot springs on condition that chemical procedures were known to release these materials from rocks and sands…" – see Fig. 1.

Ólafsson concluded his paper with a statement on the present condition of metallurgy in Iceland, listing the metals commonly imported to the island: "…gold, silver, iron, steel, copper, brass, copper, tin, lead and other cheap metals …" (Ólafsson 1737, Steinþórsson 2002, 2003).

Nevertheless, some other authors were more optimistic in their statements. In the years 1749–1751, Iceland was visited by the Danish lawyer Niels Horrebow (1712–1760). His journeys on the island were spent by studying economics, social life and natural phenomena. In his report he mentioned that "…silver is abundant here…" and described that local farmers were proudly displaying buttons smelted from domestic precious metal (Horrebow 1752). He was so convinced of the yield of Icelandic silver deposits that he proposed to the King of Denmark to send miners there without any fear of failure (Anonymus 1988b).

These scholars and travellers were followed by many others who pursued the dream of ore mines in Iceland. Their efforts, achievements and failures are the subject of the book you are holding in your hands now.

[1] Þorkell A. Vídalín and Jón Ólafsson were close friends (Springborg 1991).

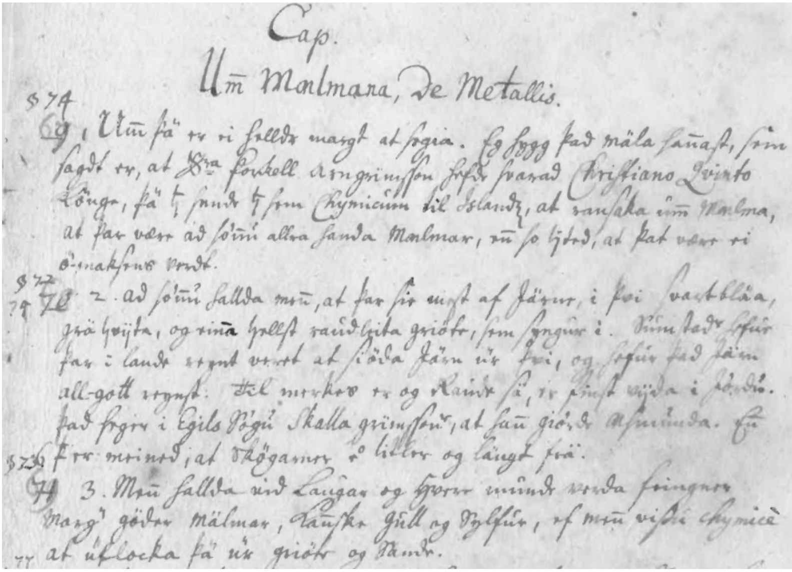

Fig. 1 Excerpt from Jón Ólafsson's manuscript (1737), the introduction to the chapter *Um málmana / De metallis*.

Tab. 1 List of base metal-bearing minerals and their sites in Iceland from important mineralogical databases (Schalkhausser 1984, Sæmundsson and Gunnlaugsson 2010, Guðmundsson 2011, Mindat.org). As will be shown in the following text, there are significantly more locations with the occurrence of ore minerals in Iceland.

Mineral name	Chemical formula	Area	Site
IRON			
hematite	Fe_2O_3	Southwest Iceland	Hvalfjörður fjord
		South Iceland	Ölfus municipality
		West Iceland	Snæfellsnes Penninsula
		Southwest Iceland	Svínahraun
		Southwest Iceland, Krýsuvík geothermal area	Krýsuvík hot spring
		North Iceland, Skútustaðahreppur	Krafla Volcano
		South Iceland, Vestmannaeyjar	Heimaey Island, Eldfell
		South Iceland, Rangárþing eystra	Fimmvörðuháls 2010 eruption site
		Southwest Iceland, Reykjanesbær	Helguvík
limonite	$FeO(OH)\cdot nH_2O$	Southeast Iceland, Lón	Össurá Valley
		Southwest Iceland, Krýsuvík geothermal area	Krýsuvík hot spring
		Northwest Iceland, West Fjords	Óshlíð
		West Iceland	Skarðsheiði
		West Iceland	Snæfellsnes Penninsula
		Southwest Iceland, Reykjanes Penninsula	Trölladyngja
maghemite	$\gamma\text{-}Fe_2O_3$	North Iceland, Skútustaðahreppur	Krafla Volcano
magnetite	$Fe^{2+}Fe^{3+}{}_2O_4$	West Iceland	Borgarfjörður area
		Southwest Iceland	Reykjavík, Geldinganes
		South Iceland	Raufarhólshellir

