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The Glacial History of Iceland During the Past Three Million Years

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The glacial history of Iceland during the past three million years

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Iceland is built up of volcanic rocks with sedimentary interbeds, which have been piled up continuously since Miocene times. In the Pleistocene rock series, sediments of fluvial, lacustrine, marine and glacial origin and soils are very common and frequently thick. A sudden climatic deterioration took place at about 3 Ma BP. The Pliocene lusitanic marine fauna was replaced by a boreal fauna. Conifers and deciduous forest vanished and the flora became similar to the present one. From 3 to 2 Ma BP, inland ice caps were common during cold spells. From then on ice sheets reaching down to sea level have covered most of the country at least 12 times during glacials.

Introduction

Iceland is situated on the active Mid-Atlantic Ridge in the North Atlantic. It forms the middle part of the extensive Brito-Arctic volcanic area. The opening of the North Atlantic Ocean in late Cretaceous and early Tertiary times was accompanied by volcanic activity in the adjacent regions; volcanic activity persists at present only in Iceland and Jan Mayen.

Iceland is almost wholly built up of volcanic rocks which have been piled up more or less continuously since Miocene times. The oldest rocks so far dated by the K–Ar method show ages of 14–15 Ma (Gale *et al.* 1966; Moorbath *et al.* 1968; Albertsson & Einarsson 1982; McDougall *et al.* 1984). The bedrock in Iceland can be divided into three major formations: the Tertiary Plateau Basalt Formation, the Grey Basalt Formation (3–0.7 Ma), and the upper Pleistocene Palagonite Formation (younger than 0.7 Ma).

Sediments of varying origin make up 2–10 % of the thickness of the Tertiary strata, whereas their Quaternary counterpart constitutes, in places, up to 50 % of the thickness of the Quaternary pile. Some of the sediments are good indicators of climate, i.e. the palaeosols and tillites (diamictites); others contain fossils, which are also useful for the interpretation of past climates. Volcanic rocks are in themselves evidence of past environments; for example, hyaloclastite ridges and table mountains can in most cases be considered to have been heaped up subglacially during glacials and lava flows formed during interglacials.

Present climate

The climate of Iceland is affected very much by both the movement of the polar front, i.e. the boundary between cold air masses from the polar regions and the warm air masses from the south, and also by the movements of the boundary between Arctic and Atlantic sea water. The mean temperature in southern and western Iceland is 10–11 °C in July and 0 to −1 °C in January. The corresponding figures for northern and eastern Iceland are 8–11 °C and −2 to −4 °C respectively. At present, glaciers cover 11 260 km² or 11 % of the country; the biggest is Vatnajökull, which has an area of 8300 km². The annual precipitation varies greatly from about 400 mm in northern Iceland, to 800 mm in the southwest, and to some 3600 mm

on the southeastern coast. The precipitation on southern Vatnajökull above the snowline at 1000–1100 m is 4000 mm; on Mýrdalsjökull the precipitation is some 6000 mm. North of Vatnajökull the snowline lies above 1700 m (Eythorsson & Sigtryggsson 1971).

The Irminger Current flows clockwise around Iceland. The temperature on the south coast is 11 °C in August and 6–7 °C in March; on the north coast it is 8 °C and 2–3 °C respectively. In cold years, drift ice can occasionally block the north and east coast; this last happened during the winters of 1965 and 1968. In cold years the cold East Greenland Current can block off the Irminger Current at the northwestern peninsula, causing the north and east coasts to be dominated by the Arctic seawater (Stefánsson 1981).

The Last Glacial and Holocene as a model for past glaciations in Iceland

At the maximum of last glaciation, Iceland was almost completely covered by glaciers. End-moraines, probably of Weichselian age, have been found on the shelf, approximately 130 km off Breiðafjörður, west Iceland, at 150–250 m depth (Ólafsdóttir 1975). The ice divide of the main glacier was some 50 km south of the present water divide. According to the height of subglacially formed table mountains of Weichselian age, the surface of the ice sheet was probably no higher than 2000–2500 m at the ice divide. On the northwestern peninsula and Snæfellsnes and the highlands in northern and eastern Iceland, there were independent ice caps and valley glaciers. During the retreat some re-advances occurred, the latest being the Álftanes stage (about 12 ka BP correlated with the Older Dryas) and the Búði stage (11–10 ka BP, Younger Dryas). Marine beds of Kópasker age (i.e. Bølling) and Saurbær age (i.e. Allerød) have been found at different places in western and northern Iceland. By 8 ka BP the glaciers were probably smaller than the present ones (Einarsson 1985).

