Manifestations of the Cretaceous High Arctic Large Igneous Province in Svalbard

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ABSTRACT

Major Cretaceous Large Igneous Provinces (LIPs, e.g., Kerguelen and Ontong Java) show Aptian magmatic peaks and are linked to global mantle overturning and anomalous surface conditions. Widespread Cretaceous igneous activity in the High Arctic has recently been identified as a LIP. Exposed components on Svalbard, Franz Josef Island, adjacent shelf areas, Axel Heiberg and Ellesmere Islands, and perhaps North Greenland, cover several hundred thousand square kilometers and were peripheral to a LIP center at the Alpha Ridge. Manifestations of LIP development on Svalbard include (1) extensive sills, rare dikes, and extrusives in the east, (2) slow regression within the upper part of thick, black shales punctuated by locally abrupt uplift, with overlying coastal plain sandstones, (3) development of a regional, Late Cretaceous, low-angle unconformity associated with a second regression, and (4) a widespread Early Aptian transition from quartz arenites to lithic arenites and feldspathic sandstones reflecting new northern volcanic source terranes. The unconformity likely reflects LIP thermal doming with >1 km of erosion. The sedimentologic record provides important insight into this LIP since much of it is inaccessible or eroded. Analysis of published geochronology indicates magmatism within a 135–90 Ma window, with more detailed interpretations being problematic. Two regressions suggest two pulses of igneous activity (Barremian and Albian). Multiple pulses have been documented for other LIPs and may result from a deep and large plume. Present evidence that magmatism was coeval in Svalbard and Franz Josef Land is inconsistent with a hotspot track hypothesis and suggestive of a large initial plume head.

Introduction

Large Igneous Provinces (LIPs) have been increasingly recognized as the remnants of important events in earth history. The Cretaceous superchron has been identified as a time of accelerated sea-floor spreading and LIP activity (Larson 1991), with formation of two very large provinces, the Ontong Java and Kerguelen–Broken Ridge in particular (Coffin and Eldholm 1993). These LIPs provided insight into patterns of mantle convection and suggested the existence of global "overturning" events that significantly affected global surface conditions (Larson 1991). In this light, magmatic activity in the High Arctic area has been identified as a High Arctic LIP (Tarduno 1998; Tarduno et al. 1998), which will be referred to as HALIP in this article. It includes three areas with exposed Lower Cretaceous volcanics and associated hypabbysal intrusives (Franz Josef Land, Svalbard, and the Canadian Arctic Islands), while a dike swarm in North Greenland may also be of appropriate age and position (fig. 1). Multiple authors proposed a connection of this LIP with the development of the Alpha Ridge and the opening of the Amerasian Basin (e.g., Wiegand and Testa 1982; Worsley 1986; Lawver and Muller 1994; Grogan et al. 1998).

HALIP manifestations on Svalbard can be argued to include (1) extensive mafic sills up to 50 m thick, (2) basalt flows in eastern Svalbard, (3) an upper Jurassic to lower Cretaceous regressive record, (4) an abrupt regressive contact at the base of the Barremian Helvetiafjellet Formation, (5) influx of plagioclase rich feldspathic sandstones in the Aptian-Albian Carolinefjellet Formation, and (6) an upper Cretaceous unconformity with the truncation of Mesozoic units to the north suggesting gentle southward tilting. Factors obscuring previous recognition of this LIP include subsequent rift margin and oceanic basin development and dispersal, consequent erosion or submergence, a diffuse charac-

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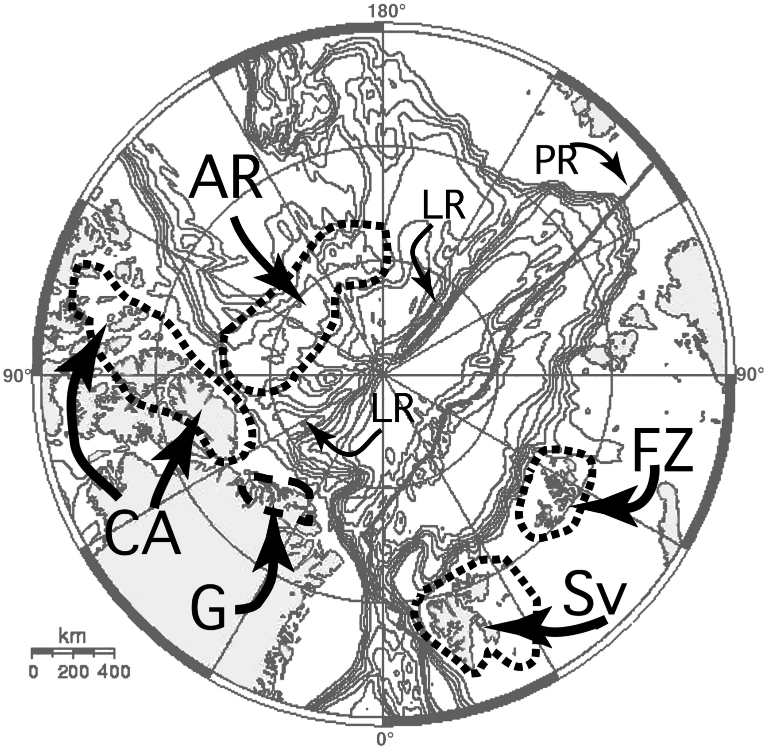

Figure 1. Polar projection showing position of HALIP localities. Base map of land mass outlines and bathymetry produced using http://www.aquarius.geomar.de/omc/make_map.html. *FZ*, Franz Josef Land; *Sv*, Svalbard; *G*, North Greenland; *CA*, Canadian Arctic; *AR*, Alpha Ridge. *LR* is the Lomonosov Ridge and *PR* is the presently active spreading ridge in the Eurasian Basin. Closure of the Eurasian Basin brings the northern Barents Shelf with *FZ* and *Sv* on it back into close proximity with *LR*, *AR*, and *CA*.

ter, and difficult logistics and consequently more poorly known geology for some portions. The purpose of this effort is to describe the magmatic, stratigraphic, and structural manifestation of the HALIP on Svalbard, compare it with other HALIP localities, and make some summary conclusions.

