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Tjörnes, North Iceland: A Bibliographical Review of the Geological Research History

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ABSTRACT

The Tjörnes sequence spans Late Tertiary and Quaternary lava flows and fossiliferous sedimentary rocks. The great thickness of the sediments is unusual in Iceland which consists mainly of volcanic rocks. The sequence is unique in the North Atlantic area in its lithological character and long Quaternary record. The Tjörnes sequence combines lithological and palaeontological evidence about past temperature conditions and climate. The present paper is a review of the geological research history of the Tjörnes area. The earliest contributions deal mainly with the fossil material. While the palaeontological research has continued up to the present, studies combining stratigraphical, palaeontological, and sedimentological aspects of the sequence became more frequent in the 20th century. During the last two decades the main emphasis has been on palaeomagnetic stratigraphy, K/Ar dating, and lithostratigraphy of the upper part of the Tjörnes sequence, where lithological evidence and changes in mollusc assemblages indicate the onset of recurrent glaciations.

INTRODUCTION

Tjörnes has been frequented by geologists for over a century. This is reflected by the wealth of literature concerning the area. Two features set the Tjörnes sequence apart from other exposed sequences in Iceland. Firstly, it contains thick marine sediments of Pliocene and Pleistocene age. Secondly, Tjörnes (Fig. 1) represents a horst structure bounded in the east by a subsiding volcanic zone (*Thoroddsen* 1902, *Th. Einarsson et al.* 1967, *Sæmundsson* 1974). The presence of up to 500 m thick, predominantly marine sediments in this uplifted segment has obvious implications about the nature of the nearby shelf area. Clearly, the study of the Tjörnes sequence is of local importance in evaluating offshore data in the Tjörnes area. Ever since *Pjetursson* (1905b) found glacial signs in the Tjörnes sequence in the Bay of Breiðavík, the controversy about the Pliocene/Pleistocene boundary in Iceland has involved the Tjörnes sequence. On the basis of the fossil evidence, the sequence has been used to define that boundary in Iceland (*Th. Einarsson* 1968). *Th. Einarsson et al.* (1967) reported ten glacial horizons in the upper Tjörnes sequence and attempted a correlation with the palaeomagnetic time scale. The investigation of the sequence is thus of importance for the local stratigraphy of Iceland, and for the evaluation of the climatic evolution before and during the Late Cainozoic ice age in the North Atlantic area.

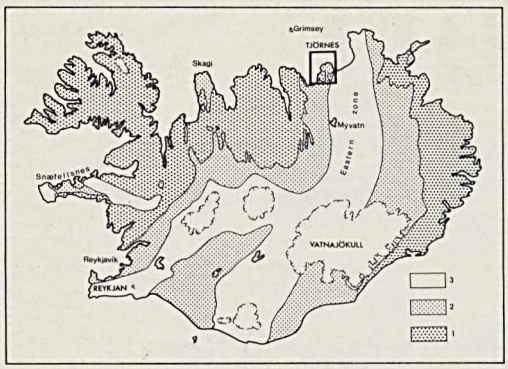


Fig. 1. Geological map of Iceland showing location of Tjörnes. Legend: 1. Bedrock older than ca. 3 Ma. 2. Bedrock younger than ca. 3 Ma. 3. Active volcanic zones. (After *Th. Einarsson* (1974), *K. Sæmundsson* (1978) and *H. Jóhannesson* (pers. comm.)). — *Mynd 1. Jarðfræðikort af Íslandi með ramma um Tjörnes. Skýringar: 1. Berggrunnur eldri en 3ja milljón ára. 2. Berggrunnur yngri en 3ja milljón ára. 3. Virk gosbelti. (Teiknað eftir Þorleifi Einarssyni (1974), Kristjáni Sæmundssyni (1978) og Hauki Jóhannessyni (munnlegar upplýsingar)).*

The Tjörnes sequence is mentioned in a few compilatory works. *Woldstedt* (1965) related evidence on climate from Tjörnes, and referring to *Strauch's* (1963) work, concluded that glaciations were becoming imminent at the time of deposition of the Breiðavík beds (Table 1). *Woldstedt* viewed reports of earlier glaciations with scepticism and suggested that the "tillites" might be explained in some other way. *Flint* (1971) discussed the evidence about ten glaciations in Iceland dating back to 3 Ma and also reviewed the evidence about the extent and nature of a separate Pleistocene ice cap in Iceland. *Berggren* and *Van Couvering* (1974) discussed the chronology of glaciations in the Northern Hemisphere, and considered the ice rafting chronology to be corroborated by the evidence from Tjörnes. Their review of *Zagwijn's* (1974) climatic levels during the Pleistocene and at the Pleistocene/Holocene boundary also involves the Tjörnes sequence.

Confusion in the use of local place names on Tjörnes in the geological literature has recently been discussed and rectified by *Björnsson* (1977).

This survey of the geological literature about Tjörnes is an offspring of a recent phase of sedimentological work on Tjörnes which was originally inspired by Professor *Th. Einarsson* and organized concurrently with a dating effort by Dr. *K. J. Albertsson.* The objective of the sedimentological work was to study the origin of the sedimentary rocks and to analyze the vertical cyclicity of the upper part of the sequence. Several uncertainties about the stratigraphy of the Breiðavík area were investigated, and a formal lithostratigraphical scheme was erected. Areal extent of the four major lithological units on Tjörnes is shown in Fig. 2 and a composite vertical section in Fig. 3. The results included a new interpretation of the origin of the sedimentary rocks in terms of glacial-interglacial cycles and have recently been presented in a thesis (*Eiríksson* 1979).

The new results about the age and origin of the upper Tjörnes rocks confirm some of the conclusions of earlier workers, while other results now seem controversial. It is hoped that the literature survey will be useful in the assessment of the present state of knowledge and understanding, show up weaknesses or gaps in the knowledge, and stimulate further work.

