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Late Ordovician to Silurian ensialic magmatism in Liverpool Land, East Greenland: new evidence extending the northeastern branch of the continental Laurentian magmatic arc

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Abstract – New U–Pb ID-TIMS geochronological and whole-rock geochemical data from the Hurry Inlet Plutonic Terrane in Liverpool Land provide evidence of a Late Ordovician to Silurian magmatic arc in the East Greenland Caledonides. These voluminous granitoid rocks range from meladiorite to monzonite and granite, they are alkali-calcic to calc-alkaline and magnesian, and have characteristic arc granitoid trace element signatures. Zircon data give ages of 446 ± 2 and 438 ± 4 Ma for two phases of the Hurry Inlet Composite Pluton, 426 ± 1 Ma for a meladioritic xenolith in the anatectic Triaselv granite, and 424 ± 1 Ma for the Hodal-Storefjord Pluton. The Late Ordovician plutons can be correlated with similar plutons in the uppermost nappes of the Scandinavian Caledonides, likely representing the northern branch of magmatic arcs formed on the Laurentian margin. Magmatism appears to have continued sporadically until about 425 Ma when a major, short-lived, magmatic event formed the bulk of the batholith on Liverpool Land. This activity was likely mantle-driven and can be correlated with the Newer Granites in Scotland, for which a slab break-off mechanism has been proposed. The increased heat flow from this process can also explain the generation of the crustally derived, syntectonic, two-mica granites, which are the areally most important Caledonian suite in East Greenland.

Keywords: East Greenland, Caledonides, U–Pb ID-TIMS zircon geochronology, magmatic arc, tectonics.

1. Introduction

Closing of the Iapetus Ocean in Late Ordovician–Early Silurian time is generally envisioned to have involved subduction of the oceanic plate underneath the Laurentian margin (Stephens & Gee, 1985; Grenne, Ihlen & Vokes, 1999; Yoshinobu *et al.* 2002; Meyer, Grenne & Pedersen, 2003; Cocks & Torsvik, 2006). Island arcs and active margin magmatic arcs related to this event are well documented in the Appalachians, Scotland and Ireland (e.g. Friedrich *et al.* 1999*a*,*b*; Van Staal *et al.* 1999, 2009; Whalen *et al.* 2006; Zagorevski *et al.* 2006; Oliver, Wilde & Wan, 2008; Steinhofel, Hegner & Oliver, 2008). Few of them are present in autochthonous crust, the majority being preserved in allochthons thrust upon the Laurentian continent during the continent collision phases of the Caledonian–Appalachian orogeny (e.g. Heaman, Erdmer & Owen, 2002; Goodenough, Young & Parsons, 2004; Whalen *et al.* 2006; Van Staal *et al.* 2009).

Magmatic arc rocks with Laurentian affinities are also found in the highest nappes of the Scandinavian Caledonides, where they were thrust during the Silurian–Devonian continent–continent collision between Laurentia and Baltica (Grenne, Ihlen & Vokes, 1999; Yoshinobu *et al.* 2002; Meyer, Grenne & Pedersen, 2003; Barnes *et al.* 2007). The Laurentian origin is indicated by faunal, geochronological and detrital zircon evidence (Bruton & Bockelie, 1980; Stephens & Gee, 1985; Pedersen, Bruton & Furnes, 1992; Grenne, Ihlen & Vokes, 1999; Yoshinobu *et al.* 2002; Meyer, Grenne & Pedersen, 2003; Roberts, Melezhik & Heldal, 2002; Roberts, Nordgulen & Melezhik, 2007; Barnes *et al.* 2007). These arc rocks are apparently all of island arc type and no occurrences of *continental* Laurentian crust intruded by subduction-related arc magmas have been described (with the possible exception of the Skattøra migmatite complex of the Tromsø Nappe Complex; Selbekk, Skjerli & Pedersen, 2000).

In the Caledonides of East Greenland (Fig. 1) the dominant magmatic rocks are Silurian two-mica granites, inferred to be derived by partial melting of sedimentary cover during crustal thickening attributed to the Laurentia–Baltica continent collision (Hartz *et al.* 2000, 2001; Kalsbeek, Jepsen & Jones, 2001; Kalsbeek, Jepsen & Nutman, 2001; White *et al.* 2002; Leslie & Nutman, 2003; Andresen, Rehnström & Holte, 2007; Kalsbeek *et al.* 2008). Two recent studies have, however, also described the presence of *c.* 454 to 420 Ma I-type intrusive rocks in Caledonian Allochthons composed of Laurentian continental crust (Kalsbeek *et al.* 2008; Rehnström, 2010). Further evidence for arc magmatism in the East Greenland Caledonides is documented in the present paper,

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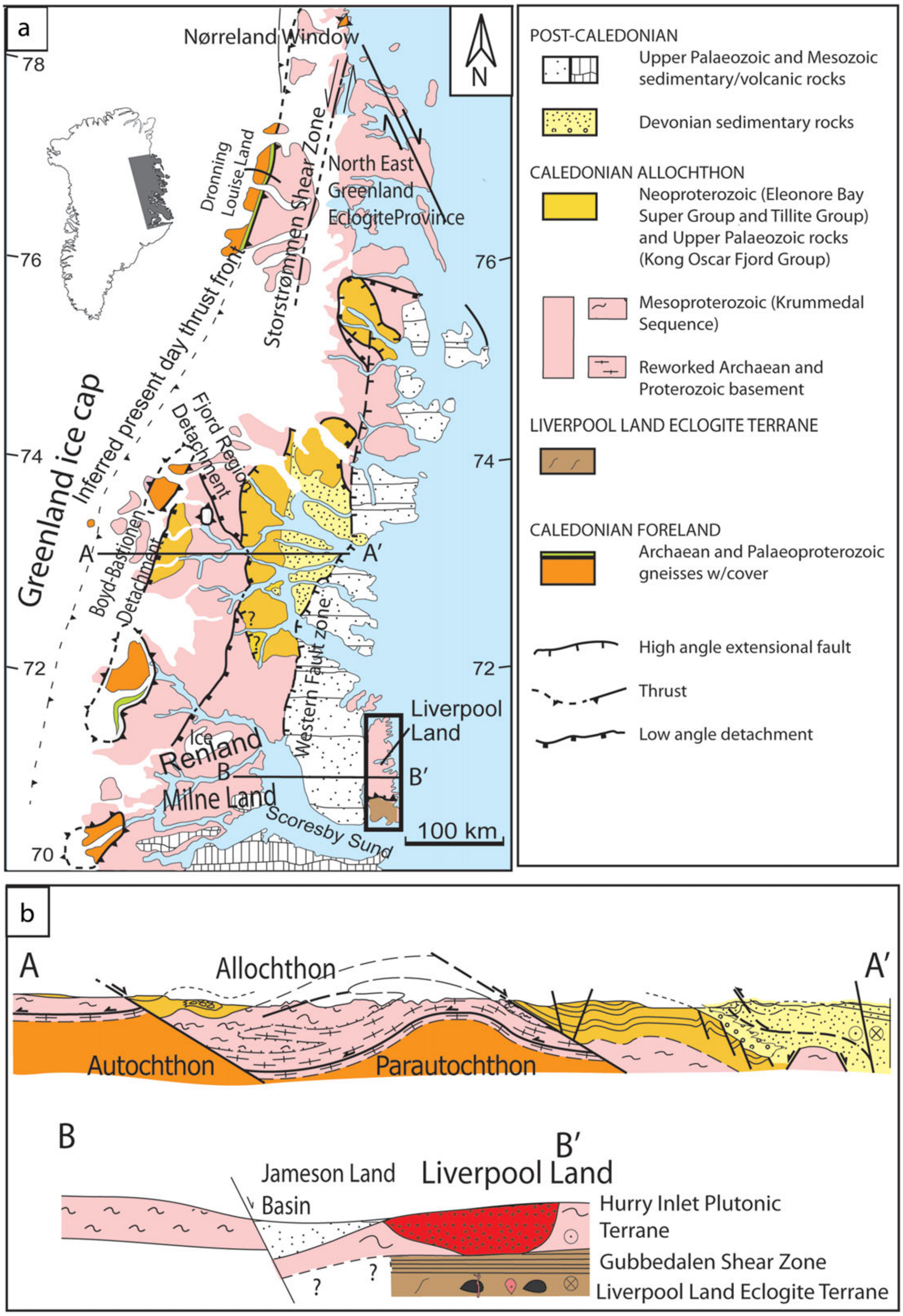

Figure 1. (a) Simplified geological map with (b) a representative profile of the main lithotectonic units of the East Greenland Caledonides. Modified from Andresen, Rehnström & Holte (2007). Rectangle indicates the Liverpool Land study area of Figure 2.

where we report new U–Pb isotope dilution thermal ionization mass spectrometry (ID-TIMS) and whole-rock major and trace element data from a large plutonic complex in Liverpool Land (Figs 1, 2). We discuss the previously available evidence and evaluate the tectonic implications of the data and their significance in the context of the Caledonian–Appalachian orogen.