		Southeast Iceland, Lón	Össurá Valley
		North Iceland, Skútustaðahreppur	Krafla Volcano
		Southwest Iceland, Grindavík town	Svartsengi Power Station
		West Iceland, Snæfellsnes Penninsula	Ljósufjöll Volcano
		Southwest Iceland, Reykjanesbær	Helguvík
		South Iceland	Þórsmörk
		South Iceland, Rangárþing ytra	Torfajökull central volcano
		Northwest Iceland, West Fjords	Kleifaheiði quarry
		East Iceland	Þingmúli
pyrite	FeS_2	Southeast Iceland, Lón	Svínhólar
		Northwest Iceland, Króksfjörður	Kambsfjall
		Southwest Iceland	Reykjavík
		North Iceland	Mývatn
		Southwest Iceland	Hvalfjörður fjord, Hvalstöðin
		North Iceland	Gljúfurá Valley
		South Iceland	Ölfus municipality
		Southwest Iceland, Krýsuvík geothermal area	Krýsuvík hot spring
		Southeast Iceland, Lón	Össurá Valley
		North Iceland, Skútustaðahreppur	Krafla Volcano
		Southwest Iceland, Grindavík town	Svartsengi Power Station
		East Iceland, East Fjords	Seldalur Valley, Oddskarðsvegur
		North Iceland	Siglufjörður (quarry)
		North Iceland	Vaðlaheiði Tunnel
		Southwest Iceland, Krýsuvík geothermal area	Trölladyngja, Sog Valley

pyrrhotite	Fe_xS	North Iceland, Skútustaðahreppur	Krafla Volcano
		West Iceland, Snæfellsnes Penninsula	Ljósufjöll Volcano
siderazot?	FeN_x	Southwest Iceland,	Krýsuvík geothermal area
siderite	$FeCO_3$	Northwest Iceland	Fitjárdalur
		Southeast Iceland, Lón	Svínhólar
		Southwest Iceland, Krýsuvík geothermal area	Trölladyngja, Sog Valley
		West Iceland, Snæfellsnes Penninsula	Vestfjarðavegur (Nr. 60)
szomolnokite	$FeSO_4 \cdot H_2O$	North Iceland, Skútustaðahreppur	Krafla Volcano

COPPER

brochantite	$Cu_4(SO_4)(OH)_6$	Southwest Iceland, Krýsuvík geothermal area	Krýsuvík hot spring
covellite	CuS	Southwest Iceland, Krýsuvík geothermal area	Krýsuvík hot spring
		Southeast Iceland, Lón	Össurá Valley
chalcanthite	$CuSO_4 \cdot 5H_2O$	Southwest Iceland, Krýsuvík geothermal area	
chalcopyrite	$CuFeS_2$	Southwest Iceland, Grindavík town	Svartsengi Power Station
		Southeast Iceland, Lón	Össurá Valley
kröhnkite	$Na_2Cu(SO_4)_2 \cdot 2H_2O$	South Iceland, Rangárþing eystra	Fimmvörðuháls 2010 eruption site
malachite	$Cu_2(CO_3)(OH)_2$	Southeast Iceland, Lón	Össurá Valley
rosasite	$(Cu,Zn)_2(CO_3)(OH)_2$	Southeast Iceland, Lón	Össurá Valley

LEAD

galena	PbS	Southeast Iceland, Lón	Össurá Valley

ZINC

sphalerite	ZnS	Southeast Iceland, Lón	Össurá Valley
rosasite	$(Cu,Zn)_2(CO_3)(OH)_2$	Southeast Iceland, Lón	Össurá Valley

TITANIUM

aenigmatite	$Na_4[Fe^{2+}{}_{10}Ti_2]O_4[Si_{12}O_{36}]$	South Iceland, Rangárþing eystra	Þórsmörk extrusive occurrence
anatase	TiO_2	Southwest Iceland, Krýsuvík geothermal area	Krýsuvík hot spring
		North Iceland, Skútustaðahreppur	Mývatn, Krafla Volcano
		Vestmannaeyjar town	Heimaey Island, Eldfell volcano 1973
ferrian ilmenite	$(Fe,Ti)_2O_3$	West Iceland, Snæfellsbær, Snæfellsnes	Ljósufjöll volcanic system
ilmenite	$Fe^{2+}TiO_3$	East Iceland, Fljótsdalshérað	Þingmúli
		South Iceland, Rangárþing eystra	Þórsmörk extrusive occurrence
		West Iceland, Snæfellsbær, Snæfellsnes	Ljósufjöll volcanic system
"leucoxene"	mixture of Fe-Ti oxides	North Iceland, Húnaflói	Vatnsdalur, Skessusæti
pseudobrookite	Fe_2TiO_5	North Iceland, Húnaflói	Miðfjörður, Berg
rutile	TiO_2	Southeast Iceland, Lón	Austurhorn and Vestrahorn intrusions
		Southeast Iceland, Hornafjörður	Laxádalur Valley