RESEARCH HISTORY

Early discovery

The research history of Tjörnes as reflected by the geological literature dates back to 1749, when the Icelandic naturalist *Ólafsson* (1749) first mentioned the Hallbjarnarstaðir locality in his work on natural conditions in Iceland. The locality was later described more fully by *Ólafsson* (1772), who noted some extinct mollusc species in the marine beds there, and also discussed the lignite beds briefly. The next contribution came nearly a century later, when *Winkler* (1863) mentioned 24 mollusc species from Tjörnes. He ascribed the marine

deposits to the Pliocene Formation and compared them with the Crag Formation in England. *Paijkull* (1867) described the coal beds and marine Pliocene deposits at Tjörnes in some detail and collected fossils. He published a list of mollusc species that had been identified by *Mörch,* who later published a paper on the molluscs of the Crag Formation of Iceland. *Mörch* (1871) inferred a higher sea temperature than at the present and presumed that the shelly deposits corresponded to the Older Red Crag in England and Belgium. *Johnstrup* (1877) visited Tjörnes and found that the fossiliferous beds and lignites were more extensive than previously thought. He concluded that the lignites had been deposited as coastal driftwood as they occurred along with marine fossils. *Johnstrup* collected fossils from various beds in Tjörnes and presented the material to *Mörch.* In the archives of the Geological Museum in Copenhagen there is an unpublished manuscript dated at 1884 (cf. *Pjetursson* 1905b) on the fossil Crag molluscs of Tjörnes (*Poulsen* 1884). *Poulsen* mentioned 117 species from the Hallbjarnarstaðir deposits, discussed the geographical distribution of those still living, and concluded that the deposits must be younger than the youngest part of the English Crag Formation. Fossil material was collected on Tjörnes by *Starkie Gardner* (1885) and analyzed by *Jeffreys* and *Wood,* who both suggested similarities between the faunas of the Tjörnes Crag and the English Red Crag. *Jeffreys* considered a younger age possible. The first plant remains to be identified from the Tjörnes deposits were reported by *Windisch* (1886), who found remnants of trees in the Húsavík area, North Iceland.

Early ideas on the position of Tjörnes with respect to the general geology of Iceland

At the turn of the century important contributions towards the knowledge of the geology of the Tjörnes area were made by *Thoroddsen* and *Pjetursson. Thoroddsen* (1902) gave the first geological account of the Tjörnes peninsula as a whole, which according to him was built up of old basalts, late Pliocene

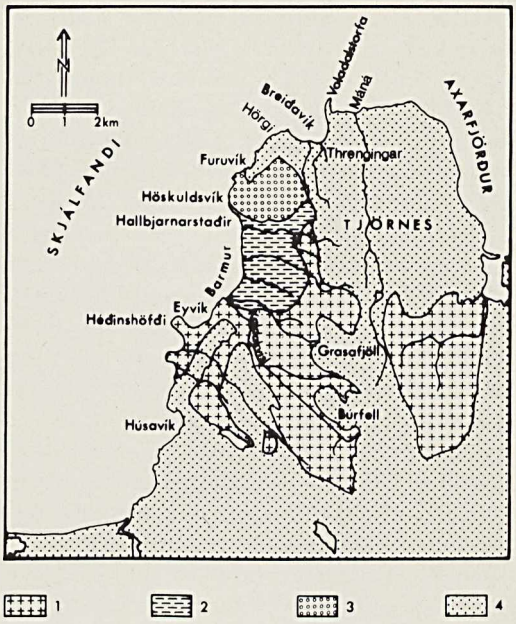


Fig. 2. Major lithostratigraphical units on Tjörnes. Legend: 1. Kaldakvísl lavas. 2. Tjörnes beds. 3. Höskuldsvík lavas. 4. Breiðavík Group. — *Mynd 2. Helstu jarðlagasyrpur á Tjörnesi. Skýringar: 1. Köldukvíslarhraunlög. 2. Tjörneslög. 3. Höskuldsvíkurhraunlög. 4. Breiðuvíkurhópur.*

sediments, tuffs, and breccias covered by dolerites, and glacial sediments. Based on his extensive studies of the geology of Iceland during the last decades of the nineteenth century, *Thoroddsen* (1906) divided the Icelandic sequence into formations. His division is schematically presented in Table 1 along with later stratigraphical schemes involving Tjörnes.

The old basalts of Tjörnes belonged to *Thoroddsen's* Miocene Basalt Formation, which he considered to be some 4000 m thick, the uppermost 1000 m being separated from the lower basalts by an extensive horizon of lignites and sedimentary beds. According to *Thoroddsen* a phase of tectonic disturbances and subsidence set in towards the end of the Miocene, followed by considerable coastal

erosion, during which an extensive shelf was carved into the Icelandic plateau. The "Red Crag" deposits of Tjörnes were thought to have been deposited during the highest level of this period of abrasion, resting unconformably on the tilted and subsided basalts. *Thoroddsen* described the eastern part of Tjörnes as a basaltic horst, where the old basalts dipped 4—5° towards northwest, compared to a dip of 4° towards north within the "Red Crag" deposits. In Thoroddsen's scheme the Palagonite Formation and the Dolerite Formation were considered to have been formed simultaneously during the time from early Pliocene up into the Glacial Period, which *Thoroddsen* considered to have been uninterrupted by interglacials, and to have begun with the formation of mountain glaciers in late Pliocene time. The youngest rocks of Iceland belonged to a formation consisting of moraines and other sediments and lava flows from the Glacial Period and Postglacial time.