2. Geological setting

The East Greenland Caledonides are part of the Early Palaeozoic Caledonian–Appalachian orogenic system exposed in eastern North America, the British Isles, Scandinavia and Svalbard. The East Greenland Caledonides consist of three main lithotectonic units

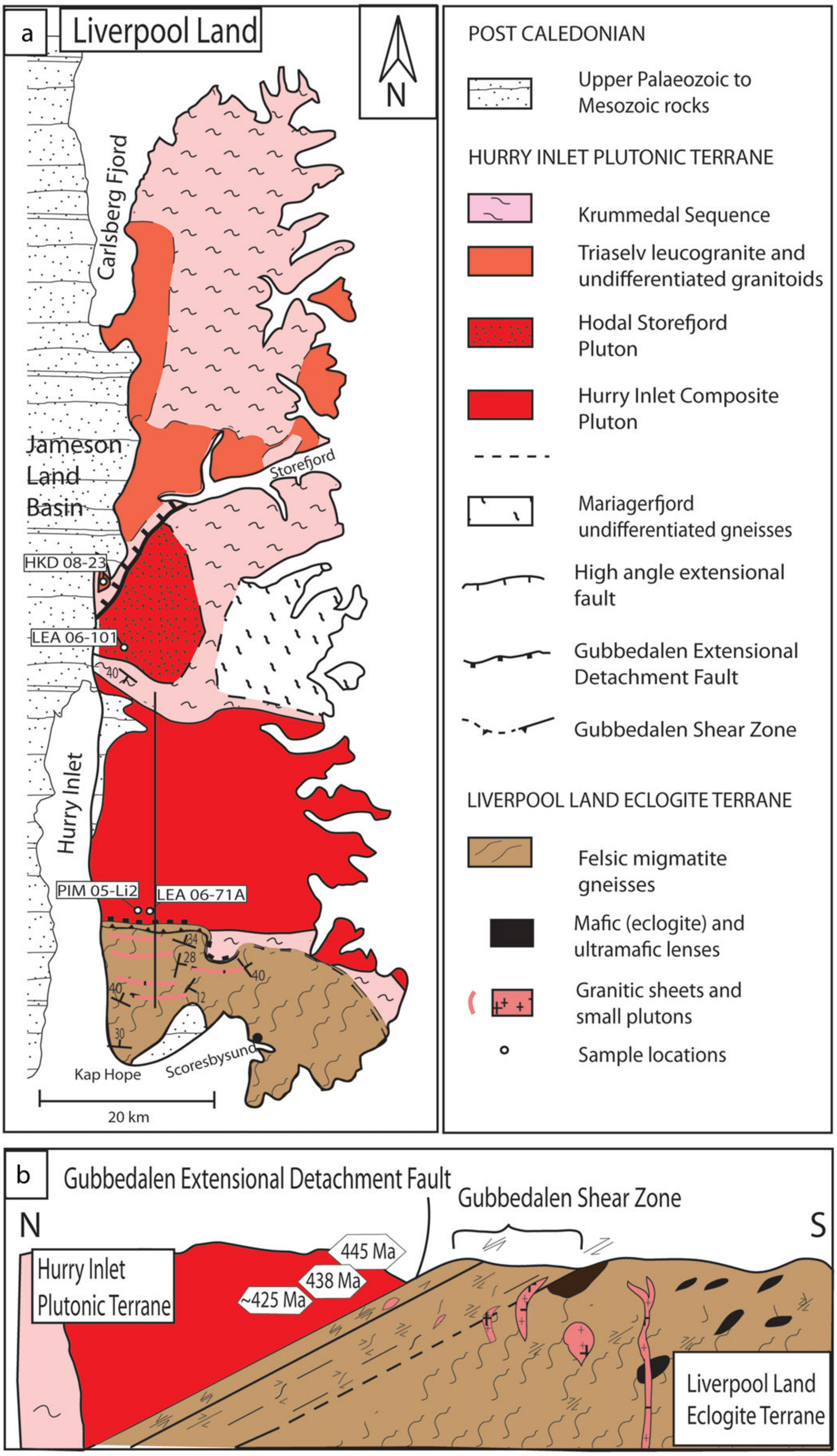

Figure 2. Simplified geological map of Liverpool Land (location in Fig. 1), and a representative schematic profile across the Gubbedalen Shear Zone (after Augland, Andresen & Corfu, 2010). Position of the N–S profile is indicated by the black line on the map. Selected representative foliation measurements are plotted. The geology of areas north of Storefjord and east of the village of Scoresbysund are based on the map by Coe & Cheeney (1972).

(Fig. 1): (i) parautochthonous foreland basement composed of Archaean and Palaeoproterozoic rocks with a variably preserved cover of Neoproterozoic and Cambrian–Ordovician sedimentary rocks; (ii) allochthonous Archaean to Palaeoproterozoic gneisses overlain, with a depositional contact, by the Mesoproterozoic Krummedal supracrustal sequence, again overlain, either unconformably or (in most places) over an extensional detachment, by a thick package of Neoproterozoic (Eleonore Bay Supergroup) to Lower Ordovician sediments (Higgins *et al.* 2004; Andresen, Rehnström & Holte, 2007; Higgins & Leslie, 2008); (iii) Devonian continental deposits appearing in fault-controlled basins (Larsen & Bengaard, 1991; Hartz *et al.* 2002; Larsen, Olsen & Clack, 2008). The Krummedal Sequence and the Eleonore Bay Supergroup are intruded by *c.* 430–425 Ma leucogranites, interpreted to be derived from partial melting of the Krummedal Sequence metasediments (Hartz *et al.* 2000, 2001; Kalsbeek, Jones & Jepsen, 2001; Kalsbeek, Jones & Nutman, 2001; White *et al.* 2002; Leslie & Nutman, 2003; Andresen, Rehnström & Holte, 2007; Kalsbeek *et al.* 2008). In the very south of the exposed East Greenland Caledonides (in Renland and Milne Land; Fig. 1) there are Middle Ordovician to Silurian I-type granitoids with geochemical and isotopic signatures typical of arc magmas (Kalsbeek *et al.* 2008; Rehnström, 2010).

Liverpool Land is the most internal Caledonian domain exposed in East Greenland and is isolated from the main area of Caledonian rocks by a cover of Permian and Mesozoic sedimentary rocks in the Jameson Land Basin (Fig. 2). The northern part of Liverpool Land is dominated by a plutonic complex, named here the Hurry Inlet Plutonic Terrane, whereas the southern part comprises eclogite-bearing gneisses of the Liverpool Land Eclogite Terrane (Kranck, 1935; Sahlstein, 1935; Coe & Cheeney, 1972; Coe, 1975; Friderichsen & Surlyk, 1981; Cheeney, 1985; Augland, Andresen & Corfu, 2010). The Hurry Inlet Plutonic Complex is separated from the Liverpool Land Eclogite Terrane by a major, N-dipping shear zone, the *c.* 400 m thick Gubbedalen Shear Zone, which is characterized by a complex kinematic history. The shear zone has top-up-to-the-S amphibolite to greenschist-facies contractional structures, subsequently superimposed by a zone of localized top-down-to-the-N semi-ductile to brittle extensional structures and an extensional detachment fault (Fig. 2) (Augland, Andresen & Corfu, 2010). The Liverpool Land Eclogite Terrane is interpreted, based on its composition, age relations and the preserved magmatic and metamorphic record, to represent a piece of Baltican crust amalgamated to Laurentia in Mid-Devonian time (Augland, Andresen and Corfu, 2011). By contrast the Hurry Inlet Plutonic Terrane (Corfu & Hartz, 2011) is interpreted to represent the tectonostratigraphic level equivalent to the allochthonous Caledonian rocks exposed west of the Jameson Land Basin (Fig. 1). This correlation is based on similarities between partly migmatitic metasedimentary rocks on Liverpool Land and the Krummedal Sequence to the west (Higgins, 1988; Johnston *et al.* 2009, 2010).

2.a. Hurry Inlet Plutonic Terrane

The Hurry Inlet Plutonic Terrane is dominated by Caledonian granitoid rocks intruding partly migmatitic metasedimentary rocks (Kranck, 1935; Hansen & Steiger, 1971; Coe & Cheeney, 1972; Coe, 1975; Friderichsen & Surlyk, 1981; Hansen & Friderichsen, 1987; Higgins, 1988; Johnston *et al.* 2009, 2010; this study). The largest of these granitoid intrusions are the Late Ordovician to Silurian Hurry Inlet Composite Pluton (see Section 3.a; Kranck, 1935; Hansen & Friderichsen, 1987) and the Silurian Hodal-Storefjord Pluton (Fig. 2) (see Section 3.b; Coe & Cheeney, 1972; Hansen & Friderichsen, 1987). The Hurry Inlet Composite Pluton and the Hodal-Storefjord Pluton probably belong to the same batholithic complex, both intruding the Krummedal Sequence metasedimentary rocks. A brittle extensional fault separates the Hodal-Storefjord Pluton from the Triaselv leucogranite to the north (Fig. 2).

The Hurry Inlet Composite Pluton can roughly be divided in three major units visible on a map scale: (i) mainly undeformed granite to monzonite rocks in the west; (ii) mainly undeformed diorite to monzonite in the east; and (iii) foliated granodiorite in between (Coe & Cheeney, 1972; Coe, 1975). However, in the field and in thin-section at least six different intrusive rock types have been recognized based on texture and modal compositions. The varieties examined here range from monzonite to granodiorite to granite and from equigranular to porphyritic in texture. Some intrusive phases contain more than 20 % amphibole and no biotite. Others contain biotite as the only major mafic phase. Hansen & Friderichsen (1987) obtained a whole-rock Rb–Sr isochron from six different samples from the Hurry Inlet Composite Pluton of 438 ± 42 Ma (MSWD = 0.99). The Hodal-Storefjord Pluton ranges from diorite to quartz-monzodiorite and most samples are equigranular, although some porphyritic varieties occur close to its margin. Amphibole content of the samples ranges from *c.* 5 to 20 % and biotite content ranges between *c.* 5 and 15 %. Some samples contain up to 13 % pyroxene. At one locality a mafic rock (HKD 08-18) comprised of amphibole (80 %), olivine (2 %), plagioclase (*c.* 8 %) and opaques (10 %) occurs as an enclave in the Hodal-Storefjord Pluton. The enclave itself contains inclusions of the Hodal-Storefjord Pluton, testifying to their comagmatic nature.

