Petrography of Lower Cretaceous sandstones on Spitsbergen

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The sandstone petrography of sample suites from four sites spanning the Rurikfjellet (Hauterivian) to Carolinefjellet (Aptian–Albian) formations in central Spitsbergen was investigated. The sandstones show a distinct stepwise shift in composition from quartz arenites to sublitharenites and lithic arenites, typically within the upper part of the Helvetiafjellet Formation. This shift is related to the introduction of 10 - 25 % (grain %) plagioclase grains and volcanic lithics, and a notable increase in basement and sedimentary lithics. Quartz grain character also changes, and grain shapes become more varied. The shift is also associated with the transgressive arrival of marine sediments in the area, and the introduction of sands from the east-northeast by shore-parallel transport. Regional regression and subsequent transgression, and the change in sandstone composition is attributed to the development of the High Arctic Large Igneous Province in the region. The relative constancy of sand composition and volume of volcanic detritus within the Carolinefjellet Formation suggests long term (≈ 20 M) stability of the sediment system and a large volcanic source area, consistent with LIP (Large Igneous Province) derivation, along with significant exposure of basement rocks. Sample spacing and sediment recycling and mixing do not allow detection of events that would have changed sandstone composition that were less than ≈ 1 M duration. Preservation of significant amounts of plagioclase in a sediment-starved shelf can be explained by relatively cold climatic conditions.

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Some 180 Ma of platform cover sedimentation culminated with the deposition of a Lower Cretaceous clastic sequence in the Svalbard region that has an unconformable relationship with overlying Tertiary foreland basin sediments. This sequence is characterized by a regression–transgression megacycle (Gjelberg & Steel 1995) that has been linked to development of a High Arctic Large Igneous Province (Tarduno 1998), hereafter referred to as HALIP (Maher 2001). HALIP includes Cretaceous mafic intrusives and extrusives in Svalbard, Franz Josef Land, and the Canadian Arctic, with the Alpha Ridge (an oceanic plateau) in the Amerasian oceanic basin forming a core. This magmatism has also been linked to the development of the Amerasian oceanic basin (Wiegand & Testa 1982; Worsley 1986; Lawver & Muller 1994; Grogan et al. 1998). Previous work comments on a change in Lower Cretaceous sandstone composition, and suggests the sources for a distinctive plagioclase component were roughly contemporary mafic extrusives found to the east (Kong Karls Land and Franz Josef Land), and possibly to the north (e.g. Spatz 1983; Worsley 1986). In an attempt to understand the sedimentologic consequences and record of

HALIP we have studied Lower Cretaceous units in central Spitsbergen. This report looks at the petrography, in a stratigraphic context, of sandstones from four sites (Fig. 1), and explores the implications of these data for regional source terrane and paleogeographic evolution.

Stratigraphic context of the samples

A Lower Cretaceous regression initiates with the appearance of sand and a coarsening upwards section, known as the Ullaberget Member (e.g. Dypvik et al. 2002), within an otherwise shale-dominated, marine Rurikfjellet Formation (Fig. 2). In western and central Spitsbergen an erosive boundary marks the base of the overlying, terrestrial to near-shore, Helvetiafjellet Formation strata, which are dominated by coarse sandstones. The erosional base is attributed to uplift, regression, and erosion, with the Helvetiafjellet Formation representing deposition from a subsequent transgressive sand system (Gjelberg & Steel 1995). The overlying marine Carolinefjellet Formation has a transitional lower contact, and the basal Dalkjegla Member represents the continuation of the same transgressive tract. Close to this formational contact the first signs of mafic volcanic detritus have been noted (e.g., Spatz 1983; Worsley 1986).

The Carolinefjellet Formation varies from 220 m thick in the north-west up to 1000 m thick in the south-east part of Spitsbergen (Nagy 1970), with isopachs that trend in a north-east–south-west direction (Maher 2001). The upper contact is an unconformity, with greater uplift to the north, that has been associated with initial development of the Eurasian oceanic basin (Harland 1997, p. 383) and/or with a second pulse of HALIP activity (Maher 2001). Less has been published about the Carolinefjellet Formation than about other Mesozoic and Tertiary stratigraphic units in Svalbard. The formation has been subdivided into five formal and informal members (Fig. 2) on the basis of sandstone–shale proportion (Nagy 1970; Dallmann 1999). While a unique marker horizon of iron ooids (Mutrux et al. 2003) allows regional correlation of the lowermost, sandstone-dominated Dalkjegla Member, the other sandstone-dominated members have not been mapped regionally, lack known distinctive horizons that allow correlation, and may or may not be laterally continuous.

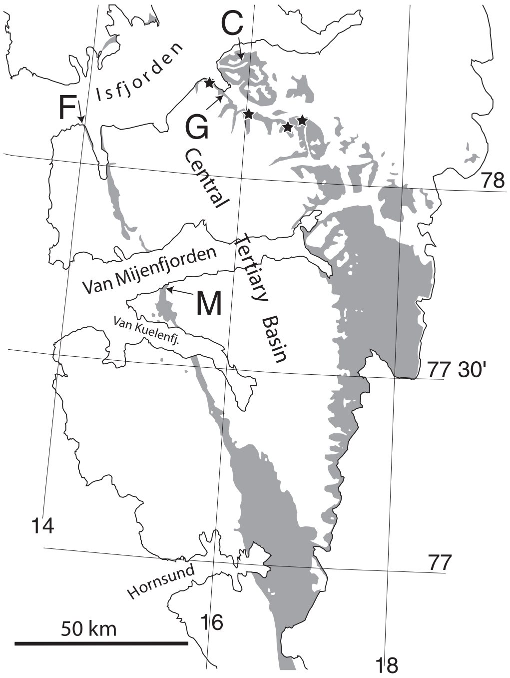


Fig. 1: Map of southern Spitsbergen showing sampling sites (labelled C, F, G, and M) and study sites marked as stars. C – Carolinefjellet site, F – Festningen site, G – Gruvdalen site, M – Midterhuken site.

The paleogeography of the Helvetiafjellet Formation is described as consisting of a north-east–south-west trending deltaic shoreline along the south-eastern edge of Spitsbergen, with a coastal or delta plain and a source terrane to the north (Steel et al. 1978; Edwards 1979; Worsley 1986; Nemec et al. 1988). Gjelberg & Steel (1995) suggest the whole system transgressively retreated to the north-northwest, onlapping a sequence boundary, and that the Helvetiafjellet formation consisted of a complex, retrogradational parasequence set of fluvial distributory, delta-plain, mouth-bar, barrier bar and tidal estuary facies.

Nagy (1970) indicates that as the total thickness of the overlying Carolinefjellet Formation increases towards the south the proportion of sandstone decreases and individual sand bodies pinch out. This is consistent with an uplift generally to the north and deeper water to the south. The Carolinefjellet Formation at the four study sites (Fig. 1) varies from 220 to 580 m in thickness. Given the above paleogeography, for time-equivalent strata, the Midterhuken site would represent the most offshore (and thicker) section,

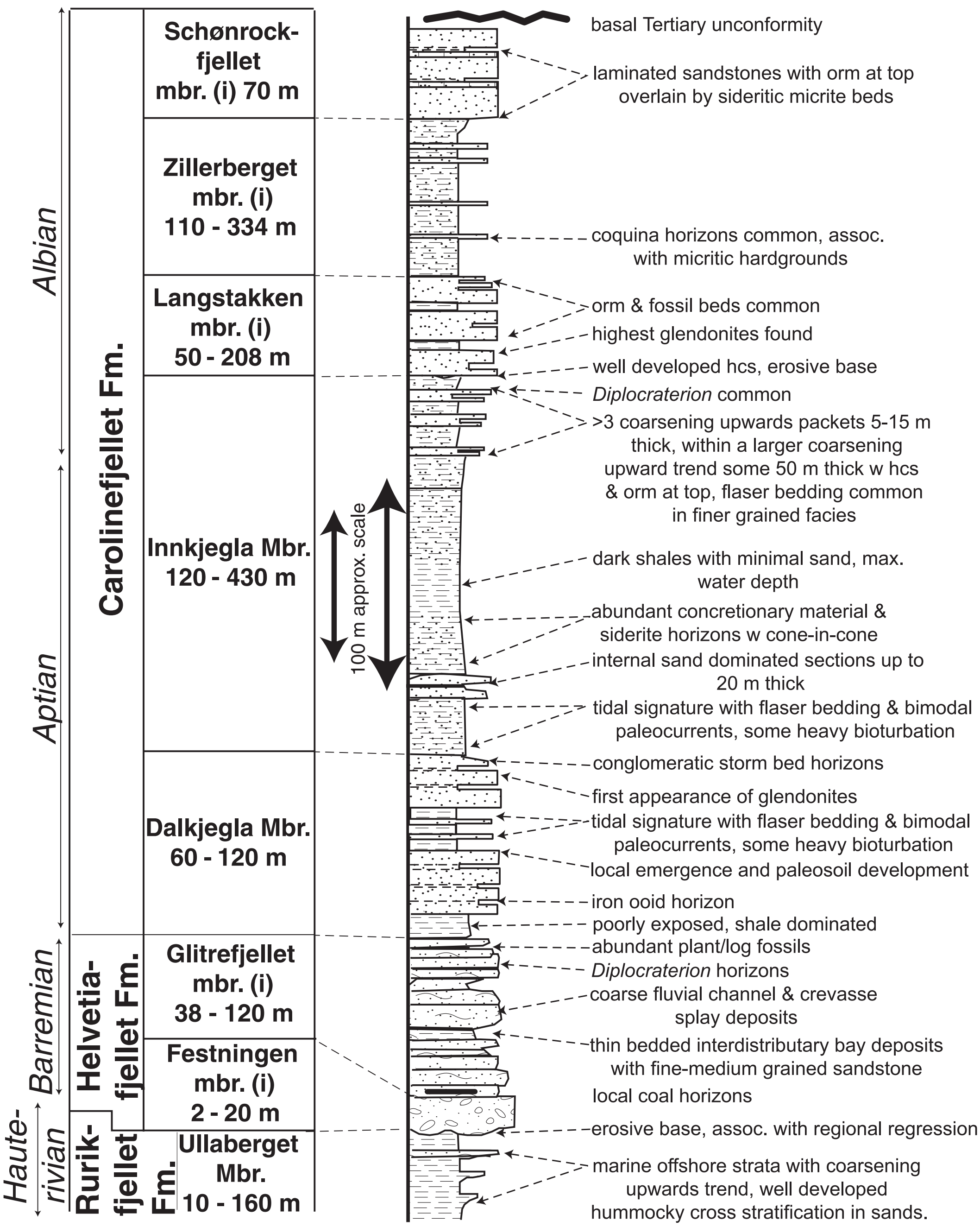


Fig. 2: Composite stratigraphic diagram of Cretaceous strata. i = informal member designation, orm = oscillation ripple mark, hcs = hummocky cross stratification.