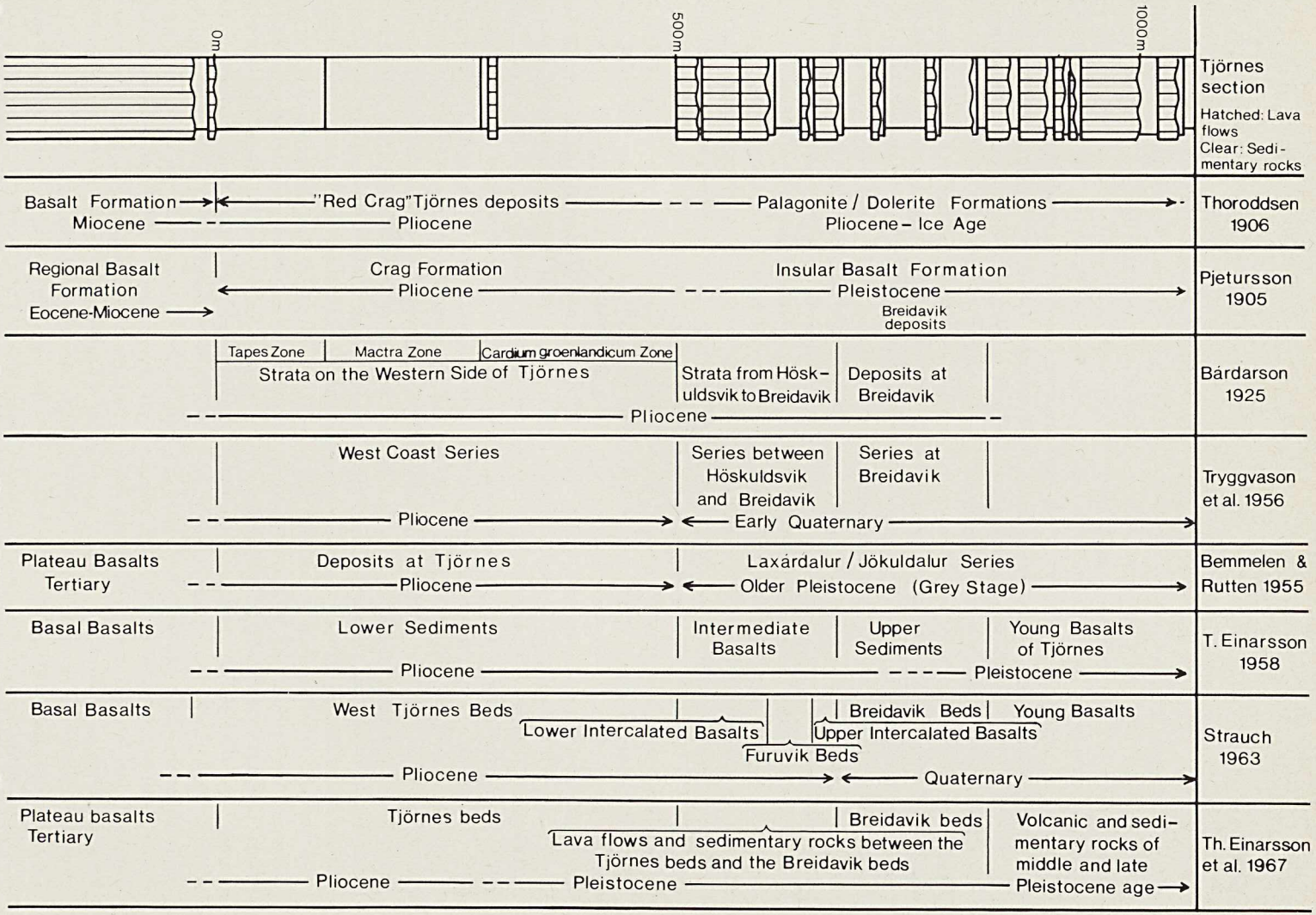
Thoroddsen's "classic" division was challenged by *Pjetursson* in a number of papers during the first decade of the twentieth century. Tjörnes played an important part in *Pjetursson's* new contribution (*Pjetursson* 1901, 1905a, 1905b, 1906a, 1906b, *Pjetursson* 1908, 1910, 1924). He divided the Icelandic sequence into three major formations (Table 1). A Regional Basalt Formation was built up during middle Eocene to early Miocene time as a part of the North Atlantic basalt region. In the uppermost part of the Regional Basalt Formation *Pjetursson* (1905b) found evidence of repeated Tertiary glaciations, and originally defined a "Grey Stage" at that level. This conclusion was partly based on the assumption that intercalated tillites west of Tjörnes belonged to a stratigraphical level below the Pliocene deposits on Tjörnes. Later, *Pjetursson* (1939) abandoned the idea of Miocene glaciations in Iceland. According to *Pjetursson* (1905b) the piling up of the Regional Basalt Formation was followed by a reduction in volcanic activity, and the thick Pliocene Crag deposits on Tjörnes were deposited in a littoral environment during subsidence, disturbed towards the end of the Pliocene by local uplifts. During the Pliocene volcanic lull Iceland had become separated from the rest of the North Atlantic basalt region, after which extensive eruptions set in again and the Insular Basalt Formation was now built up during the Pleistocene. On Tjörnes Peninsula *Pjetursson* found dolerites and glacial sediments, including an interglacial marine sequence between two lithified "moraines" in Breiðavík above the Crag Formation, but near the base of the Insular Basalt Formation. He did not exclude the possibility that the uppermost part of the Crag deposits reached up into the Pleistocene (*Pjetursson* 1908). *Pjetursson* found evidence of at least four or five glaciations separated by interglacials in various sections through the Insular Basalt Formation, and suggested that marine fossils found at several localities might yield information about climatic conditions during the Pleistocene.

Clarification of the stratigraphy and palaeontology

Schlesch visited Tjörnes in 1921 and studied the palaeontology of the Tjörnes sequence (*Schlesch* 1924, 1925a, 1925b, 1931). He presented an outline of the geological relationships, largely based on the work of *Pjetursson*. *Schlesch* (1924) identified 146 species of molluscs out of which 39 were extinct or unknown at that time. He concluded that the fauna showed similarities with the English and Belgian Crags although the Tjörnes Crag did have a more northern character. *Schlesch* suggested that the very mixed faunistic character indicated that the climate had undergone some changes during the time of deposition.

The first detailed investigation of the stratigraphy of the coastal sections between Héðinshöfði and Voladalstorfa (Fig. 2) was carried out by *Bárðarson* (1925), who mapped individual beds and analyzed the fossil material. Several workers have referred to *Bárðarson's* work as a classic one for the sequence on Tjörnes. Earlier, *Bárðarson* (1918, 1922) had published general descriptions of

Table 1. Review of the stratigraphy of Tjörnes. — *Tafla 1. Yfirlit um jarðlagaskipun Tjörness.*



the Tjörnes sequence. *Bárðarson* was convinced of an angular unconformity and a considerable hiatus between the basalts at Kaldakvísl where he observed dips of 20—30° towards north, and the Pliocene Crag strata which dipped up to 10° towards northwest. After an initial transgression, subsequent Crag strata had accumulated in sheltered places such as a fiord or quiet creeks and possibly lagoons. According to *Bárðarson* the lignite seams and barren sandstones were dry land deposits or possibly formed in fresh water lakes cut off from the sea. He considered most of the marine deposits to be shallow water to littoral sediments. He divided the sedimentary sequence of alternating shelly marine and terrestrial beds between Kaldakvísl and Höskuldsvík into three biozones (Table 1). For the lowest of these, the *Tapes* Zone, *Bárðarson* inferred a sea temperature similar to that of the present day west or south coast of Norway. At the time of formation of the *Mactra* Zone, *Bárðarson* suggested climatic conditions at least as favourable as those now prevailing on the warmest range of the Norwegian coast or possibly approximating the climate of the British Isles to-day. When it came to the deposition of the *Cardium* (=*Serripes*) *groenlandicum* Zone the temperature must, according to Bárðarson, have varied from at least that of the west coast of Iceland to-day up to that of the British Isles to-day. *Bárðarson* did not accept *Pjetursson's* conclusions about a glacial origin of any of the Breiðavík deposits, and concluded that the temperature remained similar to the present conditions on the west coast of Iceland. He considered both the three biozones of the Tjörnes beds and the Breiðavík beds to be of Pliocene age. *Bárðarson* pointed out that the Icelandic Pliocene fauna was altogether very closely allied to the English Crag fauna. A revised outline of the geology of Tjörnes was included in the second edition of *Bárðarson's* (1927) textbook on geology.