Owing to isostatic and eustatic sea-level adjustments, the greater part of the lowlands was flooded by the sea as the glaciers retreated. The highest shorelines are approximately 100 m above present sea level in south Iceland and 30–60 m elsewhere. They are probably of Saurbaer age (12–11 ka BP). The isostatic readjustment was very rapid and by 9 ka BP the shore was everywhere lower than today and probably at −20 m by 8 ka BP.

The late glacial and early Holocene marine fauna was similar to the present one. However, arctic species like *Portlandia arctica* are seen to have lived only at glacier snouts in fiords. In late-glacial times the temperature of the sea on the south and west coast of Iceland can be considered to have been only 2 °C lower than at present (Einarsson 1985). It is also worth mentioning that only two ice-wedge casts have been found in late-glacial sediments in northern Iceland; this observation indicates that the climate was not very cold during late-glacial times (Norðdahl 1983).

No plant-bearing deposits (peat or lacustrine sediments) have been found in Iceland from late-glacial times, although up to one half of the country was already ice-free during the Saurbær and Búði stages. The oldest organic sediments so far found are of Preboreal age and contain a flora similar to the present one.

Several hypotheses have been presented on the origin of the Icelandic flora, which contains about 450 species of vascular plant of which over 98% are of European affinity. One of the hypotheses assumes that one half of the flora survived the last glacial in ice-free areas, mainly in northwest, north and east Iceland. About 25% were introduced after the human settlement

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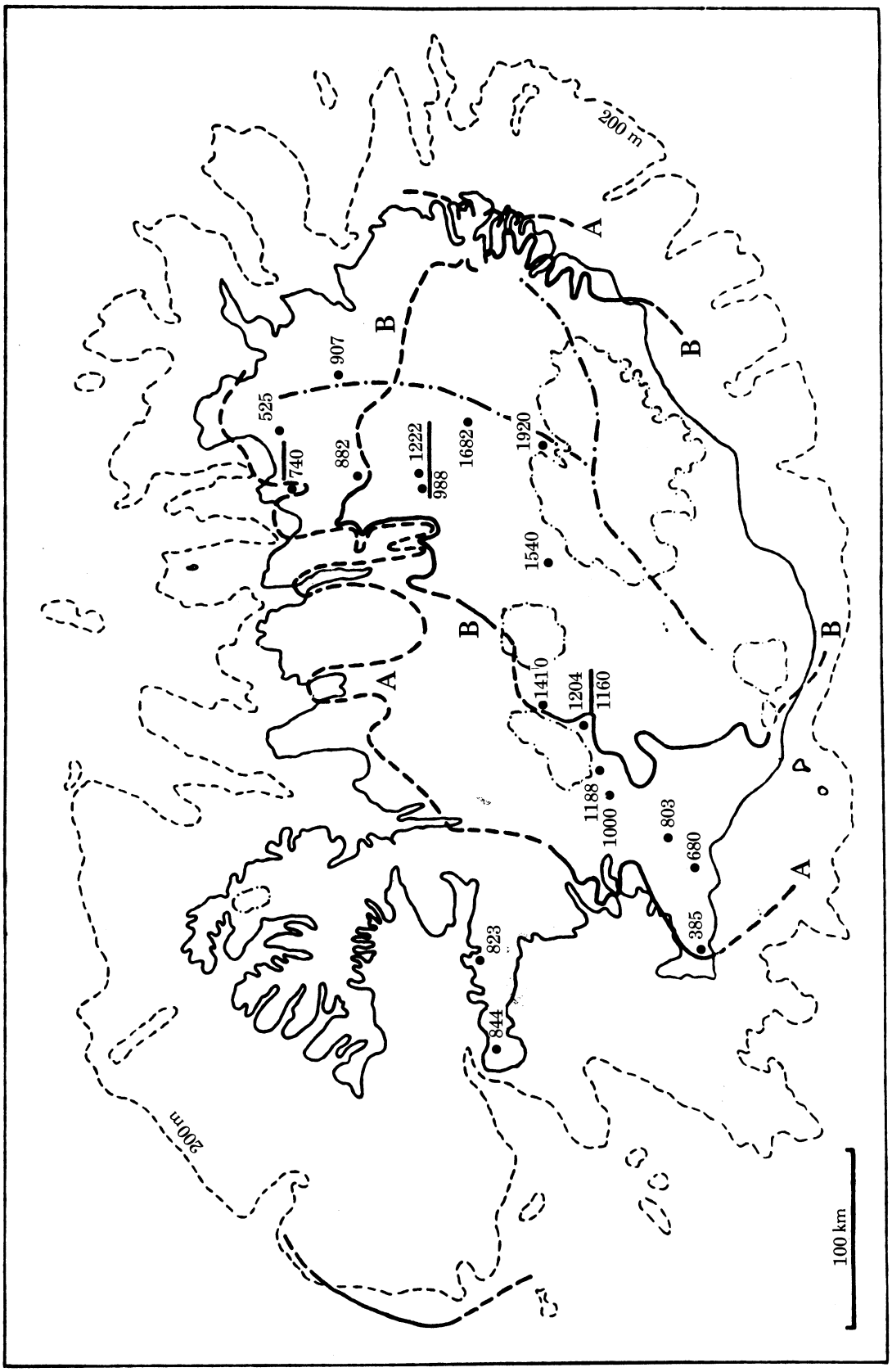

