

Provenance and Terrane Evolution of the Kalak Nappe Complex, Norwegian Caledonides: Implications for Neoproterozoic Paleogeography and Tectonics

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ABSTRACT

The Kalak Nappe Complex (KNC) within the northernmost Arctic Norwegian Caledonides has traditionally been interpreted as representing the tectonically shortened margin of Baltica, consisting of a Precambrian basement and a late Precambrian to Cambrian cover deposited on the margin of the Iapetus Ocean. However, new geochronology indicates a distinctly different scenario. Detrital zircon U-Pb dating, together with the magmatic and deformation history, shows that the KNC metasediments, previously considered as a single stratigraphic sequence, belong to at least two distinct successions. Metasediments of the Svaerholt Succession, within the lower (Kolvik and Olderfjord) nappes of the KNC and affected by the late Grenvillian Rigolet deformation phase, were deposited between ca. 980 and 1030 Ma, constrained by intrusive granites and the youngest detrital zircons. The Sørøy Succession occurs within the Sørøy-Seiland Nappe, the Havvatnet Imbricate Stack, and Veines Nappe (the upper nappes of the KNC). It was affected by the Porsanger Orogeny at or before ca. 840 Ma and contains detrital zircons as young as 910 ± 15 Ma, and it was thus deposited between ca. 840 and 910 Ma. The Eidvågeid Paragneiss, classically interpreted as the basement to the KNC metasediments, has a similar detrital zircon population to the Sørøy Succession and may be correlative to it. It cannot represent the basement to the entire KNC and was affected by metamorphic events at ca. 710, 670, 560, and 520 Ma. The detrital zircon populations of both KNC successions are consistent with a Laurentia-Baltica affinity, with age peaks corresponding to Labradorian/Gothian, Pinwarian, and Grenville/Sveconorwegian events. The detrital age populations of the Sørøy Succession bear strong similarity to those from the Moine Supergroup of Scotland, while the Svaerholt Succession is comparable with the Krummedal supracrustal sequence in Greenland. The provenance data are consistent with episodic amalgamation of two terranes, exotic to the Baltoscandian margin of Iapetus, which developed in successor basins to the Grenville Orogen along the indented Rodinia margin.

Online enhancements: appendixes, including figures, table.

Introduction

Sedimentary basins and their detrital provenance are both a consequence and valuable archive of major tectonic reorganizations of Earth's lithosphere. Detrital zircon geochronology is a powerful method of provenance analysis that can help to constrain paleogeography and hence tectonic reconstructions and crustal evolution (e.g., Murphy et al. 2004).

Because the Neoproterozoic (1.0–0.545 Ga) is such a significant time in earth history, involving