Fossil shell collections from Tjörnes were examined and described by *Harmer* (1914—1925) in his work "On the Pliocene Mollusca of Great Britain".

Emilsson (1929) made some observations on Tjörnes. He discovered that the Tjörnes beds have an extension as far south as the farm Rauf (now Eyvík), where he collected and identified marine fossils. *Emilsson* also examined fossil plant remains from lignite seams, and concluded that the lignite material had been supplied by local vegetation. He also mentioned a thin fossiliferous shale bed near Húsavík, interbedded between two moraines.

During the second quarter of this century, stratigraphical investigations in Iceland continued within the framework provided by *Pjetursson's* work, which became generally accepted (e.g. *Nielsen* and *Noe-Nygaard* 1936). *Áskelsson* (1935a, 1935b, 1938, 1939) studied the fossiliferous beds in Breiðavík on Tjörnes, and interpreted the presence of the cold-water species *Portlandia arctica* as a proof of their Pleistocene age. Later he published general descriptions of the Tjörnes sequence and the fossil material conserved there (*Áskelsson* 1941, 1960a, 1961). *Áskelsson* (1960b) compared the marine fossils of the Tjörnes beds with the Pleistocene Skammidalur fauna in South Iceland and concluded that the Skammidalur formation was of the same age as the *Serripes* Zone of Tjörnes. Accordingly, he stated, the *Serripes* Zone must be of old Quaternary age.

A general description of the Tjörnes beds was presented by *Laursen* (1936), who discussed temperature changes reflected by the fossils and ascribed the beds to the Pliocene. *Líndal* visited Tjörnes in 1939 and 1941 and made several observations on stratigraphy and the origin of the sedimentary beds, especially in the Furuvík and Breiðavík outcrops as well as in the Búrfell area (Fig. 2). His discovery of lava flows intercalated in the Breiðavík sediments is of particular importance. *Líndal's* diaries were published in 1964.

A brief account of the Tjörnes sequence was given by *Kjartansson* (1952), who considered the Tjörnes beds to be of Pliocene age and to have been deposited in a graben.

The Lexique Stratigraphique International includes a section on the stratigraphy of Iceland compiled by *Tryggvason et al.* (1956). The

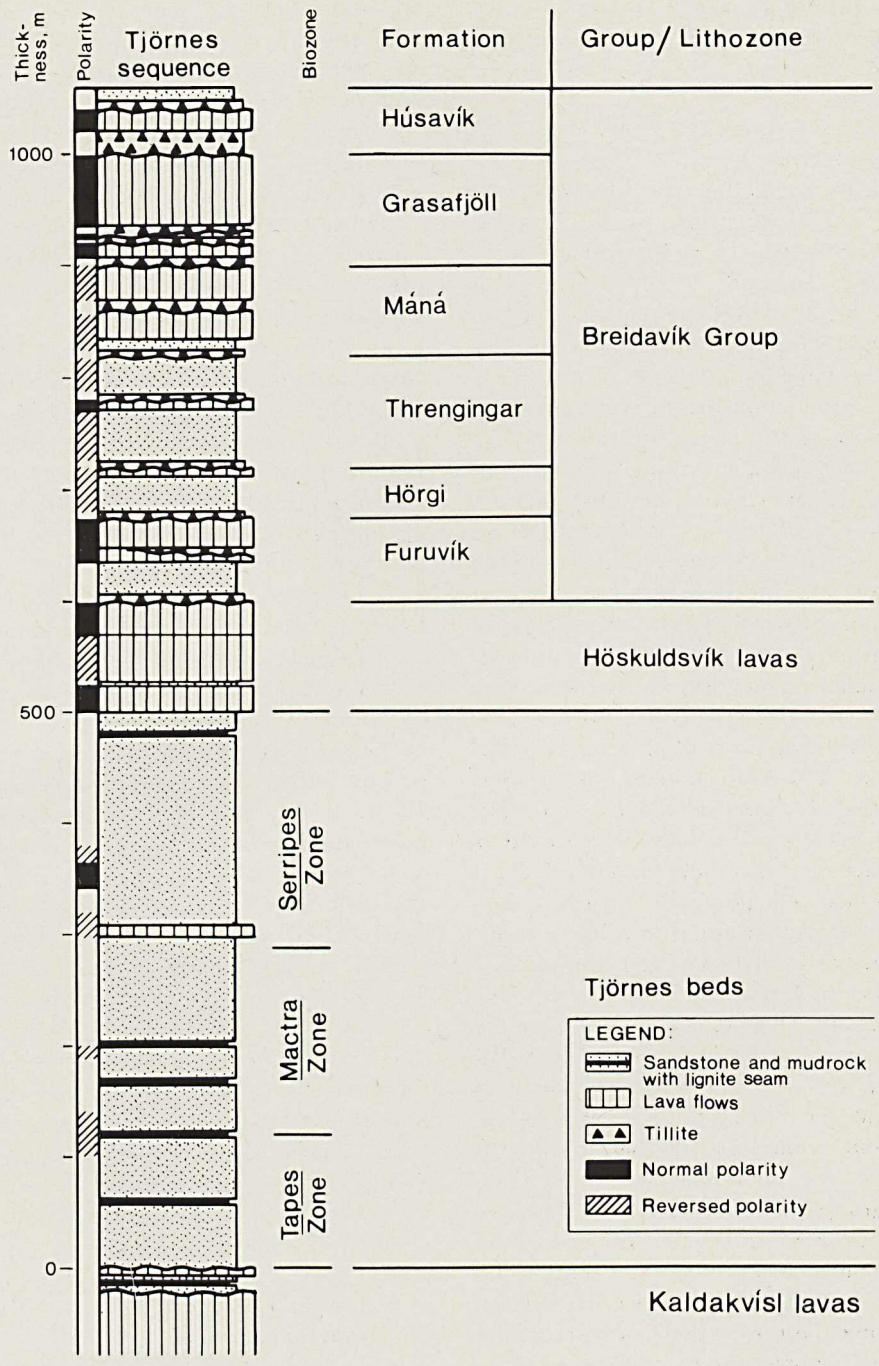


Fig. 3. Composite vertical section of Tjörnes strata, based on coastal sections. — *Mynd 3. Samsett jarðlagasúla Tjörness, byggð á strandsniði.*

Tjörnes sequence is divided into Series (Table 1). Old Quaternary age is assigned to the Breiðavík Series with reference to *Áskelsson's* work.

