# Stratigraphy and age of the Eocene Igtertivâ Formation basalts, alkaline pebbles and sediments of the Kap Dalton Group in the graben at Kap Dalton, East Greenland

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A NE–SW-trending graben at Kap Dalton on the Blosseville Kyst contains an at least 600 m thick succession of Eocene basalt lavas and sediments. The succession has been investigated by new field work, geochemical analysis and radiometric dating by the $^{40}Ar$-$^{39}Ar$ incremental heating method. The results show that the volcanic succession comprises about 220 m of the uppermost plateau basalt formation, the Skrænterne Formation. This is separated from the overlying lava flows of the Igtertivâ Formation by 7 m of sediments that represent a period of around six million years. The two formations can be distinguished by different trace element ratios. The Igtertivâ Formation comprises an at least 300 m thick main succession of flows dated to 49.09 ± 0.48 Ma, overlain by sediments of the Bopladsdalen Formation. A basal conglomerate in the sediments contains pebbles of alkaline igneous rocks of which three were dated at 49.17 ± 0.35 Ma, 47.60 ± 0.25 Ma, and 46.98 ± 0.24 Ma. The sediments are thus younger than 47 Ma. Above 30 m of sediments occur two Igtertivâ Formation lava flows dated to 43.77 ± 1.08 Ma. The overlying sediments of the Bopladsdalen and Krabbedalen Formations are therefore not older than about 44 Ma and palynological evidence shows that they are also not much younger than this. Use of the Geological Time Scale 2012 has resulted in good agreement between radiometric and palynological ages.

The Igtertivâ Formation lava flows were fed from a regional coast-parallel dyke swarm indicating a new rifting episode at 49–44 Ma. This coincides with a major mid-Eocene plate reorganisation event in the North Atlantic and the start of northward-propagation of the Reykjanes Ridge through the continent. The Igtertivâ rift may have been directly instrumental for the initiation of this process.

*Keywords*: Igtertivâ Formation, plateau basalts, alkaline pebbles, Bopladsdalen Formation, radiometric ages, Kap Dalton, East Greenland, ridge propagation.

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The East Greenland flood basalts belong to the North Atlantic Igneous Province and were erupted in connection with continental breakup and the start of formation of the North Atlantic Ocean in the early Tertiary (e.g. Upton 1988; Eldholm & Grue 1994; Saunders *et al*. 1997; Skogseid *et al*. 2000; Brooks 2011). The basalts in East Greenland occurring between 68°N and 70.5°N cover around 65 000 km$^2$ with an up to 6–8 km thick lava succession (Pedersen *et al*. 1997), forming the most voluminous part of the onshore Tertiary basalts in the North Atlantic Igneous Province. A Paleocene part, the Lower Basalts, is present in a limited area east of Kangerlussuaq (Nielsen *et al*. 1981) whereas the overlying 'plateau basalts' extend over the whole area (Pedersen *et al*. 1997). The stratigraphy of the plateau basalts was established by Larsen *et al*. (1989) who defined five regionally extensive basalt formations, *viz*. the Magga Dan, Milne Land, Geikie Plateau, Rømer Fjord and Skrænterne Formations. In contrast, the sixth and youngest formation, the Igtertivâ Formation, was found only in a small downfaulted area at Kap Dalton on the Blosseville Kyst. Data on this formation were therefore scarce and the boundary to the underlying Skrænterne Formation was not identified, resulting in a stratigraphic gap in the known succession.

The precise age of the Milne Land to Skrænterne Formations was established with $^{40}Ar$-$^{39}Ar$ dating by Storey *et al*. (2007a) who found that all were erupted within a very narrow interval around 55.5 Ma within the earliest Eocene. No reliable age was obtained for the Igtertivâ Formation.

The promontory of Kap Dalton is situated at 69°27'N in the northern part of the Blosseville Kyst in central East Greenland (Fig. 1). The Igtertivâ Formation is preserved in a small graben behind the headland and is overlain by the oldest known post-basaltic sediments, including conglomerates with pebbles of exotic alkaline igneous rocks (Wager 1935). The succession spans a crucial time period during which large changes in volcanism, sedimentation and palaeogeography took place.

This paper presents a much extended volcanic stratigraphy of the Kap Dalton area together with the first radiometric age determinations of the lavas of the Igtertivâ Formation and the alkaline pebbles.

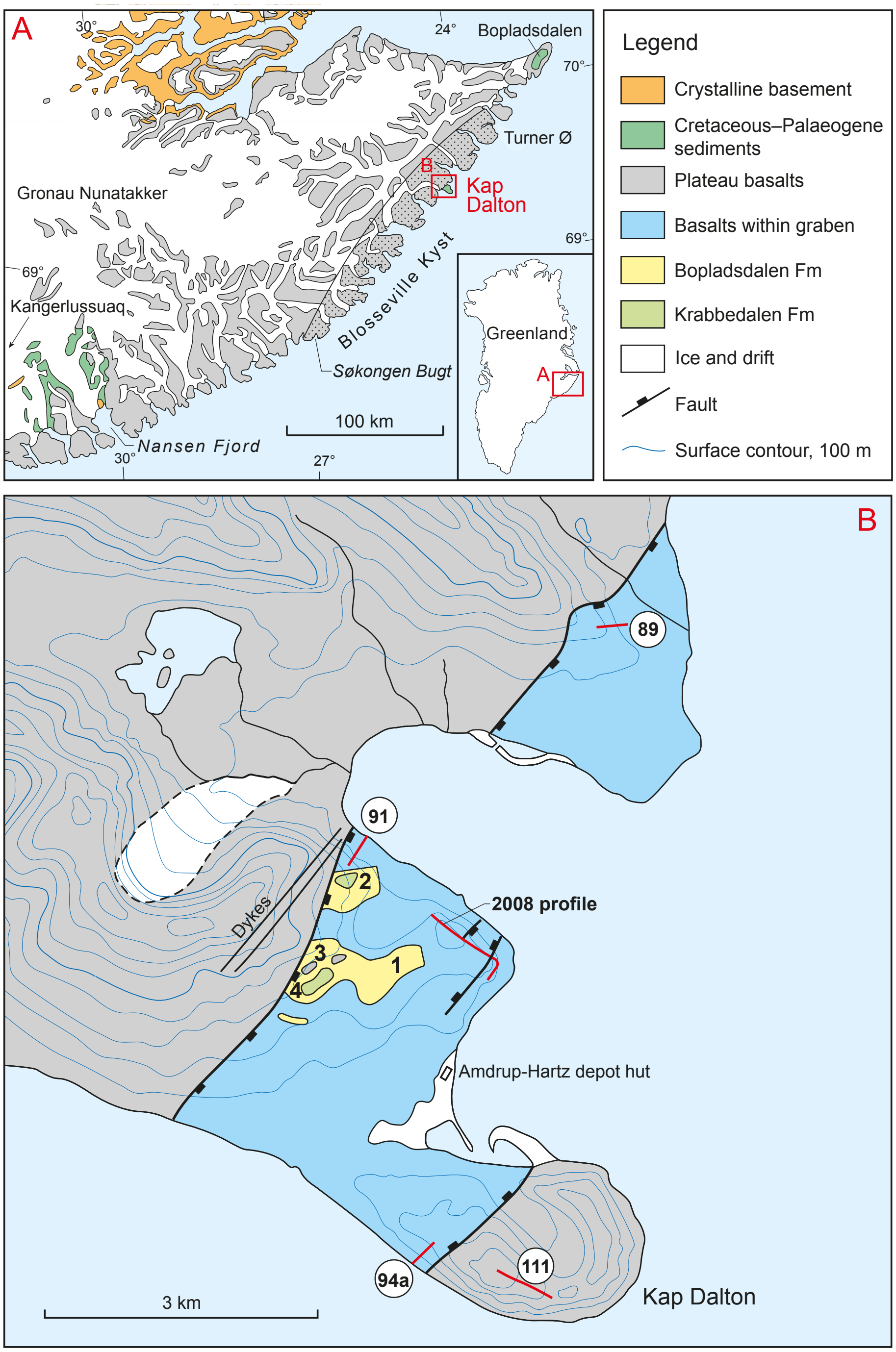


Fig. 1. Geological map of the Kap Dalton area, modified from Larsen *et al*. (2005). Sampled profiles through the volcanic succession are shown by red lines; ringed numbers are profiles from 1975. The numbers 1–4 in the sediments are localities of Larsen *et al*. (2005). The dotted basalt areas in A are cut by a slightly arcuate coast-parallel dyke swarm.

# Geological setting and previous work

Due to the remoteness of the Kap Dalton area it has been visited only infrequently. The sediments overlying the basalt lavas were found by O. Nordenskiöld and N.E.K. Hartz during the Danish Amdrup–Hartz expedition in 1900, and the collected fossil material was examined by Ravn (1904). The area was visited again in 1932 during the Scoresby Sound Committee's Second East Greenland Expedition, when L.R. Wager found that the sediment succession had a basal conglomerate with pebbles of a variety of exotic alkaline igneous rocks (Wager 1935). The area was mapped by the Geological Survey of Greenland in 1975 when both sediments and lavas were investigated (Watt *et al*. 1976; Soper & Costa 1976; Soper *et al*. 1976). The next visit was by the Geological Survey of Denmark and Greenland (GEUS) in 2001 when the sediments were investigated in detail for the first time (Larsen *et al*. 2002, 2005; Heilmann-Clausen *et al*. 2008). In 2008 two GEUS geologists briefly visited the Kap Dalton area, taking series of stereo-photographs of the lava succession in the coastal cliffs and sampling the lava succession and the alkaline conglomerate pebbles. The present paper is mainly based on this work.

The graben in the Kap Dalton area is around 3.5 km wide and bounded on both sides by major, NE-running faults (Wager 1935; Watt *et al*. 1976). The north-western boundary fault can be followed for 8 km on the Kap Dalton peninsula and the smaller peninsula immediately to the north (Fig. 1). The down-faulted block is itself cut by a number of small faults. In the northern peninsula the succession is upturned along the edge by drag along the main fault, whereas on the Kap Dalton peninsula the main part of the succession dips around 10°NW (Watt *et al*. 1976; Larsen *et al*. 1989). The resulting small southerly dip component around 2° means that any stratigraphic level drops about 100 m from north to south across the peninsula (Sørensen 2011).