Form and Distribution of Magmatism in the Svalbard Area. Cretaceous magmatic material occurs mostly as sills, with less common dikes (Birkenmajer 1986; Murosko 1981), and some flows preserved in eastern Svalbard (Kong Karls Land; fig. 2), collectively known as the Diabasodden Suite (Dallmann 1999). Sills are typically tens of meters thick and attain an aggregate thickness of 50–100 m in many areas. Sills exposed in the Tertiary fold-and-thrust belt in western Spitsbergen tend to be found in Carboniferous and Permian strata, and given estimates of timing (discussed below) were thus emplaced at a depth of 1.5–2 km (e.g., Murosko 1981). They are mostly absent in overlying Mesozoic strata. The intrusion level within eastern Spitsbergen is commonly in Mesozoic strata, where sills also often take on a more irregular form. Farther east flows interbedded with the Helvetiafjellet Formation are described from Kong Karls Land (e.g., Smith et al. 1976; Worsley 1986). Smith et al. (1976) reported flows and intrusives from the underlying marine Rurikfjellet shales, but these were reinterpreted as shallow intrusives by Grogan et al. (1998).

The above suggests a west-to-east stratigraphic ascent of the emplacement level with a culmination in flows that are restricted to the east. Murosko (1981) also reported a consistent northwest to southeast pattern of local ascent of individual sills within the Midterhuken area. The reason for this pattern is unclear but may be related to regional tilt (discussed later) and/or differential vertical load. Associated dikes have variable north to northwest strikes. The prevalence of sills over dikes is suggestive of a compressive stress field (sigma three vertical).

Older basement rocks and Devonian basin strata exposed in north Spitsbergen are beneath the level that typically hosts the sills, with the exception of the Lomfjorden area where platform cover strata pre-

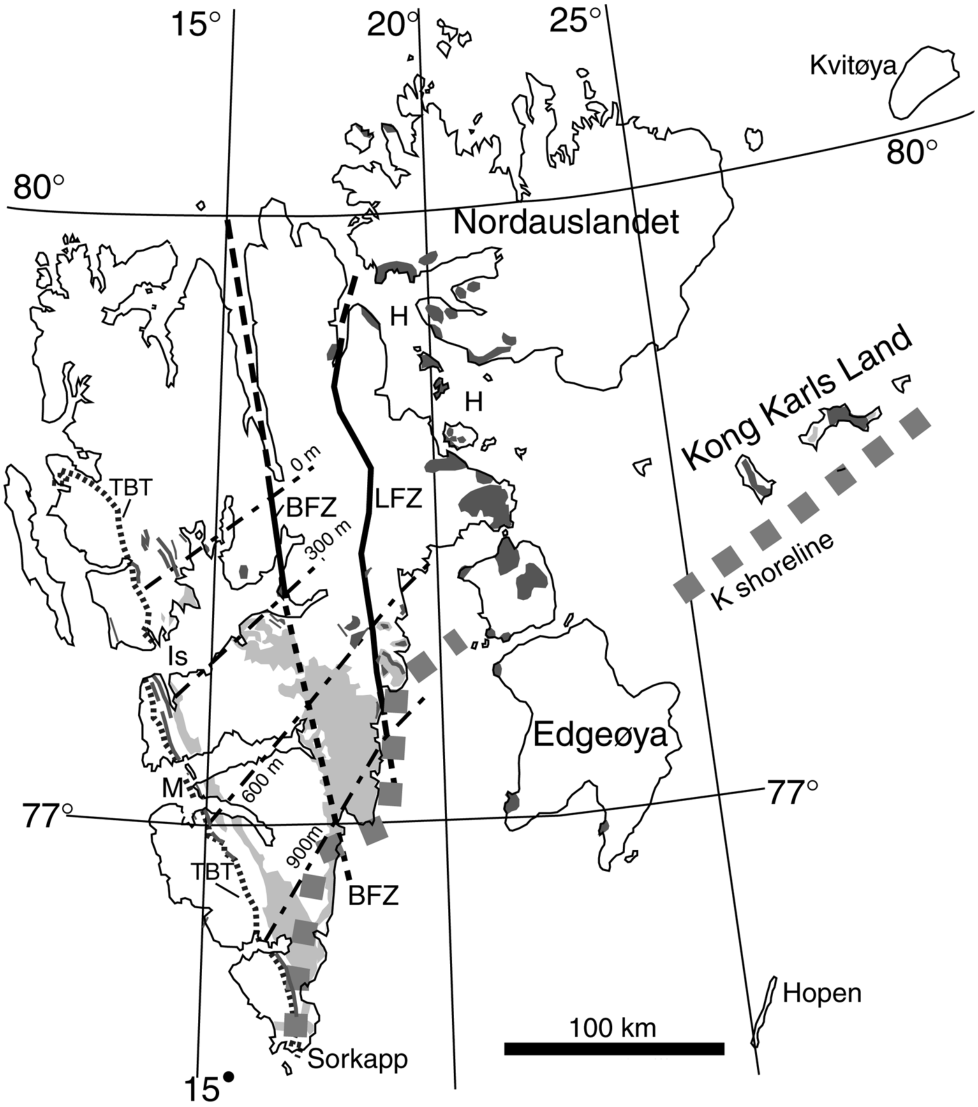

Figure 2. Map of Svalbard Islands showing relevant geologic components and localities. Dark pattern shows approximate distribution of some of the larger Cretaceous igneous outcrop. Light pattern shows distribution of Janusfjellet Subgroup and Helvetiafjellet and Carolinefjellet Formations. *BFZ*, Billefjorden Fault zone; *LFZ*, Lomfjorden Fault zone; *TBT*, eastern edge of basement involved Tertiary folds and thrusts; *Is*, Isfjorden; *M*, Midterhuken; thick dashed line, K shoreline for Helevetiafjellet Formation; thin dashed line, isopachs on the Carolinefjellet Formation.

served contain sills (fig. 2). This suggests that sills also existed in the north Spitsbergen area but were mostly destroyed by subsequent erosion. Sills are also found in Carboniferous strata within a tectonized lineament in the very western crystalline hinterland of the Tertiary fold-and-thrust belt (Maher et al. 1997). Given Tertiary contraction, sills would be restored to positions tens of kilometers farther west. Strong reflectors seen in seismic sections from central Spitsbergen were interpreted as sills in Triassic or Permian strata (Braathen 1994; Nottvedt and Eiken 1994*a*, 1994*b*) and indicated continuity of intrusion between west- and east-coast exposures. In aggregate, intrusive material is widespread within appropriate intrusion levels. McCann and Dallmann (1996) postulated a concentration of intrusive material along a subtle west-northwest-trending hinge line extending from Kongsfjorden to east central Spitsbergen. At Sørkapp, the southern tip of the Spitsbergen, there is evidence that sills pinch out. However, they are well-known from equivalent latitudes in the Edgøya area to the east, and based on geophysical, dredge, and seismic data, Grogan et al. (1999) proposed they occur as far south as 75° in the Gardarbanken High area. Sill distribution in the Sørkapp area may be diminished because it was a structural high with a much thinner late Paleozoic cover. Magmatism in the Svalbard area thus affected at least a 600-km north-south and a 400-km east-west stretch, with an overall minimum area of circa 200,000 km^2.