titanite	$CaTi(SiO_4)O$	East Iceland, Fjarðabyggð	Reydarfjörður drill hole
		North Iceland, Skútustaðahreppur	Mývatn, Krafla Volcano
var. titaniferous magnetite (=Ti-magnetite)	$Fe^{2+}(Fe^{3+},Ti)_2O_4$	South Iceland, Rangárþing ytra	Torfajökull central volcano
		North Iceland, Skútustaðahreppur	Mývatn, Krafla Volcano
		West Iceland, Snæfellsbær, Snæfellsnes	Ljósufjöll volcanic system

CHROME

chromite	$Fe^{2+}Cr^{3+}{}_2O_4$	East Iceland, Fljótsdalshérað	Þingmúli

COBALT

heterogenite?	$Co^{3+}O(OH)$	Southwest Iceland, Krýsuvík geothermal area	Trölladyngja, Sog Valley
um2008-29-f:cofehn?	$(NH_4)(Fe,Co)_2F_6$	South Iceland, Rangárþing ytra	Hekla volcano

I
GEOLOGY OF ICELAND

Iceland is a part of the Mid-Atlantic Ridge and covers an area of approximately 103.000 km^2. The Mid-Atlantic Ridge comes ashore in Reykjanes in southwest Iceland and continues to central Iceland where it joins the southern volcanic zone. The volcanic zone then extends to the western Vatnajökull glacier where the zone changes direction and strikes due north where it jumps to the west along the Tjörnes Fracure Zone and continues towards Jan Mayen.

The Mid-Atlantic Ridge marks the boundary between the Eurasian and American tectonic plates. The ridge exhibits seismic and volcanic activity as the plates move towards the east-southeast and west-northwest respectively.

The volcanic zone in Iceland is characterised by fissure swarms and active volcanic systems along the divergent plate boundary. Volcanism is most active in the volcanic systems, which sometimes evolves into a central volcano with basic, intermediate and acid volcanics, often accompanied by a high-temperature geothermal area. The fissure swarms are 10-100 km long and up to 20 km wide, and consist of open fissures, normal faults, graben structures and dykes at deeper levels. Tectonic fissures are commonly arranged en echelon and the volcanic fissures as well. The active period of the volcanic systems has been found to vary from 300.000 years to over 1 m.y. (Sæmundsson 1979).

Two volcanic areas lie outside the main volcanic zone, the Snæfellsnes volcanic zone in the west and the Öræfjajökull volcanic zone in the southeast. The last eruption in the Snæfellsnes zone occurred shortly after 870 in the Rauðhálsar volcano. In the Öræfajökull central volcano, a significant acid eruption (10 km^3) took place in 1862, and a small basaltic eruption occurred in 1727.

The opening of the North Atlantic Ocean 55-60 m.y. ago is demonstrated by extensive basalts in the British Tertiary Province in Ireland and Scotland and the Faroe Isles and the basaltic provinces in E and W Greenland and Baffin Island. The basalts are mainly lava flows from eruptions on land or from subaquatic eruptions. In the British Tertiary Province extinct central volcanos with caldera collapses and variable chemistry are similar to the younger Icelandic central volcanos e.g. in eastern Iceland (Sigmundsson 2006).

The spreading of the Mid Atlantic Ridge i.e. the central rift zone is controlled by a mantle plume beneath Iceland and is reflected e.g. in anomalies of isotope ratios such as $^{87}Sr/^{86}Sr$ and $^{3}He/^{4}He$ being elevated over Iceland (Schilling 1986, Sigmundsson 2006).

The stratigraphy of Iceland extends from the Miocene with few interruptions to the present day. During the Pliocene (5.3-2.6 my) the climate gradually cooled, and glaciers began to develop in high mountains. In the Pleistocene, i.e. the Ice Age (2.6-0.001 my), glacial periods alternated with warmer interglacials. Modern Icelandic landscapes formed to a large extent during the Ice Age when glaciers sculpted the surface during the cool periods.

The oldest rocks are located in the northwest, north and northeast, dating back ca. 16 million years in the Western fjords (Moorbath et al. 1968). Volcanic activity has been more or less continuous, including postglacial times with eruptions occurring, on average, every 5 years. The petrology has not changed much from the Miocene to the present being mainly basaltic. In postglacial times the active rift zone has been producing mostly basaltic rocks (92%), basaltic-andesite (4%), andesite (1%) and dacites and rhyolites (3%) most of which are lava flows (Jakobsson 1979).