The plateau basalts bounding the graben to the NW are nearly flat-lying and belong to the Geikie Plateau, Rømer Fjord and Skrænterne Formations, indicating a downthrow of the graben succession in excess of 1500 m (Larsen *et al*. 1989). The plateau basalts bounding the graben to the SE on the Kap Dalton headland belong to the uppermost part of the Skrænterne Formation and are downthrown about 1400 m relative to the lavas on the mainland; thus the downthrow of the succession in the graben relative to the SE fault may only be a few hundred metres.

The lava succession in the graben was defined as the Igtertivâ Formation by Larsen *et al*. (1989). (Igtertivâ is the old Greenlandic name for Kap Dalton). The stratigraphy of this formation was based on two short sample profiles from 1975 which could not be correlated. In particular, the lower boundary was undefined. The lavas of the Igtertivâ Formation are not cut by any dykes, in contrast to the surrounding lavas where cross-cutting NE-running dykes are frequent (Watt 1975). The majority of the dykes were intruded before the main graben-forming faulting took place (Watt *et al*. 1976), and because of compositional similarities these dykes were considered to have fed the Igtertivâ Formation (Larsen *et al*. 1989).

Sediment layers are commonly present between the lava flows of the Igtertivâ Formation. Red and green siltstones, coal and tuffs have been described, and some layers contain sparse marine microfossils that have been used to constrain the age of the volcanic succession (Soper & Costa 1976; Soper *et al*. 1976; Jolley 1998; Heilmann-Clausen *et al*. 2008).

The sediments overlying the lavas of the Igtertivâ Formation belong to the Bopladsdalen and Krabbedalen Formations of the Kap Dalton Group. The sediments, and their contained fossils, have been described by several authors, notably Ravn (1904, 1933), Wager (1935), Soper & Costa (1976), Soper *et al*. (1976), and Larsen *et al*. (2002, 2005). Larsen *et al*. (2005) provided the most detailed description of the sediments and the lateral variations in four profiles logged in detail (localities 1–4 in Fig. 1).

The alkaline pebbles in the conglomerate at the base of the Bopladsdalen Formation were only re-found in 2001 and no descriptions of them have appeared since Wager's (1935) work.

## Age relations

The age of the post-volcanic sediments of the Kap Dalton Group has been revised repeatedly. Most recently Larsen *et al*. (2005), based on detailed palynological data, suggested that the sediments were deposited during a time span of less than 3 million years in the early middle Eocene (early Lutetian), correlating to the upper NP14 to middle NP15 nannoplankton zones. This corresponds to the time interval 47–44 Ma in the Geological Time Scale 2012 (GTS 2012) (Vandenberghe *et al*. 2012).

Heilmann-Clausen *et al*. (2008) presented palynological data for the interbasaltic sediments in the Igtertivâ Formation, 50–100 m below the top of the formation. The dinoflagellate assemblage includes a reliable indicator for an age not older than late Ypresian, latest NP12, corresponding to 50–51 Ma according to GTS 2012. They also presented palaeomagnetic results for two lava flows: the topmost flow just below the Kap Dalton Group sediments is normally magnetised and was referred to either magnetochron C22n (49.34–48.56

Ma) or C21n (47.35–45.73 Ma) (ages according to GTS 2012). A lava flow close to the Amdrup-Hartz depot hut is reversely magnetised and was therefore placed in either C22r or C21r; however, based on the present study the flows near the hut belong to the Skrænterne Formation (see later), and the magnetochron is considered to be C24r as for the rest of the plateau basalt succession (Storey *et al*. 2007a).

Tegner *et al*. (1998) quoted an unpublished $^{40}Ar$-$^{39}Ar$ result for the Igtertivâ Formation as suggesting eruption around 48–49 Ma. This is in accordance with the palynological age and is significantly younger than the underlying plateau basalts which are dated by the $^{40}Ar$–$^{39}Ar$ method to 56.4–55.3 Ma (Heister *et al*. 2001; Storey *et al*. 2007a).

## Field work 2008

In 2008 two of the authors (AKP and EVS) spent two and a half days at Kap Dalton. Because of the crumbling sediments and the relatively smooth topography, exposures are often poor as noted by all earlier workers. However, Wager's (1935) conglomerate locality with pebbles of alkaline igneous rocks was easily found following his map (Fig. 1, locality 1). This is a scree-covered surface where rounded polished pebbles and platy bits of grey volcaniclastic sandstone lie loose as shown in Fig. 3A. In addition, alkaline pebbles were also found at a higher level at locality 3 (Fig. 1) in scree belonging to the Krabbedalen Formation.

The lava succession was sampled in a profile along the top of the steep NE-facing cliff within the graben (Fig. 2; profile line in Fig. 1). The steep cliff face provides good exposures and the stratigraphic control is enhanced by the colour stereo-photographs. This is necessary because the cliff succession dips 7°NW and is cut by one large and two small faults.

At the top of the succession a 30 m thick sediment horizon is present, repeated in two neighbouring fault blocks (Figs 2, 3B, 3C, 4). The sediment is a greenish-grey fissile volcaniclastic sandstone to siltstone with subordinate thin claystone horizons with plant remains. It contains scattered centimetre-sized rounded polished pebbles (Fig. 3D). At the base of the sediment horizon is a poorly exposed conglomerate with a larger concentration of pebbles up to 22 cm in diameter, comprising alkaline igneous rocks. The conglomerate and the volcaniclastic sediments correlate with the Bopladsdalen Formation and Wager's conglomerate at locality 1, as described by Larsen *et al*. (2005). In contrast to locality 1 where two 2 m and 6 m thick quartzitic sandstone horizons are present,

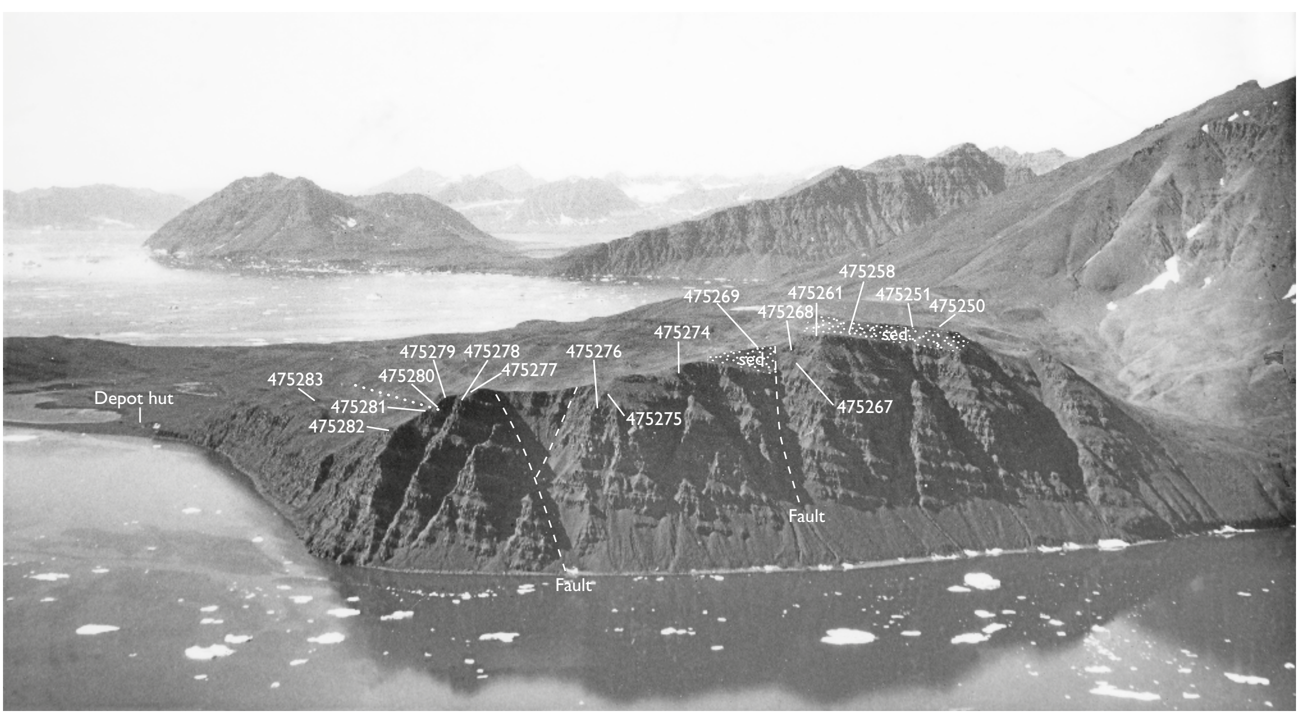


Fig. 2. Overview photograph of the NE-facing cliff where the sample profile in 2008 was taken. Sample numbers are indicated. The 30 m thick sediment horizon near the top of the succession, cut by a fault, is highlighted with small white dots and annotated 'sed'. The dotted line to the left of the cliff, near the location of sample 475280, indicates the position of the boundary between the Skrænterne and Igtertivâ Formations. The headland of Kap Dalton is outside the picture to the left. Height of cliff up to 310 m. Photo by M. Watt 1974.

no quartzitic sandstone horizons were found in the profile at the cliff edge.

The sediment horizon at the cliff edge is overlain by at least two basalt lava flows (Fig. 3B). The lower flow is present in both fault blocks; it is about 8 m thick, vesiculated and coarsely columnar jointed. In the western fault block this flow is overlain by another fairly altered lava flow of which only about 2 m is preserved. Higher parts of the succession are not preserved at the cliff edge where they have been removed by erosion (Fig. 2). No such lava flows are present at locality 1.

The sediments rest on the eroded top of a lava flow. The lava succession below the sediments comprises about ten 20–30 m thick flows of which the upper five were sampled. There is around 5 m of yellow-brown claystone and tuff below the uppermost flow; farther down no sediments are visible between flows but may be present beneath the scree (Fig. 4). All flows have the morphology of subaerial flows.