Geochemistry of Svalbard's HALIP Rocks. The Cretaceous igneous rocks are predominantly quartz tholeiites with a few hawaiites and alkali basalts. Relatively little work has been done on the trace-element geochemistry (table 1). What work exists suggests that consistent traits of the magmatic suite include a high (>3%) TiO_2 content (Murosko 1981; Wiegand and Testa 1982; Ohta et al. 1991), depletion of heavy rare earth elements (REE), and trace-element discriminant diagrams that reflect a continental setting. Rare earth elements plots from three areas in Svalbard spanning the east-west width of the area showed similar normalized values and trends (fig. 3). Bailey and Rasmussen (1997) suggested that "they formed by higher degrees of partial melt at greater pressures of melt segregation, say 20% at 16 kbars." Because of limited sampling, more work needs to be done before more substantial conclusions can be drawn.

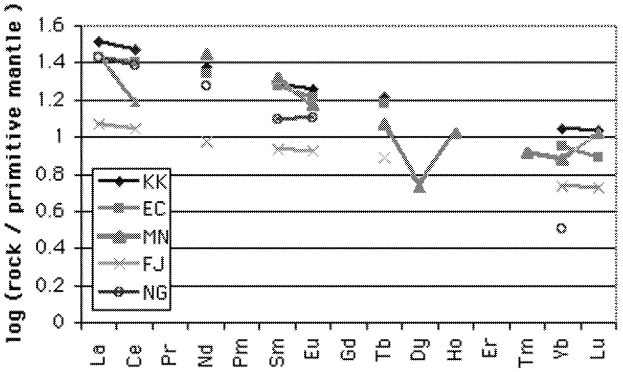

Figure 3. Plots of normalized (McDonough and Sun 1995) average REE values of samples from Kong Karls Land (*KK*, $n = 6$; Bailey and Rasmussen 1997), localities along the east coast (*EC*, $n = 3$; Bailey and Rasmussen 1997), Midterhuken West Coast (*MN*, $n = 12$; Murosko 1981), Franz Josef Land (*FJ*, $n = 6$; Bailey and Brooks 1988), and North Greenland (*NG*, $n = 2$; Brown et al. 1987).

Stratigraphic Expression of HALIP on Svalbard. Svalbard's Jurassic and Cretaceous stratigraphic nomenclature is given in figure 4 (Harland 1997). A distinctive unit of organic rich shales and silts with minor sands hundreds of meters thick comprises the Janusfjellet Subgroup, which is subdivided into the Agardhfjellet and Rurikfjellet Formations. The Agardhfjellet Formation shales represent a platform-wide transgression initiated in the Bathonian or Callovian (Birkenmajer et al. 1982; Backstrom and Nagy 1985). The Brentskardhaugen Bed at the base of the Agardhfjellet Formation can be interpreted to represent an aggregate storm peneplanation deposit preserved by the transgression (Maher 1989). Overlying shales have abundant pelecypod, belemenite, and ammonite fauna.

The contact between the Agardhfjellet and Rurikfjellet has been interpreted to be a maximum flooding surface (Dypvik et al. 1992). The upper 50–80 m of the Rurikfjellet, the Ullaberget Member, is a coarsening-upward shallow-marine regressive sequence (Edwards 1974; Miloslavskij et al. 1993). This regressive sequence runs counter to the global eustatic pattern (e.g., Worsley 1986) and culminates in the deposition of the Barremian Age

Table 1. Summary of Trace Element Geochemistry Studies on Svalbard Diabases and Basalts

Study author	Sampling location	No. of samples	Rock type(s)	Plot(s)	Geochemical character	Setting
Murosko 1981	Midterhuken central W Spitsbergen	14	Quartz tholeiites, hawaiites, alkali basalts	Y-Ti-Zr, normalized REE	Ti rich, depleted in heavy REE	Intraplate continental
Bailey and Rasmussen 1997	Kong Karls Land and east coast	9	Fe-rich quartz tholeiites	Ti/Nb vs. Ti/Y, normalized REE	Ti rich and Ti poor, depleted heavy REE	Initial riftin
Weigand and Testa 1982	Hinlopen area, Wilhelmøya	10	Quartz tholeiites	$Ti0_2$ vs. Al_2O_3, $TiO_2/K_2O/P_2O_5$	Ti rich	Amerasian Basin extension
Ohta et al. 1992	Isfjorden, W Spitsbergen	4	Quartz tholeiites	None	Ti rich	Unstated