The stratigraphy of Iceland is correlated to the international time scale but it is also divided into local units which can be distinguished in the field and be mapped out. The local stratigraphy relies to a large extent on the geomagnetic polarity of the volcanic rocks, measured in the field and laboratories. The four most recent polarity epochs are the Brunhes epoch of normal polarity (0.8 m.y. to present), Matuyama reverse (2.2-0.8 m.y.), Gauss normal (3.6-2.2 m.y.) and Gilbert reversed polarity epoch (5.2-3.6 m.y.).

The Brunhes normal epoch started some 800.000 years ago and rocks from this time are usually unaltered and easy to map in the field. Rocks from Brunhes are marginal to the rift zone which itself is also from Brunhes.

Tab. 2 Stratigraphy of Iceland and local usage and naming of certain geological periods which are practical for e.g. geological mapping.

Years/m.y.	System/Period	Series/Epoch	Local usage
871-0	Quaternary	Holocene	Historic
11.700-871			Recent
/0.8-0.012		Pleistocene	Upper Pleistocene
/1.6-0.8			Pleistocene
/2.6-1.6			Plio-Pleistocene

/3.3-2.6	Tertiary/ Neogene	Pliocene	
/5.3-3.3			Upper Tertiary
/16-5.3		Miocene	Tertiary

The term Plio-Pleistocene refers to the period from the base of the Mammouth reverse polarity event at 3.3 m.y. to the top of the Gilsá event at 1.6 m.y. This covers the lower part of the reverse polarity epoch Matuyama into the Gauss epoch. The Tertiary is to a large extent formed by extensive lava flows interlain with thin red dustbeds, and numerous central volcanoes can be identified in the Tertiary series. From the onset of the Plio-Pleistocene cooler climate is evident as conglomerates of fluvial and fluvioglacial origin become more frequent in the lava pile in contrast to the more regular Tertiary lava pile. The Plio-Pleistocene series becomes more varied and evidence of subglacial eruptions appears frequently in the lava pile.

The relatively long geomagnetic chrone named Anomaly 5 of normal magnetic polarity (chrone 5n.2) has been identified in the Western Fjords and correlated to magnetic anomalies of the ocean bottom west of Iceland. This anomaly dates from 10.95-9.74 m.y. and is also observed in eastern Iceland (Sæmundsson 1979, Cande and Kent 1995).

Conglomerates and tillites older than the Mammouth event suggest cold periods in the upper Tertiary and the presence of local glaciers in higher places. Evidence of regional glaciations in Iceland is observed in the Jökuldalur and Fljótsdalur valleys in eastern Iceland from about 3.3 m.y. Older cool periods have been observed in marine sediment cores, but from 4-5 m.y. to 11.000 years some 20 glacials and interglacials have been identified in the lava pile by hyaloclastites (subglacially formed volcanics) and tillites (Geirsdóttir et al. 2007). During glacials the country was to large extent covered by ice but in the interglacials the country was much like today. Subglacial eruptions produced hyaloclastite mountains, while lavas were formed during warmer periods.

Volcanism continued throughout the Ice Age but as the magma in subglacial eruptions could not spread along the surface it piled up beneath the glaciers. In eruptions along volcanic fissures the volcanic material piled up to form long hyaloclastite ridges which are today very conspicuous in the landscape. In eruptions along short fissures or in a restricted area the material piled up above the eruption site and formed round hills, often shaped by later glaciers. In prolonged eruptions the magma sometimes managed to break through the glacier and subaerial lavas could flow from the crater and form lava-capped mountains (tuya), which stand out in the present landscape.

Icelandic landscapes of today were to a large extent formed during the Pleistocene when hyaloclastite mountains and ridges formed in subglacial eruptions and glaciers carved the surface to form deep valleys exposing deeper levels of the strata. The depth of erosion is a few hundred metres to ca. 1000 m at the most. The level of erosion can be roughly estimated from different mineral zones, using, calcite, zeolites, epidote and other minerals.

The deepest erosional levels extend into the epidote-actinolite zone representing temperatures above 230°C, mainly near old and extinct central volcanoes and at depths below 1000 m (Nouraliee 2000).