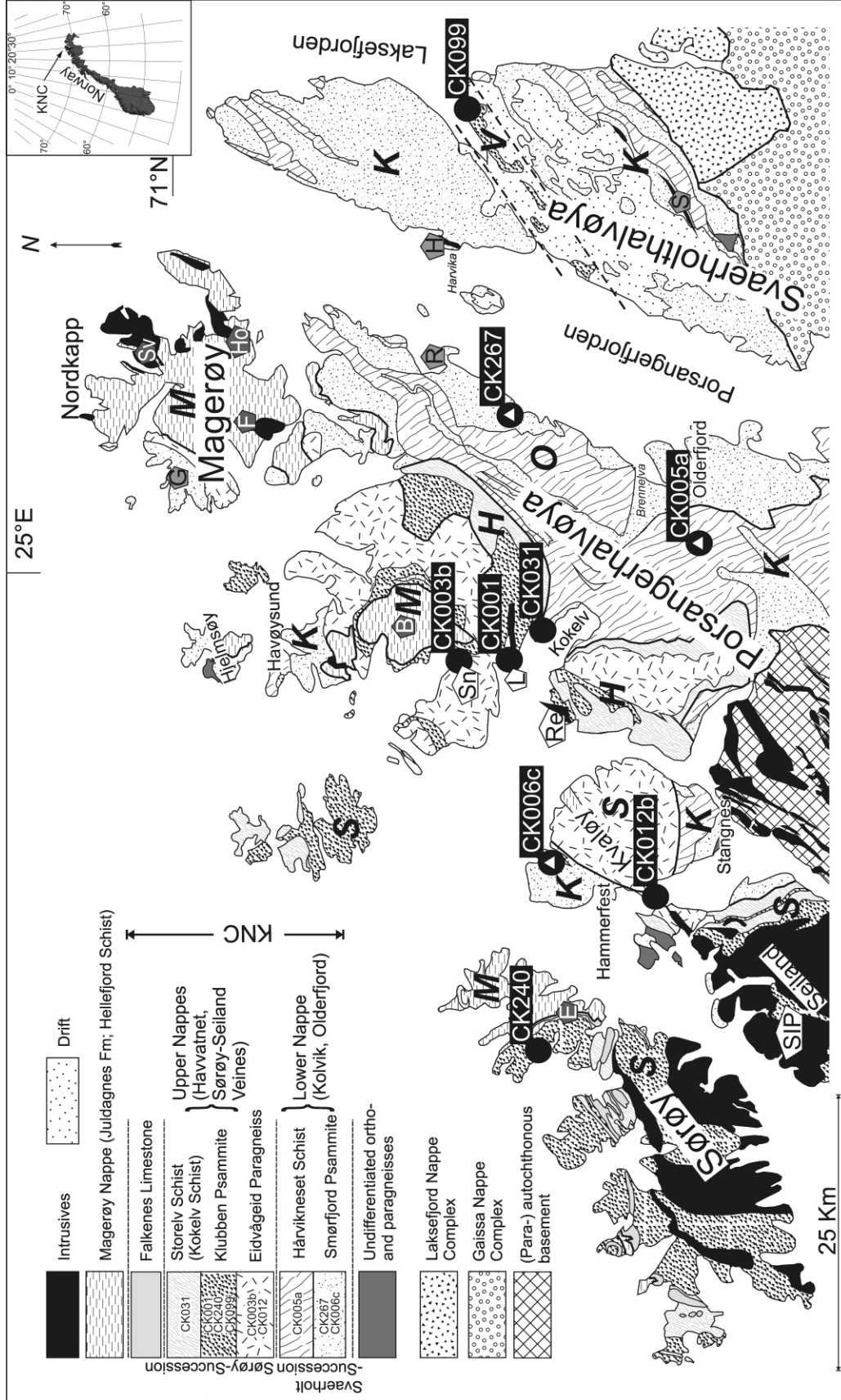
the creation and destruction of the Rodinia supercontinent (Young 1995; Karlstrom et al. 2000), climatic extremes (Kaufman et al. 1997; Hoffman et al. 1998), and the eventual development of the first hard-bodied organisms (Grotzinger et al. 1995), there is great interest in its paleogeography (Thomas 1991; Rainbird et al. 1996, 2001; Lund et al. 2003; Cawood et al. 2004) and tectonic history (e.g., Hartz and Torsvik 2002). However, actualistic paleogeographic reconstructions are hampered by the allochthonous nature of much of the rock record, which resulted from major plate reorganization in the Paleozoic and is associated with the Caledonian-Appalachian Orogen.

Neoproterozoic-age magmatism and deformation

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events are known from many allochthonous sequences in the North Atlantic region (Daly et al. 1991; Rogers et al. 1998; Watt and Thrane 2001; Paulsson and Andréasson 2002; Tanner and Evans 2003; Daly and Flowerdew 2005; Kirkland et al. 2006), but the original locations of these rocks are poorly constrained.

A case in point is the Kalak Nappe Complex (KNC) in Finnmark, northern Norway (fig. 1), within the Scandinavian Caledonides. The KNC is a stacked series of thrust nappes whose protoliths classically have been interpreted as originating in sedimentary basins on the Ediacaran continental margin of Baltica during the development of the Iapetus Ocean (Sturt et al. 1978; Ramsay and Sturt 1986; Siedlecka et al. 2004). However, the fact that the KNC contains rocks affected by Neoproterozoic orogenic structures (Daly et al. 1991; Corfu et al. 2004; Kirkland and Daly 2004; Kirkland et al. 2006) and a component of juvenile Mesoproterozoic crust (Aitchison 1990) undermines the conventional model. Moreover, Kirkland et al. (2006) have demonstrated the presence of Grenvillian material within the lower nappes of the KNC, inviting a more exotic origin for the entire complex.