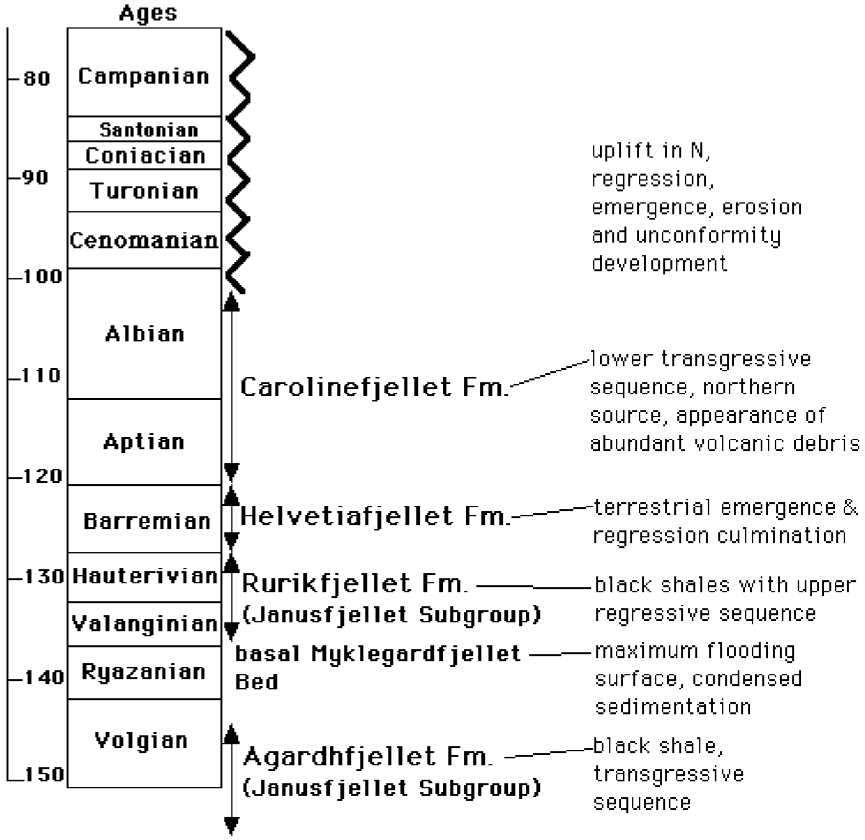

Figure 4. Jurassic-Cretaceous stratigraphic nomenclature for Svalbard with interpretation of associated events

Helvetiafjellet Formation sandstones, a suite of coal-bearing, fluviatile sandstones some 50–100 m thick, found from Isfjorden to Sørkapp and as far east as Kong Karls Land, where intercalated lavas occur. Locally, Iguanodon and possible Allosaurus trackways occur (Worsley 1986).

The basal contact of the Helvetiafjellet Formation is sharp and erosive, although there is no time gap at the age level. One explanation for the sharp erosive contact is reworking of exposed underlying Rurikfjellet strata removing any transitional shoreline or shallow-marine strata. An upper transitional contact exists with the overlying Carolinefjellet Formation. Paleocurrent data indicate a predominant southerly component and, hence, a northern source (Steel et al. 1978). Worsley (1986) described a color change in the sandstones of eastern Spitsbergen (Kvalhoden) that reflects "increasing contents of volcanic material in the delta's source area with an eastern and northern source area." This same color change was seen on Midterhuken in western Spitsbergen (Spatz 1983) and reflects a change from mostly quartz arenites to arkoses with sands composed of up to 50% plagioclase, and with volcanic lithics. Samples recently collected from the Adventdalen region show a similar development of a mafic volcanic source terrane. The An content of the feldspars is consistent with a mafic source, and very well preserved and delicate euhedral laths suggest pyroclastic input.

Worsley (1986) suggested that a sudden uplift with establishment of a shoreline somewhere south of Spitsbergen, followed by a gradual northeastward retreat of the shoreline during a subsequent transgression, was responsible for the Helvetiafjellet Formation. Steel et al. (1978) interpreted the depositional environment as a fluvial-dominated delta-plain setting, while Edwards (1974, 1979) considered it a coalesced-fluvial, coastal-plain setting. The northeast transgression (Worsley 1986) culminated in the deposition of the Carolinefjellet Formation, whose lower boundary was taken either as the bottom of marine shales (Birkenmajer 1984) or the first appearance of the feldspar-rich yellow sands (Parker 1967).

The overlying Carolinefjellet Formation consists of marine sandstones, siltstones, and shales that are up to 1100 m thick. Thin deltaic coarsening-upward packages, common oscillation ripple marks, and storm-related features suggest a shallow, well-oxygenated, marine shelf. Worsley (1986) suggested a shoreline to the north-northeast and basin to the south-southwest (fig. 2). The unit thins to the north due to both condensed sedimentation and subsequent postformation uplift (Worsley 1986; Harland 1997). Less has been published on the Carolinefjellet Formation compared with underlying units. The upper contact of the Carolinefjellet is an unconformity with overlying coal-bearing Paleocene strata of the Central Tertiary Basin and the upper Cretaceous missing. Locally, basal conglomerates occur, but in the field the contact is conformable to the eye (Maher et al. 1995). Tilting may have been on the order of <1°. Isopach lines of the truncated Carolinefjellet Formation trend 60° (fig. 2).

The stratigraphic history described earlier can be modeled in terms of HALIP development. The regional regression that initiated in the upper Rurikfjellet Formation in Hauterivian times could represent onset of the thermal plume and associated magmatism and uplift in the Svalbard region. Grogan et al. (1998) noted synsedimentary and very gentle folds with roughly north-south axes in the Kong Karls Land area (fig. 2), suggesting the crust area here was in general compression. This is mechanically consistent with a predominant sill-emplacement mode noted earlier. The base of the Barremian Helvetiafjellet Formation would represent a regressive culmination of HALIP-induced uplift. Then either local HALIP activity waned, or eustatic changes outstripped uplift, and the Helvetiafjellet to Carolinefjellet Formation transgression occurred (fig. 4). At this time, the newly developed volcanic-source terrane in the north and east produced a strong sedimentologic signature. The compositional change in turn affected diagnesis, as possibly did an elevated geothermal gradient.

The paleogeography consistently indicates greater uplift and an Aptian-Albian source terrane to the north, in keeping with a plume centered on the Alpha Ridge, with Svalbard in a peripheral position. The creation of the upper Cretaceous unconformity, again independent of contemporaneous faulting or folding, suggests renewed Albian or post-Albian uplift and possibly renewed plume activity. More than 1 km of cover strata were eroded at this time. Note that in this model, the stratigraphic history would suggest two pulses of HALIP activity in the Barremian and in the late Albian or Cenomonian on Spitsbergen (fig. 4). The broad span of HALIP activity suggested by the stratigraphic model is consistent with published geochronologic data.

On a speculative note, the existence of coeval sills in the strata beneath suggests sill emplacement as a parsimonious mechanism for sudden uplift of the sedimentary platform. An aggregate typical sill thickness of 50 m is adequate. This would explain the sharp and erosive contact and widespread, yet very thin, nature of the Helvetiafjellet Formation.