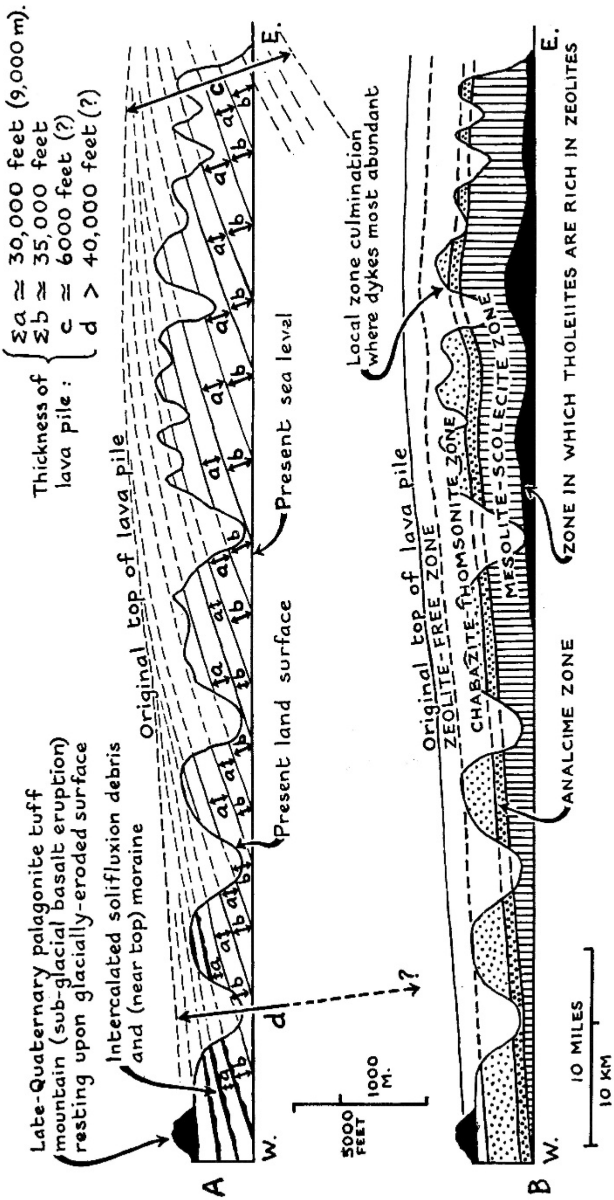

Fig. 2 Schematic sections across the Tertiary lava pile in eastern Iceland and the top of the original surface as inferred from zeolite zones (Walker 1960).

After the Ice Age ended ca. 11.000 years ago volcanic activity has mainly consisted of basaltic lavas from fissure eruptions. In the central volcanoes, on the other hand, explosive volcanism was mainly due to more viscous rhyolitic magma or when basaltic eruptions occurred beneath glaciers still occupying high places (Katla, Grimsvötn).

The volcanic zone in Iceland is chacterized by fissure swarms and active volcanic systems which are found along the divergent plate boundary. Seismicity is mainly confined to the axial rift zone, the South Iceland Seismic Zone (SISZ), a left-lateral transform zone in the southern lowlands and the Tjörnes Fracture Zone (TFZ), a right-lateral transform zone in northern Iceland (Sigmundsson 2006). Earthquakes are usually small, rarely exceeding M 4.5, the largest ones having been estimated to have been up to M 7-7.5 in the southern lowlands (SISZ) and N Iceland M 6.2-7 (TFZ). Volcanic eruptions are usually preceded by periods of lifely earthquakes (Einarsson and Björnsson 1979, Sigmundsson 2006).

Volcanism in the last 1100 years is most active in the central volcanos (Hekla, Katla, Grímsvötn, and Askja) and is confined to the 41 volcanic systems within the volcanic zones. Eruptions outside the central volcanos are mainly in crater rows producing basaltic lavas. The central volcanos have built up large mountains ranging up to 2110 m (Öræfajökull) and with glaciers covering all or large parts of the volcano (Eyjafjallajökull, Katla, Bárðarbunga, Öræfajökull, Grímsvötn, Kverkfjöll). Eruptions beneath glaciers produce vast quantities of tephra (airborne pyroclastics of all sizes), either basic or acid. The widespread tephra layers are very useful for e.g. dating soil horizons, eruptive history of volcanoes and in archaeological studies. The basic tephra layers are black but the acid ones are white to yellow in colour.

In historic times the subglacial eruptions have produced vast quantities of tephra but also large glacial floods have accompanied these eruptions. These floods have accompanied subglacial eruptions in e.g. Katla in southern Iceland, the latest one in 1918. These floods carry with them large quantities of sediments which have formed the large sandur areas in southern and southeastern Iceland.

The island of Surtsey, south of the Vestmannaeyjar Isles, was formed in an eruption in 1963-1967 where the volcano was built up from the oceanic bottom at 130 m below sea level. Surtsey consisted in the beginning only of tephra but in the end lavas were extruded and formed a cap which still protects the island from breaking down and disappearing into the ocean.