The eastern part of the cliff is cut by a fault across which the lava flows cannot be correlated. The lava succession east of the fault consists of about eleven 10–40 m thick flows of which the upper five were sampled. Thick purplish red-brown sediment horizons occur between many of the flows (Fig. 5). Again, all lava flows have the morphology of subaerial flows. This lava succession forms the SE-facing cliff at the end of which the Amdrup-Hartz depot hut is located (Fig. 2).

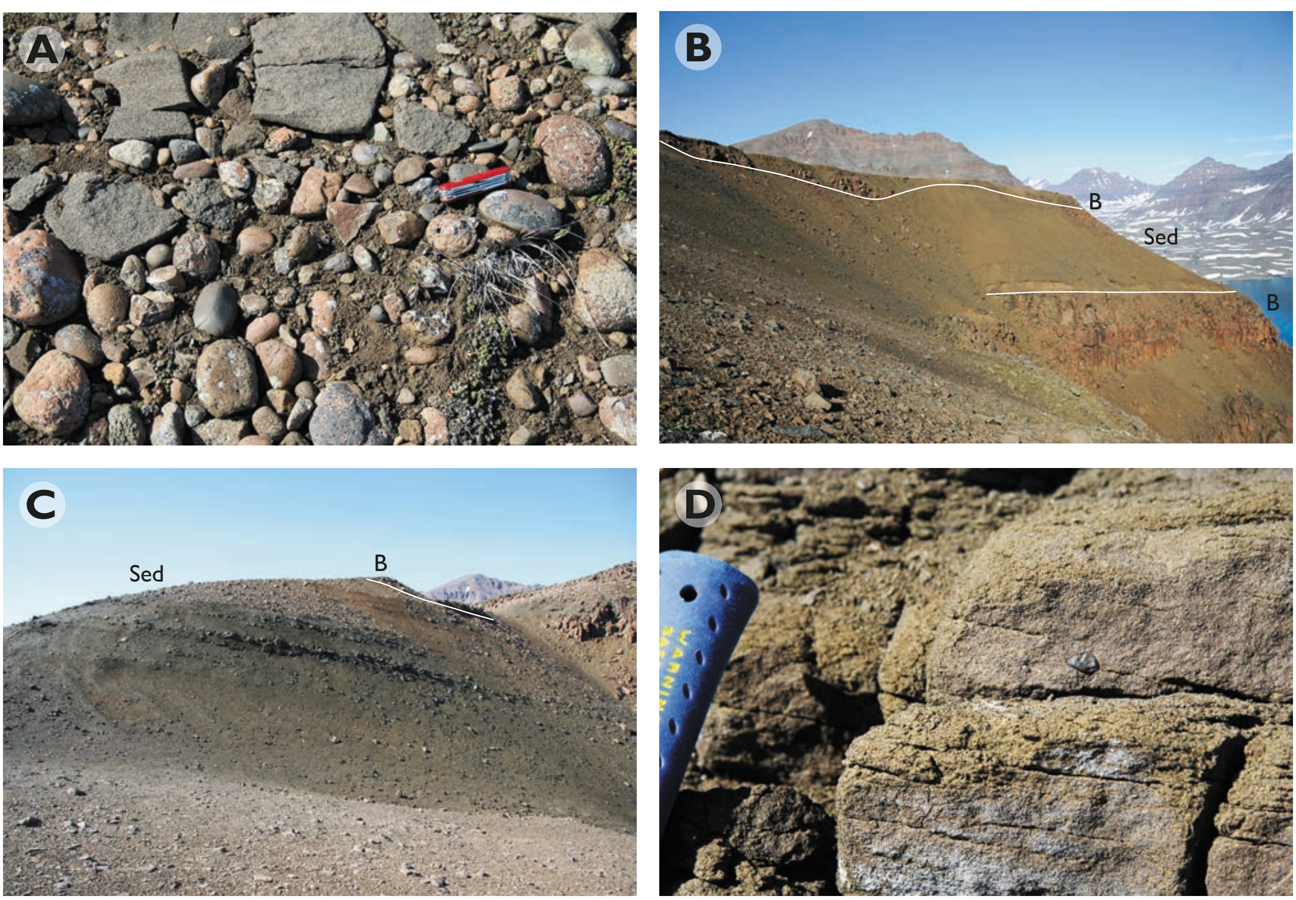


Fig. 3. The Bopladsdalen Formation at Kap Dalton. **A**: Small slabs of volcaniclastic sandstone and rounded polished pebbles of alkaline rocks in scree at locality 1 in Fig. 1. Length of knife handle 8 cm. **B**: Around 30 m of volcaniclastic sediments (Sed) of the Bopladsdalen Formation in the cliff shown in Fig. 2, overlying basalt lavas (B) of the Igtertivâ Formation and capped by two lava flows (B; only one is visible); western of the two fault blocks with sediments, looking west towards the plateau basalts on the mainland. **C**: Bopladsdalen Formation sediments (Sed) capped by a lava flow (B); same succession as shown in 3B but in the eastern of the two fault blocks; height of exposure close to 30 m. **D**: Close-up of fissile volcaniclastic sandstone with a single 1–2 cm pebble.

# Analytical methods

## Major and trace element analyses

Bulk rocks were analysed for major elements by X-ray fluorescence spectrometry (XRF). Samples with FeO determination were analysed at GGU/GEUS, following procedures given in Kystol & Larsen (1999). Samples with all iron as $Fe_2O_3$ were analysed at University of Edinburgh, following procedures given in Fitton *et al.* (1998). Results from the two laboratories are closely comparable, as shown by Larsen *et al.* (1998).

Trace elements were analysed by inductively coupled plasma mass spectrometry (ICP-MS) at GEUS, using a PerkinElmer Elan 6100 DRC Quadrupole mass spectrometer. Sample dissolution followed a modified version of the procedure used by Turner *et al.* (1999) and Ottley *et al.* (2003). Calibration was done using two certified REE solutions and three international reference standards. Results for reference samples processed and run simultaneously with the unknowns are normally within 5% of the reference value for most elements with concentrations > 0.1 ppm.

## Radiometric age determinations

Samples were dated by the $^{40}Ar$-$^{39}Ar$ incremental heating method in the Noble Gas Mass Spectrometry Laboratory at Oregon State University. The instrument is a MAP 215-50 gas mass spectrometer with all-metal extraction system equipped with a 10W $CO_2$ laser and Heine low-blank, double-vacuum resistance furnace connected to an ultra-clean, low volume (~1000 cc) gas cleanup line. Samples were degassed in 8–17 temperature steps, from 500°C to fusion at around 1400°C. Zr-Al getters removed active gases. Ion beam currents are measured with the electron multiplier at m/z = 35, 36, 37, 38, 39, and 40, and intervening baselines. Measurement times, peak/baseline voltages, data acquisition and storage are computer controlled. Mass discrimination is monitored using an air pipette system. All resulting ages are calculated using the ArArCALC software package (Koppers 2002).

Unaltered phenocrysts were separated by standard mineral separation techniques. Fine grained, unaltered whole-rocks were cored with a 5 mm diameter diamond-tipped drill bit, then sectioned into disks

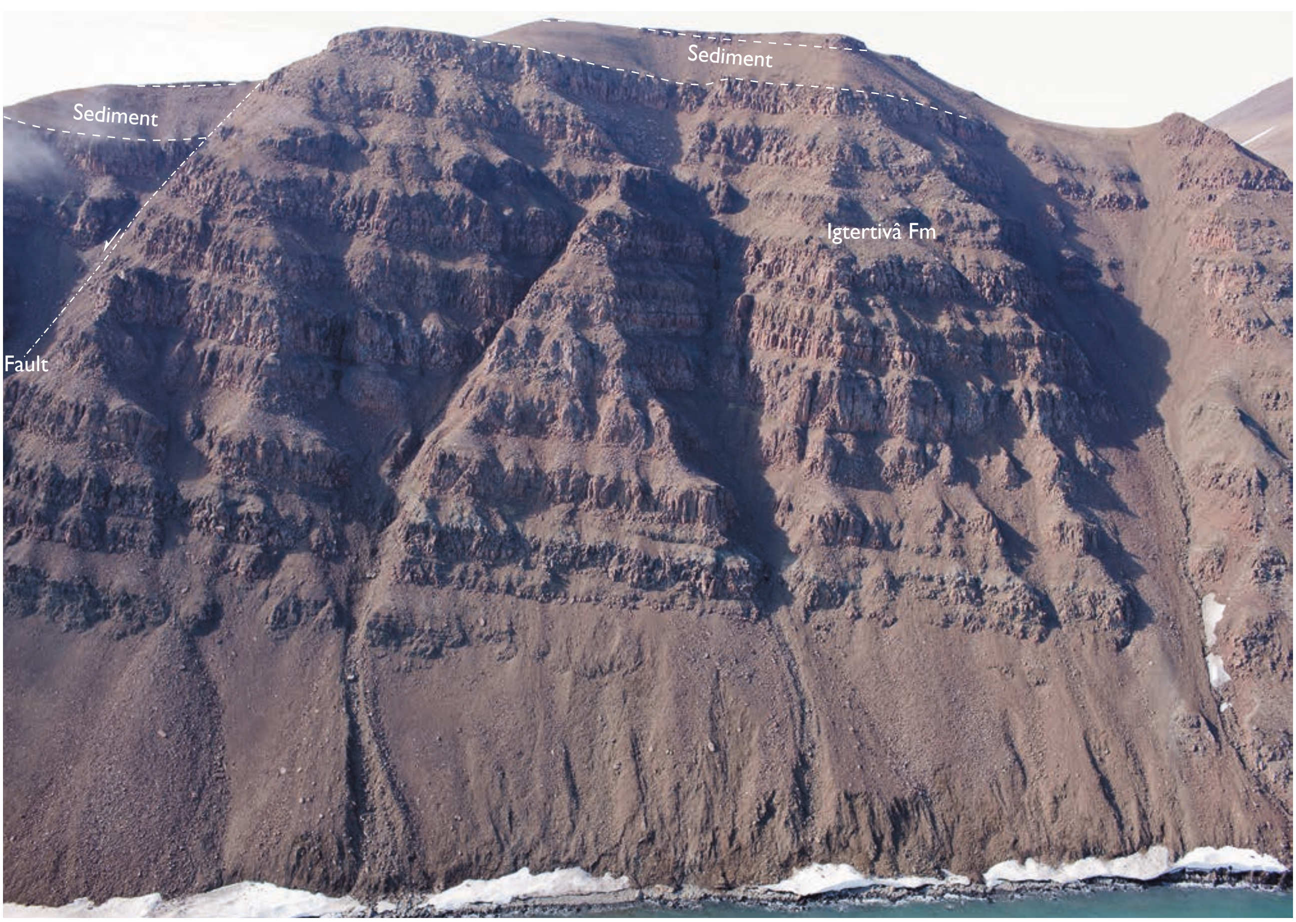


Fig. 4. The volcanic succession of the Igtertivâ Formation in the central part of the cliff face in Fig. 2. The lavas are overlain by 30 m of volcaniclastic sediments belonging to the Bopladsdalen Formation which are again capped by two lava flows. The succession is repeated across a minor fault in the left part of the picture. Height of cliff 310 m.