Voice of a sceptic — early palaeomagnetic studies

A tone of scepticism towards *Pjetursson's* glacial history was struck by *T. Einarsson* (1940a, 1940b, 1946), who interpreted many of *Pjetursson's* moraines ("grey conglomerates") as being entirely of volcanic origin, being mudflow deposits either directly erupted by volcanic vents or formed as a secondary product of certain eruptions. Earlier, *Hawkes* (1938) had studied some of *Pjetursson's* localities, including Tjörnes, and rejected a glacial origin of the conglomerates in question. *T. Einarsson's* investigations on Tjörnes began in 1939 and continued until the early sixties. In the first instance he dealt mainly with the stratigraphy and structure of the peninsula, but the origin of the sediments and the palaeomagnetism of the lava flows were also investigated (*T. Einarsson* 1957a, 1957b, 1958). The study of palaeomagnetism on Tjörnes had been initiated by *Hospers* (1953, 1954). *T. Einarsson* (1957b) found that the youngest rocks on Tjörnes consisted of two groups of lava flows separeded by a "moraine-like" conglomerate, an upper normally magnetized group, and a lower reversely magnetized one that rested conformably on the Breiðavík sediments (cf. Fig. 3). The upper part of these in turn consisted of an old Quaternary sequence (of presumed Villafranchian age). In this paper *T. Einarsson* stated that the Tertiary/Quaternary boundary should be drawn at the base of R1 (the Quaternary thus spanning the two youngest polarity groups). *T. Einarsson* (1958) presented the first detailed survey of the interior of Tjörnes peninsula, and identified angular unconformities within the sequence. He defined stratigraphical units for the Tjörnes sequence (Table 1). Tectonic aspects and age relationships were again discussed in later papers (*Thorarinsson et al.* 1959, *T. Einarsson* 1960). While earlier authors had generally assumed an unconformity beneath the "Lower sediments", *T. Einarsson* (1958) concluded that they were conformable with and partly of the same age as the "Basal Basalts" at Kaldakvísl. He visualized the early Pliocene Tjörnes as a subsiding area of low relief, the subsidence amounting to 700—800 m during the Pliocene. After an emergence (still within the Pliocene, at which time he suggested a regional uplift of some 300 m predating the Breiðavík sediments) the area was covered by lavas. *T. Einarsson* pointed out that Tjörnes is cut off from the area south of Húsavík village by a fault running from Húsavík to the southeast. To the north of the fault, the "Basal Basalts" have been uplifted to an altitude of 700 m, while they cannot be seen to the south of the fault. *T. Einarsson* suggested that the fault was of Pleistocene age.

T. Einarsson collected pollen samples from lignite horizons and terrestrial sediments in the Tjörnes sequence. The palynological results were discussed along with the problem of provenance of rhyolitic pebbles in his work on Upper Tertiary and Pleistocene rocks in Iceland, and in later papers (*T. Einarsson* 1962, 1963a, 1963b, 1964). The results of his study of palaeomagnetism on Tjörnes were compiled on a map in a paper where *T. Einarsson* (1965) also delt with lavas resting on fossiliferous shale to the south of Húsavík. The stratigraphy and sedimentological aspects of the Tjörnes sequence were briefly dealt with in *T. Einarsson's* (1972) textbook on geology. In a recent paper he emphasized a Pliocene age of the Breiðavík beds on Tjörnes and emphatically rejected the interpretation that intercalated glacial signs were produced by Pleistocene ice caps. Instead, he suggested, they were in many cases formed in the vicinity of high ice capped volcanoes (*T. Einarsson* 1977).

Climatic evidence examined

In his study of the climatic history of Iceland, *Schwarzbach* (1955) examined the climatic evidence of the Tjörnes beds and

suggested a maximum sea water temperature of 5 °C higher than now. He considered the analyses of trees to show that air temperature was also higher. *Schwarzbach* concluded that the Breiðavík deposits must be considered of Pleistocene age as they rested on a moraine. In his work "Climates of the Past", *Schwarzbach* (1963) discussed Tertiary and Quaternary climatic evidence from Tjörnes. The pollen flora of the Pliocene deposits (Tjörnes beds) and the Pleistocene deposits (Breiðavík beds) on Tjörnes was described for the first time by *Schwarzbach* and *Pflug* (1957), and was found to point to a climate similar to that of the Holocene Atlanticum of Central Europe. A climatic cycle with an optimum in the *Mactra* Zone was inferred. *Pflug* (1959) studied spores from the Tjörnes and Breiðavík beds. He concluded that the *Tapes* and *Mactra* Zones were of Pliocene character and age, but that the Breiðavík beds were of Quaternary age. *Schönfeld* (1956) studied tree remnants from the *Tapes* Zone and suggested similarities between the Icelandic Tertiary flora and the present North American one.

Reinterpretation of the position of Tjörnes with regard to the geology of Iceland

Apart from palynological studies, the fifties brought a new effort by Dutch scientists towards an understanding of the origin of the Palagonite Formation of Iceland and the structure of the Icelandic Central Graben. The first contribution from this direction came from *Hospers* (1953, 1954), who studied palaeomagnetism in eastern North Iceland. *Bemmelen* and *Rutten* (1955) studied amongst other things questions of tillites and breccias, morainic and fluvioglacial sediments, and related phenomena. Tjörnes was among the areas visited by *Bemmelen* and *Rutten.* They agreed with the generally held view (*Thoroddsen* 1906, *Bárðarson* 1927) that Iceland was symmetrical about a central depression, and that the country represented a horst structure. According to *Bemmelen* and *Rutten* the oldest rocks, the Tertiary Plateau Basalts, were covered by a series of Older Pleistocene Basalts with intercalations of tillites (Laxárdalur Series to the west of the graben in Northeast Iceland, corresponding to the Jökuldalur Series on the eastern side, both being identical with *Pjetursson's* Grey Stage unit). In the extreme north, the marine Pliocene deposits of Tjörnes were intercalated between the Tertiary Plateau Basalts and the Laxárdalur Series. The Tjörnes sediments had, according to *Bemmelen* and *Rutten,* accumulated in a top depression of the Icelandic horst. *Rutten* and *Wensink* (1960a, 1960b) discussed the structure of the Central Icelandic Graben as well as palaeomagnetic dating, glaciations, and the chronology of the Plio-Pleistocene in Iceland. They correlated the Grey Stage unit with the N1, R1 and N2 palaeomagnetic groups of Plio-Pleistocene age (Astian — Villafranchian), and suggested that the Tertiary/Quaternary boundary should be defined at the reversal between the N2 and R1 groups in Iceland, providing a much better datum line than any index fossils or climatic indices. The palaeomagnetic studies were continued by *Wensink* (1964), who correlated the Tjörnes sequence with the palaeomagnetic groups. His correlation was based on a geological and palaeomagnetic study of the sequence by *Broekman* (1961). *Wensink* correlated the Tjörnes beds with the N2 geomagnetic period and placed the Breiðavík deposits at the geomagnetic N2/R1 boundary, thus being of a possible early Pleistocene age. The correlation of the Jökuldalur Series with the geomagnetic groups suggested by *Rutten* and *Wensink* (1960a, 1960b) was later confirmed by radiometric dating of the Jökuldalur Series, and the R1 and N2 polarity groups were found to correspond to the Matuyama reversed and the Gauss normal polarity epochs respectively (*McDougall* and *Wensink* 1966). *McDougall* and *Wensink* found a tillite immediately above a basalt dated at 3.10 ± 0.10 Ma and suggested that the base of the Pleistocene might be as old as 3 Ma.