Major element analyses of 25 samples and trace element analyses of 24 samples reported by Coe (1975) for the Hurry Inlet Composite Pluton, define a calc-alkaline trend in the AFM diagram and plot in the high-K field in the K_2O–SiO_2 diagram (Fig. 3a, c). All samples except no. 23 are magnesian according to the classification of Frost *et al.* (2001) and all samples except no. 23 are alkali-calcic to calc-alkalic as defined

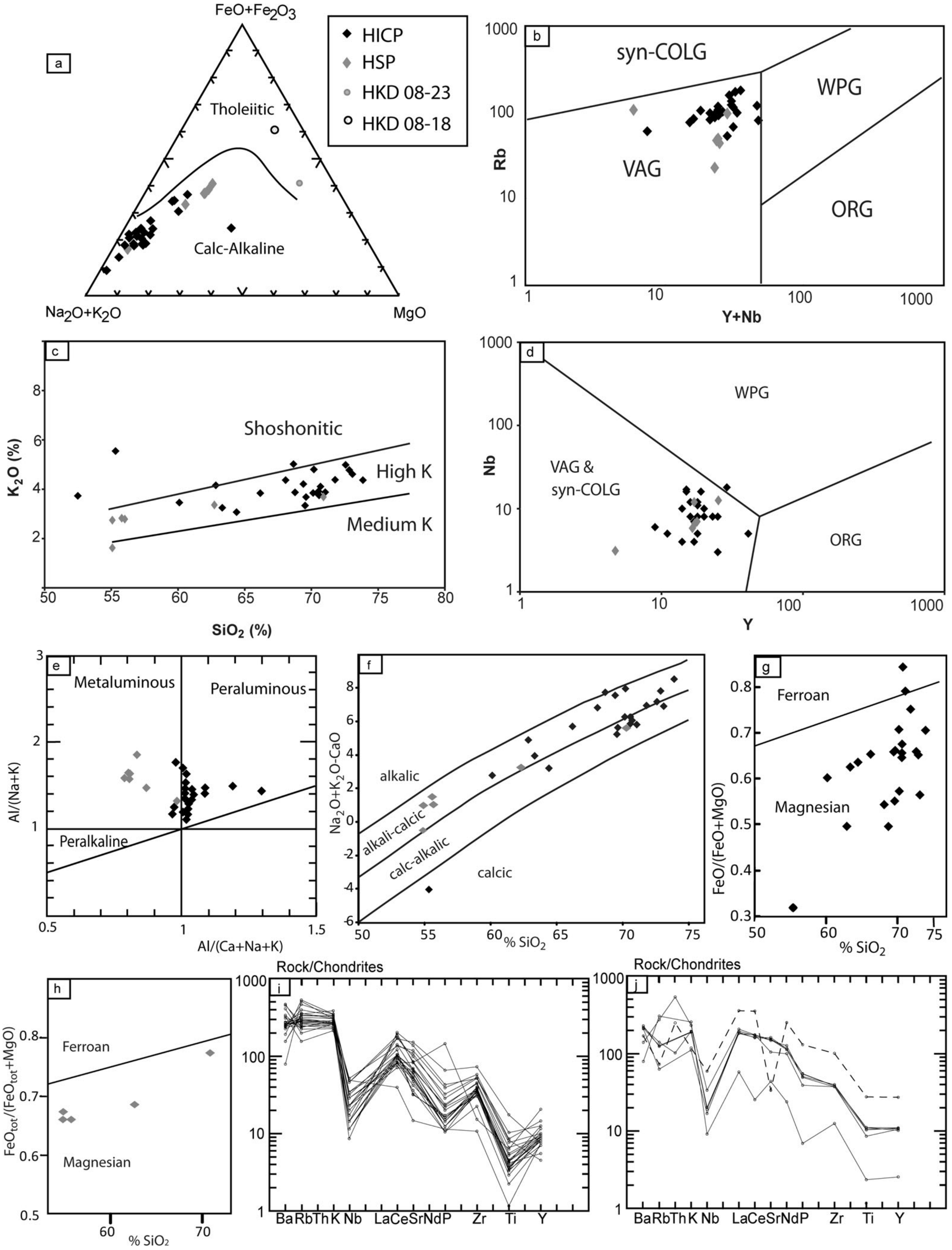

Figure 3. Diagrams illustrating aspects of the chemical compositions of the Hurry Inlet Composite Pluton (HICP) and the Hodal-Storefjord Pluton (HSP) (data from Coe, 1975; and this study). (a) AFM diagram. (b) Nb + Y v. Rb discrimination diagram (Pearce, Harris & Tindle, 1984). (c) SiO_2–K_2O diagram (Peccerillo & Taylor, 1976). (d) Y v. Nb discrimination diagram (Pearce, Harris & Tindle, 1984). (e) Shand's index plot (Maniar & Piccoli, 1989). (f) $Na_2O + K_2O–CaO$ v. SiO_2 diagram. (g) FeO/(FeO + MgO) v. SiO_2 diagram for the HICP. (h) $FeO_{tot}/(FeO_{tot} + MgO)$ v. SiO_2 diagram for the HSP. (i) Limited element spider diagram of trace elements for the HICP. Chondrite normalization values from Thompson (1982). (j) Limited element spider diagram of trace elements for the HSP. Chondrite normalization values from Thompson (1982). Dashed line represents analysis from the mafic enclave (HKD 08-18).

Table 1. Major and trace element analyses of samples from the Hodal-Storefjord Pluton including the mafic enclave (HKD 08-18) and the xenolith in the Triaselv leucogranite (HKD 08-23)

Sample id.	HKD08-01	HKD08-02	HKD08-03	HKD08-08	HKD08-16B	HKD08-17	HKD08-18	HKD08-23
GPS positions	70° 52.628′ N 22° 18.708′ W	70° 52.684′ N 22° 16.813′ W	70° 52.656′ N 22° 18.410′ W	71° 14.524′ N 22° 13.366′ W	70° 59.243′ N 22° 20.585′ W	70° 59.168′ N 22° 20.271′ W	70° 59.236′ N 22° 20.477′ W	70° 58.790′ N 22° 23.089′ W
SiO_2	54.9	70.6	54.9	62.5	55.6	55.7	43.8	51.4
Al_2O_3	17.4	14.7	18.3	15.8	17.5	17.2	8.76	11.7
Fe_2O_3	6.77	1.68	6.65	4.84	6.43	6.28	18.20	10.70
TiO_2	1.15	0.243	1.15	0.887	1.10	1.07	2.86	1.05
MgO	3.46	0.487	3.25	2.23	3.29	3.24	9.00	11.70
CaO	6.32	2.30	6.94	4.29	6.09	6.34	10.50	5.43
Na_2O	4.49	4.16	4.77	4.19	4.73	4.56	1.12	1.21
K_2O	2.74	3.72	1.61	3.36	2.82	2.77	1.71	1.70
MnO	0.096	0.028	0.087	0.075	0.087	0.094	0.257	0.165
P_2O_5	0.582	0.073	0.577	0.412	0.535	0.521	1.38	0.37
LOI	1.33	0.37	1.50	1.12	1.19	0.72	1.89	3.83
Total [%]	99.3	98.4	99.7	99.8	99.4	98.6	99.5	99.2

Sample id.	HKD08-01	HKD08-02	HKD08-03	HKD08-08	HKD08-16B	HKD08-17	HKD08-18	HKD08-23
Ba	1580	548	1450	967	1520	1480	1170	467
Ce	141	22	139	152	152	149	307	56
Co	22.4	< 4	21.6	14.4	21.2	20.3	55.4	47.1
Cr	32.3	18.9	23.7	16.9	24.8	24.4	89	613
Cu	4.6	< 2	10.5	3	32.6	25.4	4.7	15.8
Ga	22.8	16.9	23.6	21.1	23.1	22.9	20.3	16.3
La	60	19	62	68	60	64	118	15
Mo	1.3	< 1	< 1	1.3	< 1	1	2.3	1.6
Nb	7.1	3.2	5.9	11.8	6.7	6.7	20.8	7.6
Nd	73	15	73	63	71	80	159	30
Ni	21.6	2.9	18.3	12.5	19.9	18.9	49.9	202
Pb	32	60.5	29.9	45.4	32.7	35.8	37.6	46.8
Rb	43.5	107	22.1	96.1	49.2	44.5	25.6	82.6
Sc	14.3	< 5	14	8.9	13.3	14.8	38.8	23.2
Sr	1830	518	1910	1240	1800	1750	397	480
Th	< 4	< 4	< 4	22.7	4.3	< 4	10.5	< 4
U	4.1	< 2	4	5.6	4.5	4.1	< 2	2.7
V	116	18.7	117	73.9	109	103	343	130
Y	22	5.1	20.4	21.1	21.5	21.9	54.6	27.6
Zn	98.2	27.3	95.5	81.6	94.4	89	274	116
Zr	263	85.6	262	256	272	255	691	32.4
Hf*	6.6	< 5	< 5	8.3	9.6	5.8	18.4	< 5
Sm*	12	< 10	< 10	< 10	12	17	20	< 10
Te*	16	< 10	< 10	< 10	< 10	< 10	14	< 10

All data determined with a PanAlytical Axios wavelength dispersive X-ray fluorescence (WD-XRF) spectrometer at the Norwegian Geological Survey, Trondheim, Norway.

by the modified alkali–lime index of Frost *et al.* (2001) (Fig. 3f, g). Most samples are slightly peraluminous, except a few samples with a clear Al-enrichment (Fig. 3e; Maniar & Piccoli, 1989). The samples plot in the volcanic-arc granite field of the (Y + Nb) v. Rb and the Y v. Nb discrimination diagrams of Pearce, Harris & Tindle (1984) (Fig. 3b, d). In a chondrite-normalized (Thompson, 1982) spider diagram, the trace elements show high Ba and Sr values, a distinct negative trough for Nb and smaller, negative P and Ti anomalies (Fig. 3i).