FIGURE 1. The Weichselian ice sheet in Iceland. The maximum extent (end-moraines off west Iceland) and the readvance stages Álftanes (A) and Búði (B). Numbered dots show the altitudes of Weichselian table mountains and the highest glacial striae on Saalian table mountains (outlined). Also shown is the 200 m depth contour of the shelf and ice divide in late Weichselian time.

by cultivation and occasionally, like weeds and the remaining part, through oceanic currents, winds and birds (Steindórsson 1962). Similar hypotheses have also been put forward to explain the origin of the other biotas. Other hypotheses assume that the flora and other biotas have been introduced by drift ice, ocean currents and winds (cf. Buckland *et al.* 1986). Recently, confirming evidence has been presented on the existence of ice-free areas from the last glaciation on a mountainous peninsula between two main fiords in northwest Iceland (Sigurvinsson 1983). Similar conditions may well have existed in numerous places in northwest, north and east Iceland and on the outer shelf of the north coast.

From the early Holocene up to the arrival of man in the late 9th century A.D., there were no significant changes in the flora except for ecological changes induced by climatic changes. The only forest-forming tree was *Betula pubescens*, which appeared in west and south Iceland 9 ka ago but seems to have existed at least during the Preboreal in north Iceland. Floristically the Holocene can be divided into the *Betula*-free period up to 9 ka BP in south and west Iceland, the older birch period (9–7 ka BP), the older bog period (7–5 ka BP), the younger birch period (5–2.5 ka BP) and the younger bog period, after 2.5 ka BP (Einarsson 1985).

A sudden climatic deterioration took place 2.5 ka BP: glaciers descended from high mountains (Thorarinsson 1964) and the birch forest declined rapidly (Einarsson 1963, 1985). Probably many of the present ice caps began to form at this time too. Very soon after the beginning of the settlement of Iceland a remarkable floristic change took place. The birch forest was suddenly cleared, whereupon a very rapid soil erosion began and cultivated plants and weeds turned up (Einarsson 1963, 1985).

Tertiary climate

The Tertiary Plateau Basalt Formation (TPB) is the oldest geological formation of Iceland. It is of Miocene and Pliocene age: the oldest rocks dated (K–Ar) yield ages of approximately 14 Ma (cf. Albertsson & Einarsson 1982; McDougall *et al.* 1984).

The Tertiary Plateau Basalt Formation occurs in two main areas: (i) east Iceland and (ii) west, northwest and north Iceland. These two areas are separated by a broad zone of younger rocks, the neovolcanic zone. The TPB is mainly built up of lava flows from volcanic fissures, shield- and stratovolcanoes (volcanic centres). Palaeobotanical studies of sedimentary interbeds indicate a mixed forest of conifers and warmth-loving trees, i.e. a warm-temperate climate (Friedrich 1966). During the Pliocene the climate became temperate and many of the trees suited to warmer climates disappeared. Towards the end of the Miocene and during the Pliocene, the earliest tillites formed locally on high stratovolcanoes (Watkins & Walker 1977; Sæmundsson 1980; Albertsson 1981; Einarsson 1985).