The origin of breccias and conglomerates in the Icelandic Palagonite Formation was discussed in a treatise on the geomorphology of

Iceland by *Bout* (1953), who also presented an outline of the stratigraphy of Iceland and included the Tjörnes sequence in his scheme.

Reexamination of the Tjörnes sequence

In the early sixties *Strauch* (1961, 1963) carried out a detailed study of the stratigraphy and palaeontology of the Tjörnes sequence. He agreed with earlier authors about an early Quaternary age of the Breiðavík beds (Table 1), and suggested that the "West Tjörnes Beds" might correspond to the Jökuldalur Series of *Bemmelen* and *Rutten* (1955). *Strauch* also studied climatic evidence, tectonic aspects, and the palaeogeographical evolution of Tjörnes. He agreed with earlier views on the Pliocene topography of Iceland, which was considered a relatively flat country. A slight depression, *Strauch* suggested, was formed in the vicinity of the present Central Icelandic Graben, where the 550 m thick "West Tjörnes Beds" accumulated during slow and uninterrupted subsidence. *Strauch* concluded that sedimentation in the Pliocene Kaldakvísl area began with bog formation and deposition of fluviatile sands coupled with an initial subsidence of the area and a lull in volcanic activity. Only occasional lava flows reached the area during an early phase of relative sea level changes. Sedimentation then continued in a fiord which according to *Strauch* was open towards north with sediment supply from the south. From time to time the sediment supply exceeded the rate of subsidence and the shallow fiord was rapidly filled with sediments. The relief of the area was gentle, but when it came to the deposition of the upper "West Tjörnes Beds" an increased rate of subsidence and local uplifts in border areas enhanced the topographical relief. Soon after that volcanic activity set in and the intercalated basalts were piled up in an environment characterized by tectonism and volcanism. Coastal and fluvioglacial sedimentation began in the present Breiðavík area, but continued subsidence to the west and uplift of the Tjörnes horst led to relative sea level changes and unconformities. *Strauch* suggested that the upper Breiðavík beds had accumulated in a fiord of similar proportions as the earlier "West Tjörnes Beds" fiord. Sedimentary dykes in the Tjörnes sequence were the subject of separate publications (*Strauch* 1966, 1968a), and sedimentological and palaeontological evidence from Tjörnes was used in a later paper on a North Atlantic land bridge (*Strauch* 1970). Palaeontological results from Tjörnes were to a various extent the subject of further publications (*Strauch* 1968b, 1968c, 1972a, 1972b, 1972c).

The Tjörnes sequence was reexamined and sampled for palaeontological analysis and palaeomagnetic measurements by *Doell, Th. Einarsson,* and *Hopkins* (*Hopkins et al.* 1965, *Th. Einarsson et al.* 1967, *Th. Einarsson* 1966, 1967, 1969, *Doell* 1972). They found evidence of ten regional glaciations within the sequence and attempted a correlation with the geomagnetic polarity time scale. According to their preferred alternative the *Mactra/Serripes* Zone boundary lay close to the Gilbert/Gauss reversal, and the Breiðavík beds corresponded to the Matuyama epoch. The fossil material was analyzed by *MacNeil* (1965, 1967) and *Zullo* (1968), and discussed by *Durham* and *MacNeil* (1967) and by *MacNeil* (1973) in terms of faunal migrations between the Pacific and Atlantic Oceans. *Durham* and *MacNeil* identified 32 mollusc species of Pacific origin in the Tjörnes sequence, 22 out of which appeared for the first time in the *Serripes* Zone. *Th. Einarsson et al.* (1967) correlated the *Serripes* Zone with the Red Crag of England, and suggested that the Zone was largely and perhaps entirely of early Pleistocene age. They pointed out that the mollusc fauna of the two lower Zones was similar to that of the Coralline Crag of East Anglia (Astian or late Pliocene). In his textbook on general geology and the geology of Iceland, *Th. Einarsson* (1968) correlated the *Mactra/Serripes* Zone boundary with the Gilbert /Gauss reversal and interpreted the faunal and floral changes at this boundary as evidence of a sudden dramatic deterioration of climate. The Pliocene/Pleistocene boun-

dary was defined at this level, for which an age 3.0—3.35 Ma was suggested. In a later edition, *Th. Einarsson* (1971) divided the Pleistocene sequence in Iceland into two units, the Grey Basalt formation (3.35—0.7 Ma)and the Palagonite Formation (0.7 Ma — Late Weichselian, cf. also *Th. Einarsson* 1973, 1974).

During the late sixties several geothermal boreholes were sunk in the Húsavík area on Tjörnes. The borehole sections and stratigraphical evidence were published in two reports of the National Energy Authority in Iceland (*Tómasson* 1969, *Tómasson et al.* 1969). The inference was that the Tjörnes beds were penetrated by some of the boreholes, and thus had a subsurface extension towards south across the Húsavík fault swarm. There was no direct evidence of marine sediments, however, and although the boreholes may have penetrated a terrestrial equivalent of the Tjörnes beds, the relationship is not clear. An alternative interpretation of the Húsavík borehole sections was presented by *Sæmundsson* (1974), who argued against a subsurface extension of the Tjörnes beds across the faults at Húsavík.

A continued effort has been directed towards the geology of Tjörnes during the seventies. Several members of the Soviet Geodynamic Expedition in Iceland visited Tjörnes for consecutive field seasons in the early seventies (*Akhmetiev et al.* 1978). Sedimentary and volcanogenic deposits in Breiðavík were studied by *Geptner* (1972, 1973, 1976, 1977, *Geptner* and *Lavrushin* 1972), who verified the existence of tillites and volcanic tuffs in the sequence, and contributed to the solution of stratigraphical problems in Breiðavík. *Gladenkov* studied the palaeontology and stratigraphy of Tjörnes, and presented correlations of the Tjörnes sequence with other areas (*Gladenkov* 1974a, 1974b, 1974c, 1978, *Gladenkov et al.* 1975, *Th. Einarsson* and *Gladenkov* 1973). The palaeomagnetism of the Tjörnes sequence was studied by *Gladenkov* and *Gurari* (1976), and the palaeobotany by *Akhmetiev et al.* (1975, 1978).