of 100–300 mg. Samples were irradiated at the Oregon State University TRIGA experimental reactor for six hours at 1 MW power. The neutron flux was monitored with the FCT-3 biotite monitor. All ages are here calculated relative to an age of 28.201 Ma for the Fish Canyon Tuff, following Kuiper *et al.* (2008) and Schmitz (2012), and using the decay constant for $^{40}K$ of Steiger & Jäger (1977).

# Chemical stratigraphy

The profile sampled in 2008 is shown schematically in Fig. 6 together with three shorter profiles (89, 91, 94a) sampled in 1975 (Watt *et al*. 1976). The profile locations are shown in Fig. 1. The four profiles can be confidently placed in relation to each other by combined field and geochemical correlations. Selected chemical analyses, including the dated samples, are shown in Table 1, and all analyses are available in Supplementary data file 1 at the web site http://2dgf.dk/publikationer/bulletin/191bull61.html.

The lavas are all tholeiitic basalts with 4.8–7.2 wt% MgO and 2.0–3.2 wt% $TiO_2$ (Fig. 7A). Specific correlations can be made at four levels, based on the detailed trace element characteristics of the flows. Three single flows and a group of two flows can be correlated between profiles; these flows are joined by lines in Fig. 6 and encircled in the plots in Fig. 7.

Because of the correlation between the upper flows in profiles 2008 and 91 (Fig. 6, level 4), the conglomerates in these profiles cannot be the same. In profile 91 the lateral correlative to the 30 m sediment horizon and the conglomerate with alkaline pebbles must be situated in the 50 m unexposed interval between samples 116346 and 116347. The conglomerate on top of profile 91 contains only non-alkaline basalt pebbles (N.J. Soper, personal communication 1975), confirming that it is another unit.

## Presence of the Skrænterne Formation in the graben at Kap Dalton

A significant discontinuity in trace element ratios is used as datum line in Fig. 6 (correlation level 1). Below this level all flows have higher HREE (Gd/Lu) ratios


Fig. 5. The eastern part of the cliff face in Fig. 2. The fault block to the left, which continues into the background, contains the uppermost lava flows of the Skrænterne Formation. They are overlain by 7 m of red sediment and the two lowermost lava flows of the Igtertivâ Formation. The flows to the right of the fault zone all belong to the Igtertivâ Formation. Height of central cliff section 220 m.

at given LREE (La/Sm) ratios than the flows above this level (Fig. 7B). This difference is accompanied by differences in other incompatible element ratios such as Nb/Y and Zr/Y (Fig. 7C). The flows below the level are shown in green colours in Figs 6 and 7.

The principal difference between the established Igtertivâ and Skrænterne Formations (Larsen *et al.* 1989) was lower $TiO_2/P_2O_5$ and Zr/Nb ratios in the Igtertivâ Formation than in the Skrænterne Formation (and the underlying plateau basalt formations).

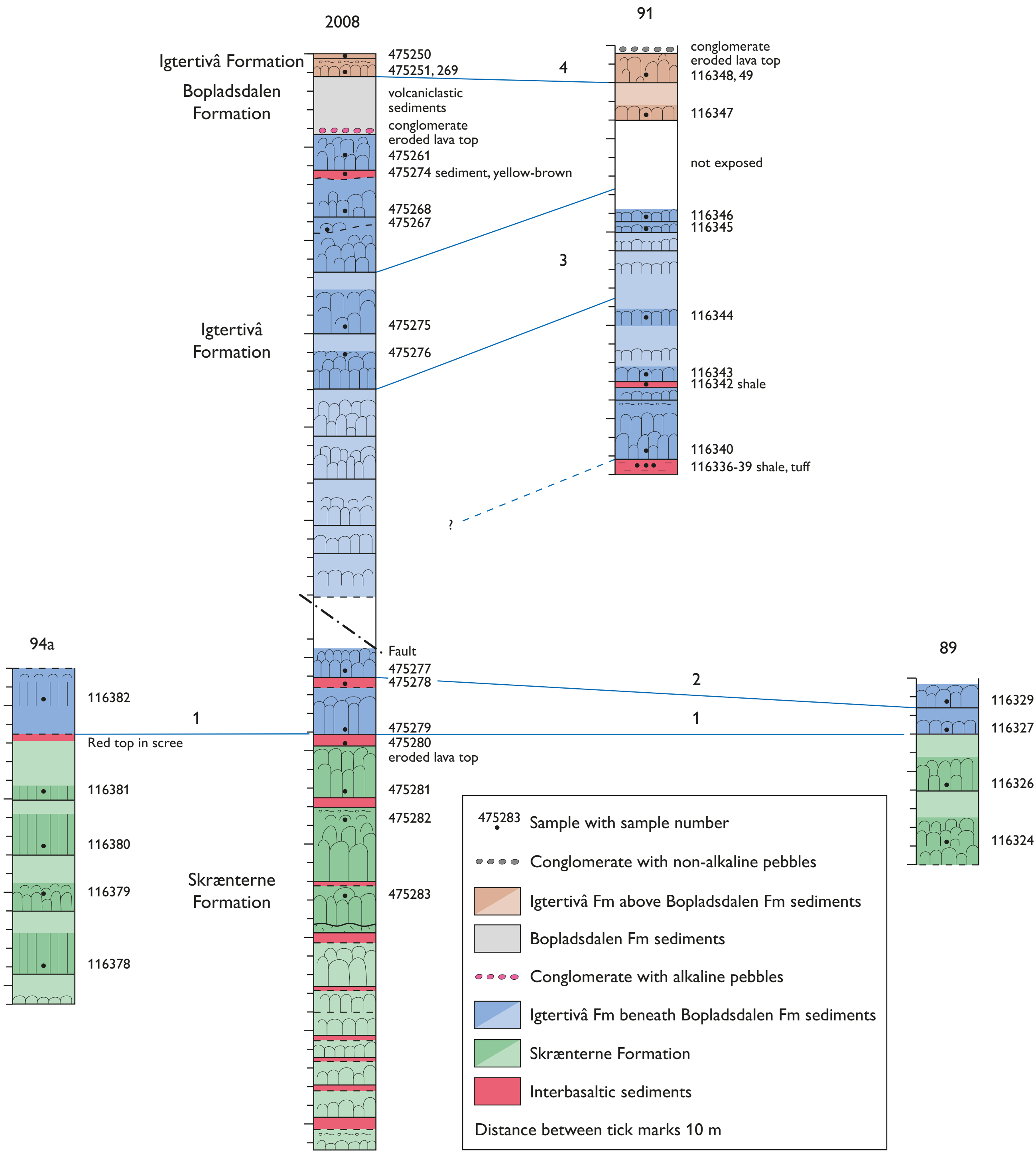


Fig. 6. Diagrammatic representation of the four sampled lava profiles through the Igtertivâ Formation in the Kap Dalton area, with sample numbers indicated. Profile numbers at tops refer to profiles located in Fig. 1. Correlation lines between flows are based on geochemical characteristics, and numbers 1–4 refer to plot groups in Fig. 7. Unsampled parts of the successions have pale colours. The 'decorations' within the lava flows are simplified depictions of the physical appearance of the flows.

As the flows below correlation level 1 in Fig. 6 have significantly higher Zr/Nb than those above, they could actually belong to the Skrænterne Formation. To test this possibility, profile 111 through the upper Skrænterne Formation in the headland of Kap Dalton (Fig. 1; Larsen *et al*. 1989) was analysed for trace elements. The results (Table 1 and Supplementary data file 1) showed that the flows below correlation level 1 in Fig. 6 have trace element contents and ratios that are indistinguishable from the Skrænterne Formation flows in profile 111 (Fig. 7). We conclude that the flows below correlation level 1 belong to the Skrænterne Formation, thereby defining the base of the Igtertivâ Formation.

In the field, the boundary between the Skrænterne and Igtertivâ Formations is unexposed in two profiles although a red sediment was noted in scree in profile 94a (Fig. 6). However the boundary is excellently exposed in the 2008 profile (Fig. 5) where 6.5–7 m of sediment overlies an eroded lava flow whose rubble top has been completely removed (Fig. 8). The sediment comprises, in succession, 0.6 m red laterite overlying the lava, c. 1 m sediment mottled in red-brown and yellow ochre colours, c. 3 m red-brown sediment, 1.6 m dark purplish sediment, and 0.5 m dark, nearly black claystone. A thin top zone is bleached, probably by the overlying lava flow. The sediment horizon represents a considerable time interval, as shown below.