Magmatic Volume of HALIP in the Svalbard Area. Grogan et al. (1999), using multiple geophysical means, identified the extent of mafic intrusives in the subsurface in the Kong Karls Land area. Combining this with the area over which exposures occur, an estimate of the areal extent of Cretaceous igneous rocks in the Svalbard area was some 200,000 km^2. Burov et al. (1975) indicated that the total thickness of sills was 30–60 m and the thickness of dikes was 10–15 m. Within thrust slices at Midterhuken, two sills were typically found with an aggregate thickness of ca. 50 m (Murosko 1981). Applying a 50-m average thickness over this area led to a crude estimate of 10,000 km^3 for the volume represented by Mesozoic igneous rocks in the Svalbard area. This would represent only a peripheral part of a larger LIP.

Several arguments indicate the original volume in the area was significantly greater. First, the present erosion level in eastern Svalbard is such that only the base of the sequence that might have flows is preserved. Second, due to the Late Cretaceous southward tilting, the rocks that might harbor sills and flows have been removed by erosion in the north. Yet, given a northern source, this would be exactly where a greater volume of material might be expected. Third, evidence for not only more recent erosion but also Cretaceous erosion of flows or exposed shallow intrusives exists in the arkosic sands of the Carolinefjellet Formation. As discussed earlier, arkosic sands at three widely separated sites in the southern half of Spitsbergen have been attributed to a new volcanic source (Spatz 1983; Worsley 1986; this article). These Carolinefjellet sands presently cover an area greater than 14,000 km^2. Considering likely continuations to the east and west, if not south, the original extent of the unit may be several times that. The extent of volcanic detritus in, and areal extent and thickness of, the Carolinefjellet Formation suggests a sizable volcanic source, much larger than that exposed at present. In the future it may be possible to make a crude estimate of the volume of the source necessary to create this detritus.

Geochronology of HALIP Rocks on Svalbard. The timing of magmatism within this province is important for global correlations, for possible detection of a hotspot trace, and for models of plume development. For example, multiple peaks of magmatism may form from plumes generated at the core-mantle interface (Bercovici and Mahoney 1994).

Smith et al. (1976) described the stratigraphic ages of flows in eastern Svalbard as being from Kimmeridgian to Barremian. Any younger flows were removed by erosion. Grogan et al. (1998, 1999) reinterpreted some material to be shallow sills and not flows and suggest that the flows are Barremian to Albian in age.

Isotopic data for Svalbard consists primarily of conventional K-Ar Dates. Burov et al. (1977) examined 45 samples that had K-Ar ages from 90 to 167 Ma and, on the basis of a frequency diagram, postulated two magmatic peaks at 144 ± 5 Ma and another at 105 ± 5 Ma. This span and suggestion of two peaks has been repeated in many subsequent works (e.g., Weigand and Testa 1982; Worsley 1986; Bailey and Rasmussen 1997). Eight subsequent dates (Murosko 1981; Birkenmajer 1986; Ohta et al. 1992) are of similar age but extend to as young as 66 Ma.

Excess argon and partial resetting by Tertiary tectonism have increased the range of ages beyond the actual span of magmatism. Burov et al. (1977) noted one age older than the enclosing sediment, clearly indicating excess argon. Younger ages tend to occur in the west where Tertiary deformation was concentrated. Sharma (1997) described the history of thought on the Siberian traps (a LIP) where early conventional K-Ar studies suggested a span of 40 m.yr., while later, more detailed work narrowed it down to the bulk erupting around 250 Ma, possibly within a period of 1 m.yr.

Figure 5 shows a histogram of 53 published K-Ar ages. This is not a standard histogram, but one where each age was treated as a normal probability distribution and the distributions were then summed. This can also be viewed as assigning a fraction of an age to a given histogram interval on the basis of the probability that it is that age. In this way, the quality of the age is taken into account. Some of the ages of Burov et al. are given without error bars. Taking a conservative approach, a maximum error of 30 Ma was assigned to them. I interpret the results to indicate that (1) the data do not support the two pulses postulated by Burov et al. (1977), and (2) crystallization ages were primarily within a 135–90-Ma time span. Subsequent geochronologic studies will likely narrow this time span. Data from Franz Josef Land (Dibner 1998) plotted in the same way shows similar results.

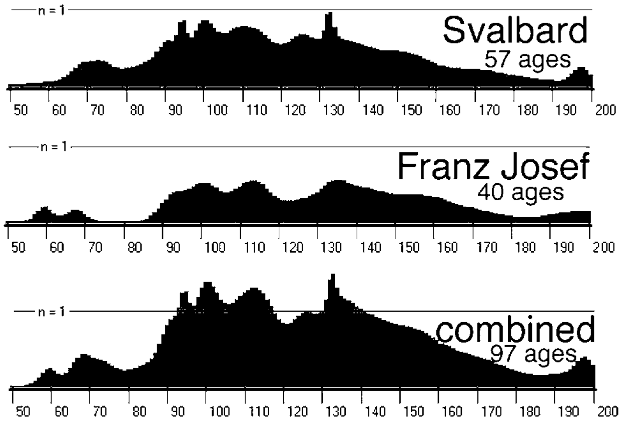

Figure 5. Histograms of published conventional K-Ar dates of intrusives in Svalbard, Franz Josef Land, and the two combined. 1-Ma increments for histogram with fractional age assignment. See text for explanation.

Comparison of Svalbard with Other HALIP Localities. *Franz Josef Land.* Similar occurrences of mafic intrusions and extrusions occur in Franz Josef Land (fig. 1; 300 km east of East Spitsbergen; Dibner 1998). The extrusives are intercalated with Barremian to Albian terrestrial, coal-bearing sediments, and the intrusives include 80–100-m-thick dikes. Lateritic soils formed on the top of some flows. Strong stratigraphic similarities with Svalbard include (1) maximum Callovian transgression, (2) a regression culminating in continental deposits in the Hauterivian, and (3) a Late Cretaceous gap and implied regression that was preceded by a transgression. One difference is in the timing of the second transgression, which occurred in the Cenomanian (Dibner 1998) instead of the Barremian, leading to a much greater thickness and duration of terrestrial sedimentation in the Franz Josef Land area. This may been due to a greater magmatic flux and resultant greater uplift. Note that a double uplift/regression history is also evident on Franz Josef Land.

The tectonic setting at the time of magmatism is unclear. Dibner (1998) described gently folded sills in Triassic-Jurassic strata that are truncated by an erosional surface, overlain by a basalt flow. Very broad folding of basalt sheets is also evident. Listric normal faults dissect some flows. These relations suggest a contractional setting similar to that described by Grogan et al. (1998) for eastern Svalbard, followed by an extensional episode. The great majority of dikes trend northwest, highly oblique to the present continental margin and to the length of the Lomonosov Ridge. These suggest local extension in a complex stress field, perhaps mitigated by a plume center to the northwest. Similarities in the geochemistry between Kong Karls Land and Franz Josef Land were noted by Bailey and Rasmussen (1997), and the REE pattern (Bailey and Brooks 1997) was broadly similar (fig. 3).