while the Festningen site would represent the most onshore (and thinnest) section, with Carolinefjellet and Gruvdalen sections representing sites a little more offshore and significantly to the north-east of Festningen. Dypvik et al. (2002) indicate a more east–west Aptian–Albian (Carolinefjellet Formation times) shoreline located in the northern reaches of inner Isfjorden. Nøttvedt & Kreisa

(1987) and Maher et al. (2002) suggest the wave/storm dominated shelf at this time included offshore sand complexes with significant shore-parallel transport from the east-northeast. Dallman (1999) indicates a prodelta setting for the Dalkjegla Member. In this case, the Dalkjegla Member and the lower portion of the Innkjegla Member could represent the more distal part of the transgressive tract that initiated with the underlying Helvetiafjellet Formation. Such prodelta sands might be expected to have been physically connected to Helvetiafjellet Formation shoreline equivalents that onlap a lower sequence boundary associated with the transgression. A detailed discussion of the lateral continuity, or lack thereof, of the sandstone dominated units within the Carolinefjellet Formation is beyond the scope of this paper. A report focused on the sedimentology and paleogeography of the Carolinefjellet Formation is in progress. However, the sandstone petrography does provide some constraints on the transgressive tract model.

Methodology

The stratigraphic position of samples is given in Table 1. Sampling was opportunistic, with a typical stratigraphic spacing of tens of metres. Sand appearance in the field (grain size, colour, grain alignment) was fairly uniform in the Carolinefjellet Formation, and more diverse in the Helvetiafjellet Formation. Sandstone samples collected were judged in the field as typical of the local section. Stratigraphic position was determined either by Jacob's staff measurements from a known stratigraphic position, or by GPS with a barometer-based altimeter with an accuracy of plus or minus one metre. Where GPS position and altitude were used, corrections were made for stratal inclination and for relative position. Thicknesses based on GPS and Jacob's staff agreed within 10 %.

Point counts (grain count = 100) tracked 18 constituents (Table 2), and QFL (quartz, feldspar, lithics) and VSB (volcanic, sedimentary, basement) ternary discrimination plots were constructed and compositional means computed. For the VSB plots, plagioclase grains and volcanic lithics were attributed to a volcanic source (V); chert, carbonate and intraclast lithics were attributed to a sedimentary source (S); detrital micas, phyllite clasts, polycrystalline quartz, microcline, andalusite and tourmaline were attributed to the basement source (B). Note that some of the chert grains are likely of basement origin (see below). Chert represents a significant component of many of the samples, and thus the actual basement component could be underrepresented. Also note that the percentages computed are of assignable grains only, and that quartz and opaques are not included. With quartz arenites this leads to spurious results, where a single grain encountered in the count leads to a high (even 100 %) value. Such results are identified below, and were seen more commonly in Rurikfjellet Formation samples.

The sandstone classification scheme of Dott (1964) is used. Plots of compositional descriptors versus relative stratigraphic position were inspected for breaks and patterns. As one test for temporal trends in a stratigraphic context, Runs tests, using the Z statistic as described by Swan & Sandilands (1995), were conducted on various measures of sandstone composition. A run is defined as a portion of a numerical sequence where there is a string of consecutive increases or decreases (irrespective of the magnitude of the increase or decrease). For example, a section where quartz content consistently increased upwards would be one long run. The Runs test compares the number of runs in an observed sequence, versus the number of runs expected in a random sequence of the same length. A large negative Z statistic would represent fewer runs than would be statistically expected from a random sequence, suggesting a real stratigraphic trend. A large positive Z statistic represents more runs than would be randomly expected, suggesting some type of oscillatory behaviour. With a significance threshold of 0.05, the critical Z values are greater than 1.96 or less than –1.96.

Table 1: Opposite page.
Sample stratigraphic affiliation, position and compositional descriptors. C = Carolinefjellet site, F = Festningen site, G = Gruvdalen site, M = Midterhuken site, H is Halwylfjellet. Kr = Rurikfjellet Formation, Kh = Helvetiafjellet Formation. In ascending order, Kcd, Kci, Kcl, Kcz, Ksc represent the Dalkjegla, Innkjegla Member, Langstakken, Zillerberget and Schønrockfjellet member of the Carolinefjellet Formation. T = Tertiary. In stratigraphic affiliation the first lower case letter refers to the formation that starts with same letter, the second lower case letter refers to the member. See figure 2 for the stratigraphic units. Position is relative to the base of the Helvetiafjellet Formation, except for Gruvdalen where it starts within the Dalkjegla Member (near the base of the upper sand sub-unit), and Halwylfjellet where it is metres below the basal Tertiary strata. Q%, F%, L%, V%, S%, B% = quartz, feldspar, lithic, volcanic, sedimentary, basement grain percentages.

Site	Strat. unit	Strat. position	Q %	F %	L %	V %	S %	B %
C	Kr	-11	98	2	0	100	0	0
C	Kh	1	97	1	1	0	0	100
C	Kh	15	96	3	1	0	0	100
C	Kh	23	98	2	0	100	0	0
C	Kh	25	78	13	9	51	28	21
C	Kh	30	94	2	4	0	0	100
C	Kh	45	87	4	9	18	5.9	76
C	Kh	49	97	0	3	0	0	100
C	Kh	59	99	0	1	0	100	0
C	Kh	69	97	0	3	0	0	100
C	Kh	69	87	4	10	27	18	55
C	Kcd	83	66	21	13	60	26	15
C	Kcd	102	69	19	12	57	26	17
C	Kcd	109	70	10	19	32	32	36
C	Kcd	145	68	13	19	30	22	48
C	Kcd	163	60	18	22	26	39	35
C	Kcd	180	64	22	14	45	34	21
C	Kcd	212	62	23	15	52	21	27
C	Kci	229	62	22	16	56	26	18
C	Kci	250	56	18	26	38	29	32
C	Kci	275	62	14	24	38	63	0
C	Kci	315	66	11	23	32	17	51
C	Kci	335	62	19	19	50	21	29
C	T	378	65	18	18	45	22	33
F	Kr	-67	94	3	3	14	14	71
F	Kr	-44	83	4	14	9.4	31	59
F	Kr	-38	89	5	5	33	17	50
F	Kh	1	96	0	4	0	0	100
F	Kh	6	97	0	3	0	50	50
F	Kh	62	97	0	3	0	100	0
F	Kh	70	80	1	19	0	24	76
F	Kh	71	98	1	1	0	0	100
F	Kh	93	53	5	42	42	30	28
F	Kcd	104	62	27	11	65	3.2	32
F	Kcd	137	64	12	24	29	50	21
F	Kcd	168	53	18	30	39	53	8.3
F	Kcd	172	55	21	24	32	38	30
F	Kcd	194	59	21	20	43	33	24
F	Kcd	202	52	18	30	35	58	6.5
F	Kci	203	60	7	33	18	65	18
F	Kci	224	58	20	22	44	44	12
F	Kci	244	53	15	32	31	51	17
F	Kci	267	64	11	26	21	56	23
F	Kci	319	64	11	25	28	52	20
G	Kcd	1.5	52	29	19	52	5.6	42
G	Kcd	8.8	49	25	26	49	16	35
G	Kcd	20.2	63	10	27	22	55	23
G	Kcd	24	69	15	16	48	43	8.7
G	Kcd	40	14	4	82	4.5	93	2.2
G	Kci	48	70	11	19	25	40	35
G	Kci	77	65	17	18	48	44	8
G	Kci	99	62	17	20	29	32	40
G	Kci	127	64	12	23	25	51	24
G	Kcl	152	68	18	14	43	26	31
G	Kcl	180	60	20	20	48	34	18
G	Kcl	203	58	16	26	26	33	42
G	Kcl	204	59	16	25	39	35	26
G	T	261	56	7	37	15	69	15
M	Kr	-40	86	1	13	0	80	20
M	Kh	0	86	0	14	0	92	7.7
M	Kh	39	75	0	25	0	50	50
M	Kh	89	91	0	9	0	63	38
M	Kh	121	54	9	38	26	41	33
M	Kcd	129	66	9	25	25	33	41
M	Kcd	139	63	4	33	3.6	39	57
M	Kcd	146	63	6	32	11	48	41
M	Kcd	152	78	5	17	11	40	49
M	Kcd	176	53	16	31	32	39	29
M	Kcd	189	57	16	28	33	41	26
M	Kcd	189	60	17	23	33	26	41
M	Kcd	197	34	10	56	15	81	4.5
M	Kcd	197	58	15	26	26	29	45
M	Kcd	228	43	5	52	9.4	84	6.3
M	Kcd	233	72	8	19	29	43	29
M	Kci	255	53	11	36	21	43	36
M	Kci	255	55	9	36	20	29	51
M	Kci	291	48	10	43	21	64	15
M	Kci	304	76	15	9	62	23	15
M	Kci	330	61	13	26	23	38	38
M	Kci	385	64	13	24	29	29	42
M	Kci	440	65	8	28	20	33	47
M	Kcd	485	65	15	20	18	29	53
M	Kci	536	53	13	34	20	36	45
M	Kcl	571	62	13	25	27	48	26
M	Kcl	586	59	17	24	33	19	47
M	Kcl	611	55	14	31	31	31	38
M	Kcl	628	52	18	30	32	19	49
M	Kcz	671	62	12	26	21	51	28
M	Kcz	674	43	19	38	21	44	35
M	T	702	76	4	21	15	55	30
H	Ksc	-70	48	16	36	30	49	21
H	Ksc	-50	57	15	28	28	43	29
H	Ksc	-30	53	14	33	32	45	24
H	Ksc	-4	91	2	8	6.3	50	44