The Hodal-Storefjord Pluton samples (Table 1) define a calc-alkaline trend in the AFM diagram and all samples except the mafic enclave plot in the high-K field of the K_2O–SiO_2 diagram (Fig. 3a, c). The samples are magnesian, alkali-calcic to calc-alkalic and metaluminous (Fig. 3f, h) (Maniar & Piccoli, 1989; Frost *et al.* 2001). The Hodal-Storefjord Pluton samples plot in the volcanic-arc granite field in the (Y + Nb) v. Rb and the Y v. Nb diagrams (Fig. 3b, d) (Pearce, Harris & Tindle, 1984). In a chondrite-normalized (Thompson, 1982) spider diagram the trace elements show elevated Ba and Sr values and a distinct Nb trough (Fig. 3j).

The mafic enclave (HKD 08-18) has a very low Al_2O_3 and high Fe_2O_3 content, and based on the field relations with inclusions of both the mafic rock within a monzodioritic variety of the Hodal-Storefjord Pluton and the monzodiorite within the mafic enclave, magma mingling or mixing must have occurred. The rock has elevated Ni (50 ppm) and Cr (89 ppm) concentrations. This sample has negative Nb and Sr spikes (Fig. 3j). The latter probably reflects the crystallization of plagioclase in the dominant granitoid phase synchronously with mingling or mixing.

Major and trace elements are also reported for a two-amphibole-mica meladiorite (containing *c.* 25 % hornblende, *c.* 25 % cummingtonite, partly altered to actinolite along the grain margins, *c.* 25 % biotite and *c.* 25 % plagioclase) occurring as a xenolith in the Triaselv

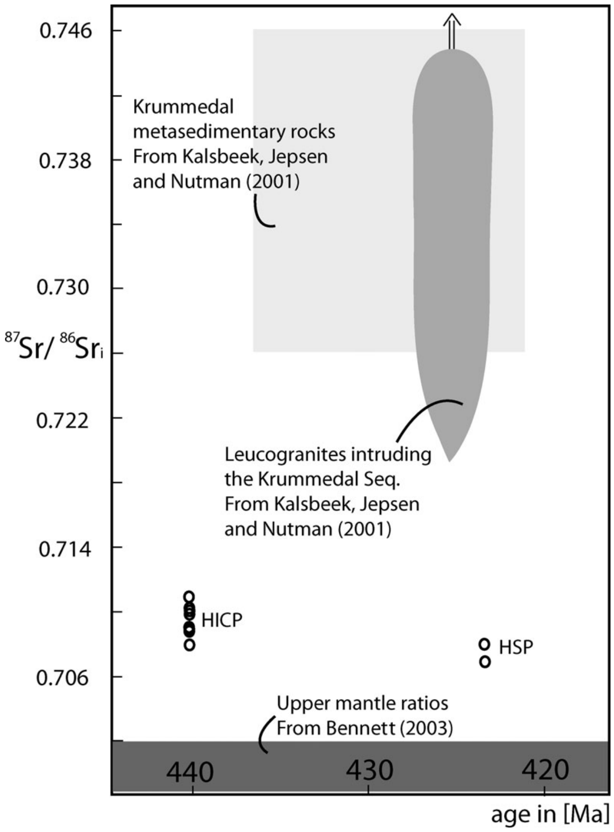

Figure 4. Age v. initial $^{87}Sr/^{86}Sr$ ratios from the Hurry Inlet Composite Pluton and the Hodal-Storefjord Pluton. Data from Hansen & Friderichsen (1987). Also plotted are data from the Krummedal Sequence metasedimentary rocks, typical two-mica leucogranites (Kalsbeek, Jepsen & Nutman, 2001) and upper mantle ratios (Bennett, 2003).

leucogranite (Fig. 2). The sample (HKD 08-23; Table 1) has an Mg no. of 52 (Fig. 3a) and has high Cr (613 ppm) and Ni (202 ppm) concentrations.

2.b. Rb–Sr isotope data

Rb–Sr analyses of eight samples from the Hurry Inlet Composite Pluton were reported by Hansen & Friderichsen (1987). Initial $^{87}Sr/^{86}Sr$ ratios of 0.708 to 0.711 were calculated at an age of 440 Ma (Fig. 4; Table 2). Two samples from the Hodal-Storefjord Pluton (Hansen & Friderichsen, 1987), calculated at 424 Ma, yield initial $^{87}Sr/^{86}Sr$ ratios of 0.707 and 0.708 (Fig. 4; Table 2).

3. Geochronology

Zircons from two phases of the Hurry Inlet Composite Pluton, and one sample from the Hodal-Storefjord Pluton and a dioritic xenolith included in the Triaselv leucogranite have been dated (Fig. 2). The U–Pb analyses were conducted by isotope dilution thermal ionization mass spectrometry (ID-TIMS) at the Department of Geosciences, University of Oslo. The reader is referred to appendix A of Augland, Andresen & Corfu (2010) for a thorough description of the analytical procedure.

Table 2. Rb/Sr and Sr isotope data for the Hurry Inlet Composite Pluton and the Hodal-Storefjord Pluton

Hurry Inlet Composite Pluton $^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$Sr_{initial}$
0.161	0.71084	0.710
0.146	0.71066	0.710
0.730	0.71407	0.709
0.741	0.71470	0.710
0.419	0.71183	0.709
0.499	0.71248	0.709
0.679	0.71248	0.708
0.598	0.71432	0.711
Hodal-Storefjord Pluton $^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$Sr_{initial}$
0.085	0.70790	0.708
0.122	0.70823	0.707

Initial Sr isotopic ratios calculated at 440 Ma for the HICP and 424 Ma for the HSP.
Data from Hansen & Friderichsen (1987)

3.a. Hurry Inlet Composite Pluton

Samples PIM 05-Li02 and LEA 06-71A are from medium-grained, equigranular K-feldspar-rich, amphibole and minor clinopyroxene-bearing granitic phases in the southernmost part of the Hurry Inlet Composite Pluton (Fig. 2; Table 3).

The zircon population of LEA 06-71A is relatively homogeneous. Most grains are colourless, with some weakly red and yellow metamict grains. Prismatic grains dominated by {100} and {101} forms are most common, with elongation ratios ranging from 2 to 6. The grains are generally rich in inclusions and seldom contain visible cores. The U content in the analysed fractions ranges from *c*. 130 to *c*. 1700 ppm with moderate Th/U ratios of 0.29 to 0.53 (Table 3).

The zircons from PIM 05-Li02 have similar shapes and morphologies to LEA 06-71A, but are more heterogeneous, ranging from colourless to reddish or brown, in part metamict and some contain cores. The U content in the analysed fractions ranges from *c*. 379 to *c*. 1034 ppm with moderate Th/U ratios of 0.37 and 0.50 (Table 3).

Of the eight fractions analysed from LEA 06-71A (Fig. 5b), two contain inheritance (nos 5 and 8). Five other analyses define a discordia age, anchored at 0 Ma, with an intercept age of 445 ± 4 Ma (2σ, MSWD = 0.92). Analysis no. 1 is concordant and gives a concordia age of 446 ± 2 Ma (2σ, MSWD = 0.69), concurrent with the upper intercept age of the five point discordia line, and we consider that age as the best estimate of crystallization of this intrusive phase. The eighth fraction yields a concordant analysis (no. 6) that does not fit the line (*c*. 434 Ma), indicating either some disturbance or growth in response to younger intrusions or hydrothermal effects, or less likely, due to some unknown analytical bias. An alternative explanation is that the older fractions represent antecrysts from an older magmatic pulse in the Hurry Inlet Composite Pluton and the young concordant zircon fraction dates the actual crystallization of this particular phase (Miller *et al.* 2007).

Table 3. U–Pb analytical data for the for the Hurry Inlet Composite Pluton, Hodal-Storefjord Pluton and dioritic xenolith in the Triaselv leucogranite All 2σ errors are absolute.