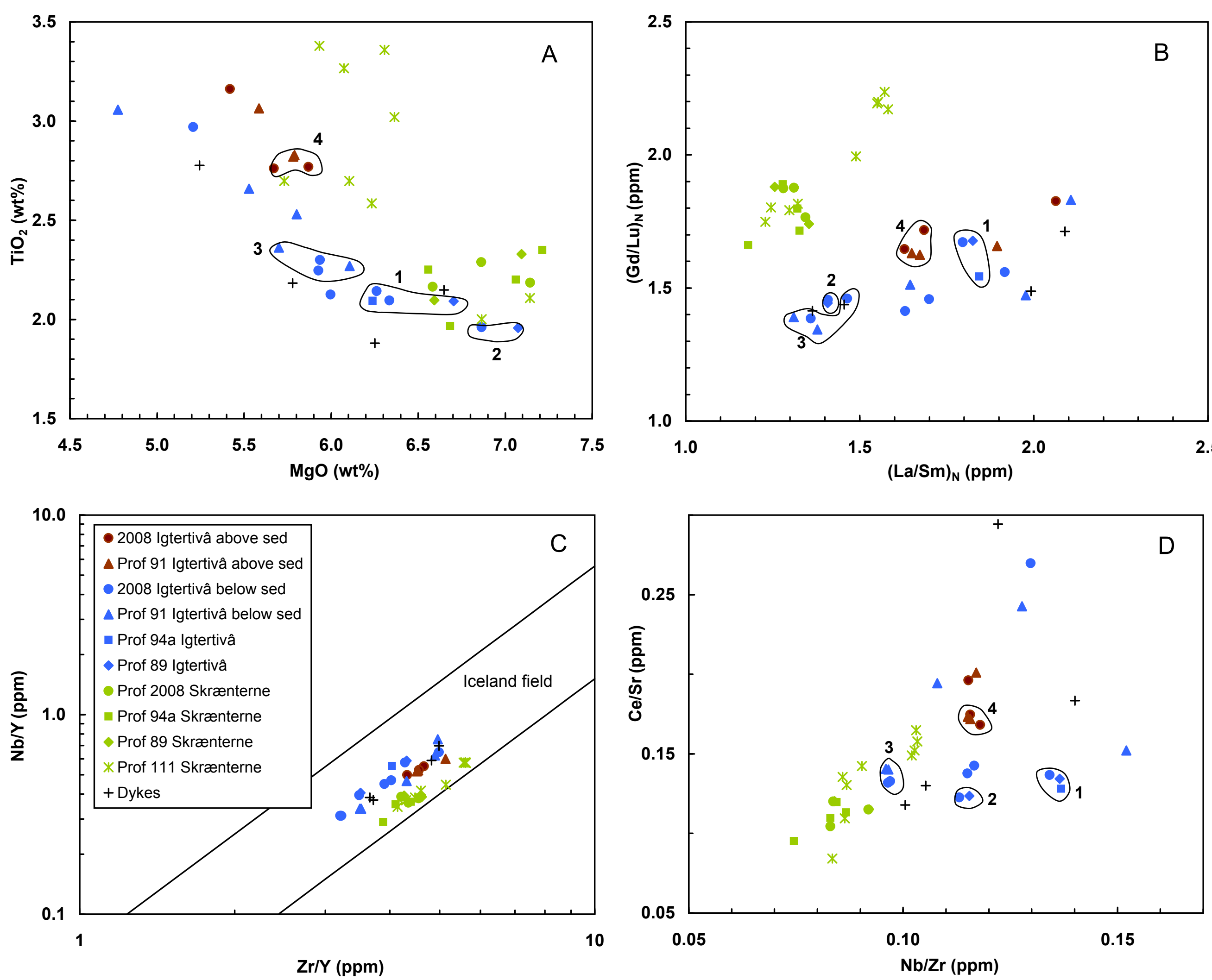


Fig. 7. Geochemical plots of analysed samples from profiles 89, 91, 94a, 111, and 2008. **A**: major elements; **B**, **C**, **D**: various trace element ratios. The subscript N (in B) indicates chondrite normalised concentrations. The differences between the Skrænterne and Igtertivâ Formations are apparent in B and C, whereas the major elements are less diagnostic. Correlated flows at four levels are encircled, and the individuality of these flows is particularly clear in B and D. Numbers 1–4 refer to correlation levels in Fig. 6. The Iceland field in C is after Fitton *et al*. (1998).

Table 1. Analyses of lavas and alkaline pebbles from the Kap Dalton area

| **GGU-nr** | **215605** | **475282** | **475279** | **475275** | **116344** | **475261** | **475269** | **475239** | **475245** | **475258** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Profile** | 111 | 2008 | 2008 | 2008 | 91 | 2008 | 2008 | Trachybas. | Trachyte | Phonolite |
| **Formation** | Skrænterne | Skrænterne | Igtertivâ | Igtertivâ | Igtertivâ | Igtertivâ | Igtertivâ | Pebble | Pebble | Pebble |
| Major elements, wt% | | | | | | | | | | |
| **$SiO_2$** | 48.05 | 48.10 | 48.28 | 47.58 | 49.14 | 48.95 | 47.81 | 47.21 | 58.08 | 51.16 |
| **$TiO_2$** | 3.22 | 2.11 | 2.08 | 2.23 | 2.49 | 2.90 | 2.68 | 3.12 | 0.48 | 0.55 |
| **$Al_2O_3$** | 13.08 | 14.14 | 13.73 | 14.00 | 14.19 | 13.09 | 13.36 | 17.43 | 18.70 | 20.31 |
| **$Fe_2O_3$** | 4.02 | 13.78 | 13.57 | 14.45 | 5.45 | 15.57 | 14.96 | 10.33 | 5.02 | 4.78 |
| **FeO** | 10.31 | | | | 7.33 | | | | | |
| **MnO** | 0.22 | 0.29 | 0.23 | 0.26 | 0.22 | 0.24 | 0.24 | 0.60 | 0.19 | 0.19 |
| **MgO** | 5.99 | 6.43 | 6.09 | 5.77 | 5.71 | 5.08 | 5.51 | 4.02 | 0.87 | 0.75 |
| **CaO** | 10.83 | 11.48 | 11.42 | 11.55 | 10.83 | 9.39 | 10.79 | 9.15 | 3.11 | 2.75 |
| **$Na_2O$** | 2.43 | 2.20 | 2.41 | 2.31 | 2.62 | 2.78 | 2.61 | 3.45 | 5.51 | 7.16 |
| **$K_2O$** | 0.35 | 0.17 | 0.43 | 0.10 | 0.51 | 0.55 | 0.23 | 1.82 | 4.49 | 4.91 |
| **$P_2O_5$** | 0.32 | 0.19 | 0.21 | 0.20 | 0.30 | 0.38 | 0.28 | 0.53 | 0.08 | 0.12 |
| **LOI** | 1.39 | 0.46 | 0.69 | 0.81 | 1.50 | 0.16 | 0.48 | 1.62 | 3.20 | 4.66 |
| Sum | 100.21 | 99.35 | 99.14 | 99.27 | 100.29 | 99.08 | 98.95 | 99.28 | 99.72 | 97.33 |
| Trace elements, ppm | | | | | | | | | | |
| **Sc** | 37.2 | 37.7 | 40.8 | 45.3 | 41.3 | 37.4 | 38.8 | 14.7 | 2.40 | 2.46 |
| **V** | 405 | 348 | 362 | 416 | 361 | 386 | 406 | 215 | 20.12 | 70.78 |
| **Cr** | 127 | 248 | 90.2 | 44.5 | 123 | 34.1 | 83.5 | 18.8 | 0.72 | 0.48 |
| **Co** | 54.0 | 50.5 | 50.3 | 56.2 | 50.3 | 42.6 | 47.9 | 29.7 | 16.3 | 10.2 |
| **Ni** | 81.6 | 103 | 65.5 | 49.5 | 67.1 | 36.5 | 51.3 | 25.9 | 17.5 | 1.95 |
| **Cu** | 263 | 161 | 177 | 260 | 235 | 214 | 234 | 94.7 | 4.54 | 3.84 |
| **Zn** | 125 | 101 | 106 | 115 | 114 | 128 | 120 | 111 | 103 | 129 |
| **Ga** | 22.7 | 20.4 | 19.5 | 20.2 | 20.6 | 20.6 | 21.0 | 26.6 | 25.7 | 39.0 |
| **Rb** | 2.85 | 4.66 | 7.20 | 0.37 | 10.52 | 5.71 | 0.92 | 46.3 | 160 | 129 |
| **Sr** | 272 | 245 | 249 | 205 | 210 | 207 | 237 | 855 | 1154 | 519 |
| **Y** | 35.5 | 30.3 | 31.8 | 43.9 | 45.2 | 50.0 | 41.1 | 31.3 | 33.8 | 25.6 |
| **Zr** | 198 | 132 | 136 | 142 | 195 | 249 | 188 | 309 | 676 | 1058 |
| **Nb** | 20.4 | 10.9 | 18.3 | 13.7 | 21.0 | 32.4 | 21.7 | 66.6 | 147 | 329 |
| **Cs** | 0.037 | 0.020 | 0.066 | 0.010 | 0.058 | 0.067 | 0.027 | 1.388 | 3.542 | 3.131 |
| **Ba** | 96.7 | 72.1 | 105 | 34.8 | 106 | 157 | 97.2 | 761 | 3919 | 12080 |
| **La** | 17.52 | 10.00 | 14.47 | 11.71 | 17.51 | 24.33 | 17.44 | 48.60 | 80.71 | 54.38 |
| **Ce** | 42.94 | 25.52 | 34.06 | 26.93 | 40.75 | 55.69 | 41.41 | 99.53 | 130.95 | 101.39 |
| **Pr** | 6.23 | 3.78 | 4.67 | 4.08 | 5.68 | 7.43 | 5.72 | 12.17 | 13.51 | 10.62 |
| **Nd** | 29.18 | 17.88 | 20.54 | 19.03 | 25.87 | 32.73 | 25.32 | 48.53 | 43.60 | 35.64 |
| **Sm** | 7.06 | 4.88 | 5.03 | 5.38 | 6.65 | 7.93 | 6.46 | 9.38 | 6.72 | 6.11 |
| **Eu** | 2.27 | 1.64 | 1.64 | 1.81 | 2.08 | 2.36 | 2.05 | 3.05 | 2.78 | 2.34 |
| **Gd** | 7.76 | 5.57 | 5.60 | 6.70 | 7.69 | 8.98 | 7.39 | 9.03 | 7.11 | 5.46 |
| **Tb** | 1.19 | 0.93 | 0.93 | 1.12 | 1.28 | 1.47 | 1.22 | 1.24 | 0.99 | 0.84 |
| **Dy** | 6.88 | 5.41 | 5.55 | 7.13 | 7.87 | 8.98 | 7.22 | 6.25 | 4.93 | 4.72 |
| **Ho** | 1.309 | 1.089 | 1.156 | 1.538 | 1.586 | 1.879 | 1.468 | 1.110 | 0.914 | 0.896 |
| **Er** | 3.42 | 2.90 | 3.10 | 4.26 | 4.35 | 5.13 | 4.09 | 2.80 | 2.50 | 2.58 |
| **Tm** | 0.477 | 0.439 | 0.465 | 0.650 | 0.643 | 0.784 | 0.590 | 0.376 | 0.392 | 0.413 |
| **Yb** | 2.97 | 2.62 | 2.89 | 3.99 | 4.07 | 4.84 | 3.63 | 2.16 | 2.58 | 2.64 |
| **Lu** | 0.438 | 0.367 | 0.414 | 0.598 | 0.629 | 0.712 | 0.532 | 0.300 | 0.379 | 0.385 |
| **Hf** | 5.22 | 3.37 | 3.41 | 3.64 | 4.91 | 6.20 | 4.76 | 7.15 | 12.09 | 14.61 |
| **Ta** | 1.282 | 0.957 | 1.273 | 0.943 | 1.325 | 2.447 | 1.458 | 4.059 | 6.00 | 7.20 |
| **Pb** | 1.602 | 0.907 | 1.199 | 0.644 | 1.377 | 1.998 | 1.275 | 3.329 | 14.3 | 14.1 |
| **Th** | 1.416 | 0.859 | 1.192 | 1.057 | 1.704 | 2.709 | 1.633 | 4.422 | 20.4 | 24.7 |
| **U** | 0.420 | 0.247 | 0.346 | 0.286 | 0.407 | 0.737 | 0.465 | 1.131 | 3.55 | 15.4 |