Potential source rocks

Four types of potential source rocks for the Cretaceous sandstones are identified: a) Caledonian and older, metamorphic and plutonic, basement rocks, b) Devonian through lowermost Cretaceous sediments, including a Permian through Cretaceous platform cover sequence of widespread extent, c) mafic extrusives of the HALIP suite, and d) intraclasts. Basement rocks exposed in Svalbard to the north are considerably varied, and include low grade metasediments, to mica–garnet schists, to migmatites (Dallmann et al. 2002). Quartzitic units are common. A distinctive batholithic complex of granites and minor gabbro intruding Mesoproterozoic low grade metasediments occurs in Nordaustlandet to the north-east. Another complex of migmatites and granites occurs in north-west Spitsbergen.

The platform cover rocks in the area consist of a suite of carbonates and clastics (Dallmann 1999). Monocrystalline quartz could be derived by reworking of this material, but would in thin sections be indistinguishable from similar quartz from other sources (e.g. basement granites). Much of the platform cover rock source material would not be expected to leave a distinctive clast signature. An exception is the several hundred metres of dark, and spiculitic cherts of the Permian Kapp Starostin Formation. Larger chert clasts observed in a conglomeratic storm bed at the Dalkjegla–Innkjegla Member transition retain the spiculitic texture, and identify the Kapp Starostin Formation as source material. However, cherts also exist in basement carbonates, and as a clastic constituent of the older Carboniferous Billefjorden Group orthoquartzites.

HALIP extrusive material is exposed intercalated with Helvetiafjellet Formation equivalent strata on Kong Karls Land in easternmost Svalbard (Bailey & Rasmussen 1997), and is abundant in much greater volume and in myriad

Table 2: Average grain constituent amount with standard deviations for formations and members. These are number of counts out of one hundred. Stratigraphic units are in Table 1.

Stratigraphic unit	**quartz**	**round plag**	**broken plag**	**euhedral plag**	**microcline**	**unknown feldspar**	**muscovite**	**biotite**	**chlorite**	**glauconite**	**quartz lithics**	**phyllite lithics**	**volc. lithic**	**carbonate clast**	**chert lithics**	**clay intraclasts**	**cement**	**opaques**	**other**
Kr ave. n=5	**68**	**0.4**	**0.2**	**0**	**0**	**1.8**	**1**	**1**	**0**	**0**	**0.8**	**1.2**	**0**	**0.6**	**1**	**1.6**	**18**	**2.8**	**0**
Kr st. dev.	8.9	0.9	0.4	0	0	0.8	1.2	1.4	0	0	1.1	1.6	0	0.9	1.2	2.1	9.1	3	0
Kh ave. n=20	**69**	**0.4**	**0.2**	**0**	**0.3**	**0.9**	**0.6**	**0.1**	**0**	**0**	**2.8**	**0.2**	**1.8**	**0.2**	**2.5**	**0.3**	**19**	**1.5**	**0**
Kh st. dev.	14	0.7	0.5	0	0.4	1.4	1.7	0.2	0	0	3	0.4	4.8	0.5	4	0.6	6.3	2.7	0
Kc-all ave n=67	**45**	**3.6**	**1.9**	**0.1**	**0.8**	**4.7**	**0.9**	**0.4**	**0.1**	**0.1**	**5**	**1.8**	**0.3**	**4.2**	**6.7**	**2.6**	**23**	**3.4**	**0.5**
Kc-all st. dev.	11	2.4	1.5	0.2	1	2.4	1	0.8	0.3	0.5	3.5	2.1	0.5	15	3.3	2.3	12	2.4	1.4
Kcd ave. n = 29	**49**	**4.1**	**1.9**	**0**	**1.2**	**4.7**	**0.9**	**0.4**	**0**	**0**	**5.6**	**1**	**0.4**	**7.1**	**6.1**	**2.9**	**24**	**2.9**	**0.9**
Kcd st. dev.	13	3	1.9	0	1.2	2.7	1	0.9	0	0.2	3.5	1.6	0.7	23	3.3	2.5	16	1.8	2
Kci ave. n=24	**43**	**3.1**	**1.8**	**0**	**0.5**	**4.3**	**1**	**0.3**	**0.1**	**0.2**	**4.5**	**1.5**	**0.2**	**2.3**	**7.6**	**1.7**	**24**	**4.3**	**0.2**
Kci st. dev.	6.2	1.5	1.1	0.2	0.6	2.1	1.1	0.6	0.4	0.5	3.3	1.6	0.4	3.5	3.3	1.6	9.1	3.2	0.5
Kcl ave. n = 8	**50**	**4.3**	**2.3**	**0.4**	**1.3**	**6.1**	**0.8**	**0.1**	**0**	**0.4**	**6.4**	**4.3**	**0.1**	**1.3**	**6.4**	**2.5**	**16**	**2.7**	**0.4**
Kcl st. dev.	8.7	1.8	1.2	0.5	1	2.3	1	0.4	0	1.1	4.5	2.4	0.2	1	2.1	1.1	5.4	1.4	0.7
Kcz&sc ave. n=6	**42**	**2.2**	**1.7**	**0**	**0.7**	**4.8**	**0.5**	**0.8**	**0.2**	**0.3**	**2.3**	**3.8**	**0.3**	**2.2**	**6.3**	**5.5**	**24**	**3**	**0**
Kcz&sc st. dev.	11	2	1	0	0.8	2	0.8	1	0.4	0.8	1.4	2.6	0.5	2.7	4.2	3.1	11	0.9	0

forms in Franz Josef Land (Dibner 1998). Given a bigger footprint for HALIP that includes parts of the Canadian Arctic, the Alpha Ridge, and possibly north Greenland (Maher 2001), other sources may have existed. HALIP extrusives have not been found on Spitsbergen, but HALIP sills and dikes occur as little as 900 m below the basal Helvetiafjellet Formation surface.

Cretaceous sandstone compositions

Sandstones from the Ullaberget Member, within the Rurikfjellet Formation, vary from quartz arenites to sublitharenites (Fig. 3, Table 1). Lithics include chert, phyllite, quartzite lithics, and clay aggregates (intraclasts). Detrital muscovite, biotite and chlorite grains occur in amounts up to several percent. Feldspar occurs in amounts up to 5 %, but usually less. The quartzite and phyllite lithics suggest a basement source component. Material associated with a mafic volcanic source (volcanic lithics and plagioclase) is not evident, and the compositions are similar to those of the overlying Helvetiafjellet Formation samples.

Helvetiafjellet Formation quartz grains are typically well rounded and mostly free of pre-depositional deformational features and inclusions (Fig. 4). Most undulose extinction is related to grain-to-grain contacts, and appears post depositional. In some cases post-depositional fluid inclusion planes are obvious and may be related to Tertiary deformation (Pray et al. 1992). Small muscovite and tourmaline inclusions were observed in some quartz grains. A trace of coarse microcline exists. Chert and quartzite are the most common lithics in the Helvetiafjellet Formation, excluding the upper portion described below. Andalusite is a trace component in many of the Helvetiafjellet Formation sandstones, and in samples from Midterhuken (Spatz 1983) and from a site near Carolinefjellet (not included in the point count analysis here), it constitutes several percent of the grains.

The Helvetiafjellet sandstones are predominantly quartz arenites as plotted in QFL space (Fig. 3). However, a suite of outlier samples plot as sublitharenite, lithic arenites, and one arkose. These skew the average composition of our Helvetiafjellet Formation sample suite to plot just within the sublitharenite field. All but one of these outliers occur in the uppermost part of the formation (Table 1), and mark a distinct shift in sandstone composition that occurs within the upper portion of the Helvetiafjellet Formation. A similar pattern can be seen on the VSB plots (Fig. 5). In these outliers, basaltic lithics can comprise as much as 20 % of the grains, and plagioclase becomes the dominant feldspar. It can be noted that the proportion of basalt lithics may be underestimated because they are notably deformed and pressure-solved between quartz grains (Fig. 3). Pressure solution is common in the sandstones without a carbonate cement. Basalt lithics dominate in the coarser samples, while plagioclase grains occur in the finer samples. The influx of basalt lithics is the first HALIP detritus seen stratigraphically in our sample suites (Table 1). These samples also show either typical amounts or in some cases slightly higher amounts of HALIP detritus in comparison to stratigraphically higher samples, and, at the scale of sampling, a transitional introduction of volcanic detritus is not seen. In the field these samples often show a decrease in overall grain size, and a change in colouration (darker grey, and weathering yellowish) in comparison to the underlying lighter coloured orthoquartzites. An interesting exception occurs in the samples from the Carolinefjellet area (Table 1). A sample from within the lower half of the Helvetiafjellet Formation shows a composition, with significant plagioclase feldspar, that is typical of the overlying Carolinefjellet Formation sandstones, while overlying samples in the Helvetiafjellet Formation return to a quartz arenite composition. The significance of this is discussed later.