Fraction analysed	No	Mineral characteristics	Weight [ug]	U [ppm]	Th/U	Pbcom [pg]	$^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$	$^{207}\mathrm{Pb}/^{235}\mathrm{U}$	2 sigma [abs]	$^{206}\mathrm{Pb}/^{238}\mathrm{U}$	2 sigma [abs]	rho	$^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$	2 sigma [abs]	$^{206}\mathrm{Pb}/^{238}\mathrm{U}$	2 sigma [abs]	$^{207}\mathrm{Pb}/^{235}\mathrm{U}$	2 sigma [abs]	$^{207}\mathrm{Pb}/^{206}\mathrm{U}$	2 sigma [abs]	Disc. [%]
Hurry Inlet Composite Pluton (70° 36.194′ N, 22° 16.502′ W)																					
LEA 06-71A 142/58	1	3 euh. High aspect ratio zirc. Light pink	5	721	0.53	7.4	2200	0.5509	0.0026	0.07163	0.00028	0.84	0.05578	0.00014	446.0	1.7	445.6	1.7	443.5	5.7	−0.6
LEA 06-71A 142/59	2	2 inclusion-rich euh. Zircons. Light pink	5	239	0.29	3.5	1472	0.5293	0.0029	0.06863	0.00029	0.74	0.05593	0.00021	427.9	1.7	431.3	1.9	449.7	8.1	5.0
LEA 06 71A 142/60	3	4 euh. Low aspect ratio zirc. Light pink	7	292	0.44	4.4	2070	0.5402	0.0034	0.07018	0.00048	0.73	0.05583	0.00027	437.2	2.9	438.6	2.2	445.7	10.8	2.0
LEA 06 71A 145/53	4	1 euh. High aspect ratio zirc. Light pink	1	191	Not m	1.1	764	0.5364	0.0052	0.06960	0.00026	0.43	0.05590	0.00049	433.8	1.6	436.1	3.5	448.3	19.5	3.3
LEA 06 71A 145/55	5	6 euh. large zirc. Med. aspect ratio. Light pink	12	377	0.42	2.7	7452	0.5689	0.0014	0.07182	0.00016	0.90	0.05745	0.00006	447.1	1.0	457.3	0.9	508.7	2.5	12.5
LEA 06 71A 145/56	6	9 euh. large zirc. Med. aspect ratio. Light pink	6	549	0.46	3.0	4848	0.5338	0.0022	0.06973	0.00024	0.85	0.05553	0.00012	434.5	1.4	434.4	1.5	433.6	4.8	−0.2
LEA 06 71A 147/57	7	4 euh. High aspect ratio zirc. Light pink	3	134	Not m	1.2	1530	0.5439	0.0071	0.07100	0.00089	0.87	0.05556	0.00036	442.2	5.3	441.0	4.7	434.8	14.4	−1.8
LEA 06 71A 147/58	8	6 euh. Med. aspect ratio zirc. Light pink	1	1701	0.52	12.6	691	0.6713	0.0041	0.07951	0.00029	0.62	0.06123	0.00029	493.2	1.7	521.5	2.5	647.3	10.2	24.7
PIM 05-LI02 145/57	1	1 euh. High aspect ratio zirc. Light pink	1	432	0.37	2.3	842	0.5288	0.0042	0.06876	0.00018	0.49	0.05577	0.00039	428.7	1.1	431.0	2.8	443.3	15.6	3.4
PIM 05 LI02 145/58	2	1 euh. Med. aspect ratio zirc. Light pink	1	1025	Not m	4.0	1096	0.5165	0.0154	0.06787	0.00192	0.70	0.05519	0.00124	423.3	11.6	422.8	10.2	420.0	49.3	−0.8
PIM 05 LI02 145/62	3	1 tip. zirc.	1	1034	0.50	1.1	4124	0.5220	0.0026	0.06809	0.00029	0.74	0.05560	0.00019	424.7	1.8	426.5	1.7	436.4	7.6	2.8
PIM 05-LI02 154/62	4	5 euh. Low. aspect ratio zirc. Pink	11	379	0.37	6.1	2978	0.5322	0.0038	0.06937	0.00048	0.93	0.05564	0.00015	432.4	2.9	433.3	2.5	438.1	5.9	1.4
Hodal-Storefjord Pluton (70° 53.044′ N, 22° 20.557′ W)																					
LEA 06 101 142/52	1	8 euh. Med. aspect ratio zirc. Light pink	9	176	0.82	4.9	1384	0.5163	0.0026	0.06747	0.00025	0.73	0.05550	0.00019	420.9	1.5	422.7	1.8	432.5	7.7	2.8
LEA 06-101 142/56	2	3 euh. Med. aspect ratio zirc. Light pink	1	1651	0.75	2.6	2703	0.5179	0.0037	0.06780	0.00058	0.71	0.05540	0.00034	422.9	3.5	423.8	2.5	428.6	13.6	1.4
LEA 06-101 142/57	3	1 tip zirc.	1	61	0.87	2.4	127	0.5136	0.0264	0.06773	0.00041	0.49	0.05499	0.00268	422.5	2.5	420.8	17.6	411.9	106	−2.7
LEA 06 101 145/59	4	1 euh. large zirc. Med. aspect ratio. Light pink	10	225	0.82	48.7	215	0.5169	0.0088	0.06822	0.00021	0.24	0.05495	0.00091	425.4	1.3	423.1	5.9	410.3	36.4	−3.8
LEA 06 101 145/60	5	1 euh. small zirc. Med. aspect ratio. Light pink	3	68	0.89	3.4	277	0.5119	0.0091	0.06777	0.00027	0.42	0.05478	0.00091	422.7	1.7	419.7	6.1	403.2	36.6	−5.0
LEA 06 101 147/60	6	9 euh. zirc. Med. aspect ratio. Light pink	6	179	0.74	3.2	1429	0.5170	0.0026	0.06782	0.00019	0.67	0.05529	0.00021	423.0	1.1	423.2	1.7	424.0	8.4	0.2
Dioritic xenolith in the Triaselv leucogranite (70° 58.790′ N, 22° 23.089′ W)																					
HK-08-23 207/13	1	1 euh. zirc. Med. aspect ratio. Colourless	1	2200	0.31	3.3	2873	0.51874	0.01059	0.06805	0.00138	0.99	0.05529	0.00015	424.4	8.3	424.3	7.1	424.0	5.8	−0.1
HK-08-23 207/14	2	5 euh. Low aspect ratio zirc. Colourless w/some incl.	19	354	0.39	4.2	6848	0.51637	0.00123	0.06770	0.00014	0.92	0.05532	0.00005	422.3	0.8	422.7	0.8	425.2	2.1	0.7
HK-08-23 207/15	3	1 clear, colourless tip	11	820	0.28	8.3	4595	0.51422	0.00140	0.06742	0.00015	0.89	0.05532	0.00007	420.6	0.9	421.3	0.9	425,1	2.8	1.1
HK-08-23 207/16	4	4 euh. zirc. Med. aspect ratio. Colourless w/ few incl.	17	546	0.30	3.6	11049	0.51663	0.00124	0.06771	0.00014	0.94	0.05534	0.00005	422.3	0.9	422.9	0.8	426.0	1.9	0.9

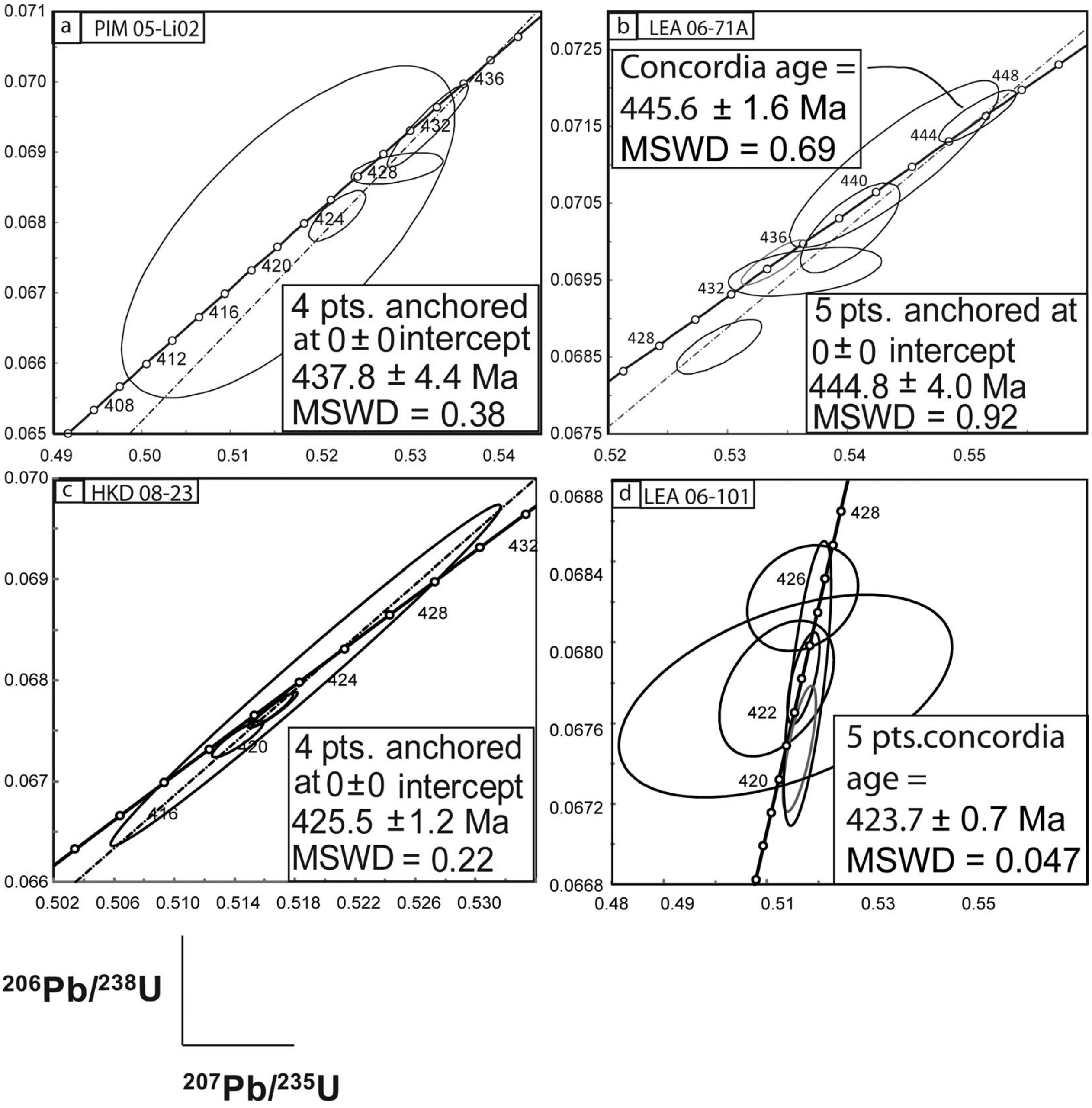

Figure 5. Concordia diagrams: (a, b) Hurry Inlet Composite Pluton; (c) dioritic xenolith of the Triaselv leucogranite; (d) Hodal-Storefjord Pluton. Data point error ellipses are 2 sigma. Decay constant errors are not included. Grey error ellipses of (b) and (d) are not included in the reported age calculations.