Símonarson (1974) examined fossil material from the Tjörnes sequence in his study of the genus *Cyrtodaria,* and later (1975) presented a general account of the palaeontology and age of the Tjörnes and Breiðavík beds.

The palaeoecology of the Tjörnes beds was studied by *Norton* (1975), who also discussed faunal relationships between Tjörnes and the North Sea basin (1977a, 1977b). *Zagwijn* (1974) discussed the Tjörnes sequence and its faunal, climatic, and age implications in his paper on the Plio-Pleistocene boundary in the Netherlands and elsewhere. The problem of the Neogene/Quaternary boundary in the Netherlands, England, and Iceland was recently reviewed by *Hey* (1977).

The Tjörnes Fracture Zone. Position of Tjörnes with regard to plate tectonics

The tectonic aspects of Northeast Iceland were examined by *Sæmundsson* (1974, 1977, 1978), who interpreted the geological features of the area in terms of plate tectonics and a shift of the active rifting zone from Skagi to the present rifting zone in Northeast Iceland (Eastern zone), leading to a 75 km wide, WNW trending transform fault zone (Tjörnes Fracture Zone). *Sæmundsson* (1974) described the Axarfjörður area as a downfaulted trough that had subsided 1000 m or more relative to its uplifted western margin (Tjörnes). He concluded that the 25 km wide Axarfjörður trough appeared to be undergoing ductile thinning and tensional faulting with active volcanism at the margins. This trough is, according to *Sæmundsson's* interpretation, presently accomplishing most of the spreading within the Tjörnes Fracture Zone, while the transcurrent movement is taking place in a WNW trending zone north of Tjörnes. Previously, he argued, the strike-slip movement had been taken up by the Húsavík faults, amounting to some 60 km during the activity of a former spreading axis in the Grímsey area during the time from ca. 4—1 Ma. According to *Sæmundsson* the geological evidence supporting a right lateral movement along the Húsavík faults consists of oblique slickensides on fault planes to the north of the Húsavík faults and on the eastern continu-

ation of the latter, fault breccias and intensive secondary mineralization at the faults, and a juxtaposition at the faults of rock suites of varying age and dips. An age gap of 5 m. y was inferred across the Húsavík faults. *Sæmundsson* suggested that the Tjörnes beds were probably formed in a subsiding trough initiated approximately north of Eyjafjörður as the Eastern zone became established. A new spreading axis across the Tjörnes Fracture Zone, the Grímsey shoal, then poured lavas over the sediment filled trough during the upper Gauss epoch. Finally, opening up of the Axarfjörður spreading zone produced lava flows of late Matuyama epoch age, covering the Breiðavík beds, which had been deposited in a minor tectonic depression, a forerunner of the Axarfjörður trough.

An analysis of earthquakes and general features of the Tjörnes Fracture Zone was published by *Ward* (1970, 1971). *Schäfer* (1972) inferred a right lateral transform fault in the area. Active volcanism north of Tjörnes has been reported by *Thoroddsen* (1902, 1925), *Wolff* (1931), and *Thorarinsson* (1965). *P. Einarsson* (1976) analyzed the seismicity of the Tjörnes Fracture Zone and demonstrated that the transform motion between the Kolbeinsey Ridge and the Eastern zone occurs along three or more parallel strike slip faults. *Walker* (1975) did not accept the view that sectors of the rift zone had been offset by northwesterly trending faults and postulated an *en echelon* arrangement of spreading sectors from the Eastern zone to Tjörnes. *McMaster et al.* (1977) studied the insular shelf off North Iceland. They interpreted the arrangement of volcano-tectonic features within the Tjörnes Fracture Zone as a transient or leaky type of transform fault and stated that *Walker's en echelon* rift zone configuration was confirmed by their studies. Recent contributions to the geological history of the Eastern zone (*Aðalsteinsson* 1974, *Watkins et al.* 1975, *Albertsson* 1976, *Watkins* and *Walker* 1977) indicate that volcanism in the Eastern zone has been virtually continuous since about 13.5 Ma.

Radiometric dating and lithological studies

Aronson and *Sæmundsson* (1975) studied the plateau basalts beneath the Tjörnes beds at Kaldakvísl and the sections at Héðinshöfði, and reported radiometric ages from this part of the Tjörnes sequence. The Kaldakvísl ages confirmed a Tertiary age for the rocks in question, but the low ages obtained from the Héðinshöfði locality indicated a possible correlation with the Furuvík beds.

The first radiometric ages within the Tjörnes sequence above the basal basalts were presented by *Albertsson* (1976, 1977, 1978), who initiated an exhaustive sampling programme to this effect in 1972. *Albertsson* correlated the sequence with the geomagnetic polarity time scale and concluded that the alternative considered less likely by *Th. Einarsson et al.* (1967) was partly confirmed. According to *Albertsson* (1976, 1978) the *Mactra/Serripes* Zone boundary dates from ca. 3 Ma., and the oldest tillite bed of the sequence (in Furuvík) is ca. 2 Ma. old. The Tjörnes sequence was reviewed by *Th. Einarsson* (1977, 1978) in the light of the new radiometric ages, and palynological results from the Tjörnes sequence were also presented.

Eiríksson (1979) examined the stratigraphy and origin of the sedimentary rocks of the upper part of the Tjörnes sequence. Lithostratigraphical holostratotypes were defined for the Breiðavík Group, which includes the Furuvík beds and all higher strata of the Tjörnes sequence. Informal lithozones were defined for the lower part of the Tjörnes sequence. According to *Eiríksson* the Breiðavík Group is characterized by at least eleven or twelve lithological cycles deposited during as many climatic glacial — interglacial cycles.

DISCUSSION

Past geological research on Tjörnes has answered many questions about the origin, age, and tectonic evolution of the area. However, the answers are probably outnumbered

by questions and problems that remain unanswered or controversial. The local stratigraphy is not very well known and a formal lithostratigraphical scheme has only been proposed for the youngest major unit on Tjörnes, the Breiðavík Group (*Eiríksson* 1979). Current work in progress at the University of Iceland involves further mapping of that and older units on Tjörnes. The sequence of lavas between the Breiðavík Group and the Tjörnes beds is fairly well known. The surface extent of the two oldest lithozones, the Tjörnes beds and the Kaldakvísl lavas is also fairly well known, but there are many uncertainties about their internal structure and stratigraphy. Recent investigations at the Kaldakvísl locality (*Eiríksson* 1979) confirm *T. Einarsson's* (1958) and *Strauch's* (1963) views about the conformable relationship between the Kaldakvísl lavas and the Tjörnes beds. Preliminary radiometric ages from lava flows at that locality (*Albertsson* 1976) indicate that the Tjörnes beds may have accumulated fairly rapidly in late Pliocene time as an age of 4.30 ± 0.17 Ma was obtained from the youngest flow beneath the *Tapes* Zone.