Where no FeO is given, all iron is determined as $Fe_2O_3$

## Improved recognition of the Igtertivâ Formation

The original definition of the Igtertivâ Formation was based mainly on profile 91 with profile 94a as reference profile. Four of the five lava flows in profile 94a have now been relocated to the Skrænterne Formation. The original misplacement was possible because distinction between the formations was mainly based on different $TiO_2/P_2O_5$ ratios for which there is an overlap zone at low $TiO_2$. All flows in profile 94a are low-Ti flows that fall in the overlap zone (Larsen *et al.* 1989: fig. 79). One of these flows was analysed for trace elements in 1989, and the Zr/Nb ratio of this flow does indeed plot with the Skrænterne rather than with the Igtertivâ Formation (Larsen *et al.* 1989: figs 83 and 93).

The clear discontinuity in trace element ratios between the Skrænterne and Igtertivâ Formations found in this work provides a much improved tool for discrimination between the two formations. Relative to the Skrænterne Formation the Igtertivâ Formation has lower HREE ratios at similar LREE ratios (Fig. 7B) and higher Nb/Y ratios at similar Zr/Y (Fig. 7C). The parameter ΔNb defined by Fitton *et al.* (1998) is a useful discriminant. It is the vertical distance of a point to the lower of the two black lines defining the Iceland field in Fig. 7C and is calculated as $\Delta Nb = \log(Nb/Y) - 1.92\log(Zr/Y) + 1.74$. In the present data set the Skrænterne Formation has $\Delta Nb < 0.13$ and the Igtertivâ Formation has $\Delta Nb > 0.15$ (Supplementary data file 1). The Igtertivâ Formation also has lower $TiO_2/P_2O_5$, but the analytical uncertainty on the major elements is too large to distinguish the differences at low concentrations.

The changed trace element ratios is an expression of slightly changed melting relations or mantle sources, or both, during the time interval between the two formations. The relatively low HREE ratios of the Igtertivâ Formation suggest melting at shallower levels, possibly due to thinner lithosphere in the Igtertivâ rift zone (e.g. Fram & Lesher 1993). In this respect the Igtertivâ Formation differs from other post-breakup basaltic rocks along the East Greenland coast where 50–47 Ma gabbroic intrusions do not show signs of shallow melting (Bernstein *et al.* 1998).

The lava flows overlying the 30 m sediments high in profiles 2008 and 91 (Fig. 6) are relatively evolved and are chemically indistinguishable from the Igtertivâ Formation below the sediments (Fig. 7). They are therefore considered to be a continuation of the Igtertivâ Formation and not produced in a separate melting event. There is, however, a considerable age difference between these flows and those below the sediment horizon (see below).

## Dykes

Four NE-trending dykes cutting the plateau basalts immediately west of the boundary fault near profile 91 (Larsen *et al*. 1989) were also analysed for trace elements. Their geochemical character is completely consistent with that of the Igtertivâ Formation (Fig. 7), supporting the suggestion by Larsen *et al.* (1989) that the dykes are feeders for this formation.

Fig. 8. A sediment horizon about 7 m thick between lava flows of the Skrænterne and Igtertivâ Formations. The uppermost flow in the Skrænterne Formation is eroded and has lost its top zone.

## Radiometric ages

The lavas at Kap Dalton are generally K-poor and aphyric, with partial alteration of the groundmass to clay. Suitable candidates for radiometric dating are therefore rare. Reliable $^{40}Ar$-$^{39}Ar$ age spectra ('plateaus') were obtained for two lava flows from the Igtertivâ Formation, one flow *below* the 30 m sediment–conglomerate horizon (Bopladsdalen Formation), and one flow *above* the sediment horizon. The results (Table 2 and Fig. 9) indicate ages of 49.09 ± 0.48 Ma for the flow below the sediment, and 43.77 ± 1.08 Ma for the flow above the sediment. This leaves an interval of about 5 million years for deposition of the 30 m sediments of the Bopladsdalen Formation.

The alkaline pebbles in the conglomerate at the base of the Bopladsdalen Formation have higher contents of $K_2O$ and several are feldspar-phyric. Three pebbles of trachybasalt (hawaiite), trachyte and phonolite gave precise, well-defined ages of 49.17 ± 0.35 Ma, 47.60 ± 0.25 Ma, and 46.98 ± 0.24 Ma, respectively (Table 2 and Fig. 10).

Details of the $^{40}Ar$-$^{39}Ar$ analyses are available in Supplementary data files 2 and 3.

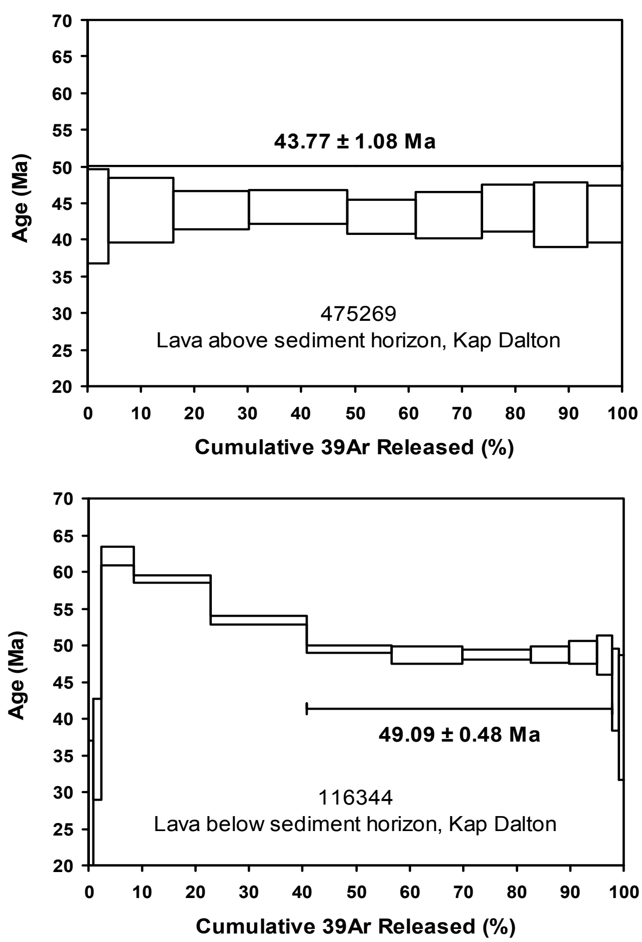


Fig. 9. $^{40}Ar$-$^{39}Ar$ age spectra and plateau ages for two lava flows from the Igtertivâ Formation at Kap Dalton. The stratigraphic position of the samples is shown in Fig. 6. The higher analytical uncertainty for the flow above the sediment is due to the very low K-content of the analysed plagioclase.