Of the four fractions analysed from PIM 05-Li02, one is concordant and the three remaining are less than 3.4 % discordant (Fig. 5a; Table 3). The four analyses of PIM 05-Li02 are collinear and a line anchored at 0 Ma give an upper intercept age of 438 ± 4 Ma (2σ, MSWD = 0.38).

3.b. Hodal-Storefjord Pluton

Sample LEA 06-101 from the Hodal-Storefjord Pluton was collected just north of the NW-trending zone of paragneisses which it intrudes (Fig. 2; Table 3). It is a medium-grained equigranular, plagioclase-rich (*c*. 50 %) diorite, with *c*. 15 % biotite, 10 % orthopyroxene, *c*. 5 % K-feldspar, *c*. 5 % quartz, *c*. 5 % amphibole, *c*. 3 % clinopyroxene, *c*. 2 % opaques and accessory zircon.

The zircon population of this sample is relatively homogeneous, with colourless, prismatic zircon grains dominated by {100} and {101} surfaces. The elongation ratio varies from 2 to 5, and the analysed fractions were generally in the upper range of these values. Most grains contain inclusions and about one third of the grains have smooth sub-rounded terminations. Cores were not observed. U content is low to moderate, varying from 61 to 225 ppm, except for fraction no. 2, with a U content of *c*. 1650 ppm. Th/U ranges between 0.74 and 0.89 (Table 3).

Six data points are clustered together on the concordia curve (Fig. 5d). One analysis (no. 1) is 2.8 %

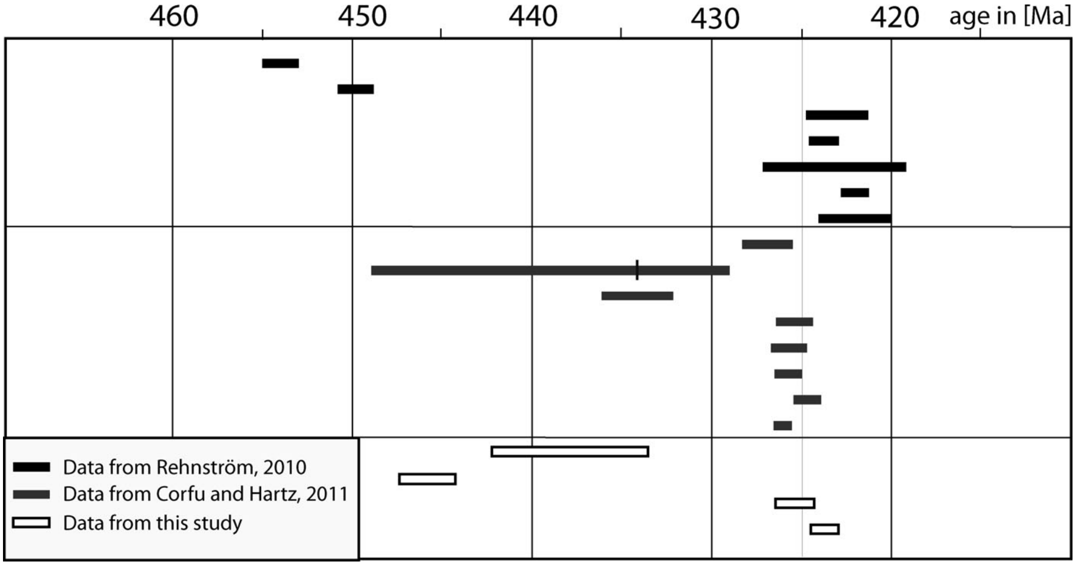

Figure 6. Diagram showing ID-TIMS U–Pb zircon ages from calc-alkaline granitoids in southern East Greenland Caledonides.

discordant and is omitted from the calculation of the concordia age of 423.7 ± 0.7 Ma (2σ, MSWD = 0.047; 5 points).

3.c. Meladioritic xenolith in the Triaselv leucogranite

Sample HKD 08-23 was collected just north of the Triaselv extensional fault (Table 3; Fig. 2), where it occurs as a meladioritic xenolith in the Triaselv leucogranite. As with sample LEA 06-71 of the Hurry Inlet Composite Pluton, this sample also contains relatively homogeneous zircons, with colourless, prismatic zircon grains dominated by {100} and {101} surfaces. Elongation ratios vary from 2 to 5. The analysed grains contain few inclusions, and no cores were observed. The U content is similar to LEA 06-71 from the Hurry Inlet Composite Pluton, varying from 354 to 2200 ppm. Th/U ranges from 0.28 to 0.39 (Table 3).

The four data points for one tip and three multigrain fractions are clustered close to the concordia curve, all analyses are less than 1.1 % discordant and the discordance is attributed to recent Pb loss (Fig. 5c). An upper intercept age including all data points, anchored at 0 Ma, of 425.5 ± 1.2 Ma (2σ, MSWD = 0.22) is interpreted as the crystallization age of the meladiorite (Fig. 5c).

4. Discussion

4.a. Timing and genesis of Ordovician–Silurian intrusives in Liverpool Land

The two intrusive phases of the Hurry Inlet Composite Pluton with ages of 446 ± 2 Ma and 438 ± 4 Ma, the meladioritic xenolith in the Triaselv leucogranite with an age of 426 ± 1 Ma, and the Hodal-Storefjord Pluton with an age of 424 ± 1 Ma, show that the Hurry Inlet Plutonic Terrane underwent repeated intrusions in a period of more than 20 Ma (regardless of whether the oldest phase dated here represents antecrysts from an earlier magmatic pulse or the actual solidification of the studied rock). This pattern confirms the geochronological data of Corfu & Hartz (2011) who obtained ages between *c.* 440 and 425 Ma for different granitoid plutons in Liverpool Land. However, it appears that the earlier intrusive activity was areally more scattered and much less voluminous than the main event at 426–424 Ma (Fig. 6). There are some indications in the zircon data of sample LEA 06-71A and in some of the samples studied by Corfu & Hartz (2011) with a spread of concordant data points, for the existence of a long-lived crystal mush producing multiple injections of magma (e.g. Miller *et al.* 2007). The alkali-calcic to calc-alkalic (Frost *et al.* 2001) nature of the Hurry Inlet Composite Pluton and the Hodal-Storefjord Pluton and their typical calc-alkaline trends in the AFM diagram are probably the result of fractional crystallization of magmas with a mixed crustal and mantle source and/or mixing of different amounts of crustal material with juvenile magmas (Barbarin, 1999). This is supported by the $^{87}Sr/^{86}Sr$ initial ratios of 0.707–0.711 (Fig. 4; Table 2) (Hansen & Friderichsen, 1987).

We interpret the described intrusive rocks from the Hurry Inlet Plutonic Terrane to be continental arc granitoids (Fig. 7). This is based on: (i) the prolonged magmatism with a calc-alkaline trend; (ii) $^{87}Sr/^{86}Sr$ initial ratios between 0.707 and 0.711 from the Hurry Inlet Composite Pluton and Hodal-Storefjord Pluton indicating that the magmas originated from a mixed crustal and juvenile source (Fig. 4); (iii) the magnesian and metaluminous to only slightly peraluminous geochemistry of the analysed rocks; (iv) the abundance of amphibole in most, and of pyroxene in some samples; and (v) the trace element patterns with strongly enriched Ba and Sr concentrations normalized to chondrite values and characteristic Nb-troughs (and also Ti-troughs) (Shand, 1943; Thompson, 1982; McCulloch & Gamble, 1991; Barbarin, 1999;