Pleistocene climate

Rock sequences of Pleistocene age are mainly exposed in the neovolcanic zone but are also found on Snæfellsnes in west Iceland and Skagi in north Iceland. They differ in many ways from the Tertiary rock sequences, mainly by their greater variety of rock facies. During the interglacial stages the volcanic activity was mainly effusive, as it had been in the Tertiary and was to be in the Holocene. A doleritic texture is a lithological characteristic of the major part of the basalt (grey basalts). During times of glaciation, when the country was covered with ice,

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

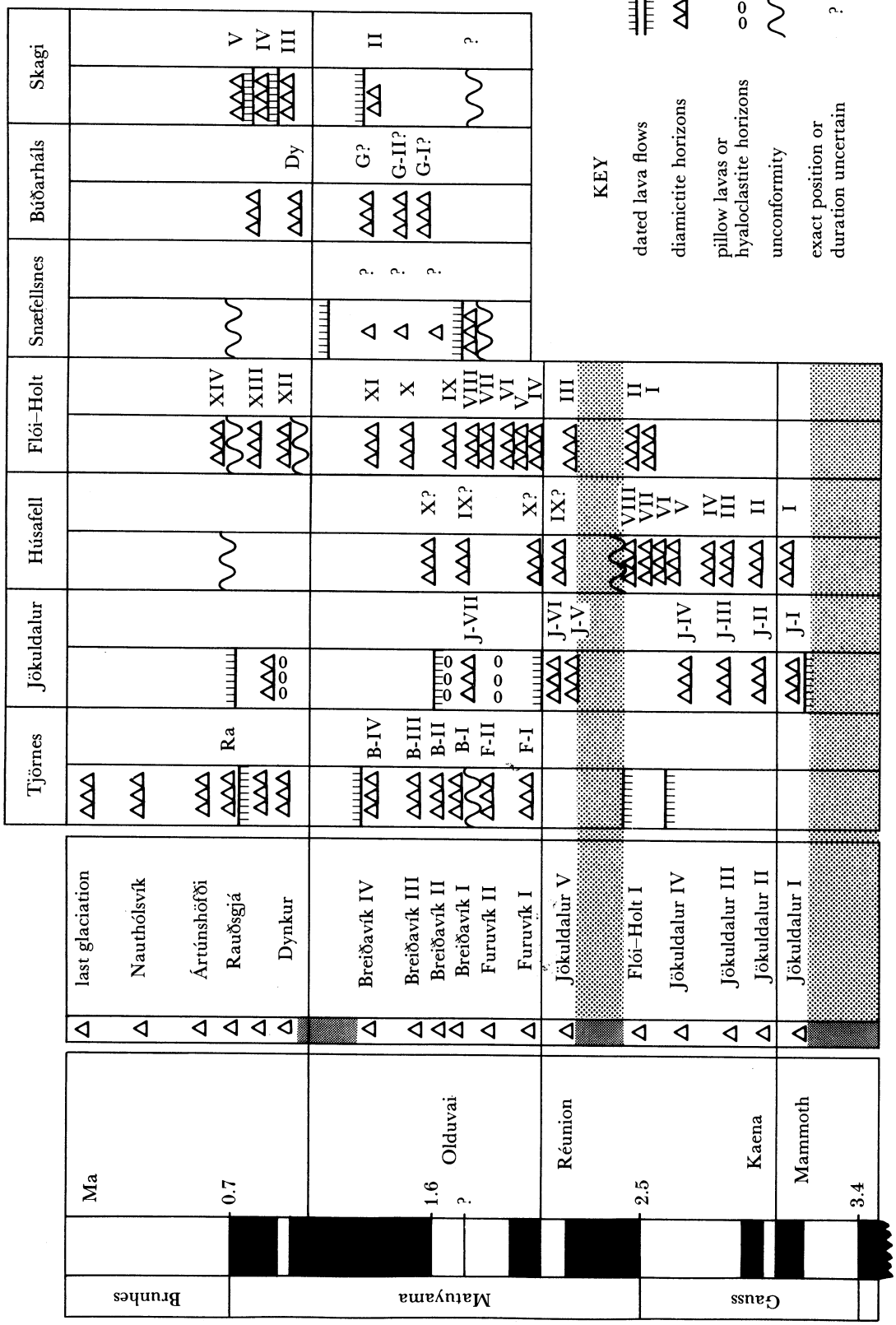

FIGURE 2. A tentative correlation of glaciations in Iceland during the past 3 million years. The fourth column shows the major glaciations in a suggested chronological order (cf. Albertsson 1976).

volcanic products were piled up over the eruption centres as tuff ridges (pillow lavas and breccias), which were capped by subaerial lava flows to form table mountains if the volcanoes were built up through the glacier sheets. The older glacial volcanoes are now for the most part eroded and buried in the pile, but those formed during the past two glacials are still impressive morphological features and can be used to define the surface altitudes of the ice sheets at the formation time of the volcanoes (Walker 1965; Sæmundsson 1980; Einarsson 1985).