Anomalous seismic zones have been traced from the subsurface of the North Barents Basin to the flood basalts of Franz Josef Land (Bogatsky et al. 1996), indicating a greater areal extent, similar to that seen for offshore eastern and southern Svalbard (Grogan et al. 1998). The similarity between Svalbard and Franz Josef Island indicates that the thermal effects extended along more than 500 km into the continental margin of the Arctic Basin at Cretaceous times (which would include the intervening Lomonosov Ridge).

The areal extent of the Franz Josef Land archipelago is some 200 by 400 km, and taking into account the overall shape, an area of ca. 50,000 km^2. A simplified cross section and stratigraphic columns of Dibner et al. (1992) indicates the extrusives are more than 400 m thick in the west and at least 150 m thick in the east (erosional top). This suggests the volcanics minimally are likely in excess of 16,000 km^3. Again, this estimate does not include intrusives, which include 80–100-m-thick dikes; nor does it include offshore continuations of the magmatic rocks, nor eroded components. Bogatsky et al. (1996) described how abundant anomalous seismic horizons can be traced from the subsurface of the eastern Barents foredeep, with its kilometers of Mesozoic fill, to Franz Josef Land to the north. Diabase retrieved from the Ludlovskaya-1 borehole was dated at 159 and 139 Ma by K-Ar methods. Thus the Cretaceous magmatism appears to extend again some 600 km south from the northern continental margin at the time.

North Greenland Area. Soper and Higgins (1991) recognized two Cretaceous magmatic events in North Greenland, a mafic dike swarm, and a 3-km-thick suite of bimodal Kap Cannon volcanics. The volcanics are dated at upper Cretaceous and overlie mid-Cretaceous(?) terrestrial deposits (Soper et al. 1982); hence, they are likely somewhat younger than the magmatic event focused on here. However, the dike swarm does not cut the volcanics and is thought to be older, although Soper and Higgins (1991) assigned it to the upper Cretaceous. The dike swarm reaches up to 50% of the rock volume locally, strikes northerly (van Gosen and Piepjohn 1999), and dies out inland, suggestive of an offshore source.

Three arguments suggest the dike swarm is possibly related to the magmatic event discussed here. Both the dike swarm and magmatic event have exceptionally high TiO_2 levels and "within plate" immobile element characteristics (Soper and Higgins 1991). The age constraints of cutting Cretaceous strata seem malleable enough to permit a somewhat older assignment. Relatively little is published on the Cretaceous stratigraphy, although leaf fossils and pollen spore index fossils used to assign Early and Late Cretaceous ages suggest a significant terrestrial component once again. These intrusive volcanics are on strike with those of north Ellesmere island, whose volcanics have a trend of increasing volume to the northeast and whose age is much better constrained (see below). Manby et al. (1998), on the basis of multiple isotopic systems, indicated that magmatism began in this area at ca. 103 Ma, suggesting a distinct temporal overlap with Svalbard and Canadian Arctic activity. Volcanic activity was followed by Tertiary thrusting (Kap Cannon thrust zone, van Gosen and Piepjohn 1999). Two basalt flow samples from North Greenland show similarities in REE patterns with those of Svalbard (fig. 3), with perhaps greater heavy REE depletion.

A potentially significant similarity of North Greenland with Svalbard is the presence of lower Cretaceous terrestrial deposits, suggesting an uplift event. In the case of North Greenland, it is not known whether there was a tectonic component to the uplift, but fault structures of this age have not been identified. The dike swarms have been used to infer east-west extension (van Gosen and Piepjohn 1999).

Canadian Arctic Islands. Flood basalts, dikes, and sills of Cretaceous age occur in the Canadian Arctic islands, especially on northern Ellesmere (Embrey 1991). An early phase of mostly basaltic magmatism spanned the Hauterivian to Cenomanian (as the Strand Fjord Formation), but with a particularly strong expression in the Aptian-Albian, correlating well with those on Svalbard and Franz Josef Island. A later phase of bimodal activity, the Hansen Point volcanics, continued into the Late Cretaceous, and U-Pb dates at 88 ± 22 and 92 ± 1 Ma (Embrey and Osadetz 1988) and K/Ar hornblende ages at 94.2 ± 10 and 91.6 ± 9.6 Ma (Embry 1991) were reported. The volcanics are exposed over an area of 200 by 700 km, are thickest to the northeast, taper to the south and west, and attain a thickness of 300–789 m (Embrey and Osadetz 1988). A crude conservative volume estimate of 21,000 km^3 resulted from using a simple linear taper model. Considering missing offshore and eroded components, this was once again a serious underestimate and did not include the volume of dikes and sills that cover a much wider area (1100 by 450 km). Individual sills are up to 150 m thick and aggregate thickness can exceed 1500 m in sections, suggesting a hypabyssal expression at least equivalent to the volcanic one. Dikes were reported to have two orientations, one parallel to the Sverdrup Basin axis and one with a north-south trend (Jollimore 1986). Extensional tectonism was concurrent (Embrey 1991) and was likely related to development of the Amerasian Basin (e.g., Lawver and Scotese 1990).

During the Late Jurassic to lower Cretaceous Valangian times, the Sverdrup Basin was characterized by offshore shelf, organic rich shales (similar to the Janusfjellet Subgroup of Svalbard). In late Hauterivian times, it was dominated by fluvial-plain deposition (Embrey 1991). Extrusives are abundant in the Aptian. Interestingly, a second regression and unconformity initiated in the late Albian-Cenomanian, consistent with the timing of uplift, regression, and erosion on Svalbard and on Franz Josef Land. The two local unconformities can be associated with the Strand Fiord Formation and Hansen Point volcanics. This suggests a double pulse was not a local but a HALIP-wide feature.