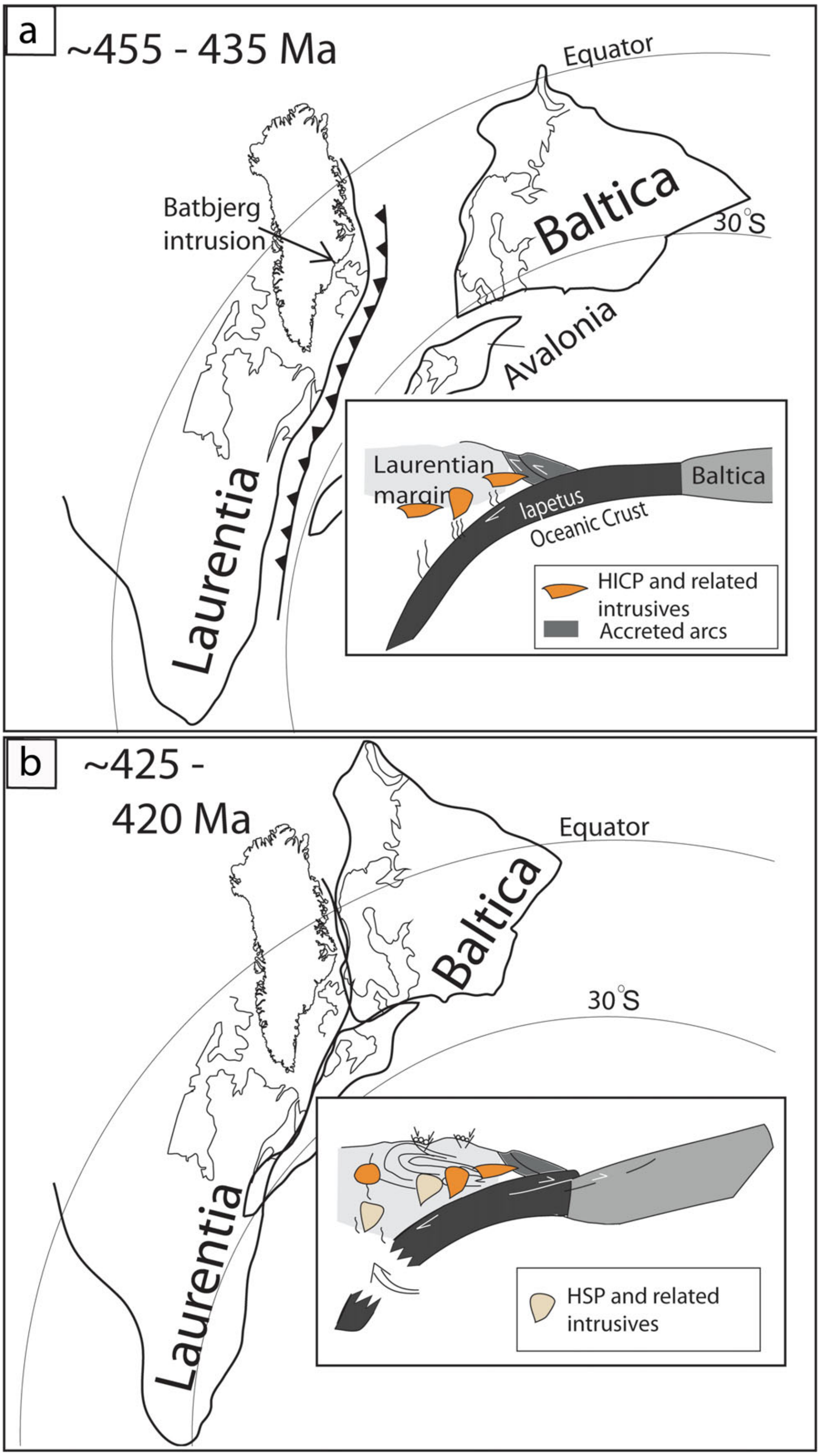

Figure 7. (a) Schematic palaeogeographic map showing the positions of Baltica and Laurentia at *c*. 440 Ma. Inset shows the inferred schematic plate tectonic setting at *c*. 455–435 Ma, during the formation of the Hurry Inlet Composite Pluton (HICP) and related granitoids. (b) Schematic palaeogeographic map showing the positions of Baltica and Laurentia at *c*. 425 Ma. Inset shows the inferred schematic plate tectonic setting at *c*. 425–420 Ma, during formation of the Hodal-Storefjord Pluton (HSP) and related granitoids. Palaeogeographic reconstructions based on Soper *et al*. (1992) and Cocks & Torsvik (2006).

Frost *et al.* 2001; Murphy, 2007). The calk-alkali to dominantly alkali-calcic compositions of the rocks could be due to a position relatively far from the trench at the time of intrusion, as the alkali–lime index in continental arc granitoids is in many cases controlled by the distance from the trench (e.g. Gill, 1981 and references therein).

The presence of the two-amphibole-biotite meladiorite xenolith (426 Ma) with a primitive character (Mg no. = 52; Ni = 202 ppm; Cr = 613 ppm) compared to the Hurry Inlet Composite Pluton, and the mafic enclave in the Hodal-Storefjord Pluton, together with the more metaluminous character of this pluton compared to the Hurry Inlet Composite Pluton, suggest that the late pulses of magmatism (at 425 Ma) in the Hurry Inlet Plutonic Terrane were associated with a more primitive parental magma (Fowler & Henney, 1996; Barbarin, 1999; Frost *et al.* 2001). If the slightly lower $^{87}Sr/^{86}Sr$ initial ratios of the Hodal-Storefjord Pluton than of the Hurry Inlet Composite Pluton are representative of their original magmas, this would also indicate that the later pulses of magmatism had a larger juvenile component than the earlier pulses. The Sr isotopic ratios of the Hodal-Storefjord Pluton are also interpreted to be the result of contamination of a juvenile source, or magma, with crustal material represented by the typical Krummedal Sequence (Fig. 4).

4.b. Coeval intrusive suites in the nappes of East Greenland

The combination of Late Ordovician plutonism, with the concluding 425 Ma magmatic episode seen in Liverpool Land, is also observed in Renland and Milne Land further west (Figs 1, 6) (Kalsbeek *et al.* 2008; Rehnström, 2010), and may be a characteristic feature of the magmatic activity in the southernmost part of the East Greenland Caledonides.

Whole-rock and trace element geochemical data of Middle to Late Ordovician granitoids in Renland and Milne Land also show patterns that are very similar to those found in the Hurry Inlet Composite Pluton and the Hodal-Storefjord Pluton, with typical magmatic arc characteristics (Kalsbeek *et al.* 2008; Rehnström, 2010). Like the Hurry Inlet Composite Pluton, they plot in the high-K field in the K_2O–SiO_2 diagram, in the volcanic-arc granite field of the (Y + Nb) v. Rb discrimination diagram, and display Nb- and Ti-troughs and high Ba values in the chondrite-normalized spider diagram (Kalsbeek *et al.* 2008). The Milne Land granitoids have been interpreted to have a mixed mantle and crustal source based on Sr and Nd isotopes (Kalsbeek *et al.* 2008). The initial $^{87}Sr/^{86}Sr$ isotope signatures recorded in these Ordovician rocks typically range between 0.707 and 0.708, only slightly lower than what is observed in the Hurry Inlet Composite Pluton (Table 2).

The younger ‘I-type’ granitoids (as young as *c.* 420 Ma) from Renland and Milne Land also show an isotopic and chemical trend compatible with a mixed mantle and crustal source (Rehnström, 2010; Kalsbeek *et al.* 2008). These rocks have Sr initial ratios of between 0.707 and 0.715, with most samples at *c.* 0.708, and ε_{Nd} ranging between −3 and −5 for most samples. Geochemically, isotopically and temporally these granitoids are very similar to the Hodal-Storefjord Pluton, and we propose a close correlation between these and the younger magmatic pulses in Liverpool Land.

Ages similar to that of the dioritic xenolith and the Hodal-Storefjord Pluton (*c.* 425 Ma) are common for leucogranites in the southern part of the East Greenland Caledonides. However, the geochemistry and modal composition of the former are distinctly different from those of the typical two-mica leucogranites in East Greenland. The difference also stands out very clearly in the Sr isotopic signature. The $^{87}Sr/^{86}Sr$ ratios reported by Hansen & Friderichsen (1987) for the Hodal-Storefjord Pluton and Hurry Inlet Composite Pluton are considerably lower (0.706–0.709) than the values reported by Kalsbeek, Jepsen & Nutman (2001) for the leucogranites and the Krummedal Sequence which the Hurry Inlet Composite Pluton and Hodal-Storefjord Pluton intrudes. The leucogranites and the metasediments mainly range from 0.72 to 0.74 (Fig. 4) reflecting an origin of the leucogranites by partial melting of the Krummedal metasedimentary rocks (Kalsbeek *et al.* 2008). A further difference is noticed in the abundance of xenocrystic zircons with sparse Caledonian zircon growth in the leucogranites (Watt, Kinny & Friderichsen, 2000; Kalsbeek, Jepsen & Nutman, 2001; Gilotti & McClelland, 2005; Andresen, Rehnström & Holte, 2007), whereas inheritance is much less common or absent in the Hurry Inlet Composite Pluton and Hodal-Storefjord Pluton.

The leucogranites have been interpreted to be the product of post-orogenic collapse (Strachan, Martin & Friderichsen, 2001), but it has also been argued that they are synorogenic resulting from contraction and extension at different levels in the crust (e.g. Andresen, Rehnström & Holte, 2007).