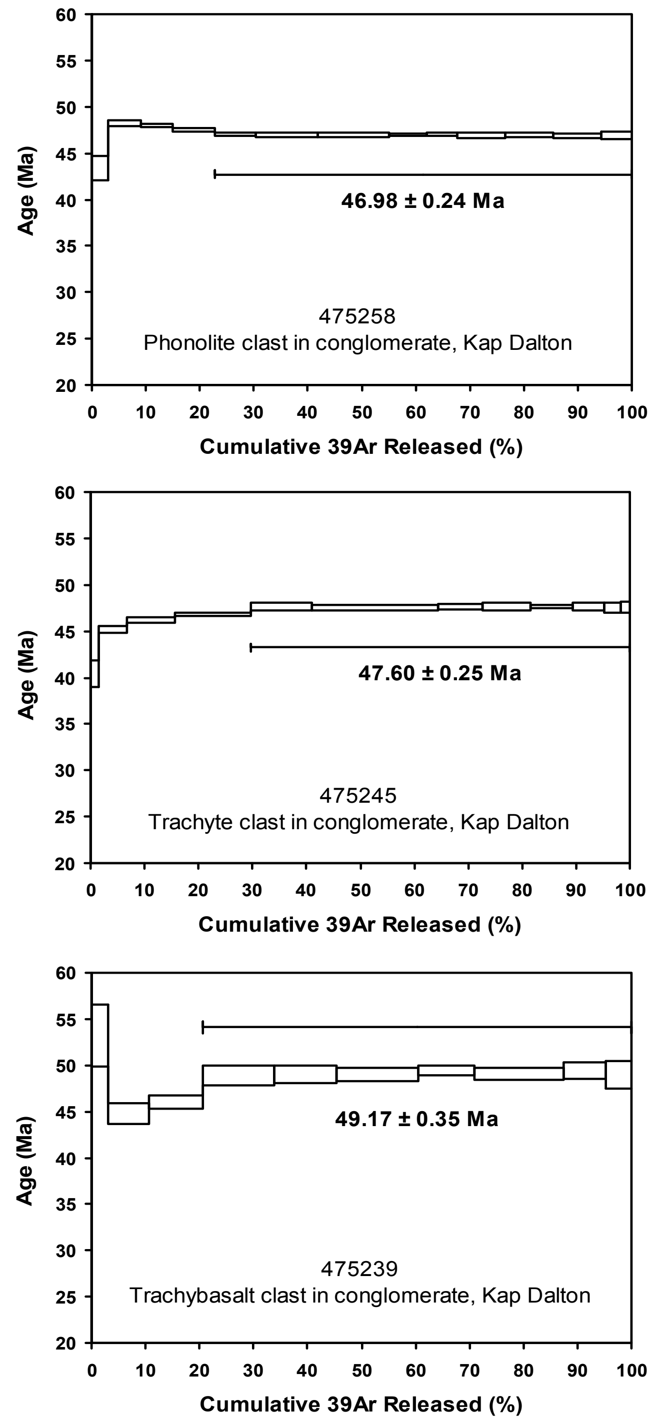


Fig. 10. $^{40}Ar$-$^{39}Ar$ age spectra and plateau ages for three pebbles of alkaline igneous rocks in the basal conglomerate of the Bopladsdalen Formation at Kap Dalton. The uncertainties are smaller than for the lavas because of the much higher K contents of the analysed feldspars.

Table 2. $^{40}Ar$-$^{39}Ar$ ages for lavas from the Igtertivâ Formation and alkaline pebbles from conglomerate at Kap Dalton

| | Sample no. | Material | Plateau age ±2 σ (Ma) | % $^{39}Ar$ | Isochron age ±2 σ (Ma) | MSWD | $^{40}Ar/^{36}Ar$ Intercept |
|---|---|---|---|---|---|---|---|
| *Lava flows* | | | | | | | |
| Flow below sediment | 116344 | Groundmass | 49.09 ± 0.48 | 57.0 | 49.06 ± 1.40 | 0.95 | 296 ± 48 |
| Flow above sediment | 475269 | Plagioclase | 43.77 ± 1.08 | 100 | 43.86 ± 1.36 | 0.12 | 294 ± 13 |
| *Pebbles in conglomerate* | | | | | | | |
| Trachybasalt (hawaiite) | 475239 | Plagioclase | 49.17 ± 0.35 | 79.5 | 49.50 ± 0.78 | 0.30 | 283 ± 28 |
| Trachyte | 475245 | Feldspar | 47.60 ± 0.25 | 70.2 | 47.58 ± 0.48 | 0.10 | 297 ± 33 |
| Phonolite | 475258 | Sanidine | 46.98 ± 0.24 | 77.2 | 46.92 ± 0.73 | 0.23 | 300 ± 54 |

All sample numbers are GGU numbers.
Isochron ages and intercept values are from the inverse isochrons. Details are provided in Electronic Appendices 2 and 3.

## Evolution of the volcanic and sedimentary succession in the graben at Kap Dalton

A 220 m thick succession of nine lava flows of the uppermost Skrænterne Formation is present within the graben zone. The best age for this succession is the 55.42 ± 0.06 Ma age for a tuff in the upper part of the Skrænterne Formation in Gronau Nunatakker obtained by Storey *et al*. (2007b). A flow from the Skrænterne Formation near the Amdrup-Hartz hut is reversely magnetised (Heilmann-Clausen *et al*. 2008), belonging in magnetochron C24r. The Skrænterne Formation belongs to the second 'megacycle' of volcanic activity defined by Larsen & Watt (1985) and Larsen *et al*. (1989). The major eruptive centres for this were considered to be situated east of the present coast line in areas that were later to form part of the Jan Mayen continental fragment.

After the deposition of the lavas of the Skrænterne Formation, an episode of erosion removed the top of the lava succession, and a 7 m thick sediment horizon was deposited. The time interval for this is around six million years between 55.4 and 49.1 Ma.

The well defined dyke swarm with a parallel fault system (Watt 1975) that fed the lavas of the Igtertivâ Formation was interpreted by Larsen & Watt (1985) and Larsen *et al*. (1989) to be produced in a distinct rifting event that affected the continent well inboard of the then continental margin towards the opening Atlantic Ocean. This rifting event led to renewed mantle melting, and the main volcanic succession of the Igtertivâ Formation was deposited. The succession is more than 300 m thick and consists of at least 12 lava flows. The radiometric age of 49.09 ± 0.48 Ma is in good agreement with palynological data for inter-basaltic sediments indicating an age "not older than latest NP12" (Heilmann-Clausen *et al*. 2008), which corresponds to younger than 50–51 Ma according to GTS 2012. Heilmann-Clausen *et al*. (2008) found that the uppermost flow below the Bopladsdalen Formation at locality 1 is normally magnetised, and according to GTS 2012 the magnetochron is unequivocally C22n (49.34–48.56 Ma).

During the period 49.2–47 Ma (at least), a number of small alkaline central volcanos and magma chambers developed not far from the Kap Dalton area, probably on higher ground away from the rift zone, either north-west or south-east of the present coast.

A period of erosion, possibly caused by relative uplift of the Kap Dalton area, removed the top of the main succession of the Igtertivâ Formation. Because lava flows reappear at higher levels it is inferred that eruption of lava flows from the Igtertivâ Formation continued elsewhere, but the uplift might have prevented later lava flows from reaching the Kap Dalton area. The alkaline volcanos were also eroded.

The sediments of the Kap Dalton Group then started accumulating. According to Larsen *et al*. (2002, 2005) the depositional environment of the sediments was coast-near, starting with a land surface where the eroded lava flows formed an irregular topography with hills and valleys in which rivers deposited conglomerates with rounded pebbles at the base of the formation. The land gradually became covered by shallow-marine sediments. There is therefore a considerable lateral variation which complicates correlation. A suggested correlation scheme for the various units of the Igtertivâ Formation and the Kap Dalton Group is shown in Fig. 11.

The Kap Dalton Group sediments cannot be older than the youngest dated pebble in the basal conglomerate, i.e. 46.98 ± 0.24 Ma (Table 2). The palynological evidence is in good agreement: Larsen *et al*. (2005) state that the dinoflagellate assemblage 1 (Fig. 11) is "not older than the upper part of the NP14 zone", and this corresponds to *c*. 47 Ma according to GTS 2012.

After deposition of around 30 m of the Bopladsdalen sediments a few lava flows from the Igtertivâ Formation reached the Kap Dalton area, perhaps as a result of relative subsidence or tilting. The flows are present in profiles 2008 and 91 and their age is 43.77 ± 1.08 Ma. Their equivalent level at locality 1 is unknown but, based on the lateral correlation of the thick quartz sandstone horizons at localities 1 and 2 (by Larsen *et al*. 2005), it must be situated somewhere below that horizon at locality 1 (Fig. 11). All sediments above this level cannot be older than 44 ± 1 Ma, including all of the Krabbedalen Formation. The palynological evidence is again in agreement with the radiometric ages: Larsen *et al*. (2005) state that the dinoflagellate assemblages 1 and 2 (Fig. 11) are not younger than respectively subzones E4d and E5a of Bujak & Mudge (1994); these two neighbouring subzones lie on each side of the P10–P11 zone boundary which in the GTS 2012 has an age between 43.5 and 44 Ma (Vandenberghe *et al*. 2012). In combination, the radiometric and palynological data constrain an age very close to 44 Ma for the sediments above the upper lava flows.

Larsen *et al*. (2005) considered that the deposition of the whole Kap Dalton Group lasted around 3 million years. While there is no conflict between the palynological and radiometric data, it may be questioned whether the Bopladsdalen Formation sediments below the upper lava flows were deposited gradually during the period post-47 Ma to 44 Ma or in a shorter period. Two lines of evidence point to a briefer interval. Firstly, the sediments above the upper lava flows are constrained within a short time span. Secondly, the occurrence of alkaline pebbles in the Krabbedalen Formation indicate that the alkaline rocks were available for erosion around 44 Ma. Such rocks are normally of small volume and extent, and if they were already eroded around 47 Ma it is likely that they would have been completely removed at 44 Ma. It is thus possible that the whole Kap Dalton Group could have been deposited within the interval 45–44 Ma.