Alpha Ridge. Because of difficult logistics, a lack of linear magnetic anomalies, a more irregular topography, and more extensive sedimentary cover, less is known about the Amerasian Basin than is typical for most oceanic crust. McWhae (1986) identified a breakup unconformity from the north coast of Alaska to the Davis Strait, which he attributed to the formation of the Canada Basin from 125 to 86 Ma. Weber and Sweeney (1990) described constraining geophysical and geological evidence and reviewed possible origins for the Alpha Ridge. It is clearly oceanic in character and can be compared with other oceanic plateaus (Jackson et al. 1986) now cast as LIPs. Heat flow data and thermal modeling, its normal magnetic polarity, and retrieved Campanian cover sediments indicate Alpha Ridge formed between 120 and 78 Ma. Dredge samples include highly altered, volcaniclastic, and vesicular alkali basalts (Weber and Sweeney 1990).

Most of the models for Alpha Ridge's formation include a hotspot component. It is presently structurally detached from the Canadian Arctic Shelf, likely due to subsequent tectonism (e.g., McWhae 1986). While the exact mechanisms of Alpha Ridge formation are unclear, it has the appropriate age and geophysical character to be a LIP, with Svalbard, Franz Josef Land, North Greenland, and Ellesmere Island as distal portions penetrating into surrounding continental margins.

Evaluation of a Plume Model for HALIP. Tarduno et al. (1998) and Tarduno (1998) proposed the existence of the HALIP and many associate LIPs with deep mantle plumes (e.g., Mahoney and Coffin 1997), although others disagree (e.g., Sheth 1999). Arguments supporting a plume model in this case are (1) the large footprint on rocks of diverse crustal character and tectonic setting, (2) the two pulses of magmatism evident in many parts of the LIP, (3) the nature of the limited geochemistry available, (4) the dike suites on North Greenland, Svalbard, and Franz Josef Land that point to the Alpha Ridge with a sub-radial pattern, and (5) the possible connection with the initiation of the Iceland hotspot. Arguments 1, 2, and 5 are discussed below.

What was the original size of this magmatic province? Cretaceous reconstructions vary, mostly dependent on the amount of motion (if any) along the Nares Strait (Lawver and Scotese 1990). In the closest configurations, northern Ellesmere, central Svalbard, and central Franz Josef Land form two subperpendicular lines circa 600 and 1000 km long, respectively (e.g., Srivastava and Tapscott 1986; Lawver and Scotese 1990). Ostensibly, since the 100-km-wide Lomonosov Ridge is continental and between Svalbard and the Alpha Ridge, it was involved in the magmatism. Combined estimates of continental crust influenced by HALIP magmatism exceed 600,000 km^2. Including the Alpha Ridge, the area is conservatively a million square kilometers. Such an extent is comparable to other LIPs (Coffin and Eldholm 1993). The original footprint may have been larger, depending on when the Makarov Basin developed between the Alpha and Lomonosov Ridges.

Due to the dispersed nature of HALIP igneous material in the continental crust, an estimate of its total volume is difficult. A conservative estimate indicates >50,000 km^3 of magma is preserved in peripheral parts of the HALIP. Abundant volcanic detritus in Cretaceous strata of both Svalbard and Franz Josef Land (Dibner 1998) clearly indicates a much larger volume was eroded. Intrusives components in Franz Josef Land, North Greenland, and the Canadian Arctic are not accounted for in this estimate and are sizable in all three localities. If these continental sites are linked to the Alpha Ridge, they represent a fraction of the total magma associated with this event. Thus it seems reasonable that the volume is on par with other LIPs (Coffin and Eldholm 1993).

Within the continental crust, the HALIP has a dispersed and uneven expression. The concentration and variety of igneous features is greater in Franz Josef Land and the Canadian Arctic than in Svalbard. Factors in the surface expression of a plume include the relative motion of the plume versus the overlying lithosphere, the geometry and size of the plume, the basal lithospheric architecture (which may channel or pond plume material), and the character of crust it ascends through (a shallow dispersal factor). In this case the large area involved can be explained as part of a large initial plume head coupled with dispersal factors. Dispersal factors explaining the diffuse character of HALIP material on Svalbard may include the several-kilometers-plus-thick platform cover, a relative absence of active faults and weak surfaces channeling vertical magmatic ascent, and a contractional stress field.

A comparison of HALIP sites (table 2) shows that a consistent temporal pattern does not appear to exist between magmatic and tectonic events for these areas. The pattern is more in keeping with a plume superimposed on a crust undergoing a temporally evolving and spatially varying stress/strain field created by changing boundary conditions.

The Ontong Java and Kerguelen-Broken Ridge LIPs exhibit two magmatic peaks at 120–115 and 90–85 Ma. This is attributed to a separation mechanism of a deep plume as it passes through the 660-km discontinuity (Bercovici and Mahoney 1994). A dual regression history evident in HALIP stratigraphy is consistent with two magmatic peaks and related uplift at these times (Barremian and Albian to post-Cenomanian). Existing geochronologic data for Svalbard and Franz Josef Land permit such an interpretation but is not of sufficient resolution to identify two peaks.

Geochemical data permitting analysis for a common plume parentage for the various parts of HALIP is not presently available. Factors contributing to compositional variability in LIPs include varying degrees of mantle entrainment, fractionation, and continental contamination, and mantle heterogeneities (e.g., Saunders et al. 1997). LIPs larger in area may be expected to be more complex in their geochemical signature. Extensive sampling and careful analysis required for identification of a HALIP common plume source may be a focus of future work. Within the Svalbard area, existing REE data suggest a common, relatively undepleted mantle source, and are similar to limited data from other parts of the HALIP (fig. 3).

Lawver and Müller (1994) suggested that the Iceland hotspot track can be traced to a position in northern Ellesmere, along the present strike of the Alpha Ridge, and favors an Icelandic model (hotspot-influenced Amerasian spreading ridge). They note that the pre-100-Ma part of the hotspot trace is less constrained and that the Alpha Ridge could represent a hotspot track that developed during rotational opening of the Canada Basin. Bailey and Rasmussen (1997) suggested a hotspot track that links up to the Siberian traps. Given the distance between Svalbard and Franz Josef Land and their alignment parallel to an inferred hotspot track, an observable difference in age would be expected. The contemporary nature of igneous activity, as indicated by both stratigraphic and geochronologic constraints suggests, instead, a large initial plume head was responsible for the HALIP instead of a more focused moving site producing a track.