The Carolinefjellet Formation sandstones appear homogeneous in the field. They are well sorted, fine to medium grained sandstones, often laminated, with well oriented muscovite flakes seen on bedding surfaces. Fresh samples are light grey, but weathered surfaces show shades of tan, yellow and orange. Darker grey, fine-grained sands are also common in much of the "shale" dominated Innkjegla and Zillerberget members in thin (cms), often significantly bioturbated, and discontinuous layers. While these units are slope formers and described as shale-dominated, the recessive character is due to thin and discontinuous bedding and a greater percentage of shale. Significant portions of the section have more sand than mud.

Carolinefjellet Formation sandstones can be characterized by their diversity of grain shapes and constituents (Table 2, Fig. 4). Rounded to angular grains occur in the same sample, suggest-

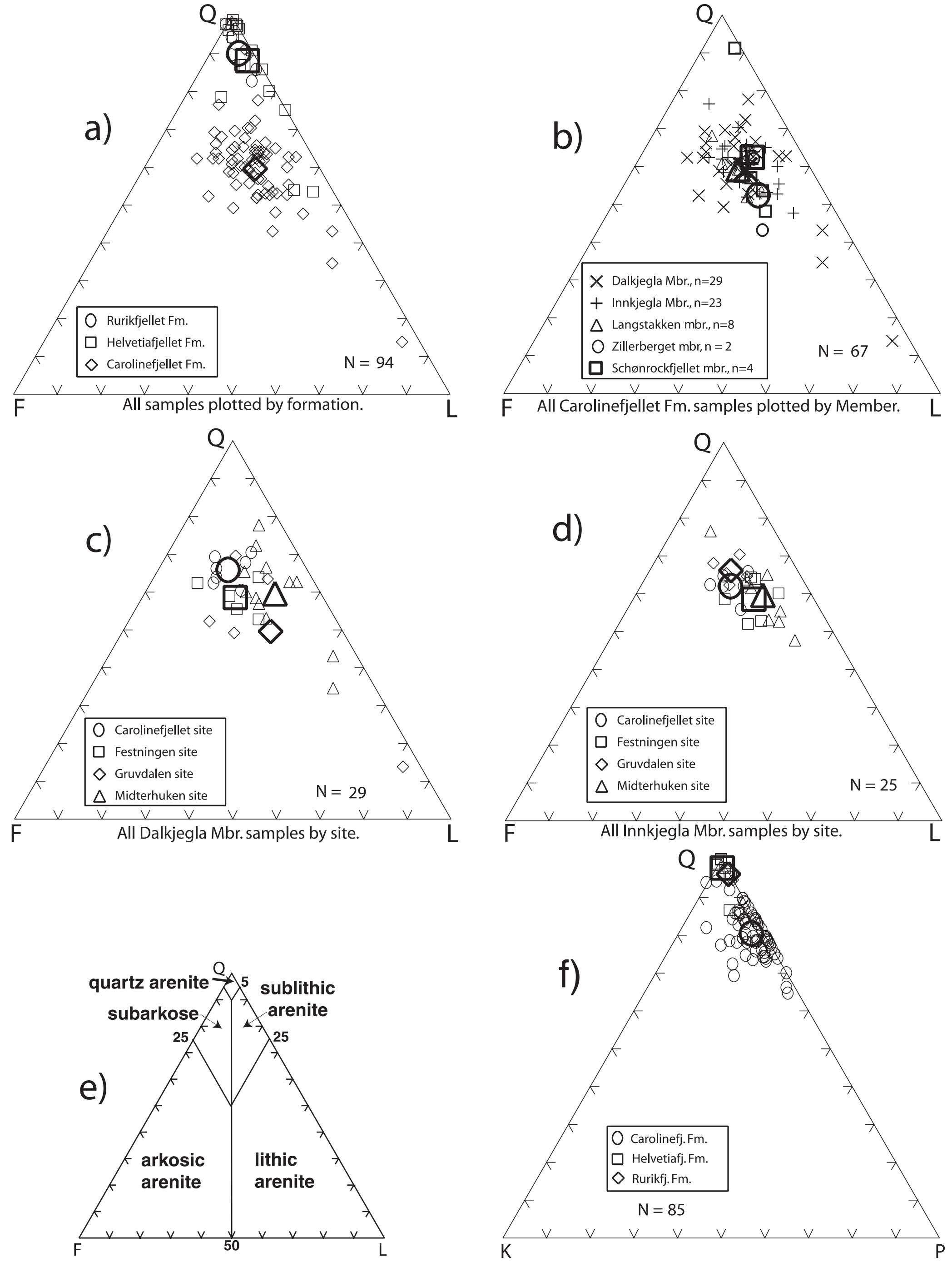


Fig. 3: Ternary plots of sandstone compositions. Quartz-Feldspar-Lithics (QFL) plots of samples by a) formation, b) member within the Carolinefjellet Formation, c) by site for the Dalkjegla Member, and d) by site for the Innkjegla Member. e) Dott's (1964) sandstone classification in QFL space. f) Quartz, potassium feldspar and plagioclase feldspar (QKP) plot by formation. Larger symbols are average composition.

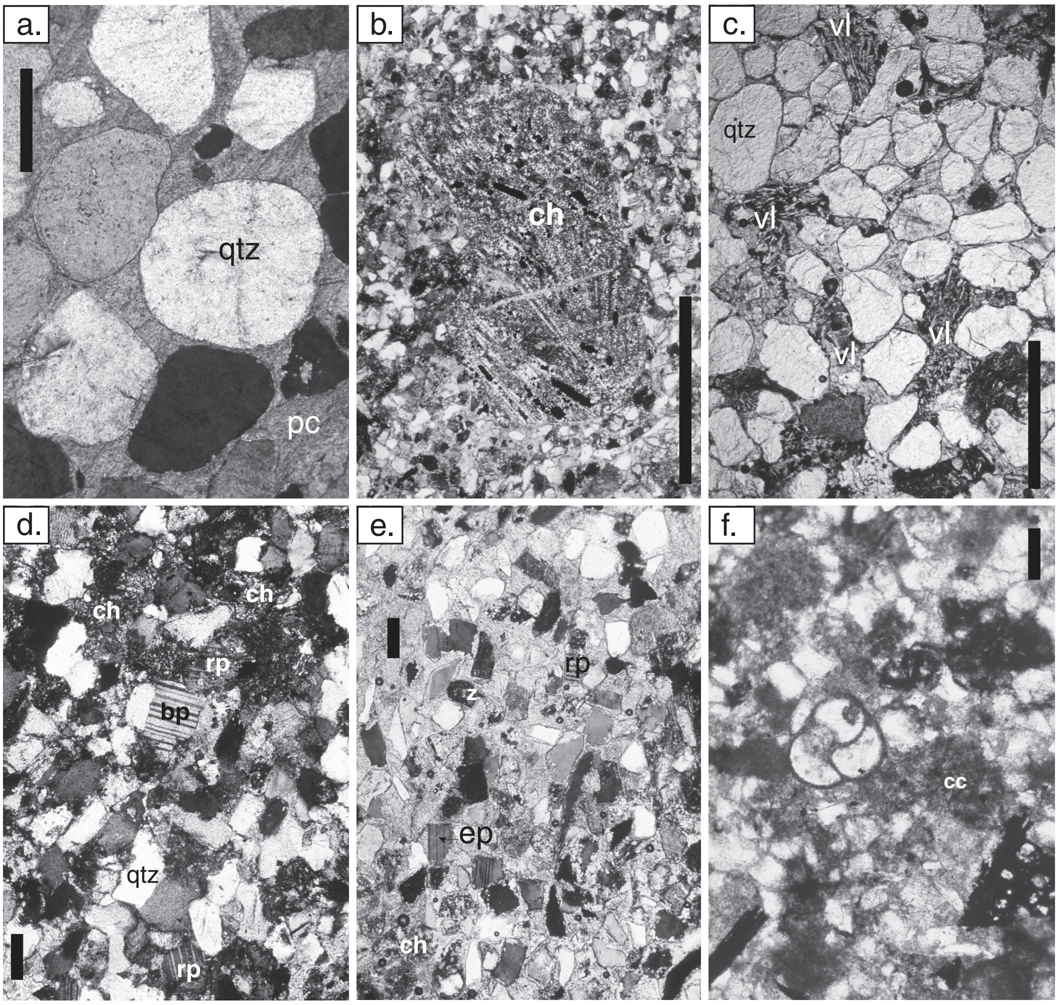


Fig. 4: Photomicrographs of Cretaceous sandstone features. Scale bar in a and d-e=0.1 mm, and in b and c=1 mm. a) Crossed nicols view of well rounded quartz grains (qtz) with poikilitic calcite cement (pc). Helvetiafjellet Formation, Festningen site, 6-7 m above base of formation. Average grain size 0.3 mm. b) Crossed nicols view of larger chert lithic (ch) showing oriented spiculitic spines, in finer-grained, heterolithologic sand matrix with poikilitic carbonate cement. c) Plain light view of molded volcanic lithics (vl) between rounded quartz grains, and with a poikilitic carbonate cement. From the Helvetiafjellet Formation on Svedenborgfjellet, Midterhuken circa 50 m above the formation base. Average grain size 0.4 mm. d) Crossed nicols view of broken plagioclase (bp) grains and more altered rounded plagioclase grains (rp). Quartz (qtz) and chert (ch) grains are identified. Quartz/clay overgrowths and significant grain molding also occur. The sample is from the basal Langstakken member of the Gruvdalen section. 1.5 mm average grain size. e) Crossed nicols view of euhedral plagioclase grain (ep) and subrounded plagioclase (rp) grain in poikilitic calcite cement. z=zircon grain. ch=chert grain. Bedding parallels the preferred grain orientation here, defining the lamination and planar character of the sandstones. Note angularity of grains. From the Dalkjegla Member, 68 m above the base, Midterhuken section. Average grain size 0.1 mm. f) Plain light view of foram and reedy plant fragment (lower left). Note carbonate clasts (cc). From the upper Dalkjegla Member, 76 m above base, Midterhuken site. Average grain size 0.1 mm.

ing mixing of grains with very different transport histories. In contrast to the Helvetiafjellet Formation quartz arenites, quartz grains in the Carolinefjellet Formation and the Helvetiafjellet outliers (mentioned) are richer in fluid and mineral inclusions (despite being finer grained). Deformation lamellae and bands and subgrains are also distinctly more common, with a geometry suggesting a pre-depositional origin. The internal quartz grain textures of the Carolinefjel-

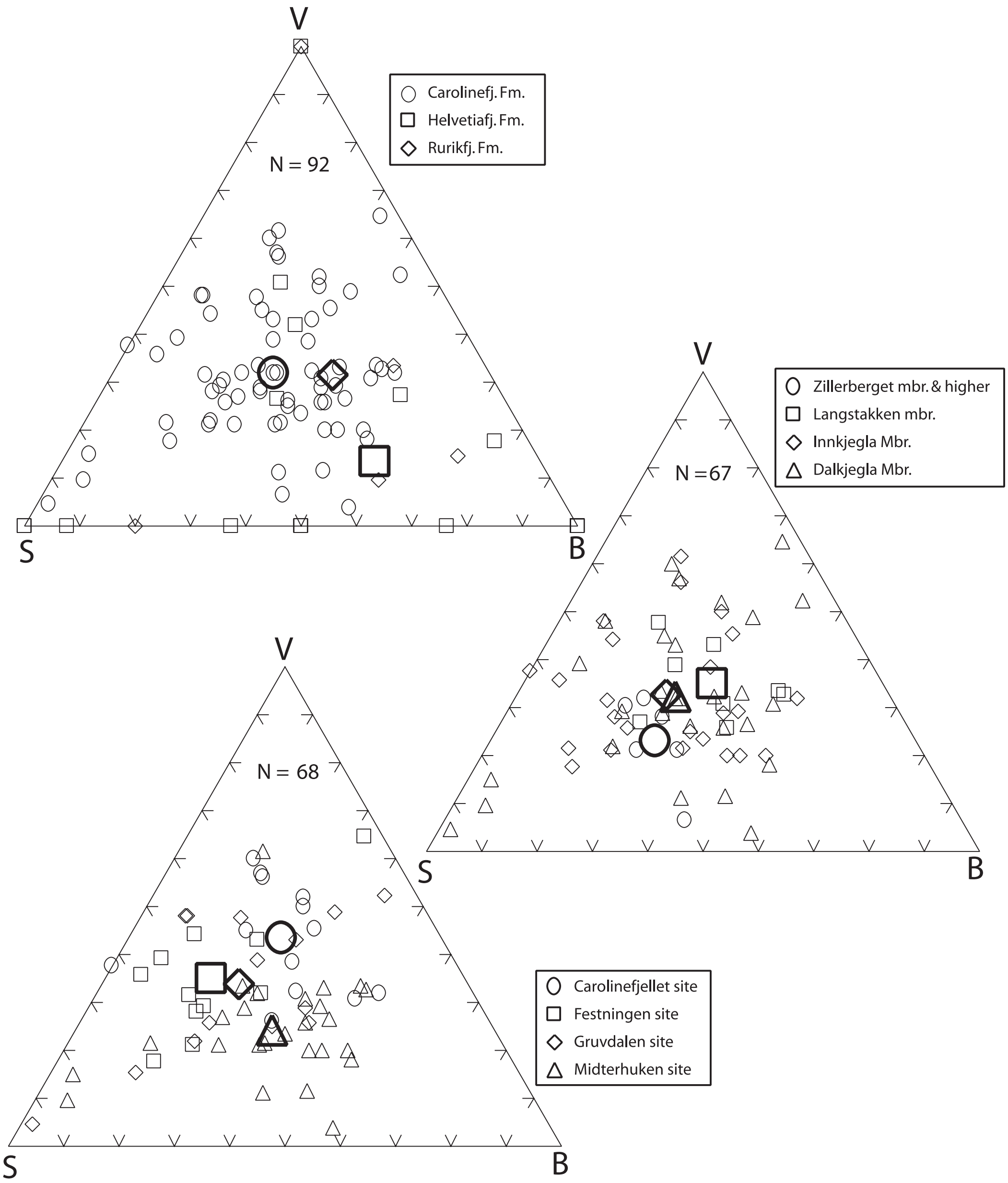


Fig. 5: V – volcanic, S – sedimentary, B – basement plot. Assignment of grains discussed in text. a) by formation, b) by member within the Carolinefjellet Formation, and c) for Carolinefjellet Formation by site.

let Formation are consistent with a greater contribution from a metamorphic basement and a decrease in sediment maturity, relative to the Helvetiafjellet Formation quartz arenites. Quartzite (including quartz ribbon mylonites) and phyllite lithics, detrital chlorite, and traces of andalusite and hornblende are associated with a basement source. Carolinefjellet Formation sandstone grains observed with perthite and myrmekite textures are consistent with a granitic source, as are microcline, euhedral zircons, monazite, and blue green tourmaline. Detrital biotite is also a consistent component attributable to either a plutonic or metamorphic basement source.

The sedimentary component shows the most variation (Fig. 5). Chert lithics are a consistent significant constituent, and larger chert clasts that retain spiculitic texture suggest the Kapp Starostin Formation was a significant contributor. Carbonate clasts consisted mainly of shell fragments and finer-grained, hardground and/or reexcavated concretionary material. Forams are common in the Innkjegla and higher members. Within the Dalkjegla Member a distinctive horizon of iron ooids (chamosite composition in part) occurs (Mutrux et al. 2003), and elsewhere clay aggregates have optical characteristics in thin section consistent with chlorite. Glauconite increases in abundance with stratigraphic ascent. Framboidal pyrite is often associated with clay pellets and with burrows, and pyrite is a common opaque mineral.

The volcanic source component of the Carolinefjellet Formation is represented by a small but consistent trace of volcanic lithics, and by a larger distinctive plagioclase component (Table 2). The volcanic lithics can be severely altered to clay and carbonate, and it is likely that some of the intraclasts are actually weathered volcanic lithics, and that this component is underestimated. Some material identified as clay cement could also be highly altered lithics. Lithics also show evidence of preferential pressure solution. Three end member morphologies of plagioclase grains were identified in the thin section suite: euhedral, broken, and rounded grains (Fig. 4). Euhedral grains have rectangular outlines with twin planes parallel to the long side, the geometry seen in plagioclase phenocrysts. These grains are somewhat rare, and more common in finer grained samples from the Innkjegla Member. Broken grains have rectangular outlines, but with twin planes parallel to the short side. The perfect cleavage of plagioclase is {001}, perpendicular to the common albite twins, and thus we associate this geometry with mechanical fracture. Broken grains are a fairly common grain constituent. Rounded grains tended to show more clay alteration. Rounded and broken grains are commonly seen in the same sample, and the relative proportion does not seem to change significantly with stratigraphic position (Table 2). Internal alteration of grains varies from none to considerable, and from fine-grained clay and/or carbonate to coarser grained white mica. Variation within the same sample indicates much of the alteration was pre-depositional. In samples with significant siderite diagenesis (more common in the Innkjegla Member), plagioclase feldspars can be seen partially replaced to varying degrees. Thus, in these samples plagioclase content is likely underestimated.

Extinction angles of albite twins were optically measured using the Michel-Lévy method (Kerr 1959) in order to help constrain the anorthite content of plagioclase grains in the sandstones. Typically, 10 measurements were made per sample on appropriately oriented grains. Figures 6a-6d show histograms of extinction angles from plagioclase grains in sandstones from the four sites. Extinction angles vary considerably from a high of 26° to a low of 3°, with peaks in the 12-18° range. Angles from 20° to 26° indicate anorthite contents of 38-48% (andesine). Those less than 12° represent oligoclase compositions, while those from 12° to 20° are either andesine or albite.

Anorthite contents of lavas from Kong Karls Land, the closest known mafic extrusives, range from 33 to 70% (Bailey & Rasmussen 1997). Anorthite content of a limited number of samples from Franz Josef Land ranges from 80 to 21% (Bailey & Brooks 1988). In both cases, the larger earlier phenocrysts are more calcic, and later smaller crystals are more sodic, with the lowest values found in grains within interstitial glass. Also, in order to gain some additional data on anorthite variability, measurements of extinction angles were made on plagioclase from phenocrystic diabase sill samples from Midterhuken (Fig. 6e). The anorthite content of Cretaceous sandstones overlaps with the more sodic end of the distribution seen in HALIP igneous material.