## Contemporaneous events in the North Atlantic

The magmatism of the Igtertivâ Formation was caused by a distinct rifting event, as indicated by the swarm of NE-trending dykes feeding the lavas of this formation. The dyke swarm (Fig. 1) is slightly arcuate and can be followed along the coast for about 100 km from Søkongen Bugt in the south to Turner Ø in the north (Watt 1975). It probably runs partly east of the coast line where there are thick volcanic rocks to both sides of the large Blosseville Kyst Escarpment (H.C. Larsen 1990). The rift zone was called the "East Greenland extinct axis" and was considered to represent the first, failed, attempt to split the Jan Mayen continental fragment away from Greenland (Larsen & Watt 1985; Larsen *et al*. 1989; H.C. Larsen 1988). The event was

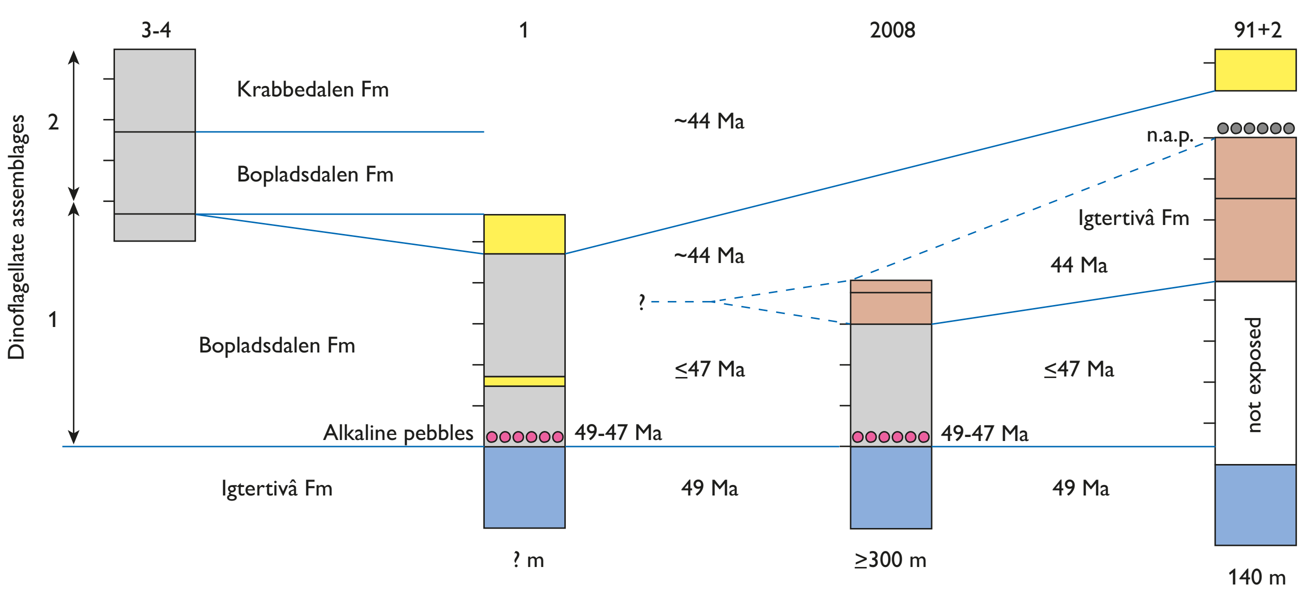


Fig. 11. Suggested correlation of the volcanic–sedimentary succession in the Kap Dalton area, with ages (Ma) indicated. Sediment profiles, with yellow horizons showing quartzitic sandstones, are partly from Larsen *et al*. (2005). Numbers 1–4 above profiles are locality numbers of Larsen *et al*. (2005), and 2008 and 91 are volcanic profiles (Figs 1 and 6). The lavas of the Igtertivâ Formation both underlie the Bopladsdalen Formation (blue) and are interbedded with it (brown). The distance between tick marks on the vertical scale is 10 m; the blue part of the Igtertivâ Formation is shown schematically only. n.a.p.: non-alkaline igneous pebbles. The conglomerate with alkaline pebbles at the base of the Bopladsdalen Formation may be present in locality 2/profile 91 but the level is not exposed.

placed in magnetochron C24n, following closely after the deposition of the main plateau basalt succession, but its re-assignment here to magnetochron C22n does not change the perception of a splitting attempt. However, the dating of the rifting to 49–44 Ma places it with other events at that time.

Gaina *et al*. (2009) and Gernigon *et al*. (2012) proposed that an important plate tectonic reorganisation event took place in the North Atlantic in the mid-Eocene around magnetochron C21r (48.6–47.4 Ma) comprising changes in spreading rate and direction. They noted coincidence in time with events along the East Greenland margin, including the deposition of the Kap Dalton Group sediments and also a peak in intrusive activity along the East Greenland margin farther south where more than 10 intrusive complexes were emplaced between 66°N and 69°N (Bernstein *et al*. 1998; Tegner *et al*. 1998, 2008). An important change was that the Reykjanes Ridge started propagating northwards from the Kangerlussuaq area. The coastal dyke swarm of the Igtertivâ Formation points south-westwards towards the Reykjanes Ridge, and if the rift extended farther south it would be close to the tip of the ridge (Fig. 12). The rift may thus have been directly instrumental to the start of propagation of the Reykjanes Ridge by easing its way through the continent. In this context it is interesting that a lava flow drilled on the shelf outside Nansen Fjord on the southern Blosseville Kyst gave an age of 48.7 ± 0.7 Ma (Thy *et al*. 2007).

The majority of the faults that cut the succession at Kap Dalton, and the formation of the exposed small graben, are later than the period considered here. They may perhaps have formed when the Reykjanes Ridge propagated past the area some time between magnetochrons C13 and C6, at 33 to 24 Ma.

## Conclusions

The graben at Kap Dalton contains around 220 m of lava flows belonging to the Skrænterne Formation, the youngest of the plateau basalt formations. This was dated at 55.42 ± 0.06 Ma by Storey *et al*. (2007b). Lavas of the Skrænterne and Igtertivâ Formations can be clearly distinguished by their trace elements, notably the HREE and Nb-Zr-Y ratios.

The transition to the overlying lava flows of the Igtertivâ Formation is well exposed and consists of 7 m

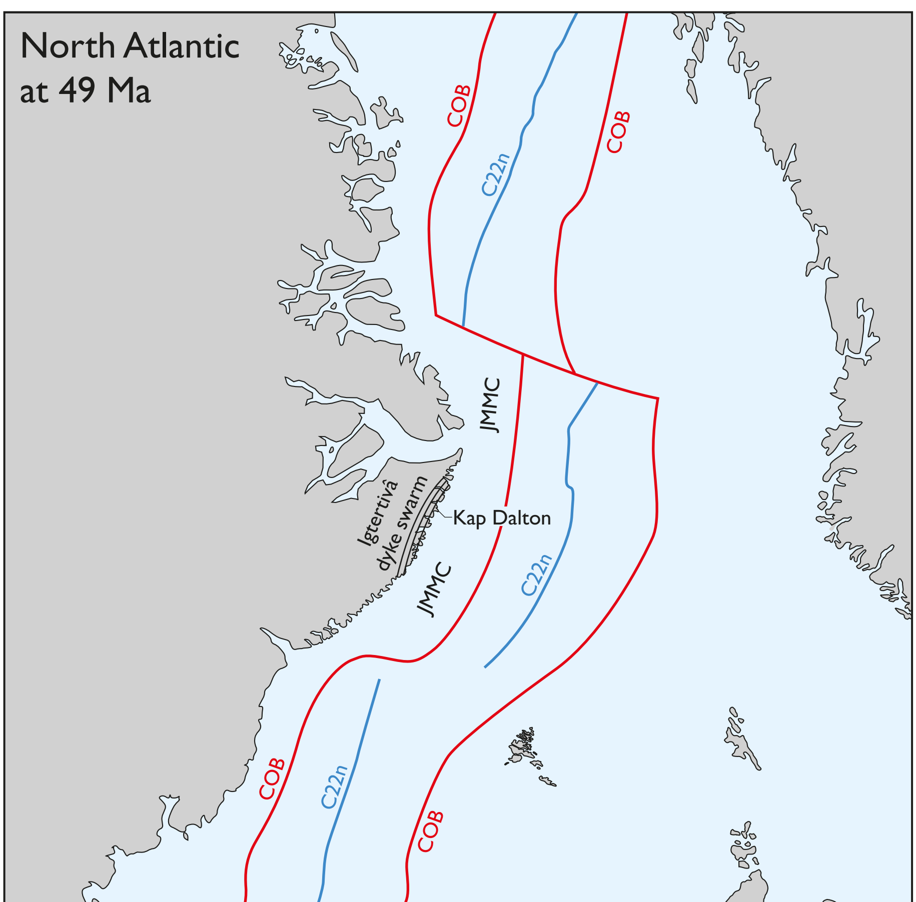


Fig. 12. Part of the North Atlantic reconstructed at 49 Ma with the program GPlates (Boyden *et al*. 2011). This time corresponds to the formation of magnetic anomaly C22n (49.34–48.57 Ma) at the mid-oceanic spreading ridge. Note that the tip of the southern spreading ridge ('Reykjanes Ridge') points directly towards the Igtertivâ dyke swarm and rift zone. COB: Continent–Ocean Boundary. JMMC: the coming Jan Mayen microcontinent.

red and black clay sediments deposited on an eroded lava surface. The horizon represents a time interval of up to six million years.

The lava flows of the Igtertivâ Formation are preserved only within the graben where the succession is more than 300 m thick and intercalated at the top with sediments of the Bopladsdalen Formation of the Kap Dalton Group. The main part of the succession below the sediments is dated at 49.09 ± 0.48 Ma while a lava flow intercalated with sediments of the Bopladsdalen Formation has an age of 43.77 ± 1.08 Ma.

Pebbles of exotic alkaline igneous rocks in the basal conglomerate of the Bopladsdalen Formation (Wager 1935) are dated at 49.17 ± 0.35 Ma, 47.60 ± 0.25 Ma, and 46.98 ± 0.24 Ma. This constrains the age of the sediments to less than 47 Ma. The age of the sediments above the intercalated lavas, comprising the upper part of the Bopladsdalen Formation and all of the overlying Krabbedalen Formation, is close to 44 Ma. There is good agreement between the radiometric and the palynological age data when the Geological Time Scale 2012 is used.

Dykes in a more than 100 km long coast-parallel dyke swarm are compositionally identical to the lavas of the Igtertivâ Formation and are considered to be part of the feeder system for the lavas. The relatively low HREE ratios of the Igtertivâ Formation suggest melting at shallower levels than the Skrænterne Formation, possibly because the melting took place beneath thin lithosphere in the Igtertivâ rift zone.

The Igtertivâ Formation magmatism was caused by a regional rifting event at 49–44 Ma. This coincides with a major mid-Eocene plate reorganisation event in the North Atlantic and the start of northward-propagation of the Reykjanes Ridge through the continent. The Igtertivâ Formation rift may have been directly instrumental to the start of this propagation.

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