4.c. Connections with Ordovician magmatic suites in the Scandinavian Caledonides

The ages of the Ordovician granitoid rocks in East Greenland overlap those of calc-alkaline granitoids in the Helgeland Nappe Complex of the Uppermost Allochthon of the Scandinavian Caledonides (Nordgulen *et al.* 1993; Yoshinobu *et al.* 2002; Meyer, Grenne & Pedersen, 2003; Tucker *et al.* 2004; Barnes *et al.* 2007). The latter granitoids are thought to have formed in a Laurentian island arc (ensimatic) setting (Stephens & Gee, 1985; Grenne, Ihlen & Vokes, 1999; Roberts, Melezhik & Heldal, 2002; Yoshinobu *et al.* 2002; Barnes *et al.* 2007; Roberts, Nordgulen & Melezhik, 2007), linked to subduction of Iapetus oceanic crust beneath Laurentia. They are further considered to represent the northern continuation of magmatic arcs preserved in the Irish and Scottish Caledonides and the Appalachians (Van Staal *et al.* 1998, 2009; Friedrich *et al.* 1999*a, b*; Armstrong & Owen, 2001; Barnes *et al.* 2007; Oliver, Wilde & Wan, 2008). Similarly aged magmatic complexes in the Upper Allochthon in Scandinavia are also attributed to ensimatic magmatism above a W-dipping subduction zone close to the Laurentian margin at the latest stages of Iapetus ocean closure (Grenne & Roberts, 1998; Grenne, Ihlen & Vokes 1999; Meyer, Grenne & Pederesen, 2003). As emphasized by Grenne, Ihlen & Vokes (1999), Baltica was rotating rapidly in an anticlockwise manner at the Ordovician–Silurian boundary (Torsvik *et al.* 1996; Torsvik, 1997), and this could have led to different regimes of contraction and extension parallel to the orogen, resulting in widespread magmatism of variable character (i.e. from extension-related back-arc rifting to convergent margin arc magmas), with certain diachroneities of magmatism along the orogen (e.g. Tucker, Boyd & Barnes, 1990; Pedersen, Furnes & Dunning, 1991; Youshinobu *et al.* 2002; Meyer, Grenne & Pederesen, 2003; Corfu *et al.* 2006; Barnes *et al.* 2007; Nilsen, Corfu & Roberts, 2007).

4.d. Connections with the Newer Granites in the Scottish Caledonides: magma generation at *c.* 425 Ma related to slab break-off

In terms of geochemistry, isotope signature and age, the younger ‘I-type’ granitoids from the Hurry Inlet Composite Pluton and Hodal-Storefjord Pluton show many similarities with the ‘Newer Granites’ of the Scottish Caledonides (e.g. Rogers & Dunning, 1991; Strachan *et al.* 2002), and a correlation between them as part of a common magmatic arc system is viable (Kalsbeek *et al.* 2008; Oliver, Wilde & Wan, 2008; Steinhofel, Hegner & Oliver, 2008). This 425 Ma phase of magmatism was temporally linked to the terminal phases of Iapetus closure and oceanic crust-subduction underneath northeastern Laurentia (East Greenland). It was the most voluminous pulse of magmatism recorded in Liverpool Land, and in Renland and Milne Land and it lasted less than 5 Ma. (Fig. 6; this study; Kalsbeek *et al.* 2008; Rehnström, 2010; Corfu & Hartz, 2011). The brevity and voluminous nature of the magmatic event is consistent with a model of slab break-off (Fig. 7b; Atherton & Ghani, 2002; Whalen *et al.* 2006; Van Staal *et al.* 2009). Slab break-off would have led to extra heat flow into the lower crust of the upper plate and thus could have provided a heat source for the melting of the Krummedal Sequence and the generation of two-mica granites (Kalsbeek, Jepsen & Nutman, 2001; Kalsbeek, Jepsen & Jones, 2001; Andresen, Rehnström & Holte, 2007; Rehnström, 2010).

4.e. Links to Caledonian intrusives in the autochthon of East Greenland

A possible subduction-related Caledonian intrusive complex in the Kangerdlugssuaq area, some 400 km southwest of Liverpool Land, may provide an important link between the allochthonous magmatic arc rocks in East Greenland described above and those further south and southwest (present-day Scotland, Ireland and eastern North America). The Batbjerg intrusion is a partly deformed ultrapotassic layered intrusion dated by K–Ar geochronology to *c.* 440 Ma (Brooks, Fawcett & Gittens, 1976; Brooks *et al.* 1981). An initial $^{87}Sr/^{86}Sr$ ratio was calculated to 0.705 (Brooks, Fawcett & Gittens, 1976). The Batbjerg pluton is intruding basement gneisses thought to be of autochthonous nature and contains screens of Palaeozoic metasedimentary rocks with crinoid fragments (Brooks, Fawcett & Gittens, 1976; Brooks *et al.* 1981). Furthermore the gneisses surrounding the Batbjerg intrusion are intruded by numerous volcanic dykes and sheets of appinitic character that are probably related to the intrusive complex itself (Brooks, Fawcett & Gittens, 1976; Brooks *et al.* 1981).

Intrusive rocks similar to the Batbjerg ultrapotassic complex are present in the Assynt culmination of the Moine Thrust Belt in the Scottish Caledonides. There, alkaline to calc-alkaline intrusive rocks (including pyroxenite to quartz syenites) intrude the (par)autochthonous Archaean basement with its sedimentary cover (Halliday *et al.* 1987; Goodenough, Young & Parsons, 2004; Styles, Gunn & Rollin, 2004). Especially the *c.* 430 Ma ultrapotassic Loch Borrelan intrusion (Van Breemen *et al.* 1979; Halliday *et al.* 1987) shares several characteristics with the Batbjerg intrusion, and a correlation of the two could be justified. Based on the structural setting and their compositions, Goodenough, Young & Parsons (2004) suggested that these intrusive rocks formed in an ensialic setting in the continental margin of Laurentia, both prior to and in the initial stage of the Scandian phase of the Caledonian orogeny (Halliday *et al.* 1987).

4.f. Ordovician–Silurian evolution of the northeastern Laurentian margin

The East Greenland Caledonides show little or no evidence of the early Taconian (Grampian, > 460 Ma) contractional events and island arc magmatism present in the North American Appalachians and in the British Caledonides (e.g. Friedrich *et al.* 1999*a, b*; Kinny *et al.* 1999; Van Staal *et al.* 1999, 2009), respectively. The one exception is an age of 466 ± 9 Ma reported by Kalsbeek *et al.* (2008) for a granodiorite from Milne Land, but that age was interpolated from scattered SHRIMP U–Pb analyses with an obvious component of inheritance. It is thus imprecise and not very reliable. It also conflicts with the occurrence of platform carbonates as young as *c.* 460 Ma in the allochthon of the Central East Greenland Caledonides (Smith & Rasmussen, 2008). These platform carbonates make it seem unlikely that active margin magmatism was initiated prior to the end of passive margin sedimentation, supporting the inference that this part of the East Greenland Caledonides was not affected by an early Taconic (Grampian) orogenic phase. However, the data of Kalsbeek *et al.* (2008) clearly showed the existence of

Caledonian granitoids older than the common 425 Ma leucogranites. A more reliable age for the same rock as the one dated to 466 ± 9 Ma by Kalsbeek *et al.* (2008) of *c.* 454 Ma was obtained by Rhenström (2010). This age shows that arc magmatism in East Greenland was synchronous with crystallization of the first arc magmas in what is now the Uppermost Allochthon of the Scandinavian allochthon (Yoshinobu *et al.* 2002). This relatively late initiation of arc magmatism in the East Greenland and Helgeland nappes is consistent with the suggestion that arc magmatism migrated northwards with time (Van Staal *et al.* 1998, 2009). A plausible hypothesis is that the initiation of arc magmatism in the *continental* margin, in the areas of East Greenland described here, was synchronous with amalgamation to the Laurentian continent of island arcs (or peri-Laurentian terranes) now preserved in the Uppermost and possibly Upper Allochthons of Scandinavia (Fig. 7a) (Stephens & Gee, 1985; Yoshinobu *et al.* 2002; Meyer, Grenne & Pedersen, 2003; Barnes *et al.* 2007). According to Yoshinobu *et al.* (2002) there could have been a switch in the subduction polarity from eastward to westward subduction (in present-day coordinates) as the outboard island arcs 'arrived' at the Laurentian margin. A similar mechanism has been proposed by Van Staal *et al.* (2009) for the late Taconian stage in the Appalachians. Such a subduction scenario would explain why arc magmatism was not initiated in East Greenland until after 460 Ma.

Such a switch in subduction polarity would also explain the protracted arc magmatism that lasted to *c.* 425 Ma in the East Greenland nappes, the northern Appalachians, the British Caledonides and the Helgeland Nappe (Fig 7b). The terranes in the latter would have been amalgamated to the periphery of Laurentia, experiencing the last pulse of subduction-related (possibly slab break-off-related) magmatism together with the true *continental* Laurentian margin before being thrust upon the Baltic Plate during the Scandian continent–continent collision. At present only a few granitoids have been dated to around 425 Ma in the Uppermost Allochthon (Barnes *et al.* 2007). However, it remains uncertain whether the scarcity of this age group is due to the relatively small number of samples dated from the total volume of intrusive rocks in the Uppermost Allochthon or whether it is a real feature that could indicate that *c.* 425 Ma magmatism occurred mostly further inland towards the Laurentian foreland. In the British Isles and in the Appalachians, arc magmatism continued into Early Devonian time due to the later arrival of Avalonia to Laurentia (e.g. Oliver, Wilde & Wan, 2008; Van Staal *et al.* 2009).

The analogies and sequence of events proposed here help to reconstruct the northeastern Iapetus palaeogeography supporting a position of the Uppermost Allochthon of the Scandinavian Caledonides close to the southern part of today's exposed allochthonous East Greenland Caledonides prior to continent–continent collision between Baltica and Laurentia.

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