Carolinefjellet samples were plotted by member (Fig. 3 & 5) on QFL and VSB diagrams. Their average compositions are well within one standard deviation of each other, with no apparent stratigraphic trends. While no significant differences were noted between the average sandstone compositions for members of the Carolinefjellet Formation, stratigraphic trends or breaks may not be coincident with member boundaries. Visual inspection of plots of sample components in ascending stratigraphic order (Fig. 7) reveals no evidence of long term trends. In addition, Z statistics were calculated for quartz, feldspar, lithic, volcanic, sedimentary, basement sample fractions, and for the average plagioclase extinction angle for each sample sequence at the four sites (Table 3). Of the 28 Z values, 19 are below the threshold for indicating a non-random pattern. The remaining 9 all are greater than 1.96, indicat-

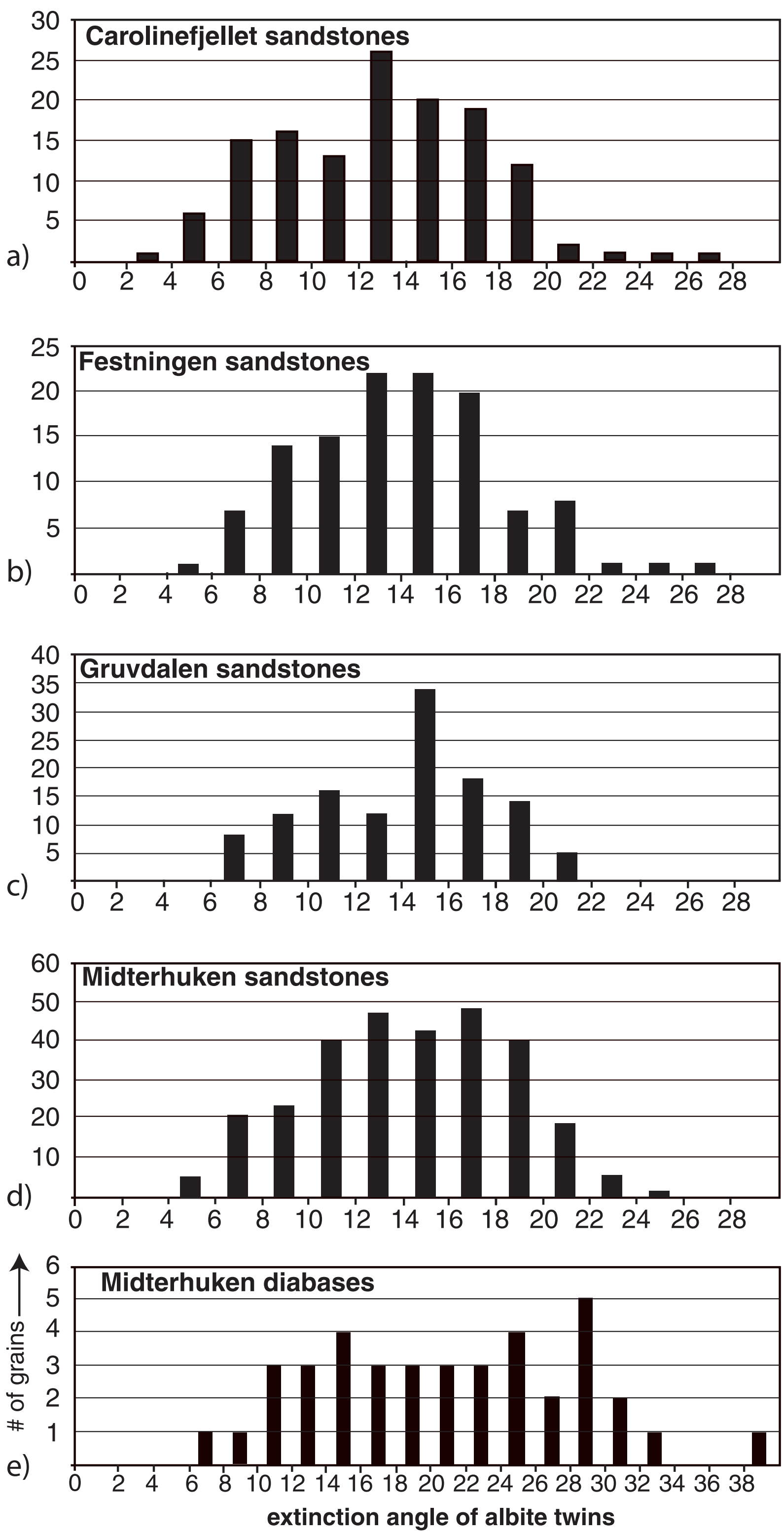


Fig. 6: Histograms of albite twin extinction angles in sandstones from various sites and from diabase samples from Midterhuken. Vertical axis is number of grains measured with extinction angles within the given histogram bin.

ing that a greater number of runs is present than would be expected from a random sequence. This would suggest an alternating or oscillatory signal with a periodicity close to or less than the sampling spacing. At present we are uncertain of the nature or cause of this result. However, the larger negative Z values that would indicate a long term trend are notably missing. In order to try to extract a longer term signal hidden by shorter term fluctuations, sliding averages with various window sizes were also used. Again, the number of runs was either greater than or the same as expected from a random distribution. This helps confirm the visual interpretation of a lack of compositional trends provided by bar charts of composition values in stratigraphic order.

Separating Carolinefjellet Formation samples by site for different members shows greater separation of average compositions on both QFL and VSB plots (Fig. 3c). This suggests that sandstone composition is relatively constant stratigraphically, but may vary spatially. Midterhuken, the more offshore site, shows less feldspar and less volcanic detritus on the QFL and VSB plots. More work is necessary in order to determine a spatial pattern.

Discussion

Two very different sandstone populations exist—quartz arenites with a minor basement component, and sublithic to lithic arenites with a distinctive plagioclase component as well as a notable basement signature. The types of basement clasts in both sandstone populations suggest a source terrane similar to that presently exposed to the north and north-east of the study area. Phyllite and/or quartzite clasts indicate a low grade metasedimentary component. Muscovite and tourmaline inclusions within quartz grains, trace amounts of zircons, coarse microcline, perthite and myrmekite suggest a granitic component, which could also provide coarse, relatively strain-free quartz grains. Andalusite is consistent with a contact metamorphic source. In the sublithic to lithic arenite sandstone population, the identifiable basement component increases dramatically, and phyllite clasts and quartzite lithics become more common. The increased basement component is associated with the introduction of mafic volcanic lithics and plagioclase grains. We associate these sublithic to lithic arenites with a source influenced by HALIP related mafic volcanism and uplift of basement and overlying platform cover rocks.

The lowest stratigraphic position of detritus that can be associated with HALIP usually occurs in the top portion (upper 10 - 20 m) of the Helvetiafjellet Formation. Plots of composition by member and by individual sample with stratigraphic ascent (Table 1) indicate the HALIP associated sands retain their composition, and lack large scale trends. At the scale of sampling, the shift in populations is a stepwise and not a gradual change at Midterhuken and Festningen. The Carolinefjellet site may be particularly instructive as to the nature of the shift in sandstone compositions. Steel (1977), who carried out detailed measurements on sections from the Helvetiafjellet Formation, interpreted coarser sandstones of the Helvetiafjellet Formation as fluvial distributory channel deposits, and intervening thinner bedded and finer grained material as tidally influenced interdistributary bay deposits. A sample from the tidally influenced Helvetiafjellet Formation sediments (at Carolinefjellet, 25 m above the formation's base, Table 1) shows a composition similar to that of the Carolinefjellet Formation sandstones, with a significant plagioclase and lithic component. In contrast, overlying coarser deposits are orthoquartzites without evidence of

Table 3: Z statistic values for the stratigraphic sequence of different compositional descriptors (Q%, F%, L%, V%, S%, B% as in Table 1) for each of the four sites. The Z statistic is described in the text.

Summary Z statistics by site	Q%	F%	L%	V%	S%	B%	average extinction angle
Carolinefjellet	0.16	0.98	-1.00	-0.42	2.37	2.68	1.35
Festningen	1.10	0.77	0.84	1.90	0.72	1.33	0.61
Gruvdalen	0.90	0.90	1.14	0.90	2.37	1.70	2.60
Midterhuken	3.11	2.08	2.82	1.24	3.25	1.46	2.12