In some regions, sediments comprise up to one half of the Pleistocene series, mainly fluvial, lacustrine and marine ones representing the interglacials and tillites the glacials. The sedimentary sequences are often cyclic, although mainly within the reach of marine transgressions and regressions caused by isostatic and glacioeustatic changes, i.e. till, succeeded by marine silt, first with arctic molluscs and then with boreal molluscs. These sediments are in turn often covered by fluviatile deposits and with plant-bearing lacustrine sediments, thin seams of lignite or soils (Eiríksson 1981, 1985). The sediments are frequently covered by lava flows, which can be radiometrically dated. Fossiliferous cyclic sediments are very useful in determining the full interglacial or interstadial character of the Pleistocene sequences. The Pleistocene sediments are also much more lithified then the Tertiary ones, owing to an admixture of volcanic material produced by subglacial eruptions. Red clayish soil beds, characteristic for the Tertiary rock series, are absent from the Pleistocene series. The absence of the red interbeds, together with the appearance of widespread tillites and subglacial hyaloclastites, are among the dominant features of the Pleistocene rock series.

Approximately 3 Ma BP a sudden climatic deterioration took place that affected both the marine fauna and the flora. The lusitanic and low boreal mollusc fauna of the Pliocene was replaced by a boreal fauna characterized by *Serripes groenlandicus*. The change in the marine fauna is to some extent obscured by the arrival of boreal Pacific molluscs, but younger rock sequences contain only species of the 'present' fauna. In the *Mactra* and *Tapes* zones of the Pliocene deposits on Tjörnes, *Glycimeris glycimeris*, *Abra alba* and other warmth-loving molluscs indicate a water temperature of at least 10 °C, i.e. 5 °C higher than present. In the *Serripes groenlandicus* zone above, which according to K–Ar dating is older than 2.5 Ma, the mollusc assemblage indicates a lowering of the water temperatures by 2–3 °C. Then *Portlandia arctica* appears in 'late glacial' marine sediments, along with the first foreign ice-dropped stones in the lower part of the Breiðavík deposits about 2 Ma BP (Einarsson *et al.* 1967; Albertsson 1978; Símonarson 1980; Gladenkov *et al.* 1980; Einarsson 1985).

The flora was also completely changed: the conifers and the temperate deciduous forest vanished and the flora became similar to the present one, with *Alnus*, *Betula* and *Salix*. *Alnus*, however, disappeared from Iceland during the third last glacial, about 0.5 Ma BP (Einarsson 1985).

Conclusions

The Tjörnes sequence shows evidence of at least four glacials during the past 0.7 Ma. The lowest one marks the boundary of the Brunhes–Matuyama geomagnetic epochs and is a common feature for all areas in Iceland where this geomagnetic boundary is exposed. During the period 0.7–2 Ma BP there is evidence of eight glacials in coastal sections; two further glacial horizons are found in inland sections in the Tjörnes area. Six of these tillites are interbedded with marine sediments. The ice sheets may well have been of similar extent as during the Weichselian (Einarsson *et al.* 1967; Albertsson 1978; Eiríksson 1981, 1985).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Ice caps or ice sheets formed during glacials or cold spells three to two million years ago in or adjacent to the active volcanic zones. They were probably comparable in size with glaciers in late Weichselian times, e.g. in the Húsafell area in southwest Iceland, in the Flói-Holt area in central South Iceland and the Jökuldalur area in eastern Iceland (Hopkins *et al.* 1965; McDougall & Wensink 1966; Einarsson *et al.* 1967; Eiríksson 1973; Sæmundsson & Noll 1975; Albertsson 1976). In each of these sequences there are 3–9 separate diamictite horizons, some of which have not been thoroughly studied but some of which are certainly tillites. The oldest dated tillite in these sequences is in Jökuldalur and has an age of little less than 3.1 Ma (McDougall & Wensink 1966).

The problem in recognizing the full interglacial or interstadial as well as the full glacial or glacial-stage character of the rock sequences is still not solved, except where full-scale cyclic sedimentation of interglacial–glacial character has been verified.

There is evidence of four glaciations during the past 0.7 Ma. During the period 0.7–2 Ma, at least eight glaciations, and possibly ten, occurred in the Tjörnes area. During the time interval 2–3 Ma, three to nine diamictite horizons, some of which are certainly tillites, are found in other regions. During this time the glaciers may have reached the sea in southern Iceland. According to this there have been 15–23 glaciations in Iceland during the past three million years.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES