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PERI-GONDWANAN ELEMENTS IN THE CALEDONIAN NAPPES OF FINNMARK, NORTHERN NORWAY: IMPLICATIONS FOR THE PALEOGEOGRAPHIC FRAMEWORK OF THE SCANDINAVIAN CALEDONIDES

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ABSTRACT. The Kalak Nappe Complex in the northern Scandinavian Caledonides has historically been interpreted as representing the pre-Caledonian margin of Baltica consisting of a Precambrian basement and a late Precambrian to Cambrian cover, which were deformed and intruded by a Late Precambrian alkalic mafic complex during the Cambrian Finnmarkian orogeny. New evidence, however, does not fit the above interpretations very well, but instead shows that the sedimentary rocks were deposited at least in part prior to about 1000 Ma and that the complex underwent repeated tectonism and granitic magmatism prior to the emplacement of the gabbroic / alkalic complex at 570 to 560 Ma. This paper presents new U-Pb data documenting distinct episodes of orogenic activity marked by the emplacement of syn-tectonic anatectic melts and in part by anatexis at about 850 Ma and 700 to 680 Ma. Another event at 600 Ma is seen in the basal unit of the overlying Vaddas Nappe. The timing of this activity is entirely atypical for the autochthonous northern segments of the Baltic Shield, which were formed in the Archean and modified in the Palaeoproterozoic. It appears much more likely that the Kalak Nappe Complex is an exotic terrane that developed outside of Baltica, probably in the pre-Gondwanan realm or the southern Iapetus, and was then translated towards, and accreted, to Baltica during the Scandian collisional phase. In view of our present understanding the various terms previously used to designate orogenic phases (Finnmarkian, Sørøyan, Porsanger) are no longer relevant or sufficient for describing the complex geological evolution of the region and we propose to terminate their use.

INTRODUCTION

The classical model for the evolution of the Scandinavian Caledonides begins with the rifting of Baltica from Laurentia at the end of the Neoproterozoic and formation of the intervening Iapetus Ocean, and ends with the eventual collision and re-amalgamation of the two blocks. The Caledonian nappe succession was constructed on the Precambrian Shield by thrusting of terranes derived from the margin of Baltica, and from outboard oceanic domains placing exotic nappes of Laurentian origin at the top of the nappe pile (Gee, 1975; Stephens and Gee, 1989). This concept provides a useful tectonic framework that can explain many of the geological features of the orogen but, like all such models, it must be tested and amended as it is developed and refined.

One of the features of the model that we deal with in this paper is the origin and development of the Kalak Nappe Complex in northern Norway. In the standard interpretation, the Kalak Nappe Complex was viewed as a stack of basement slices derived from the margin of the Baltoscandian platform, each slice carrying Late

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Precambrian to Early Paleozoic cover (Ramsay and others, 1985a). It was originally thought to have formed in the Upper Cambrian to Early Ordovician during a period of thrusting and deformation accompanying multistage emplacement of a gabbroic to alkalic plutonic suite [the 'Finnmarkian' phase of the Caledonian orogeny; Sturt and others (1978)]. This understanding had evolved mainly through mapping supported by only limited paleontological and geochronological data (Sturt and others, 1975, 1978; Ramsay and others, 1985a). Geological and isotopic studies in the subsequent decades suggested that the original concept needed to be modified. Unfortunately, not all the new ages (mostly Rb-Sr and Sm-Nd whole-rock dates) were correct (see references and discussion in Roberts and others, 2006), obscuring rather than clarifying the picture. One of the most important insights to emerge from this second wave of studies was the realization that parts of the Kalak Nappe Complex were the product of Neoproterozoic orogenic events, leading to the introduction of a new term, the Porsanger Orogeny, for the events at $\geq$ 800 Ma (Daly and others, 1991). One major problem concerned the genesis of the Seiland Igneous Complex, which according to some dates had been emplaced over some 300 m.y. New data (Roberts and others, 2006) have now rectified this part of the picture by demonstrating, using zircon U-Pb, that the bulk of the complex intruded over a much shorter period of about 10 m.y. at 570 to 560 Ma, with only minor activity related to the emplacement of nepheline syenite pegmatites some 30 to 40 m.y. later (Pedersen and others, 1989).

The next set of questions concerned the timing of development of the diverse packages and the structural features in the various nappes, since some of the new data clearly demonstrated that the tectonic evolution had been more complex than originally thought. Some of these questions are addressed in the present study. The results support the occurrence of the early orogenic event at 900 to 800 Ma (Porsanger) proposed by Daly and others (1991), but also show a more complex scenario by revealing additional events of anatexis and granitic magmatism, at least in part linked to deformation, at about 700 and at 600 Ma. In conjunction with other data our results give us a glimpse into an evolution that is very unlike the evolution of the Baltic Shield and we subsequently discuss the resulting paleogeographic implications.

GEOLOGICAL SETTING

The Scandinavian Caledonides have been subdivided into a number of major north-south trending tectonic elements (fig. 1). (1) Autochthonous basement composed of Archean crust in the north, Paleoproterozoic crust in central parts, and Meso- to Neoproterozoic crust in the south, all covered by Neoproterozoic to Early Paleozoic sedimentary rocks. (2) Lower Allochthon consisting of variably reworked, parautochtonous to allochthonous counterparts of the basement outcropping along the western margin of, and in culminations below, the Caledonian chain, plus transposed and folded Late Neoproterozoic to Early Paleozoic metasedimentary cover. (3) Middle Allochthon with allochthonous slices of Precambrian crystalline rocks and unfossiliferous psammites, locally cut by mafic intrusive rocks. (4) Upper Allochthon consisting of high-grade metamorphosed supracrustal rocks (Seve nappes) and overlying, generally greenschist facies, Paleozoic volcano sedimentary rocks and local plutons (Köli nappes). (5) Uppermost Allochthon containing a mixture of gneissic, sedimentary and Paleozoic plutonic rocks. (6) Local basins with late to post-orogenic clastic, Molasse-type deposits (Roberts and Gee, 1985). (7) The Barents Sea Terrane, a Neoproterozoic regressive succession of deep- to shallow-marine sedimentary rocks delimited by the long-lived Trollfjord-Komagelv Fault (Roberts, 1985). In the Scandian phase of the Caledonian orogeny at about 425 to 400 Ma the Caledonian nappes were thrust from the west onto the Precambrian Shield as a consequence of the collision between Baltica and Laurentia. They are thought to be of diverse derivation, the Lower and Middle Allochthon representing the margin of Pre-Caledonian Baltica, the Upper Allochthon

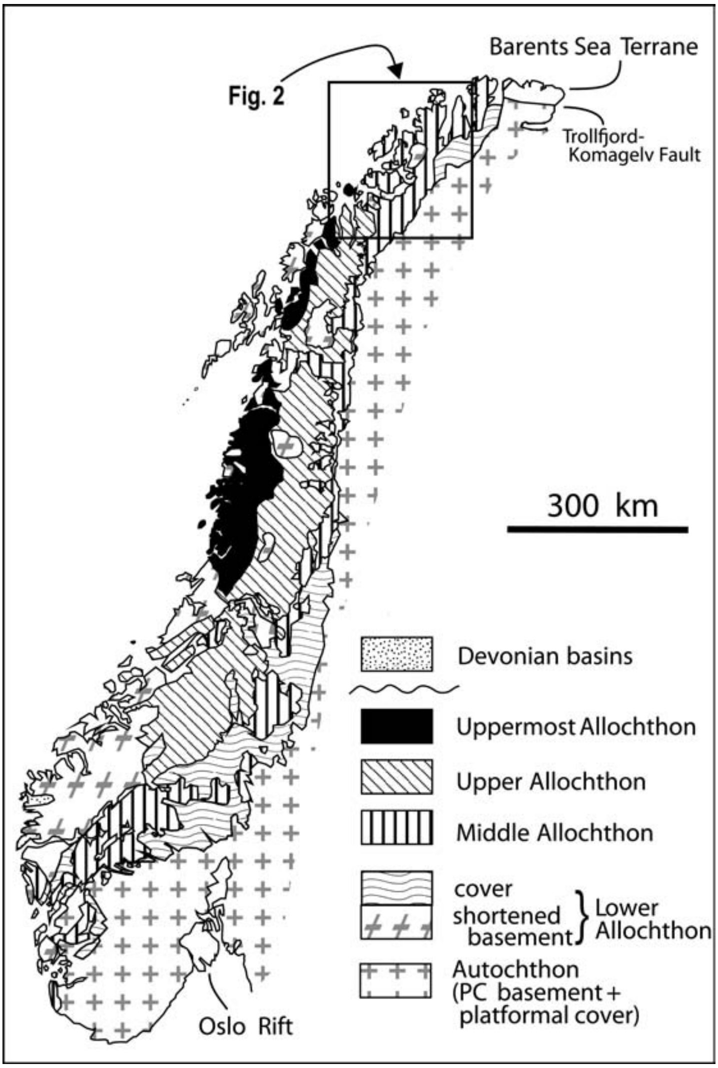

Fig. 1. Tectonic map of the Scandinavian Caledonides (after Gee and others, 1985).

representing the outermost margin of Baltica (Seve) and outboard terranes (Köli), and the Uppermost Allochthon representing exotic, probably Laurentian terranes (Stephens and Gee, 1989).

All of these major tectonic elements can be traced into the Caledonides of Finnmark in northern Norway (figs. 1 and 2A). The western part of this region is dominated by the sedimentary-plutonic Kalak Nappe Complex that tectonically overlies the sedimentary Laksefjord and Gaissa nappes farther east, themselves thrust onto the Neoproterozoic to Cambrian autochthonous cover of the Baltic basement. Basement and cover are also exposed in the Alta and the Komagfjord windows, interpreted to represent parautochtonous basement horses (Chapman and others, 1985; Gayer and others, 1987).

The Kalak Nappe Complex has been assigned to the Middle Allochthon in the compilation of Gee and others (1985) but an alternative correlation with the Seve

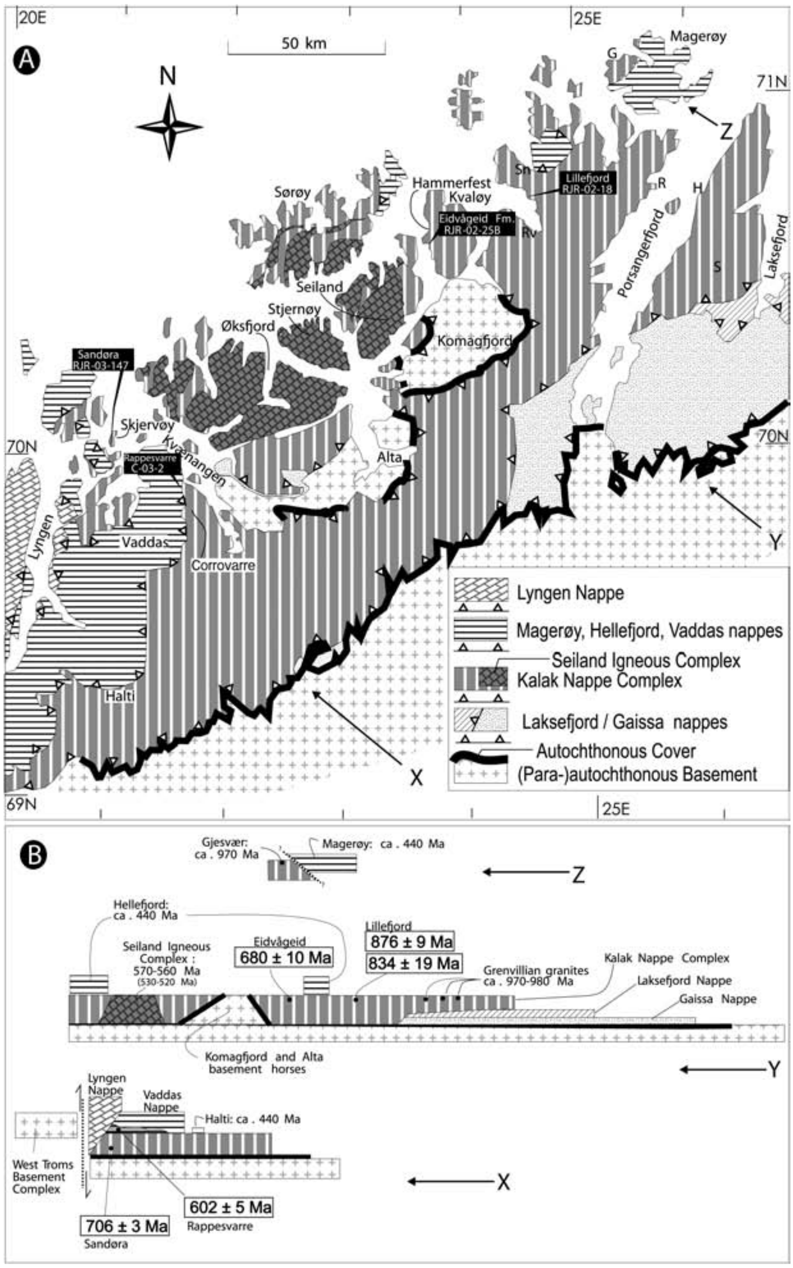

Fig. 2. (A) Simplified geological map of western Finnmark showing the distribution of the main geological elements and the sample locations. Abbreviations refer to intrusive rocks dated by Kirkland and others (2006) and referred to in the text: H = Hårvika, S = Siedogaivi, R = Repvåg, Rv = Revsneshamn, Sn = Snøfjord. (B) Very simplified cross-sections illustrating the main relationships of the various tectonic elements of the region and context of the dated samples (drawn very liberally after Chapman and others (1985) and Gayer and others (1987). The ages in the boxes are from this study. The others are from Pedersen and others (1989), Andréasson and other (2003), Kirkland and others (2006), Corfu and others (2006), Gerber (ms, 2006), and Roberts and others (2006, and unpublished data).

nappes of the Upper Allochthon has also been advocated; this is the Seve-Kalak Superterrane of Andréasson and others (1998). The Kalak Nappe Complex is itself overlain by the Magerøy and Vaddas nappes that are tectonically equivalent to the Køli nappes of the Upper Allochthon. The Uppermost Allochthon, in the form of the Lyngen Ophiolite, is only exposed in the westernmost parts of the map (figs. 2A and 2B). Metamorphic grade did not exceed the subgreenschist to greenschist facies in the Autochthon, the Laksefjord and Gaissa nappes, and the sedimentary cover of the Alta and Komagfjord windows, but it is generally in amphibolite facies, with a range from upper greenschist to locally granulite facies in the Kalak Nappe Complex and Magerøy nappes (Roberts, 1985).

The Kalak Nappe Complex is composed of nappes that typically include: (1) a crystalline basement unit, overlain by (2) a mixed paragneiss sequence, commonly with migmatitic pelites and amphibolites, (Eidvågeid Sequence), (3) a sedimentary succession of psammites (Klubben Formation), (4) muscovite-schists and psammites (Storelv Formation and locally Kokelv Formation), (5) marbles and calc-silicates (Falkenes Formation), (6) graphitic schists, calc-silicate and psammite (Åfjord Formation) (Roberts, 1974; Ramsay and others, 1985a). Another unit of pelitic schists and psammites [Hellefjord Formation, Roberts (1968)] has commonly been placed at the top of the Kalak Nappe Complex, but we now know that it is instead an unrelated Silurian assemblage (Kirkland and others, 2005; Gerber, ms, 2006). The Klubben Formation psammites are the dominant geological element of the region, whereas the other formations are not very widespread and locally missing in the stratigraphic record. There is also not always full agreement on the assignment of local rock units to specific formations. The original stratigraphy was erected based on the belief that the sedimentary rocks were largely Vendian to Cambrian, based on flawed paleontological evidence and, in part, ambiguous isotopic data. As it will be discussed below, we know now that the Eidvågeid Sequence and Klubben Formation are Precambrian sedimentary sequences, deposited before 980 Ma (Corfu and others, 2005; Kirkland and others, 2006), the marbles of the Falkenes Formation were apparently deposited between 760 and 710 Ma (Slagstad and others, 2006), and the Hellefjord Formation is Early Silurian (Kirkland and others, 2005; Gerber, ms, 2006). Uncertainties remain concerning the age of other sedimentary components of the stratigraphic package. There is also still uncertainty on the tectonic subdivision in discrete nappes, as detailed descriptions are only available for parts of the complex (Ramsay and others, 1985a, 1985b; Gayer and others, 1985; Zwaan, 1988; Binns, 1989; Lindahl and others, 2005). For these reasons, the map in figure 2A only gives the general outline of the main geological units without attempting to present more detailed nappe subdivisions.

Plutonic rocks are an important element of the regional geology. The Seiland Igneous Complex covers an area of some 7000 km^2 and consists of numerous gabbroic plutons together with ultramafic complexes, syenites, monzonites, diorites, granites, alkaline rocks (syenite and nepheline syenite), carbonatites and mafic dikes (Robins and Gardner, 1975). Uranium-lead geochronology shows that the Seiland Igneous Complex intruded mainly between 570 and 560 Ma (Roberts and others, 2006, and unpublished data) with minor activity at 530 to 520 Ma (Pedersen and others, 1989). Away from the Seiland Igneous Complex the nappes carry local granitic plutons and mafic dikes, generally metamorphosed and deformed. One of these plutons, the Lillefjord granite gneiss, had yielded an intriguing U-Pb zircon age of $\geq$800 Ma (Daly and others, 1991). More recent work on other plutons provides ages of 980 to 970 Ma for three granitic units in the lower thrust sheets in eastern parts of the Kalak Nappe Complex, 840 to 820 Ma for the Lillefjord granite and two related intrusions, and 709 Ma for leucosome in the Eidvågeid Sequence (Kirkland and others, 2006). Grenvillian ages for granite gneiss and leucosome have also been recorded in the basement underlying the Magerøy Nappe (Corfu and others, 2005; Gerber, ms, 2006).

The Kalak Nappe Complex has undergone a multistage deformation history and up to five distinct deformation phases have been recorded locally (for example, Gayer and others, 1985) but two phases are generally dominant (Ramsay and others, 1985a). The most important D2 deformation phase is manifested in recumbent folds, stratigraphic inversion, and regional foliation, and was coeval with the apex of metamorphism. The subsequent D3 deformation was associated with lower grade metamorphism (greenschist facies at most) and formed upright symmetrical to conjugate folds and a local crenulation cleavage. The intrusive rocks of the Seiland Igneous Complex are variably deformed and the relationships between intrusive and deformation phases have originally been used to define the Finnmarkian phase of the Caledonian orogeny (Sturt and others, 1978). At present, however, there is a debate as to whether the complex was emplaced in a contractional regime or whether much of the observed deformation was caused by the superimposed Scandian event (for example, Krill and Zwaan, 1987; Binns, 1989; Roberts and others, 2006). A general problem in the region is that structural elements originally correlated across the region are now known to have formed during different orogenic events. For example, Precambrian fabrics in Klubben psammites have previously been linked to structures in the Silurian Hellefjord Formation (Ramsay and others, 1985a)

This study is concentrated on rocks from four different sites (figs. 2A and 2B). The first site considered is within the Rappesvarre granite gneiss in the Vaddas Nappe. The nappe comprises two parts: a lower stratigraphic succession that is lithologically similar to parts of the Kalak Nappe Complex, and an upper succession similar in terms of lithology and age (Early Silurian) to the Magerøy Nappe. The interface between the upper and lower parts of the nappe has been interpreted to be an unconformity (Ramsay and others, 1985a). In this study we test whether the rocks below the interface could indeed be related to the Kalak Nappe Complex. The other samples represent the Kalak Nappe Complex: one is the Sandøra granitic gneiss, which intrudes Kalak Nappe Complex psammite on the island of Skjervøy, the second represents felsic leucosome in migmatites of the Eidvågeid Sequence, and the third and fourth samples represent the Lillefjord granitic gneiss and a felsic dikelet near the same pluton.

U-Pb ANALYTICAL PROCEDURE

All the minerals analyzed in the study were separated from crushed samples by standard enrichment techniques and selected under a binocular microscope. All were abraded before analysis (Krogh, 1982) unless otherwise stated in table 1. The analyses were carried out by ID-TIMS following updated versions of the Krogh (1973) technique. Details are elaborated in Corfu (2004) and references therein. Decay constants are those of Jaffey and others (1971). All the uncertainties in the tables, figures and text represent 2σ. Plotting and age regressions were done with ISOPLOT (Ludwig, 2003).

RAPPESVARRE GRANITIC GNEISS

Geological Setting

The Rappesvarre (or Rahpesvárri) granitic gneiss occurs as a complex of sills and sheets in psammites near the base of the Vaddas Nappe in the Kvænangen-Vaddas area (fig. 2A; Vogt, 1927; Pearson, 1971; Lindahl and others, 2005). The Vaddas Nappe is composed of psammites, quartzites, conglomerates, schists, marbles, metagraywackes, metabasalts, and large mafic-ultramafic plutons and local migmatites, and has been at the center of much controversy. It was originally considered as a member of the Kalak

TABLE 1

U-Pb data for intrusive rocks

Characteristics*	Weight[†,§] [mg]	U[†,§] [ppm]	Th/U[‡]	Pbc[§] [pg]	$^{206}Pb/^{204}Pb$[¤]	$^{207}Pb/^{235}U$[¶]	± 2σ [abs]	$^{206}Pb/^{238}U$[¶]	± 2σ [abs]	rho	$^{207}Pb/^{206}Pb$[¶]	± 2σ [abs]	$^{206}Pb/^{238}U$[¶]	$^{207}Pb/^{235}U$[¶]	$^{207}Pb/^{206}Pb$[¶]	± 2σ [abs]	D[^] [%]
C-03-2, Rappesvarre granitic gneiss, Vaddas nappe, Gildetun, Kvænangen peninsula 69°53´04´´ / 21°35´50´´																	
Z eu lp fr [43]	ca.17	ca.110	0.42	79	180	1.0048	0.0161	0.11239	0.00036	0.17	0.06485	0.00103	686.6	706.3	769	33	11.3
Z eu sp [27]	ca.25	ca.380	0.43	6.0	9887	0.8390	0.0022	0.10000	0.00025	0.93	0.06085	0.00006	614.4	618.6	634.0	2.1	3.2
Z eu sp [1]	<1	>600	0.39	1.1	3462	0.8255	0.0052	0.09925	0.00057	0.91	0.06032	0.00016	610.0	611.1	615.1	5.7	0.9
Z eu sp (in) [1]	<1	>200	1.26	1.3	976	0.8280	0.0079	0.09913	0.00060	0.61	0.06058	0.00046	609.3	612.5	624	16	2.5
Z eu lp fr [10]	2	46	0.50	2.5	187	0.8011	0.0251	0.09792	0.00049	0.47	0.05934	0.00174	602.2	597.5	580	62	-4.1
Z eu sp in [1]	2	311	0.93	4.1	963	0.8278	0.0057	0.10030	0.00044	0.73	0.05985	0.00028	616.2	612.4	598	10	-3.1
RJR-02-147A, Sandøra granitic gneiss, Skjervøy 70°00´29´´ / 20°55´39´´																	
Z eu tips [15]	2	3102	0.00	2.2	20028	0.9934	0.0037	0.11461	0.00042	0.97	0.06286	0.00006	699.5	700.4	703.6	2.1	0.6
Z eu tips (cr in) [15]	3	3239	0.00	2.5	27887	0.9850	0.0031	0.11379	0.00035	0.93	0.06278	0.00007	694.7	696.2	700.9	2.4	0.9
Z eu tips (in) [27]	18	1939	0.00	4.5	55625	0.9810	0.0024	0.11347	0.00025	0.97	0.06270	0.00004	692.9	694.1	698.1	1.4	0.8
RJR-02-25B, garnetiferous leucosome, Eidvågeid sequence, Akkarfjord-Hammerfest 70°37´25´´ / 23°39´27´´																	
Z eu sp [1]	4	908	0.01	1.5	19478	1.1654	0.0049	0.12773	0.00056	0.83	0.06617	0.00017	774.9	784.5	811.8	5.3	4.8
Z sb eq [1]	1	1345	0.01	1.2	8211	0.9741	0.0045	0.11217	0.00049	0.91	0.06299	0.00012	685.3	690.6	707.8	4.0	3.3
Z sb eq [1]	1	1431	0.00	1.2	8351	0.9603	0.0039	0.11184	0.00046	0.90	0.06227	0.00011	683.4	683.5	683.5	3.9	0.0
Z sb eq [1]	2	1402	0.00	1.5	13275	0.9577	0.0050	0.11089	0.00058	0.98	0.06264	0.00007	677.9	682.1	695.9	2.4	2.7
Z sb tip [1]	1	464	0.02	0.7	4744	0.9459	0.0043	0.11045	0.00045	0.87	0.06211	0.00014	675.4	676.0	678.0	4.8	0.4
M sb flat NA [1]	<1	>7900	1.70	3.7	17154	1.1381	0.0030	0.12738	0.00032	0.93	0.06480	0.00007	772.9	771.6	767.9	2.1	-0.7
M sb [1]	<1	>8300	2.91	1.9	33509	1.0990	0.0032	0.12362	0.00035	0.94	0.06448	0.00007	751.4	752.9	757.4	2.1	0.8
M sb fr NA [1]	1	22608	2.75	11	15315	0.9974	0.0027	0.11513	0.00030	0.95	0.06283	0.00005	702.5	702.5	702.6	1.8	0.0
M fr [1]	2	38986	2.93	102	5371	0.9605	0.0029	0.11149	0.00031	0.96	0.06248	0.00006	681.4	683.5	690.6	1.9	1.4
RJR-02-18AA, Lillefjord granitic gneiss 70°43´20´´ / 24°31´39´´																	
Z eu flat [5]	1	782	0.21	0.4	15771	1.3555	0.0039	0.14334	0.00034	0.88	0.06859	0.00010	863.5	869.9	886.4	2.9	2.8
Z eu flat [1]	2	973	0.10	10	1748	1.3214	0.0037	0.14153	0.00029	0.81	0.06771	0.00011	853.3	855.1	859.8	3.4	0.8
Z eu flat [3]	2	3567	0.16	1.6	28893	1.3073	0.0032	0.14041	0.00030	0.95	0.06753	0.00005	847.0	849.0	854.2	1.6	0.9
Z eu flat [1]	5	587	0.09	1.8	13941	1.2741	0.0034	0.13776	0.00036	0.88	0.06708	0.00009	832.0	834.2	840.1	2.7	1.0
Z eu lp [5]	4	759	0.07	1.3	20824	1.2644	0.0040	0.13701	0.00037	0.91	0.06693	0.00009	827.8	829.9	835.6	2.8	1.0
X eu eq NA [1]	1	43121	0.35	2.7	121474	1.1128	0.0044	0.12354	0.00047	0.98	0.06533	0.00005	750.9	759.5	785.0	1.5	4.6
X eu eq [1]	1	64206	0.36	2.4	197645	1.0687	0.0026	0.11955	0.00026	0.97	0.06483	0.00004	728.0	738.1	768.9	1.3	5.6
M an flat [1]	3	4821	13.82	3.4	35349	1.2098	0.0031	0.13334	0.00031	0.96	0.06580	0.00005	806.9	805.1	800.1	1.4	-0.9
M an flat [1]	2	5146	14.22	6.8	12171	1.1411	0.0031	0.12758	0.00032	0.95	0.06487	0.00005	774.0	773.0	770.1	1.7	-0.5
M an flat [1]	1	19948	13.09	7.5	19706	1.0235	0.0026	0.11789	0.00027	0.96	0.06297	0.00004	718.4	715.7	707.1	1.4	-1.7

TABLE 1

(continued)

Characteristics*	Weight†,§ [mg]	U†,§ [ppm]	Th/U‡	Pbc§ [pg]	^{206}Pb/^{204}Pb¤	^{207}Pb/^{235}U¶	± 2σ [abs]	^{206}Pb/^{238}U¶	± 2σ [abs]	rho	^{207}Pb/^{206}Pb¶	± 2σ [abs]	^{206}Pb/^{238}U¶	^{207}Pb/^{235}U¶	^{207}Pb/^{206}Pb¶	± 2σ [abs]	D^ [%]
RJR-02-18D, granitic dikelet near Lillefjord pluton 70 °43´33´´ / 24°31´16´´																	
Z eu tip b [1]	2	4260	0.00	1.4	50622	1.1923	0.0032	0.13131	0.00033	0.96	0.06585	0.00005	795.3	797.0	801.7	1.6	0.8
Z eu tip b [1]	1	9888	0.00	2.4	32797	1.1574	0.0042	0.12842	0.00044	0.98	0.06536	0.00005	778.8	780.7	786.1	1.5	1.0
Z eu tip b [1]	1	4964	0.00	2.5	14869	1.0695	0.0047	0.12105	0.00052	0.98	0.06408	0.00006	736.6	738.5	744.1	2.0	1.1
Z eu tip b [1]	15	3966	0.00	351	1287	1.0535	0.0036	0.11942	0.00027	0.76	0.06398	0.00014	727.2	730.6	741.0	4.7	2.0
M an eq [1]	17	3659	2.44	4.7	114396	1.2635	0.0031	0.13781	0.00031	0.97	0.06649	0.00004	832.3	829.5	822.0	1.3	-1.3
M an eq[1]	5	6752	1.84	3.9	73177	1.2028	0.0061	0.13570	0.00062	0.97	0.06428	0.00009	820.3	801.9	750.9	2.8	-9.8
M an eq [1]	6	12676	2.02	4.6	131952	1.1182	0.0028	0.12616	0.00029	0.97	0.06428	0.00004	765.9	762.1	750.9	1.3	-2.1
M an eq [1]	15	3587	2.90	3.5	119662	1.0782	0.0028	0.12270	0.00028	0.97	0.06373	0.00004	746.1	742.7	732.7	1.4	-1.9
T fr pb [11]	64	22	0.09	63	112	0.4973	0.0176	0.06750	0.00039	0.23	0.05344	0.00185	421.1	409.9	347	76	-22

*) Z = zircon; X = xenotime; M = monazite; T = titanite; eu = euhedral; sb = subhedral; an = anhedral; eq = equant; sp = short prismatic (l/w = 2–4); lp = long prismatic (l/w = >4); fr = fragment; b = brown; pb = pale-brown; in = inclusions; cr = fractured; NA = not abraded (all the others abraded); [N] = number of grains in fraction

†,§) weight and concentrations are known to better than 10%, except for those near and below the ca. 1 mg limit of resolution of the balance

‡) Th/U model ratio inferred from 208/206 ratio and age of sample.

§) Pbc = total common Pb in sample (initial + blank)

¤) raw data corrected for fractionation and blank.

¶) corrected for fractionation, spike, blank and initial common Pb; error calculated by propagating the main sources of uncertainty.

^) D = degree of discordancy

Nappe Complex and hence pre-Finnmarkian, probably Cambrian, in age (for example, Zwaan and Roberts, 1978). This hypothesis was disproved when Binns and Gayer (1980) and Binns (1989) discovered fossils indicative of deposition in the Upper Ashgill (447 – 441 Ma) in a marble within the nappe. Ramsay and others (1985a) subsequently proposed that a conglomerate horizon, found at about the same stratigraphic level as the fossiliferous marble, represented a major unconformity separating a lower unit, with an affinity to the Kalak Nappe Complex, from an upper unit of Silurian age. They suggested that the unconformity was cutting a large-scale fold structure in the underlying Finnmarkian part of the nappe. This was presumably identical to a recumbent structure described by Pearson (1971), folding the Rappesvarre granite gneiss (still considered to be a granitized metasedimentary rock at that time) and the surrounding sedimentary succession. Binns (1989) did not concur with the interpretation of Ramsay and others (1985a) that the conglomerate represented a major boundary, and he did not believe that the nappe had been affected by a Finnmarkian event. By contrast, Lindhal and others (2005) agree that the conglomerate signifies a major unconformity but they also disputed the existence of the earlier Caledonian tectonometamorphic event. About 50 km south of Vaddas there is the Halti mafic-ultramafic complex, which has yielded U-Pb ages of 434 ± 5 Ma (Vaasjoki and Sipilä, 2001) and 438 ± 5 Ma (Andréasson and others, 2003). The Halti complex is separated from the Kalak Nappe Complex by a thrust, and appears to be a klippe related to the Vaddas Nappe. Andréasson and others (2003) suggest that the metasedimentary rocks hosting the Halti Complex are Neoproterozoic in age, apparently also implying that these are parts of the Kalak Nappe Complex, an interpretation in line with the proposal of Ramsay and others (1985a). Based on these assumptions Andréasson and others (2003) concluded that the Halti Complex formed on Baltic crust above an East-dipping subduction zone, a conclusion of fundamental importance for understanding Caledonian accretionary processes. There are, thus, a number of questions regarding the essence of sedimentary rocks, specific conglomeratic units, and structures that are critical in order to understand the nature of the Vaddas Nappe. By dating the Rappesvarre granitic gneiss we address one specific point, namely the apparent affinity of this lower succession with the Kalak Nappe Complex.

Sample Characteristics

The Rappesvarre granitic gneiss is a medium grained, locally porphyritic muscovite-biotite-bearing rock. The unit occurs mainly as sheets within the psammites, with a gneissic fabric parallel to that of the surrounding units. The sampled outcrop itself was homogeneous and free of enclaves.

Zircon Characteristics and U-Pb Data

The zircon population in this sample (*C-03-2)* is heterogeneous. Zircons are generally clear but many of them contain inclusions of various minerals and probably melt. The external shape of the crystals varies from euhedral to subhedral, the latter probably representing xenocrystic grains (fig. 3A). Six analyses (table 1) were done on multigrain fractions or single crystals of zircon least likely to contain xenocrystic material. Zircon with inclusions of other minerals was also utilized to achieve this aim. Most results plot in a cluster close to Concordia (fig. 4A) except for one analysis, which evidently contained a large xenocrystic component. Five of the analyses define a line with a lower intercept age of 602 ± 5 Ma, interpreted as dating the magmatic intrusion of the granite. The upper intercept age of 1230 Ma suggests an average Mesoproterozoic age of the xenocrystic zircons. One analysis does not fit the line and plots reversely discordant, indicating some problem (natural or analytical) with the U-Pb ratio.

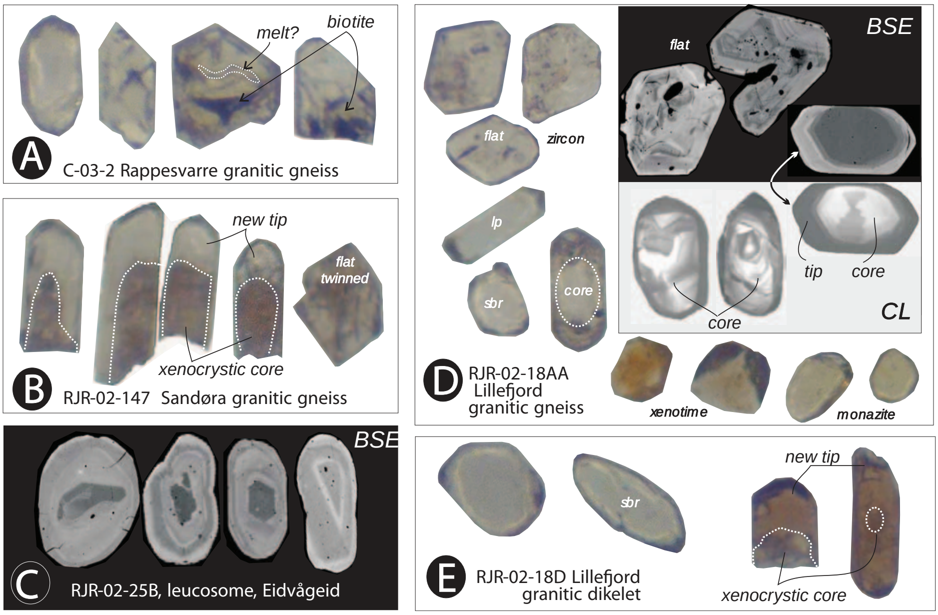

Fig. 3. Microphotographs of zircon (in D with monazite and xenotime) taken from whole grains with a binocular microscope (images shown on white background), or using polished grain mounts and back-scattered electrons (BSE, black background) and cathodoluminescence (CL, gray background). The grains were all about 100 ± 50 micrograms in size. The images exemplify the most salient characteristics of these minerals in the five samples investigated. (A) Zircon in the Rappesvarre granitic gneiss exhibits a variety of shapes. The analyses were done mainly on grains devoid of cores, such as the broken tips with visible inclusions of other minerals shown on the right, avoiding 'clean' but core-bearing grains like the one on the left. (B) Typical zircon in the Sandøra granitic gneiss consisting of turbid cores overgrown by transparent euhedral tips. To the right is one of the subordinate flat and twinned crystals (C) Dominant zircon type in the Eidvågeid leucosome. In these subequant and anhedral grains it is commonly difficult to distinguish regular growth zoning (right) from the shape of inherited cores (left). (D) The Lillefjord granitic gneiss contains mainly core-bearing zircon, such as those shown along the middle strip of the figure. To avoid cores, most of the analyses were carried out on tabular (flat) and in part twinned crystals such as those shown at the top. These crystals are rich in U and in BSE images they show both growth zoning and complex textures that may reflect some recrystallization. Typical octahedral xenotime crystals and anhedral monazite are shown at the bottom. (E) Xenocrystic components dominate most of the subhedral to anhedral zircon grains (on the left) in the Littlefjord granitic dikelet and also occur as cores in newly grown, brown, high-U zircon crystals (right). Tips broken off the latter crystals were used for analysis (abbreviations: lp = long prismatic, sbr = subrounded.

SANDØRA GRANITIC GNEISS

Geological Setting

The group of islands around Skjervøy hosts the westernmost occurrences of Kalak Nappe Complex rocks. Farther west all the lower and intermediate tectonic elements of the orogen are excised, exposing only rocks of the Uppermost Allochthon in fault contact with the Lower Allochthon, that is the Proterozoic basement of West Troms exhumed together with Lofoten-Vesterålen during the extensional process that accompanied opening of the Atlantic. Skjervøy comprises an apparently inverse stratigraphic succession of marble, pelite and psammite, affected by two deformation events and metamorphosed to amphibolite facies (Ash, 1967). The metasedimentary rocks contain a wedge-shaped orthogneiss body, the Sandøra granitic gneiss, and several mafic dikes. According to Ash (1967) the shape of the granitic gneiss may be controlled by an early recumbent fold (D1). The whole region was then overprinted by a second deformation event (D2) that refolded part of the sequence.

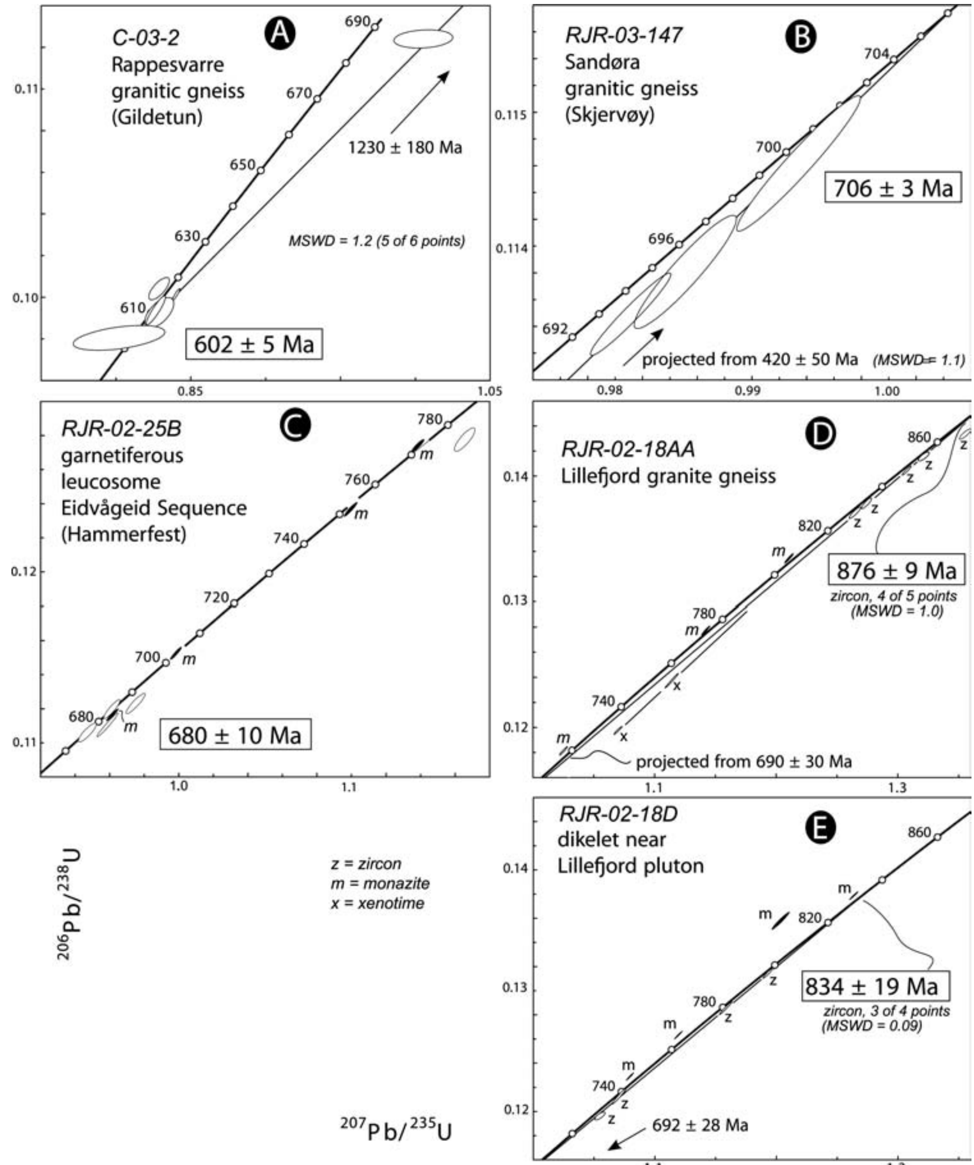

Fig. 4. (A-E) Concordia diagrams with the U-Pb data for zircon, monazite and xenotime for the five samples. Data are given in table 1 and discussed in the text. Uncertainties represent 2σ.

Sample Characteristics

The sampled quarry yielded a diverse set of granitic rocks. The degree of deformation in these rocks is generally strong but variable, with intensively folded and refolded domains cut by essentially massive and straight late pegmatitic dikes. The sample collected for dating *(RJR-03-147)* represents one of the most typical facies of the granitic gneiss. It is very coarse grained and dominated by augened K-feldspar, with abundant muscovite, rare biotite and localized garnet.

Zircon Characteristics and U-Pb Data

The dominant zircon type in this sample *(RJR-03-147)* is a prism with a murky, metamict core surrounded by a clear, transparent rim and tip (fig. 3B). There are some subordinate flat crystals and equant twinned double-pyramids without prismatic faces that commonly form in highly evolved melts (Corfu and others, 2003). Three analyses were carried out on fractions of tips detached from the turbid cores (table 1; fig. 4B). They reveal high U contents, very low Th, and yield nearly concordant data. The lack of spread prevents the calculation of a discordia line with the data alone but the systematic change in $^{207}Pb/^{206}Pb$ age indicates that the discordance is not related to modern Pb loss alone. On the assumption that Pb loss occurred most likely during the Silurian thrusting, a line was projected from 420 ± 50 Ma obtaining an upper intercept age of 706 ± 3 Ma, which is taken as the best estimate for intrusion of the Sandøra granitic gneiss. The choice of a much earlier disturbance at 600 Ma would shift the age upward by some 20 m.y.

GARNETIFEROUS LEUCOSOME IN EIDVÅGEID SEQUENCE

Geological Setting

The rocks of the Eidvågeid sequence form a peculiar lithology of the Kalak Nappe Complex. The sequence is characterized by biotite-rich migmatites, locally purple colored, with distinctive large garnets. These rocks generally occur below the Klubben pasammite, but it has been uncertain as to whether the Eidvågeid Sequence forms a basement unit to the Klubben psammite, or whether it is itself a part of the same stratigraphic sequence (Ramsay and others, 1985a; Rice, 1990).

Sample Characteristics

Granitic leucosome was sampled from a prominent exposure of migmatitic rocks representing the Eidvågeid Sequence at Akkarfjord south of Hammerfest. The main unit comprises gray biotite gneiss characterized by 0.2 to 5 cm wide garnet porphyroblasts, generally hosted in a pocket of quartzo-feldspathic material. The texture is mylonitic, and garnet and plagioclase have been rotated and abraded during the mylonitization. The leucosome occurs as thin stringers stretched out along the main fabric but locally widening into cm- to dm-wide pods and sheets, one of which was sampled for dating.

Zircon Characteristics and U-Pb Data

The sample *(RJR-02-25B)* contains an abundant zircon population mostly of equant subrounded grains, colorless to slightly brown. Many of the grains appear to be xenocrysts inherited by the leucosome from the original detrital zircon population. The challenge, however, was to identify and date grains that could be related to the migmatization process. The best candidates were equant, subhedral, faintly brown grains, which in BSE reveal a zoned texture suggestive either of simple magmatic growth (two grains to the right in fig. 3C) or of more complex growth with inherited cores or internal recrystallization (two grains to the left in fig. 3C). Four analyses of such grains (one of them a tip) scatter in an area close to Concordia, at about 680 Ma (fig. 4C). The cluster also includes the data point for a monazite fragment. Three other monazite grains, however, yield significantly older apparent ages at 703, 751 and 773 Ma. Finally, the analysis of one euhedral, short-prismatic grain, chosen because of a sulphide inclusion and deemed to be of possible magmatic origin, yielded the oldest apparent ages (>770 Ma).

The interpretation of this pattern is not simple. The equant, slightly brown zircons, which are a main component of the population, are rich in U and low in Th, a common feature of zircon in anatectic or highly fractionated magmas (for example, Corfu and Easton, 2001; Andersson and others, 2002; Corfu and others, 2006; Kirkland and others, 2006). They give reasonably coherent age indications, which also match those of one of the monazite analyses, suggesting crystallization at around 680 ± 10 Ma. The older monazites, however, clearly reflect some older magmatic or metamorphic crystallization. In detail the individual monazites were probably composite grains and hence their apparent ages are interpreted as meaningless. If they are compared to the pattern of the monazite and zircon of the Lillefjord granite gneiss and dikelet presented below, these data suggest that an event of metamorphism and/or anatexis had already affected the Eidvågeid Sequence about 880 to 830 Ma. An alternative interpretation is that the melting episode occurred at about 880 to 830 Ma and that the 680 Ma event records a high-grade overprint and the shearing of the unit. This is considered less likely at present, but more detailed future work may succeed to find unambiguous links between the isotopic and the petrological features.

Lillefjord Granite Gneiss and External Dikelet

Geological Setting

The Lillefjord granite gneiss is a tabular body intruding Klubben metapsammite on the Porsanger peninsula. The body cuts earlier folds but is itself strongly deformed and foliated (Daly and others, 1991). The age of this granite gneiss has played an important role in the development of the geological understanding in Finnmark because it showed for the first time (Daly and others, 1991) that the main deformation of the Kalak Nappe Complex had occurred during a Neoproterozoic event unrelated to a ca. 500 Ma Finnmarkian orogenic phase as originally defined by Sturt and others (1978). The U-Pb age of 804 ± 19 Ma by Daly and others (1991) was given by the lower intercept age of a suite of multigrain zircon analyses selected on the basis of grain size. Although the data were quite coherent and were supported by a Rb-Sr whole rock age from the same intrusion, some doubts remained as to whether the age might be biased by inheritance. Because of its pivotal importance for the geological interpretation of the region samples were collected to re-test the validity of the age. For the same reasons a new U-Pb study of the same body was undertaken at about the same time by Kirkland and Daly (2003). Their new results (Kirkland and others, 2006) are consistent with ours reported below, confirming the Neoproterozoic origin of the granite.

Sample Characteristics

Two samples were collected. Sample RJR-02-18AA represents the main body of the pluton. It is a coarse grained feldspar-megacrystic orthogneiss with biotite and rare muscovite. The second sample, RJR-02-18D, stems from outside the pluton at the site shown in figure 3B of Daly and others (1991). It represents a thin granitic dikelet rooted in pelitic layers and cutting across the folded psammite, but locally displaying itself evidence of some folding. Its composition is granitic with plagioclase and perthitic microcline megacrysts, abundant biotite, local garnet and rare muscovite. These minerals are strained, but to a much lower extent than in the sample from the main granitic body that also exhibits a much more intense degree of recrystallization of quartz.

Zircon Characteristics and U-Pb Data

The zircon population in the sample from the main pluton (RJR-02-18AA) contains a large proportion of xenocrysts appearing as subrounded grains or as cores visible inside euhedral prisms [fig. 3D; see also fig. 5 in Daly and others (1991)]. Newly grown magmatic zircons form euhedral prisms and also tabular crystals (top row in fig. 3D) similar to those observed in the Sandøra sample discussed above. Five analyses were carried out on tabular or on prismatic zircons judged to be free of cores.

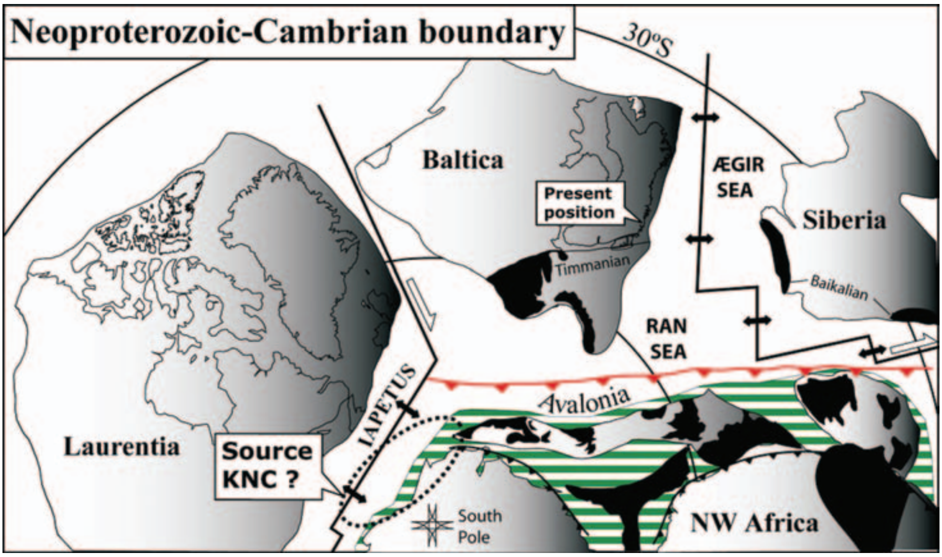

Fig. 5. Schematic plate configuration approximately at the time of the Precambrian-Cambrian transition. Based on the presently available information the Kalak Nappe Complex (KNC) matches best the geological relationships observed in the northwestern region of Gondwana, especially the various Neoproterozoic events of magmatism and tectonism. The hypothesis shown here also places the formation of the 570 to 560 Ma Seiland Igneous Complex in the extensional context that accompanied the break-up between Laurentia and Gondwana and matches similar magmatism recorded on the Laurentian side (Carolina) (from Torsvik and Cocks, 2005).

Nevertheless the uppermost data point is more discordant than the rest, and not collinear, suggesting the presence of an inherited component (fig. 4D). The four other analyses are spread along the Concordia curve, defining a line with an upper intercept age of 876 ± 9 Ma when anchored at 690 ± 30 Ma. This lower intercept age is borrowed from the zircon data in the companion sample (see below) and its validity is supported, on the one hand by the optimum probability of fit of the data and, on the other hand by the fact that the coexisting monazite appears to have been affected by a similar event. The three analyses of monazite are spread out along Concordia between about 810 and 720 Ma, reminiscent of the pattern shown by monazite in the Eidvågeid leucosome discussed above and in the dikelet presented below. All three analyses are slightly reversely discordant. This is common in monazite due to its propensity to incorporate excess ^{230}Th during its formation (Schärer, 1984), but it is strange in the present case because partial Pb loss would likely expel much of the excess ^{206}Pb, bringing the points back on or below Concordia. Excluding an unknown analytical problem, this reverse discordance likely implies that the analyzed monazites are mixtures of two primary phases that did not undergo Pb loss. Two analyses were also carried out on xenotime, which occurs as scarce octahedral crystals, generally somewhat internally turbid. The two analyses are both discordant and show a different trend than the zircons, presumably reflecting a more complex Pb loss history due to the metamictizaton and perhaps alteration caused by their very high U content. A line through the two analyses has intersections at 835 and 490 Ma, suggesting important Pb loss during the Scandian event.

The zircon population in the granitic dikelet (RJR-02-18D) comprises both a population of clear subrounded grains of likely xenocrystic origin and chocolate-brown prisms, generally hosting a clear core (fig. 3E). Four analyses of brown tips, mechanically separated from such cores, plot just off the Concordia curve. Three of the analyses define a line with an upper intercept of 834 ± 19 Ma and a lower intercept at 692 ± 28 Ma. The fourth analysis deviates slightly from the line possibly because of some superimposed younger Pb loss, or due to its very high common Pb content (table 1), which may be caused by local alteration or an analytical accident. Four monazite analyses yield the same basic pattern as in the main granitic body. They are all reversely discordant, one much more strongly than the others, and are spread out between about 830 and 740 Ma. The interpretation of the data is the same as for the previous sample: crystallization of a magmatic generation at ≥ 830 Ma followed by growth of a metamorphic phase after 740 Ma, most likely the 692 ± 28 Ma event defined by zircon. The reverse discordance likely reflects excess ^{230}Th, except for the very discordant analysis where some other effect (alteration?) might have affected the data. The sample also contains some titanite, probably grown during retrogression since monazite and titanite tend to be mutually incompatible. One titanite analysis (table 1) indicates that the mineral formed during the Scandian events.

DISCUSSION

The Vaddas Nappe – A Strange Hybrid

As detailed in the introduction of the geology, the Vaddas Nappe has a schizophrenic character as its base resembles Kalak Nappe Complex lithologies whereas the upper levels resemble Köli Nappe lithologies (and ages). The solution proposed by Ramsay and others (1985a) is that the top part of the Vaddas Nappe was deposited unconformably on an older deformed succession, which they equated with the Kalak Nappe Complex. The unconformity is marked by a discontinuous, fluvial conglomerate with quartzitic pebbles indicating erosion of the underlying unit (Lindahl and others, 2005). The above interpretation is confirmed, in principle, by the 602 ± 5 Ma age for the Rappesvarre granitic gneiss as it proves that that part of the Vaddas Nappe is clearly much older than the overlying Silurian members. In light of this evidence, the objection of Binns (1989) that similar conglomeratic units can also be found in the unit up to 7 meters below the unconformity, and hence are not likely to represent a major break, would seem to be irrelevant. The alternative to an unconformity interpretation would require a structural juxtaposition of the Silurian succession along a discrete thrust. Lindahl and others (2005) did not notice any such specific tectonic break in their mapping of the area and accept the notion of an unconformity. Further south, Binns and Gayer (1980) postulated the existence of a thrust (Stordalen Thrust) at the bottom of the fossiliferous Silurian marble, but the thrust has not been traced further north. It may possibly cut down stratigraphy, across the lower part of the Vaddas Nappe. Andréasson and others (2003) do not believe that the Stordalen Thrust is the base of the Vaddas Nappe, as they infer that the Silurian Halti complex intruded the Kalak Nappe Complex. They also point to the presence of Grenvillian age xenocrystic zircon in plagiogranite dikes of the Silurian Halti pluton. Nevertheless they agree that the Halti Complex is separated from the Kalak Nappe Complex by a thrust. Moreover, if the Silurian magmatism was emplaced through this basement unit one would expect to find Silurian intrusives also within the basement but so far no such rocks have been found. For example, mafic dikes at Corrovarre below the Vaddas Nappe (fig. 2A), give Late Precambrian rather than Silurian Sm-Nd ages (Zwaan and Van Roermund, 1990). We also note that the Rappesvarre age of 600 Ma has not been recorded yet in the Kalak Nappe Complex, hence the base of the Vaddas Nappe could well have a distinct origin unrelated to the Kalak Nappe Complex. An open question also concerns the age of recumbent folds described both in the upper and in the lower parts of the Vaddas Nappe (Pearson, 1971; Binns and Gayer, 1980; Ramsay and others, 1985a; Andréasson and others, 2003). While those in the Silurian succession must necessarily be of Scandian age, those in the lower part of the nappe have so far only been constrained to be less than 600 Ma. Could these also be Scandian?

Nevertheless, based on the presently available information we conclude that the Vaddas Nappe comprises a Neoproterozoic 'basement' and its autochthonous Silurian cover. The 'Vaddas basement' resembles the Kalak Nappe Complex, but it appears to be different in terms of age and deformation. The Vaddas cover represents the typical Early Silurian succession that can be followed in the Upper Allochthon all along the Caledonides, varying in character from syn-contractional, with bimodal magmatism and associated folding and metamorphism, to extensional and transtensional suggestive of back-arc settings (for example, Corfu and others, 2006). Analogues to the upper Vaddas succession in western Finnmark are the Magerøy Nappe and the Hellefjord Formation, the latter now also proven to be Silurian, rather than Late Neoproterozoic to Upper Ordovician as originally thought (Kirkland and others, 2005; Gerber, ms, 2006). The Magerøy Nappe is separated from the Kalak Nappe Complex by a zone of intense deformation, originally interpreted to be a thrust (Ramsay and Sturt, 1976), but possibly representing a normal fault separating basement and cover. The contact between Kalak Nappe Complex and the Hellefjord Formation is generally conformable (for example, Ramsay and others, 1985a; Slagstad and others, 2006), but it can be inferred from the fact that Silurian granitic intrusions and gabbros are only found in the Hellefjord formation and not in the Kalak Nappe Complex that a tectonic juxtaposition of the two units has occurred.

Implications for the Evolution of the Kalak Nappe Complex

The rocks investigated in this study postdate the earliest period of Grenvillian magmatism and deformation recorded in eastern parts of the Kalak Nappe Complex at 970 to 980 Ma (Kirkland and others, 2006; localities H, S, R in fig. 2A) and in western Magerøy (Corfu and others, 2005; Gerber, ms, 2006; G in fig. 2A). These granitic rocks post-date an early period of deformation and have been attributed to crustal anatexis of Late Paleoproterozoic crust (Kirkland and others, 2006).

The age of 876 ± 9 Ma for the Lillefjord granite confirms and refines the original date of 804 ± 19 Ma reported by Daly and others (1991). In detail the ID-TIMS age presented here is distinctly older than the ion probe age of 841 ± 7 Ma reported by Kirkland and others (2006). It is possible that the lower resolution of the ion probe data may have introduced a downward bias, missing the shift caused by the strong 690 Ma overprint so evident in the ID-TIMS data for zircon and monazite and also recorded by the above authors as local zircon new growth (707 ± 20 Ma) in a pegmatite at Revsneshamn, 8 kilometers southwest of Lillefjord (Rv in fig. 2A). It is, however, also possible that the two samples responded differently to the subsequent events and that the age difference is real, implying that the Lillefjord body is composite and evolved piecemeal over some 30 to 40 m.y. Indeed, the transgressive dikelet at the margin of the pluton yields an age of 834 ± 19 Ma, clearly younger than the sample of granitic gneiss but overlapping the 841 ± 7 Ma date of Kirkland and others (2006), who also obtained ages of 826 ± 5 Ma and 833 ± 9 Ma for two pegmatites in the same region. As discussed by Daly and others (1991), the Lillefjord granite post-dates two fabric forming events recorded in the Klubben quartzite and is itself deformed by a younger event. The dated dikelet is folded but shows less strain that the main body and locally transgresses folded granitic layers in the quartzite suggesting that this magmatic period was coeval with some of the deformation in the granite gneiss.

Both the granite and the dikelet offer evidence for a younger overprint at 692 ± 29 Ma that partially reset the high-U zircons and likely formed new monazite. This event can also be correlated to the emplacement of the Sandøra granite on Skjervøy, where the intrusion was deformed by at least one, and possibly two events (Ash, 1967). This granitic gneiss is locally cut by much less deformed granitic dikes suggesting that this deformation occurred approximately at the same time, but a verification of this hypothesis will require more detailed geochronology. Although they are difficult to interpret, the data from the Eidvågeid migmatites suggest that significant melting with formation of zircon and monazite also occurred in connection with this event at about 680 ± 10 Ma. The complicating factor here is that in the Eidvågeid leucosome there is also evidence for an earlier event as revealed by older, only partially rejuvenated monazite, with a pattern that is closely comparable to that of monazite in the Lillefjord granite. Clearly the two units have shared some parts of their history. Kirkland and others (2006) have investigated a similar garnetiferous granitic leucosome from the Eidvågeid Sequence at Snøfjord, 10 kilometers north of Lillefjord (Sn, fig. 2A), yielding an age of 709 ± 4 Ma. They interpret the leucosome as having formed syntectonically and suggest that the episode reflects juxtaposition of the hosting nappe sheet on the underlying nappes further east. This is at variance with the interpretation forced by monazite in our sample which suggests that the Eidvågeid Sequence was probably already in the same crustal unit as the Lillefjord pluton during the 880 to 830 Ma event. We also note that there is a possibly important difference between the 680 ± 10 Ma age for the Eidvågeid leucosome at Hammerfest and the 709 ± 4 Ma at Snøfjord. By contrast, the latter compares very well with our age for the Sandøra granitic gneiss.

Besides the Rappesvarre granite gneiss in the Vaddas Nappe there is as yet no direct evidence (yet) that the Kalak Nappe Complex was affected by an event at about 600 Ma. As discussed above, this might mean that the lower part of the Vaddas Nappe is not related to the Kalak Nappe Complex, or that the 600 Ma event was of only local importance, and/or that sampling for U-Pb dating has accidentally missed such intrusive bodies in the Kalak Nappe Complex. By contrast there is an excellent record for the subsequent event related to emplacement of the Seiland Igneous Complex at 570 to 560 Ma (Roberts and others, 2006, and unpublished data), with a secondary pulse of alkaline magmatism at 530 to 520 Ma (Pedersen and others, 1989).

A further implication of these relationships is that the Klubben Formation must have been deposited before 980 Ma, at least locally, with the possibility of deposition at different times in different basins as late as 600 Ma.

This combined information indicates an episodic but very protracted evolution with repeated episodes of deformation and metamorphism. The granites generated during the various melting episodes appear to be mainly of crustal origin judging by the abundance of zircon inheritance and lack of mafic or intermediate equivalents. By contrast, the Seiland Igneous Complex comprises a wide range of rocks from carbonatite to syenite, gabbro, peridotite and granite suggesting a primary mantle control of the magma generation processes.

Of additional interest is the timing of thrusting responsible for emplacing the Kalak Nappe Complex. The original idea that the Kalak Nappe Complex had been emplaced onto Baltica in the Cambrian to Early Ordovician has not found much supporting evidence. The 'Finnmarkian' Rb-Sr (Sturt and others, 1978) and Ar (Dallmeyer, 1988) ages have generally been obtained from units of the Seiland Igneous Complex, hence those ages can easily be explained in terms of as post-magmatic slow cooling or resetting. Most other pre-Scandian ages are based on multistage disturbed spectra (Dallmeyer, 1988) or from problematic Rb-Sr whole rock dating experiments (for example, Roberts and Sundvoll, 1990). The most convincing Ar-Ar ages suggest Scandian thrusting (for example, Dallmeyer and others, 1988). There are also no Cambrian or Early Ordovician foreland sedimentary deposits, which should represent the response to thrusting of nappes on the edge of Baltica (Bergström and Gee, 1985). An earlier age of emplacement is unlikely as the earliest possible time is constrained to the Late Vendian – Early Cambrian by the sedimentary cover of the Komagfjord window, which is overridden by the Kalak Nappe Complex (Pharaoh, 1985; figs. 2A and 2B). Thus, it is likely that the Kalak Nappe Complex was emplaced on the Baltic craton in the Silurian during the Scandian collision. It is still uncertain as to whether the nappes in the Kalak Nappe Complex were brought in piecemeal, or whether they came in as one block of already assembled Precambrian nappes, plus or minus Silurian cover, with minimal disruptions during the Scandian events.

Neither a Finnmarkian Nor a Porsanger Orogeny?

The emerging chronological relationships and their geological implications force us to consider radically different models for the evolution of the Finnmarkian Caledonides than originally proposed. As already pointed out by others (Daly and others, 1991; Kirkland and others, 2006; Roberts and others, 2006) one of the major implications of these data is the fact that the concept of Finnmarkian orogeny in its original sense is no longer applicable. The 'Finnmarkian phase of the Caledonian orogeny' had been defined based on the relationships between structural and intrusive elements of the Seiland Igneous Complex underpinned by Rb-Sr and K-Ar ages that suggested ca. 550 to 500 Ma (Sturt and others, 1978; Ramsay and others, 1985a). The concept was gradually modified and expanded as new observations and data came along, but a major step was the expansion of the term to designate a Cambrian (to Ordovician) orogenic event thought to have affected the entire western margin of Baltica through subduction of the margin, formation of an early suite of eclogites (Mørk and others, 1988), and accretion of early nappes onto the shield (Andréasson, 1994; Andréasson and others, 1998). It is now apparent, however, that the original definition of the Finnmarkian was based on incorrect premises. The Cambrian-Ordovician ages in the Kalak Nappe Complex do in fact reflect partial resetting of the K-Ar and Rb-Sr systems rather than crystallization and formation of the main fabrics, which are either Neoproterozoic or Silurian. Since it is deeply entrenched in the literature as a Cambrian event, the term 'Finnmarkian' cannot easily be redefined to describe the newly emerging Neoproterozoic tectonics and should no longer be applied to the geology of West Finnmark.

After dating the Lillefjord granite at 800 Ma Daly and others (1991) introduced the new term Porsanger orogeny for the pre-800 Ma deformation and metamorphism in the Kalak Nappes. Although reasonable at that time, the term has been coined too narrowly and does not cover the series of geological episodes that spanned most of the Neoproterozoic. Kirkland and others (2006) have now introduced the term 'Snøfjord event' for the activity at 700 Ma, which can also be problematic since there is still only a vague perspective on the tectonic significance of this event. To be consistent we would need to introduce complementary terms for each different event [for example, Rappesvarrian (600 Ma), Sipian (570 Ma)]. This is very impractical, thus it would seem to be best to just drop the terms Finnmarkian, Sørøyan and Porsanger entirely.

The Origin of the Kalak Nappe Complex

The Baltic Shield has an onion-like structure with an Archean and Paleoproterozoic core in the north and northeast, an intermediate Mesoproterozoic shell stretching across Middle Norway into southwestern Sweden and an external Late Mesoproterozoic to Neoproterozoic Sveconorwegian shell in the south. Rocks with ages between 900 and 500 Ma are rare and limited to mafic dike swarms or carbonatite complexes. In particular, there are no orogenic type Neoproterozoic rocks in the autochthonous western Baltic basement.

By contrast, the Kalak Nappe Complex comprises granitic rocks with ages around 980 to 960 Ma, 850 Ma, 700 Ma, and the Seiland Igneous Complex at 570 to 560 Ma and 530 to 520 Ma, in addition to the Archean and Paleoproterozoic components found in the crystalline slices of the nappes (this study; Sturt and Austrheim, 1985; Pedersen and others, 1989; Corfu and others, 2005; Kirkland and others, 2006; Roberts and others, 2006, and unpublished data; Gerber, ms, 2006). Apart for the latter elements, this age pattern shows absolutely no resemblance to the geochronological structure of the autochthonous Baltic basement. Even the Sveconorwegian intrusions have an exotic position since their closest equivalents in the autochthon are over 1000 km away along strike. Also exotic are the pre-980 Ma Klubben psammites, which resemble allochthonous sedimentary sequences thrust on the Laurentian margin in Greenland (Krummedal) and Scotland (Moine) but do not have any equivalents in the autochthonous Baltic basement. Andréasson (1994) suggests that Sveconorwegian elements found in the Kalak Nappe Complex and the related Seve nappes further south can be explained if the Sveconorwegian Belt Front had originally extended north-northwest and overprinted the outer- and northernmost segments of the Shield, which were then thrusted eastward to form the Kalak Nappe Complex and Seve nappe system. Daly and others (1989), however, have pointed out that the balanced cross-sections used for paleogeographic reconstructions are flawed because they were based on the assumption that all fabrics were Caledonian, whereas we now know that they are in part Precambrian. Bergström and Gee (1985) proposed that the Seiland Igneous Complex and the related metamorphism and deformation may have been formed during opening of the Iapetus Ocean along a 'deep transform' penetrating the continental margin, but they also pointed out that the notion of a Cambrian orogeny was curiously at odds with the quiet sedimentological record in the Baltic Autochton. Although the proposed explanations are by themselves plausible, to explain all the oddities of the Kalak Nappe Complex one needs to appeal to a whole series of special circumstances. There is just no simple way to rationalize a Baltic origin of the Kalak Nappe Complex.

The simplest alternative is to consider the Kalak Nappe Complex as an allochthonous terrane generated outside of Baltica. Neoproterozoic activity was widespread at the interior and on the periphery of Gondwana accompanying its assembly after the disaggregation of Rodinia and before its own break-up. Baltica was generally hovering on the periphery, largely unaffected by these continental transformations undergoing only local extensional processes and sedimentation. Only the Timanian orogeny (fig. 5) affected its northeastern margins at about 600 to 560 Ma (Roberts and Siedlecka, 2002; Roberts and Olovyanishnikov, 2004; Gee, 2005). The paleomagnetic evidence that Baltica may have been in an inverted position in the Late Precambrian (Torsvik and Rehnström, 2001; compare also Cocks and Torsvik, 2005) made it possible to consider the genesis of the Seiland Igneous Complex in a peri-Gondwanan context, relating it to the opening of the Ægir Sea between Baltica and Siberia (Hartz and Torsvik, 2002), or at a triple junction of the Ægir Sea with the extending Tamir basin (Siedlecka and others, 2004). The problem with the latter model is that at the time of formation of the Seiland Igneous Complex (570 – 560 Ma) the Timanian orogen was under contraction (Roberts and Siedlecka, 2002) whereas there is no clear evidence of contraction at this time in the Kalak Nappe Complex. Moreover, their model assumes that the Seiland Igneous Complex intruded a continental fragment detached from Baltica, an assumption inconsistent with the available age evidence as discussed above. As an alternative we can evaluate potential links to terranes outside of Baltica, connected to Siberia, Laurentia or more generally to the peri-Gondwanan realm (fig. 5).

The Kalak Nappe Complex could have been linked to Neoproterozoic terranes now integrated into the West Siberian craton. Late Grenvillian granitic rocks occur as intrusions in Proterozoic crust in Central Taimyr. Before the Late Vendian, however, these rocks and younger Neoproterozoic ophiolitic and arc assemblages were already aggregated to northern Siberia (Pease and others, 2001; Vernikovsky and Vernikovskaya, 2001). The Yenisey Belt comprises a complex tectonic assemblage of terranes that underwent intrusive activity at about 880 to 860, 760 to 720 and 700 to 630 Ma, but these, too, were already accreted to the western edge of the Siberian craton in the Proterozoic (Vernikovsky and others, 2003). Intensive Neoproterozoic activity was also a characteristic of the Baikalian region, in general fitting with events occurring throughout the Neoproterozoic in terranes at the northern periphery of Gondwana.

Among the typical peri-Gondwanan terranes a distinction can be made between those of West African affinity and those related to the Amazonian craton. The hallmark of the former is the ca. 2 Ga Eburnian orogeny, traces of which are found in Cadomia and Iberia, likely generated on or close to the West African craton. By contrast, terranes such as Western Avalonia and Carolina lack an Eburnian signature and show instead features that link them to the Mesoproterozoic and Grenvillian basement units of the Amazonian craton. In general, however, the latter terranes consist of Neoproterozoic oceanic and continental island arcs (Nance and others, 2002), differing from the situation observed in the Kalak Nappe Complex.

A third set of candidates are terranes now present at the margin of Laurentia and whose origin and setting remain uncertain (for example, Hibbard and others, 2002). Grenvillian basement in the Central Appalachians was affected by episodes of granitic magmatism (A-type) at 765 to 680 Ma and 620 to 550 Ma, in particular with extensive mafic volcanism at 570 to 560 Ma attributed to rifting or at least attempted rifting of Laurentia (Cawood and others, 2001; Tollo and others, 2004). The Moine succession in NW Scotland was deposited after about 900 Ma (Cawood and others, 2004) and underwent repeated magmatism with deformation and metamorphism at 870 to 800 Ma, the Knoydartian orogeny (for example, Highton and others, 1999; Rogers and others, 2001), about 740 Ma (Tanner and Evans, 2003), 670 Ma (Storey and others, 2004) and 600 Ma (Kinny and others, 2003). Besides the younger age of deposition and lack of Grenvillian intrusions the Moine has been affected by Ordovician (470 – 460 Ma) intrusive and metamorphic activity, which so far has not been observed in the Kalak Nappe Complex. A few analogies also exist between the Kalak Nappe Complex and the Krummedal succession in the Allochthons of Eastern Greenland in terms of probably Late Mesoproterozoic age of deposition and presence of Grenvillian granites (for example, Kalsbeek and others, 2000). The Krummedal sequence, however, has no record of intrusive activity between 900 and 450 Ma.

In summary, the Kalak Nappe Complex is quite exotic when viewed from a Baltic perspective but it shows many analogies with terranes developed on the Neoproterozoic eastern Laurentian margin, with terranes developed and transferred to the margin of the Siberian craton, and with terranes in western parts of the peri-Gondwanan realm. The most likely derivation seems to be the latter region (fig. 5). Transfer onto the Baltic craton could have occurred in two ways, either from the Ægir Sea, sweeping around in consonance with the rotation of Baltica and emplacement on the continent during closing of Iapetus in the Silurian, or, as a more likely alternative, by a transfer from the southern Iapetus or the western Ran Sea northward and sinistrally, with final thrusting onto Baltica in the Silurian. This alternative should be expanded to include the entire Kalak-Seve Nappe system, thus providing a more logical explanation for the presence in the Seve Nappe of Grenvillian elements (Williams and Claesson, 1987; Albrecht, ms, 2000; Andréasson and others, 2003) and of Neoproterozoic granite (Paulsson and Andréasson, 2002). The fact that only some segments of this system record Early and Late Ordovician high-pressure metamorphic overprints (Mørk and others, 1988; Gromet and others, 1996; Essex and others, 1997; Brueckner and Van Roermund, 2003; Andréasson and others, 2004; D. Root, personal communication, 2006) implies that diverse crustal domains were probably assembled during Scandian thrusting, each domain reflecting parts of the history recorded along the Laurentian margin in the Late Proterozoic and Early Paleozoic.

The above interpretation also provides a more rational basis for the long debated question of Ordovician unconformities linking outboard terranes to Baltica (Sturt and Ramsay, 1999) because, from the perspective outlined above, the links would be between outboard terranes (in part with faunas of Laurentian affinity) and exotic Kalak-Seve terranes rather than Baltica. If both elements were derived from western or southern parts of Iapetus there would be no paradox and no fundamental differences between competing interpretations (Pedersen and others, 1992).

Given that the Late Neoproterozoic configuration of Baltica with respect to Laurentia remains a point of debate (Cawood and Pisarevsky, 2006), it is finally also important to stress that our main conclusions do not depend on the choice of one or the other configuration.

CONCLUSIONS

(1) The Kalak Nappe Complex contains Neoproterozoic granitic rocks and migmatites with ages of ca. 876 ± 9 and 834 ± 19 Ma (Lillefjord pluton), 680 ± 10 Ma (leucosome in Eidvågeid migmatites) and 706 ± 3 Ma (Sandøra pluton). The Rappesvarre pluton intruding the basal units of the Vaddas Nappe has an age of 602 ± 5 Ma, supporting the concept that it acted as the depositional substrate to the unconformably overlying Early Silurian volcano-sedimentary cover.

(2) Together with Grenvillian (980 – 950 Ma) granites and the 570 to 560 Ma Seiland Igneous Complex, these ages demonstrate that the Kalak Nappe Complex did not evolve on the margin of the Baltic craton as inferred by earlier interpretations but that it must be derived from outside of Baltica prior to the juxtaposition during the Silurian orogeny.

(3) Geological and geochronological analogies suggest that the Kalak Nappe Complex may stem for the southeastern margin of Laurentia, from western Siberia and/or from the peri-Gondwanan realm.

(4) It is proposed that the Kalak Nappe Complex, together with its correlative Seve Nappe, were moved sinistrally from southern Iapetus, where the Seve Nappe developed Grenvillian basement, Neoproterozoic granites and Ordovician eclogites, to the northern Iapetus from where in the Mid-Silurian it was accreted to the approaching Baltic plate.

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References

Albrecht, L. G., ms, 2000, Geological setting of early Caledonian (c. 500 Ma) eclogites of the Grapesvare-Tjidjak area, Seve Nappe Complex, N Sweden. Unpublished paper, *in* Albrecht, L. G., 2000, Early structural and metamorphic evolution of the Scandinavian Caledonides: a study of the eclogite-bearing Seve Nappe Complex at the Arctic Circle, Sweden: Lund, Sweden, Ph.D. thesis, Lund University, p. 1–29.

Andréasson, P. G., 1994, The Baltoscandian margin in Neoproterozoic-early Palaeozoic times; some constraints on terrane derivation and accretion in the Arctic Scandinavian Caledonides: Tectonophysics, v. 231, p. 1–32.

Andréasson, P. G., Svenningsen, O. M., and Albrecht, L., 1998, Dawn of Phanerozoic orogeny in the North Atlantic tract; evidence from the Seve-Kalak Superterrane, Scandinavian Caledonides: GFF, v. 120, p. 159–172.

Andréasson, P. G., Gee, D. G., Whitehouse, M. J., and Schöberg, H., 2003, Subduction-flip during Iapetus Ocean closure and Baltica-Laurentia collision, Scandinavian Caledonides: Terra Nova, v. 15, p. 362–369.

Andréasson, P. G., Page, L., Ekestubbe, J., and Schöberg, H., 2004, Early to Middle Ordovician destruction of a margin of Baltica. $^{40}Ar/^{39}Ar$ and U–Pb geochronological evidence and palaeomagnetic indications from Seve-Kalak terranes of the Kebnekaise Mts., Scandinavian Caledonides: Uppsala, 26th Nordic Geological Winter Meeting, GFF, v. 126/1, p. 76–77.

Andersson, J., Möller, C., and Johansson, L., 2002, Zircon geochronology of migmatites gneisses along the southern Mylonite Zone: a major Sveconorwegian terrane boundary in the Baltic Shield: Precambrian Research, v. 114, p. 121–147.

Ash, R. P., 1967, The geology of Skjervøy, North Troms, Norway: Norges geologiske Undersøkelse, v. 255, p. 37–52.

Bergström, J., and Gee, D. G., 1985, The Cambrian in Scandinavia, *in* Gee, D. G., and Sturt, B. A., editors, The Caledonian Orogen – Scandinavia and Related areas: New York, Wiley, p. 247–271.

Binns, R. E., 1989, Regional correlation in NE Troms-W Finnmark: the demise of the "Finnmarkian" orogeny? *in* Gayer, R. A., editor, The Caledonide Geology of Scandinavia: London, Graham and Trotman, p. 27–45.

Binns, R. E., and Gayer, R. A., 1980, Silurian or Upper Ordovician fossils at Guolasjav'ri Troms, Norway: Nature, v. 284, p. 53–55.

Brueckner, H. K., and Van Roermund, H. L. M., 2003, Dunks and redunks; repeated subduction of HP/UHP terranes in the Western Gneiss region of the Scandinavian Caledonides: Geological Society of America, Annual meeting, Abstracts with Programs v. 35/6, p. 556.

Cawood, P. A., and Pisarevsky, S. A., 2006, Was Baltica right-way-up or upside-down in the Neoproterozoic?: Journal of the Geological Society, v. 163, p. 753–759.

Cawood, P., McCausland, P., and Dunning, G., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453.

Cawood, P. A., Nemchin, A. A., Strachan, R. A., Kinny, P. D., and Loewy, S., 2004, Laurentian provenance and an intracratonic tectonic setting for the Moine Supergroup, Scotland, constrained by detrital zircons from the Loch Eil and Glen Urquhart successions: Journal of the Geological Society , v. 161, p. 861–874.

Chapman, T. J., Gayer, R. A., and Williams, G. D., 1985, Structural cross-sections through the Finnmark Caledonides and timing of the Finnmarkian event, *in* Gee, D. G., and Sturt, B. A., editors, The Caledonian Orogen – Scandinavia and Related areas: New York, Wiley, p. 593– 609.

Cocks, L. R. M., and Torsvik, T. H., 2005, Baltica from the Late Precambrian to mid-Palaeozoic times: The gain and loss of a terrane's identity: Earth Science Reviews, v. 72, p. 39–66.

Corfu, F., 2004, U–Pb age, setting, and tectonic significance of the anorthosite-mangerite-charnockite-granite-suite, Lofoten-Vesterålen, Norway: Journal of Petrology, v. 45, p. 1799–1819.

Corfu, F., and Easton, R. M., 2001, U-Pb evidence for polymetamorphic history of Huronian rocks within the Grenville Front Tectonic Zone east of Sudbury, Ontario, Canada: Chemical Geology, v. 172, p. 149–171.

Corfu, F., Hanchar, J. M., Hoskin, P. W. O., and Kinny, P., 2003, Atlas of zircon textures, *in* Hanchar, J. M., and Hoskin, P. W. O., editors, Zircon: Mineralogical Society of America, Reviews in Mineralogy and Geochemistry, v. 53, p. 468–500.

Corfu, F., Roberts, R. J., Gerber, M., Torsvik, T. H., Andersen, T. B., Ramsay, D. M., and Ashwal, L. D., 2005, Exotic terranes in the Finnmarkian Caledonides: U–Pb evidence for Peri-gondwanan and Laurentian elements: Norwegian Geological Wintermeeting Røros (N), Abstracts and Proceedings No. 1, p. 22.

Corfu, F., Torsvik, T. H., Andersen, T. B., Ashwal, L. D., Ramsay, D. M., and Roberts, R. J., 2006, Early Silurian mafic/ultramafic and granitic plutonism in contemporaneous flysch, Magerøy, northern Norway: U-Pb ages and regional significance: Journal of the Geological Society, v. 163, p. 291–301.

Dallmeyer, R. D., 1988, Polyorogenic $^{40}Ar/^{39}Ar$ mineral age record within the Kalak Nappe Complex, Northern Scandinavian Caledonides: Journal of the Geological Society, v. 145, p. 705–716.

Dallmeyer, R. D., Mitchell, J. G., Pharaoh, T. C., Reuter, A., and Andresen, A., 1988, K-Ar and $^{40}Ar/^{39}Ar$ whole rock ages of slate / phyllite from allochthonous basement and cover in the tectonic windows of Finnmark, Norway: Evaluating the extent and timing of Caledonian tectonothermal activity: Geological Society of America Bulletin, v. 100, p. 1493–1501.

Daly, J. S., Aitcheson, S. J., Cliff, R. A., Gayer, R. A., and Rice, A. H. N., 1991, Geochronological evidence from discordant plutons for a late Proterozoic orogen in the Caledonides of Finnmark, northern Norway: Journal of the Geological Society, v. 148, p. 29–40.

Essex, R. M., Gromet, L. P., Andréasson, P. G., and Albrecht, L., 1997, Early Ordovician U-Pb metamorphic ages of the eclogite-bearing Seve Nappes, northern Scandinavian Caledonides: Journal of Metamorphic Geology, v. 15, p. 665–676.

Gayer, R. A., Hayes, S. J., and Rice, A. H. N., 1985, The structural development of the Kalak Nappe Complex of Eastern and central Porsangerhalvøya, Finnmark, Norway: Norges geologiske undersøkelse Bulletin, v. 400, p. 67– 87.

Gayer, R. A., Rice, A. H. N., Roberts, D., Townsend, C., and Welbon, A., 1987, Restoration of the Caledonian Baltoscandian margin from balanced cross-sections: the problem of excess continental crust: Transactions of the Royal Society of Edinburgh, v. 78, p. 197–217.

Gee, D. G., 1975, A tectonic model for the central part of the Scandinavian Caledonides: American Journal of Science, v. 275A, p. 468–515.

——— 2005, Timanides of northern Russia, *in* Selley, R. C., Cocks, L. R. M., and Plimer, I. R., editors, Encyclopedia of Geology: Oxford, Elsevier, v. 2, p. 49–56.

Gee, D. G., Kumpulainen, R., Roberts, D., Stephens, M. B., Thon, A., and Zachrisson, E., 1985, Scandinavian Caledonides, Tectonostratigraphic map, *in* Gee, D. G., and Sturt, B. A. editors, The Caledonide Orogen: Scandinavia and related areas: Chichester, John Wiley.
Gerber, M., ms, 2006, Geochronological studies in the northern Scandinavian Caledonides, Finnmark Province, northern Norway: new evidence for Grenvillian and Scandian components in the Kalak Nappe Complex and the extent of the Magerøy Nappe: University of Witwatersrand, M.Sc. thesis, 85 p.
Gromet, L. P., Sjöstrom, H., Bergman, S., Claesson, R. M., Andréasson, P. G., and Albrecht, L., 1996, Contrasting ages of metamorphism in the Seve Nappes: U–Pb results from the central and northern Swedish Caledonides: GFF, v. 118, p. A36–A37.
Hartz, E. H., and Torsvik, T. H., 2002, Baltica upside-down: A new plate-tectonic model for Rodinia and the Iapetus Ocean: Geology, v. 30, p. 255–258.
Hibbard, J. P., Stoddard, E. F., Secor, D. T., and Dennis, A. J., 2002, The Carolina Zone: overview of Neoproterozoic to early Paleozoic peri-Gondwanan terranes along the eastern flank of the Southern Appalachians: Earth Science Reviews, v. 57, p. 299–339.
Highton, A. J., Hyslop, E. K., and Noble, S. R., 1999, U-Pb zircon geochronology of migmatization in the northern central Highlands; evidence for pre-Caledonian (Neoproterozoic) tectonometamorphism in the Grampian Block, Scotland: London, Journal of the Geological Society, v. 156, p. 1195–1204.
Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C., and Essling, A. M., 1971, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U: Physical Review, Section C, Nuclear Physics, v. 4, p. 1889–1906.
Kalsbeek, F., Thrane, K., Nutman, A. P., and Jepsen, H. F., 2000, Late Mesoproterozoic to early Neoproterozoic history of the East Greenland Caledonides: evidence for Grenville orogenesis?: London, Journal of the Geological Society, v. 157, p. 1215–1225.
Kinny, P. D., Strachan, R. A., Kocks, H., and Friend, C. R., 2003, U-Pb geochronology of late Neoproterozoic augen granites in the Moine Supergroup, NW Scotland: dating of rift-related, felsic magmatism during supercontinent break-up?: London, Journal of the Geological Society, v. 160, p. 925–934.
Kirkland, C. L., and Daly, J. S., 2003, Confirmation of the Porsanger Orogeny in the Caledonides of Arctic Norway: Edinburgh, Scotland, United Kingdom, The Highlands Workshop 2003, abstract, p. 3.
Kirkland, C. L., Daly, J. S., and Whitehouse, M. J., 2005, Early Silurian magmatism and the Scandian evolution of the Kalak Nappe Complex, Finnmark, Arctic Norway: London, Journal of the Geological Society, v. 162, p. 985–1003.
——— 2006, Granitic magmatism of Grenvillian and late Neoproterozoic age in Finnmark, Arctic Norway — Constraining pre-Scandian deformation in the Kalak Nappe Complex: Precambrian Research, v. 145, p. 24.51.
Krill, A. G., and Zwaan, B., 1987, Reinterpretation of Finnmarkian deformation on western Sørøy, northern Norway: Norsk Geologisk Tidsskrift, v. 67, p. 15–24.
Krogh, T. E., 1973, A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485–494.
——— 1982, Improved accuracy of U–Pb zircon ages by the creation of more concordant systems using an air abrasion technique: Geochimica et Cosmochimica Acta, v. 46, p. 637–649.
Lindahl, I., Stevens, B. P. J., and Zwaan, B. K., 2005, The geology of the Vaddas area, Troms: a key to our understanding of the Upper Allochthon in the Caledonides of northern Norway: Norges geologiske undersokelse Bulletin, v. 445, p. 5–43.
Ludwig, K. R., 2003, Isoplot 3.0. A geochronological toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication No. 4, 70 p.
Mørk, M. B. E., Kullerud, K., and Stabel, A., 1988, Sm-Nd dating of Seve eclogites, Norrboten, Sweden - Evidence for Early Caledonian (505 Ma) subduction: Contributions to Mineralogy and Petrology, v. 99, p. 344–351.
Nance, R. D., Murphy, J. B., and Keppie, J. D., 2002, A Cordilleran model for the evolution of Avalonia: Tectonophysics, v. 352, p. 11–31.
Paulsson, O., and Andréasson, P. G., 2002, Attempted break-up of Rodinia at 850 Ma; geochronological evidence from the Seve-Kalak Superterrane, Scandinavian Caledonides: London, Journal of the Geological Society, v. 159, p. 751–761.
Pearson, D. E., 1971, Problems concerning the Kvænangen nappe fold: Norges geologiske undersøkelse, v. 269, p. 85–88.
Pease, V., Gee, D. G., Vernikovsky, V., Vernikovskaya, A., and Kireev, S., 2001, Geochronological evidence for late-Grenvillian magmatic and metamorphic events in central Taimyr, northern Siberia: Terra Nova, v. 13, p. 270–280.
Pedersen, R. B., Dunning, G. R., and Robins, B., 1989, U-Pb ages of nepheline syenite pegmatites from the Seiland Magmatic Province, N. Norway, *in* Gayer, R. A., editor, The Caledonide Geology of Scandinavia: London, Graham and Trotman, p. 3–8.
Pedersen, R. B., Bruton, D. L., and Furnes, H., 1992, Ordovician faunas, island arcs and ophiolites in the Scandinavian Caledonides: Terra Nova, v. 4, p. 217–222.
Pharaoh, T., 1985, The stratigraphy and sedimentology of autochthonous metasediments in the Repparfjord – Komagfjord Tectonic Window, west Finnamark, *in* Gee, D. G., and Sturt, B. A., editors, The Caledonian Orogen – Scandinavia and Related areas: New York, Wiley, p. 347–357.
Ramsay, D., and Sturt, B., 1976, The syn-metamorphic emplacement of the Magerøy Nappe: Norsk Geologisk Tidsskrift, v. 56, p. 291–307.

Ramsay, D. M., Sturt, B. A., Zwaan, K. B., and Roberts, D., 1985a, Caledonides of Northern Norway, *in* Gee, D. G., and Sturt, B. A., editors, The Caledonian Orogen – Scandinavia and Related areas: New York, Wiley, p. 163– 184

Ramsay, D. M., Sturt, B. A., Jansen, Ø., Andersen, T. B., and Sinha-Roy, S., 1985b, The tectonostratigraphy of western Porsangerhalvøya, Finnmark, North Norway, *in* Gee, D. G., and Sturt, B. A., editors, The Caledonian Orogen – Scandinavia and Related areas: New York, Wiley, p. 611– 619.

Rice, A. H. N., 1990, Possible basement rocks in the Kalak Nappe Complex on Sørøy, Finnmark, N. Norway: Norsk Geologisk Tidsskrift, v. 70, p. 159 –172.

Roberts, D., 1968, Hellefjord Schist Group – a probable turbidite formation from the Cambrian of Sørøy, West Finnmark: Norsk Geologisk Tidsskrift, v. 48, p. 231–244.

——— 1974, Hammerfest. Description of the 1 : 250 000 geological map: Norges geologiske Undersøkelse, v. 301, p. 1– 66.

——— 1985, The Caledonian fold belt in Finnmark: a synopsis: Norges geologiske undersøkelse Bulletin, v. 403, p. 161–177.

Roberts, D., and Gee, D. G., 1985, An introduction to the structure of the Scandinavian Caledonides, *in* Gee, D. G., and Sturt, B. A., editors, The Caledonian Orogen – Scandinavia and Related areas: New York, Wiley, p. 56 – 68.

Roberts, D., and Olovyananishnikov, V., 2004, Structural and tectonic development of the Timanide region, *in* Gee, D. G., and Pease, V., editors, The Neoproterozoic Timanide orogen of eastern Baltica: London, Geological Society, Memoirs, v. 30, p. 47–57.

Roberts, D., and Siedlecka, A., 2002, Timanian orogenic deformation along the northeastern margin of Baltica, northwest Russia and northeast Norway, and Avalonian-Cadomian connections: Tectonophysics, v. 352, p. 169 –184.

Roberts, D., and Sundvoll, B., 1990, Rb-Sr whole-rock and thin-slab dating of mylonites from the Kalak Thrust Zone, near Børselv, Finnmark: Norsk Geologisk Tidsskrift, v. 70, p. 259 –266.

Roberts, R. J., Corfu, F., Torsvik, T. H., Ramsay, D. M., and Ashwal, L. D., 2006, Short-lived mafic magmatism at 570 Ma in the northern Norwegian Caledonides- U/Pb zircon ages from the Seiland Igneous Province: Geological Magazine, v. 143, p. 1–17.

Robins, B., and Gardner, P. M., 1975, The magmatic evolution of the Seiland Province, and Caledonian plate boundaries in northern Norway: Earth and Planetary Science Letters, v. 26, p. 167–178.

Rogers, G., Kinny, P. D., Strachan, R. A., Friend, C. R. L., and Paterson, B. A., 2001, U-Pb geochronology of the Fort Augustus granite gneiss; constraints on the timing of Neoproterozoic and Palaeozoic tectonothermal events in the NW Highlands of Scotland: London, Journal of the Geological Society, v. 158, p. 7–14.

Schärer, U., 1984, The effect of initial ^{230}Th disequilibrium on young U–Pb ages: The Makalu case, Himalaya: Earth and Planetary Science Letters, v. 67, p. 191–204.

Siedlecka, A., Roberts, D., Nysturn, J. P., and Olovyananishnikov, V. G., 2004, Northeastern and northwestern margins of Baltica in Neoproterozoic time: evidence from the Timanian and Caledonian orogens, *in* Gee, D. G., and Pease, V., editors, The Neoproterozoic Timanide orogen of eastern Baltica: London, Geological Society, Memoirs, v. 30, p. 169 –190.

Slagstad, T., Melezhik, V. A., Kirkland, C. L., Zwaan, K. B., Roberts, D., Gorokhov, I. M., and Fallick, A. E., 2006, Carbonate isotope chemostratigraphy suggests revisions to the geological history of the West Finnmark Caledonides, northern Norway: London, Journal of the Geological Society, v. 163, p. 277–289.

Stephens, M. B., and Gee, D. G., 1989, Terranes and polyphase accretionary history in the Scandinavian Caledonides: Geological Society of America, Special Paper, v. 230, p. 17–30.

Storey, C. D., Brewer, T. S., and Parrish, R. R., 2004, Late-Proterozoic tectonics in northwest Scotland: one contractional orogeny or several?: Precambrian Research, v. 134, p. 227–247.

Sturt, B. A., and Austrheim, H., 1985, Age of gneissic rocks in the Caledonian nappes of the Alta district, northern Norway: Norges geologiske undersøkelse, v. 403, p. 179 –181.

Sturt, B. A., and Ramsay, D. M., 1999, Early Ordovician terrane-linkages between oceanic and continental terranes in the central Scandinavian Caledonides: Terra Nova, v. 11, p. 79 – 85.

Sturt, B. A., Pringle, I. R., and Roberts, D., 1975, Caledonian nappe sequence of Finnmark, Northern Norway, and the timing of orogenic deformation and metamorphism: Geological Society of America Bulletin, v. 86, p. 710 – 718.

Sturt, B. A., Pringle, I. R., and Ramsay, D. M., 1978, The Finnmarkian phase of the Caledonian Orogeny: London, Journal of the Geological Society, v. 135, p. 597– 610.

Tanner, P. W. G., and Evans, J. A., 2003, Late Precambrian U-Pb titanite age for peak regional metamorphism and deformation (Knoydartian orogeny) in the western Moine, Scotland: London, Journal of the Geological Society, v. 160, p. 555–564.

Tollo, R. P., Aleinikoff, J. N., Bartholomew, M. J., and Rankin, D. W., 2004, Neoproterozoic A-type granitoids of the Central and Southern Appalachians: intraplate magmatism associated with episodic rifting of the Rodinian supercontinent: Precambrian Research, v. 128, p. 3–38.

Torsvik, T. H., and Cocks, L. R. M., 2005, Norway in space and time: A Centennial cavalcade: Norwegian Journal of Geology, v. 85, p. 73– 86.

Torsvik, T. H., and Rehnström, E. F., 2003, The Tornquist Sea and Baltica-Avalonia docking: Tectonophysics, v. 362, 67– 82.

Vaasjoki, M., and Sipilä, P., 2001, U-Pb isotope determinations on baddeleyite and zircon from the Halti-Ridnitsohkka intrusion in Finnish Lapland: a further constraint on Caledonide evolution: Geological Society of Finland, Special Paper, v. 33, p. 247–253.

Vernikovsky, V. A., and Vernikovskaya, A. E., 2001, Central Taimyr accretionary belt (Arctic Asia); Meso-Neoproterozoic tectonic evolution and Rodinia breakup: Precambrian Research, v. 110, p. 127–141.

Vernikovsky, V. A., Vernikovskayaa, A. E., Kotov, A. B., Sal'nikova, E. B., and Kovach, V. P., 2003, Neoproterozoic accretionary and collisional events on western margin of the Siberian craton: new geological and geochronological evidence from the Yenisey Ridge: Tectonophysics, v. 375, p. 147– 168.
Vogt, T., 1927, Sulitelmafeltets geologi og petrografi: Norges geologiske undersøkelse, v. 121, 560 p.
Williams, I. S., and Claesson, S., 1987, Isotopic evidence for the Precambrian provenance and Caledonian metamorphism of high grade paragneisses from the Seve Nappes, Scandinavian Caledonides. II. Ion microprobe zircon U-Th-Pb: Contributions to Mineralogy and Petrology, v. 97, p. 205–217.
Zwaan, K. B., 1988, Nordreisa, berggrunnsgeologisk kart M – 1:250 000: Norges geologiske Undersøkelse.
Zwaan, K. B., and Roberts, D., 1978, Tectonostratigraphic succession and development of the Finnmarkian nappe sequence, North Norway: Norges geologiske Undersøkelse, v. 343, p. 53–71.
Zwaan, B .K., and Van Roermund, H. L., 1990, A rift-related mafic dyke swarm in the Corrovarre Nappe of the Caledonian middle allochthon, Troms, North Norway, and its tectonometamorphic evolution: Norges geologiske undersokelse Bulletin, v. 419, p. 25– 44.