Although that part of the Tjörnes sequence which contains direct lithological evidence about glaciations (i. e. the Breiðavík Group) has been bracketed in time by radiometric ages (Albertsson 1976, 1978), there are still uncertainties about the age of individual glacial-interglacial cycles. More radiometric ages are required to achieve such a goal.

The abundant palaeontological evidence of the Tjörnes sequence has yet to be integrated with sedimentological studies in a facies analysis and a reconstruction of palaeoenvironments. Such a line of research is likely to facilitate an interpretation of the fossil record in terms of climatic changes, and the general understanding of the geological history of the area.

The geological structure of Tjörnes and its relation to the tectonic history of North Iceland will probably continue to attract researchers in the future. A meaningful interpretation of the fault pattern on Tjörnes can only be attempted when a detailed geological map of the peninsula has been compiled and the age of the faults determined.

One line of research which has been neglected is a morphological analysis of Tjörnes. It seems possible that the present landscape, which is characterized by step--faults in the east, more gentle slopes in the north and west, and young valleys in the central and southern part, may hold clues to recent tectonic developments.

The subsurface geology of Tjörnes is mostly unknown and very little geophysical work has been done in the area.

CONCLUSIONS

It transpires from the review of the long research history of Tjörnes that the geological sequence there has persistently played an important part in the study of stratigraphical, climatological, and tectonic problems in Iceland and in the North Atlantic. Geologists have visited Tjörnes with questions about the age of the deposits and about the climatic evidence of the fossils and rocks. Most of the visits were brief, however, and careful analyses of the Tjörnes sequence, based on objectively planned field work, have been relatively few. *Bárðarson's* (1925) monograph on the Pliocene deposits at Tjörnes was accompanied by the statement that his investigations were still in their initial stage. *Strauch* (1963) attempted to reconstruct the palaeogeography of the Tjörnes area. Some of his conclusions, at least as far as the Breiðavík Group rocks are concerned, are let down by weaknesses in mapping (*T. Einarsson* 1963, *Eiríksson* 1979). Answers to questions about the origin and depositional environments of the Tjörnes beds can probably not be regarded as reliable until they have been mapped thoroughly. Interpretations, of which there are a legion, appear to have suffered from a lack of detailed knowledge of the stratigraphy of Tjörnes.

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ÁGRIP

SAGA JARÐFRÆÐIRANNSÓKNA Á TJÖRNESI

Jarðfræðingar við jarðfræðideild Raunvísindastofnunar Háskólans hafa fengist við samfelldar rannsóknir á Tjörnesi síðan 1972. Viðfangsefnin hafa aðallega verið aldur hraunlaga, gerð og uppruni setlaga og dreifing plöntu- og dýrasteingervinga í lögunum. Þorleifur Einarsson var upphafsmaður þessa verkefnis. Rannsóknarverkefni eiga sér gjarnan ýmsa fylgifiska og er þetta yfirlit um rannsóknasögu Tjörness einn þeirra. Yfirlitið ber með sér að fjölmargir jarðfræðingar hafa birt niðurstöður Tjörnesrannsókna sinna á prenti. Við lestur þeirra sést fljótt að svo er margt sinnið sem skinnið. Niðurstöður eru oft furðu ólíkar. Það er markmið þessa sögulega yfirlits að meta stöðu rannsóknanna. Hvaða spurningum um jarðfræði Tjörness hefur verið svarað og hverjum ekki.

Jarðlög á Tjörnesi spanna tertíer og kvarter hraunlög og setlög. Hin þykku setlög og steingervingar þeirra eru einstæð við Norður-Atlantshaf. Elstu ritgerðir um jarðfræði Tjörness fjalla einkum um steingervinga í Hallbjarnarstaðakambi, en þegar kemur fram á þessa öld snúa menn sér einnig að jarðlagaskipun og setfræði. Heimildaskráin ber þess merki að hlutur íslenskra jarðfræðinga hefur lengi verið mikill í Tjörnesrannsóknum. Þorvaldur Thoroddsen varð fyrstur til að birta heildaryfirlit um jarðfræði Tjörness. Skömmu síðar fann Helgi Pjetursson harðnaðar jökulurðir í Breiðuvík. Nákvæm kortlagning strandlengjunnar um vestanvert Tjörnes beið þó uns Guðmundur G. Bárðarson birti sitt yfirgripsmikla ritverk um plíósen jarðlög á Tjörnesi. Guðmundur naut þá leiðsagnar Kára Sigurjónssonar, bónda og alþingismanns á Hallbjarnarstöðum, sem var manna kunnugastur skeljalögunum. Jóhannes Áskelsson ritaði talsvert um jarðfræði Tjörness. Jóhannes sýndi ótvírætt fram á að Breiðuvíkurlögin eru kvarter að aldri, og eftir samanburð efsta hluta Tjörneslaga og hnyðlinga í Skammadal áleit hann að þau væru einnig frá kvarter. Um og eftir seinni heimsstyrjöldina rannsakaði Trausti Einarsson jarðfræðilegt byggingarlag Tjörness og segulstefnur hraunlaga. Við rannsóknir hans skýrðust aðalatriðin í jarðlagaskipun Tjörness. Þjóðverjinn Strauch rannsakaði steingervingafræði og jarðlagaskipun strandlengjunnar um 1960, en Þjóðverjarnir M. Schwarzbach og H. D. Pflug höfðu áður fjallað um vitnisburð setlaga á Tjörnesi um loftslag. Um þær mundir voru Hollendingar atkvæðamiklir við jarðfræðirannsóknir á Íslandi og fjölluðu m. a. um jarðfræði Tjörness (t. d. H. Wensink). Árið 1967 birtu Þorleifur Einarsson o. fl. grein um Tjörnes, þar sem sýnt var fram á merki um 10 jökulskeið, og upphaf ísaldar var tímasett við rúmar 3 milljónir ára. Á árunum eftir 1970 gerðu sovéskir jarðfræðingar sér tíðförult til Tjörness og hafa birt margt á prenti um rannsóknir sínar. Segja má að síðastliðna tvo til þrjá áratugi hafi aðaláhersla verið lögð á segulstefnutímatal, beinar aldursákvarðanir og setfræðirannsóknir á efsta hluta jarðlagastaflans á Tjörnesi. Gerð jarðlaga þar og merki um gróður og dýralíf bera vott um sveiflur í loftslagi og útbreiðslu jökla.