An alternate model for the magmatic province may be that it is related to the propagation or leakage of spreading ridge activity in the Markorov Basin or Eurasian Basin. This, however, would not explain (1) the very large footprint, (2) the role of the Alpha Ridge, (3) the lack of significant extensional tectonics and the presence of mild contractional tectonics in continental margin parts of the HALIP, (4) the double regressive pulse, (5) the orientation of associated dike swarms, (6) the REE pattern, and (7) a possible connection with the Iceland hotspot. Interactions between a HALIP initial plume head and spreading processes are likely, but discussion of this is beyond this effort.

Sedimentologic Expression of HALIP. This magmatic/thermal event was a first-order determinant of sedimentation patterns in the High Arctic, affecting paleogeography, sediment character, and possibly diagenesis. In the continental areas discussed, a general pattern is of Jurassic to earliest Cretaceous marine conditions (often organic-rich marine shales) giving way to Barremian and younger terrestrial and shallow-shelf conditions, with sources to the north in the case of Svalbard and the Canadian Arctic. A High Arctic LIP plume could account for this regressive sequence developing at a time of global transgressions (Larson 1991). Local abrupt uplift may have been caused by sill emplacement. The pattern of southward tilting is consistent with a plume center in the Alpha Ridge area. In Svalbard and Franz Josef Land a subsequent transgression occurred before development of a Late Cretaceous regional unconformity. This is consistent with two phases of HALIP development and associated uplift separated by about 25–30 m.yr. Shoulder uplift associated with the development of the Amerasian Basin may have contributed to the second pulse, increasing its magnitude, but it was likely HALIP-influenced.

The volcanics also produced a significant new source terrane and in Svalbard and Franz Josef Land, substantial and widely distributed feldspathic sandstones resulted. Plagioclase feldspars have An contents and morphologies consistent with a mafic volcanic source. Stratigraphic and areal distribu-

Table 2. Characteristics of Various HALIP Localities for Comparison Purposes

Local	Form of magmatism	Geochemical character	Age span	Initial regression	Associated tectonism	Volume
Franz Josef	Sills 80–100 m thick, NW dikes, abundant flows (3)	High Fe, low Al_2O_3, like Svalbard's, high and low Ti (1, 2, 3)	140–90 Ma (3)	Hauterivian (3)	Cretaceous contraction, very gentle folding (3)	>20,000 km^3
Svalbard	Mostly sills, rare N-S dikes, flows in E	High Ti, depleted heavy REE (2, 7)	135–90 Ma	Barremian	Late Jurassic contraction in E, stable platform, Late Cretaceous tilting (5)	>10,000 km^3
North Greenland	N-S mafic dike swarm (8)	High Ti, intraplate immobile, alkali (6, 8)	103–70? Ma	Late K terrestrial strata	Transtension, followed by Tertiary thrusting (8)	Dike swarm (8)
Canadian Arctic	Flood basalts, sills, dikes, plutons (4)	Bimodal suite (4)	138–90 Ma (4)	Hauterivian (4)	Extension (3)	>21,000 km^3 flows
Alpha Ridge	Volcaniclastic, vesicular alkali basalts (9)	Basaltic	122–85 Ma (9)	NA	Amerasian Basin opening, oceanic plateau (9)	Huge

Sources. 1, Bailey and Brooks 1988; 2, Bailey and Rasmussen 1997; 3, Dibner 1998; 4, Embrey 1991; 5, Grogan et al. 1998; 6, Manby et al. 1998; 7, Murosko 1981; 8, Soper and Higgins 1991; 9, Weber and Sweeney 1990.

tion of volcanic detritus suggest a sizable source that likely influenced at least the northern half of the Barents Shelf. Sediment transport was generally from the north, again consistent with a plume center in the Alpha Ridge area. Prior to this, the stable and mature shelf generated primarily quartz-dominated sandstones and eastern and western sources were prevalent on Svalbard. Future study of the Carolinefjellet Formation of Svalbard will likely significantly increase understanding of the HALIP and its sedimentologic signature on the Barents Shelf.

Both the more immature composition of the sediments and the increased heat flow likely affected diagenesis. Svalbard is known to have had higher thermal maturation conditions and more severe cementation of its Mesozoic and Cenozoic sediments (Edwards 1979). Subsequent Cenozoic tectonism and high heat flow undoubtedly played a role, but Cretaceous magmatism and heat flow may have contributed. HALIP magmatism and associated tilting can also be expected to have altered crustal-scale fluid flow patterns, affecting diagenesis.

HALIP in a Global Context. The existence of this High Arctic magmatic event is more evidence that the Cretaceous was a time of widely dispersed and anomalously high global magmatic activity. Other plume-related igneous provinces that can be associated with the Cretaceous magnetic superchron include the Ontong-Java LIP (Coffin and Eldholm 1994), a Caribbean-Colombian LIP (Kerr et al. 1997), the Parana-Etendeka Province LIP (Peate 1997), and the Hikurangi-West Antarctica plume (Storey et al. 1999). The global dispersion of these LIPs is consistent with a change in mode of mantle convection ("overturning").

LIPs with an extrusive terrestrial component may well contribute to climate change (Coffin and Eldholm 1993) differently than those with large submarine components. A more northern hemisphere polar position (60°–70° paleolatitudes) may also have played a role in determining the HALIP's contribution to warm surface conditions.

Conclusions

1. Contemporaneous Cretaceous igneous rocks are preserved in Franz Josef Land, Svalbard, possibly North Greenland, and in the Canadian Arctic. Several arguments indicate that the igneous material preserved is a fraction of its former volume. Together with the Alpha Ridge they form a province with the extent, volume, and character of a LIP, as indicated by Tarduno (1998). The HALIP played an uncertain role in the formation of the Amerasian Basin.
2. This magmatic event played a significant role in shaping the stratigraphic record of the region, which is characterized by two regressions during high eustatic stands. Both regressions are associated with preferential uplift to the present north of Svalbard and Franz Josef Land.
3. Both the existing geochronology and the stratigraphic history suggest LIP development between 130 and 90 Ma. Timing on Svalbard and Franz Josef Land appears identical, inconsistent with a hotspot track model, but consistent with a large initial plume head.
4. The magmatic footprint covers continental and oceanic crust with varying kinematic regimes, suggesting an interplay of a large plume and a complex stress field resulting primarily from boundary forces.
5. The existence of this event adds to the picture of the Cretaceous as a time of abnormal global magmatism and associated environmental conditions.
6. This model for a High Arctic LIP can serve as a rich core for future research.

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