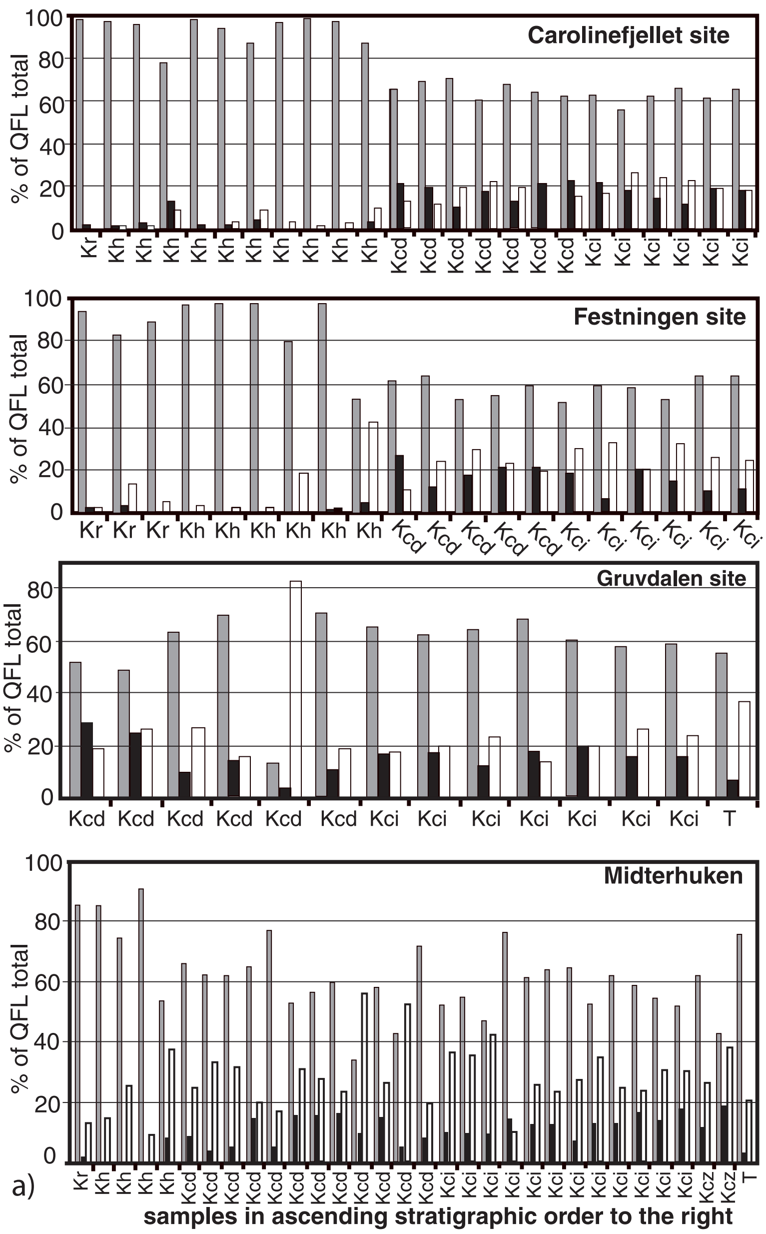
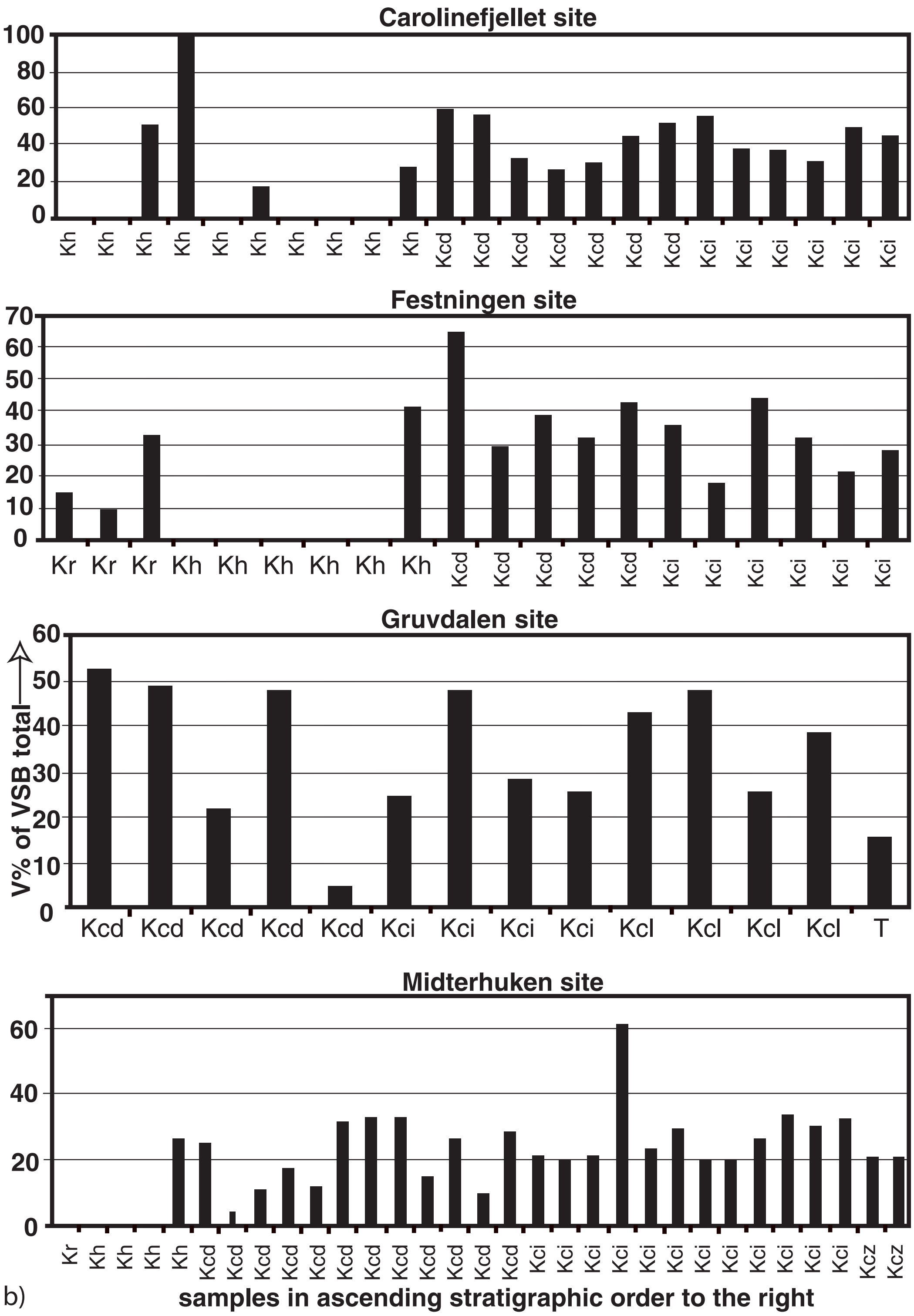


Fig. 7: Simple bar charts of quartz, feldspar, lithic grains (Q, F, L, panel a) and volcanic grains (V, panel b, opposite page) components in samples in ascending stratigraphic order from left to right by site. Kr = Rurikfjellet Formation, Kh = Helvetiafjellet Formation. In ascending order, Kcd, Kci, Kcl, Kcz represent the Dalkjegla, Innkjegla Member, Langstakken and Zillerberget member of the Carolinefjellet Formation. T = Tertiary. For bars in a: grey = quartz, black = feldspar and white = lithics. Vertical scale for 7b, is percent of assignable grains that are volcanic. As discussed in text, for orthoquartzite compositions, the amount may be spurious as it may reflect just one or two grains that are assignable as volcanic in origin.

a volcanic input. This mimics on a small scale the association seen on a large stratigraphic scale, where the appearance of mafic volcanic detritus is associated with marine incursion that helps define the Helvetiafjellet–Carolinefjellet formational boundary. This can be explained by two different sand sources: a terrestrial source to the north producing the fluvial–deltaic quartz arenites (Gjelberg & Steel 1995), and a marine source. Shore-parallel sediment transport could tap a different source to the north-east (Kong Karls and Franz Josef Land), where HALIP material is documented to have existed. Apparently, HALIP extrusive material did not exist in the local fluvial source for the Helvetiafjellet Formation. In northern Svalbard it may have taken a solely intrusive form as it does in the southern Spitsbergen area. Thus, the sandstone compositional shift does not mark the


Carolinefjellet site
100
80
60
40
20
0
Kh Kh Kh Kh Kh Kh Kh Kh Kh Kh Kcd Kcd Kcd Kcd Kcd Kcd Kcd Kci Kci Kci Kci Kci Kci
Festningen site
70
60
50
40
30
20
10
0
Kr Kr Kr Kh Kh Kh Kh Kh Kh Kcd Kcd Kcd Kcd Kcd Kci Kci Kci Kci Kci Kci
Gruvdalen site
V% of VSB total
60
50
40
30
20
10
0
Kcd Kcd Kcd Kcd Kcd Kci Kci Kci Kci Kcl Kcl Kcl Kcl T
Midterhuken site
60
40
20
0
Kr Kh Kh Kh Kh Kcd Kcd Kcd Kcd Kcd Kcd Kcd Kcd Kcd Kcd Kcd Kcd Kci Kci Kci Kci Kci Kci Kci Kci Kci Kci Kci Kci Kcz Kcz
b)
samples in ascending stratigraphic order to the right

onset of HALIP activity, but the local arrival of marine sands tapping a developed HALIP source terrane to which Svalbard was peripheral.

The sandstone petrography helps constrain models for the paleogeographic evolution of the area (Fig. 8). HALIP onset is constrained as during the Hauterivian in Franz Josef Land and Barremian in Kong Karls Land (Maher 2001). Additionally, at the Carolinefjellet site, a sandstone with a HALIP type composition exists between Helvetiafjellet Formation fluvial orthoquartzites, demonstrating temporal overlap of the sandstone populations. In a simple model, where the Helvetiafjellet Formation and Dalkjegla Member strata are linked as a deltaic shoreline and prodelta equivalents of a transgressional sequence, the sandstone compositions should reflect a common source. Yet, they appear compositionally and texturally distinct. The compositional difference is thus more consistent with the Dalkjegla Member sands representing offshore sand tracts introduced by net shore-parallel transport. The transgressive tract may have consisted of a fluvial to deltaic system of orthoquartzites separated by a lagoonal tidal flat "moat" from offshore barrier sand complexes consisting of sublithic arenites with a different source.

In the literature, plagioclase-rich sands are more commonly associated with andesitic volcanism (Pettijohn et al. 1987). Basaltic sources have been documented to produce mainly lithic material (e.g. Marsaglia 1993). The mechanism of liberating individual plagioclase grains, sometimes notably angular and unaltered in the sandstones, and more rarely even euhedral, is unclear. One possibility is the weathering of basaltic glass with plagioclase phenocrysts in it. In a marine realm the glass devitrifies quickly. A shield volcano with vitreous lavas bearing plagioclase crystals and abundant pyroclastic material is described from Franz Josef Land, as are basalt flows where the "lowermost part of sheets contains feldspathic hyalobasalt, rich in glass" (Dibner 1988, p. 110), demonstrating the existence of such source material. Crystal tuffs may have also contributed plagioclase grains, and tuffs are described from Franz Josef Land (Dibner 1988).

Several processes could account for the more sodic character of the plagioclase in the sandstones in comparison to the mafic volcanic source rock. More calcic plagioclase is notably more prone to weathering, and a shift would be expected from selective destruction during weathering, erosion and transport (Pettijohn et al. 1987). In addition, the plagioclase associated with hyalobasalts and pyroclastics, that may have been a more favourable source material in Franz Josef Land, is more sodic (Dibner 1998). Albitization during diagenesis is a well documented process (e.g. Boles 1982), and could have contributed to a shift in composition. However, the variability seen in extinction angles suggests such a diagenetic related shift is minimal.

The presence of iron ooid horizons (Mutrux et al. 2003), glauconite, hardgrounds, concretionary horizons, and storm beds suggest low sedimentation rates (e.g. Odin & Matter 1981) with significant amounts of reworking during much of Carolinefjellet Formation times (Maher et al. 2002). Feldspar preservation is thus not due to relatively quick burial. Consistent with this is the prevalence of rounded feldspar grains (Table 2). Instead, cold climatic conditions at the 60 - 70 ° high paleolatitudes may have been responsible. The preservation of glendonite horizons spanning a significant stratigraphic interval within the Carolinefjellet Formation (Maher et al. 2002), indicates at least periodic occurrence of cold (< 5 °C, De Lurio & Frakes 1999) bottom water conditions consistent with such a scenario. This may also explain the consistent trace of biotite, which otherwise weathers quickly, seen in the samples. A confounding factor, unexamined here, is possible regional climate change from the Barremian to the Albian caused by the regional transgression and changing hydrosphere–atmosphere dynamics.

A sediment system perspective (e.g. Johnson 1993) is useful for exploring how events may or may not be resolvable in sandstone compositions stratigraphically (Fig. 8). Consider how an event (e.g. instantaneous arrival of pyroclastic material) would be expressed stratigraphically. For the Carolinefjellet Formation, reworking by wave, tide and storm events would mix this and existing detritus, obscuring the event's signal. The average time a grain would spend in this environment before it no longer could mix with younger grains would be a function of depth of scour, likelihood of scour (a function of storm size–frequency relationship), and the near-surface deposition rate. Channel scour of over a metre is common for the sandstone dominated units. The long term average Carolinefjellet Formation deposition rate is 0.3 mm/yr. A single storm could rework sediment deposited tens of thousands of years before. Multiple cycles of excavation and mixing would

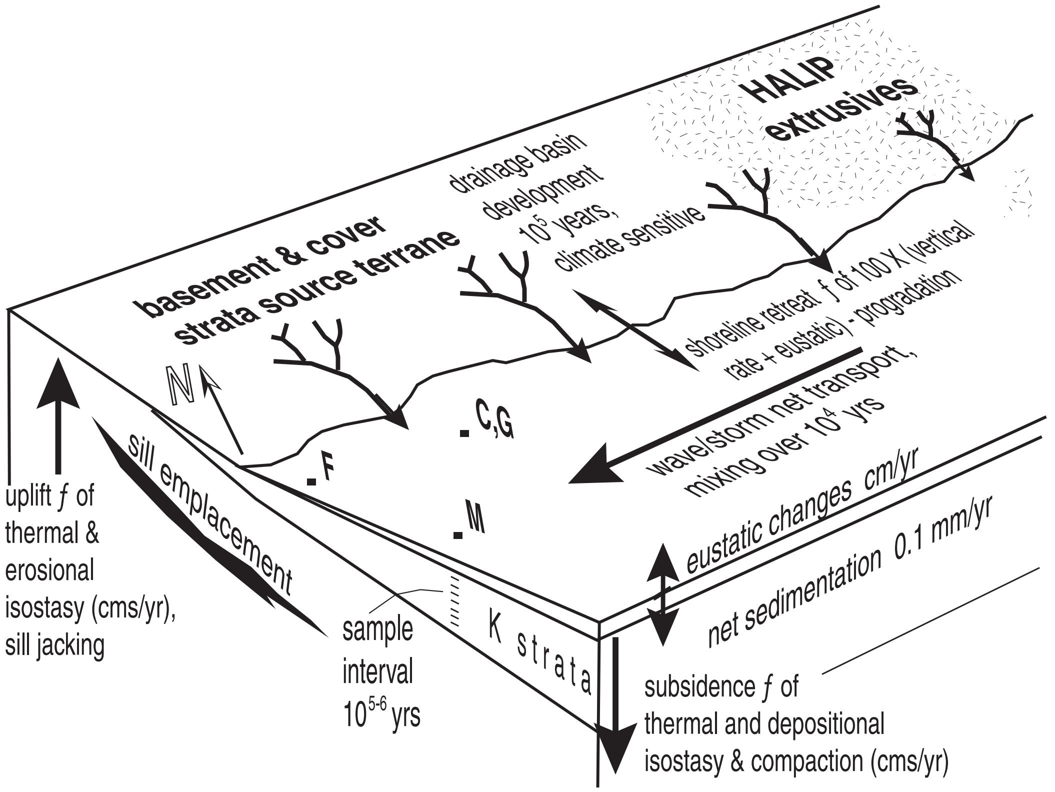


Fig. 8: System model for High Arctic Large Igneous Province (HALIP) related sandstones. F, C, G and M mark the relative positions of the Festningen, Carolinefjellet, Gruvdalen and Midterhuken sample sites.

increase the mixing significantly. The variation in grain shapes noted in individual samples, and the overall consistency of sandstone composition, is consistent with such a history of mixing. Passage through the marine setting would thus serve as a high frequency filter, preserving only longer period signals. In addition, the signal from a HALIP eruptive phase would not be instantaneous. The time span of eruptions, the geomorphic response to interrupted drainages, isostatic responses and shoreline shifts, would all influence sediment generation and delivery of HALIP detritus. The resulting signal would easily have a period greater than tens of thousands of years. Given the signal length, the effect of reworking, and our sample spacing, only events spaced in time on the order of a million years are likely resolvable within the Carolinefjellet Formation sandstone sample suite.

The relative consistency of the sandstone composition throughout the Carolinefjellet Formation suggests a lack of resolvable events or long term trends during the roughly 20 M involved. Two end member models might be invoked to create such a record: semi-continuous (short term episodic) HALIP activity, or relatively abrupt widespread emplacement of HALIP followed by establishment of a new sedimentary regime. Prolonged HALIP activity of just the right amount and temporal spacing so as to produce a relatively constant sand composition seems coincidental and less likely. The history of uplift followed by transgression is also more consistent with the second model than with the first (Maher 2001).

That HALIP served as a persistent and consistent source for 20 M suggests it was large. Maher (2001) estimated the minimum volume of HALIP igneous rock preserved. We can crudely estimate the equivalent thickness of flow material needed to produce the observed amount of volcanic detritus in our sections to further explore HALIP's size. The average volume percentage of plagioclase and volcanic lithics in our sample suite (including cement) is 9.9 % (proportioning the unknown feldspar by the ratio of known plagioclase to K-feldspar). Assuming plagioclase was circa 50 % of the original source rock, and estimating the proportion of sandstone in the Carolinefjellet Formation at 50 % (there is significant sand in the shale dominated members), then for the study area the equivalent flow thickness is 20 - 60 m. This is on par with the average HALIP sill thickness in strata below (Maher 2001). Michelson & Khorasani (1991) estimate up to 1000 m of Upper Cretaceous strata were removed by erosion associated with the basal Tertiary unconformity. While the amount of volcanic detritus in these missing strata is unconstrained, some likely existed. A source equivalent thickness of 100 m applied regionally in the Svalbard area equates to a volume on the order of 10^4 km^3. In the context of known LIP volumes on the order of 10^{5-7} km^3 (Coffin & Eldholm 1993), and considering the relative size and marginal position of Svalbard to the large footprint of HALIP (Maher 2001), a LIP source area is considered reasonable. However, based on the VSB plots and the types of quartz grains, the volumetric contribution of basement rocks to the Carolinefjellet Formation was the most significant in the central Spitsbergen area.

Conclusions

The following conclusions are drawn.

- Four sources can be recognized in the Cretaceous sandstones: 1) a low-grade metamorphic and plutonic terrane, 2) a volcanic source terrane, 3) reworked platform cover strata, and 4) intraclasts (hardgrounds, and reworked concretions).
- Two distinct sandstone populations are associated with a stepwise stratigraphic change from quartz arenites to sublitharenites.
- Plagioclase grains and volcanic lithics of the second population are associated with an extensive HALIP source to the east and north-east. The greater compositional and textural variability and implied immaturity of the second population is thought to be a byproduct of HALIP-related uplift, and marine mixing.
- The change coincides with the arrival of marine facies, typically in the upper portion of the Helvetiafjellet Formation. Thus the appearance of HALIP detritus in the sections does not mark the onset of surface volcanism, but the arrival of marine detritus that taps a developed HALIP source. HALIP volcanics were largely absent in the drainage basin that fed the Helvetiafjellet Formation fluvial and deltaic sediments of the study area.
- Dalkjegla Member sandstones are likely not prodelta sand bodies once attached to a shoreline, but disconnected bodies associated with shore-parallel net transport in a wave dominated, offshore margin of an epicontinental sea tapping sources to the east-northeast.
- The preservation of significant plagioclase in a sediment-starved, shallow marine setting may be explained by a colder climate, as indicated by the presence of glendonites.
- Overall, Carolinefjellet Formation sandstones retain a consistent character with stratigraphic ascent, suggesting the sediment system was in a semi-equilibrium mode for the Aptian and a portion of the Albian.
- This history is consistent with initial development of HALIP and development of a new sedimentary regime followed by system stability. Such a punctuated history is consistent with models for other large igneous provinces (Coffin & Eldholm 1993).
- The volume of volcanic detritus represented in the Carolinefjellet Formation is consistent with derivation from a LIP, but detritus from the basement dominates volumetrically.

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