Geological Setting

The KNC was traditionally considered to consist of metasedimentary rocks unconformably overlying para- and orthogneisses (Ramsay 1971; Roberts 1985). The metasedimentary rocks are unfossiliferous and strongly deformed by Caledonian structures, which makes it difficult to constrain their age. The sequence, as originally defined on Sørøy (Ramsay 1971; fig. 1), included quartzose and feldspathic psammites (Klubben Psammite) overlain by muscovite-rich (Storelv Schist) or biotite-rich (Kokelv Schist) pelites (Gayer et al. 1985), marbles and pelites, (Falkenes Marble and Åfjord Pelite), and

greywackes and pelites (Hellefjord Schist). The KNC metasedimentary rocks were interpreted as a continuous depositional sequence, from an alluvial or shallow marine environment to shelf deposition and finally distal pelagic deposits with intercalated turbidites (Roberts 1968a, 1968b, 1971; Ramsay 1971; fig. A1; note that appendix figures A1–A3 are available in the online edition or from the *Journal of Geology* office).

In contrast to the traditional view of the stratigraphy, recent geochronological (Kirkland et al. 2005b, 2006) and geochemical (Slagstad et al. 2006) studies have demonstrated that the KNC metasediments cannot belong to a continuous depositional sequence. The term “Sørøy Succession” that was originally applied to the entire package has been proposed to refer only to the Klubben Psammite and Storelv Schist (Kirkland et al. 2005b).

Orthogneisses (Fagervik Complex) and paragneisses (Eidvågeid Paragneiss) have been interpreted as basement plinths upon which the KNC metasedimentary rocks were deposited (Akselsen 1982). Unconformable contacts between the orthogneiss and the overlying psammitic units have been described at Stangnes on Kvaløy (Ramsay and Sturt 1977; fig. 1) and on Hjelmsøy (Ramsay et al. 1979; fig. 1). Although Ramsay et al. (1985) loosely treated all of the gneissic units in the KNC as basement, it must be emphasized that no primary unconformity is preserved between the paragneiss and the metasediments. The nature of the contact is challenging to assess because of extensive reworking by Caledonian deformation (Ramsay et al. 1985).

The KNC is classically considered as part of the Middle Allochthon (Gee 1975; Roberts 1985), one of the major tectonostratigraphic divisions of the Scandinavian Caledonides (Roberts and Gee 1985). However, the association of Precambrian crystalline rocks, meta-arkoses, and amphibolitized dol-

Figure 1. Simplified geological map of western Finnmark, modified in part after Gayer et al. (1987) and Siedlecka and Roberts (1996), showing the distribution of the stratigraphic and tectonic units discussed in the text. Sample locations: *filled circles* = upper nappes (Sørøy Succession); *filled circles with triangles* = lower nappes (Svaerholt Succession). Nappes are labeled with bold italic letters: ***M*** = Magerøy (Scandian), ***S*** = Sørøy-Seiland, ***H*** = Havvatnet, and ***V*** = Veines (upper nappes of the Kalak Nappe Complex [KNC]); ***K*** = Kolvik; ***O*** = Olderfjord (lower nappes of the KNC). Pentagons represent selected dated igneous rocks and migmatites: ca. 980-Ma intrusives and migmatite are in black text on gray background, ***S*** = Siedgoaivi granite, ***H*** = Hårvika granite, ***R*** = Repvåg granite (Kirkland et al. 2006), and ***G*** = Gjesvær migmatite (Corfu et al. 2005); ca. 840-Ma intrusives and ca. 710-Ma migmatite are in black text on white background: ***L*** = Litlefjord granite, ***Re*** = Revsneshamn granite, and ***Sn*** = Snøfjord leucosome (Kirkland et al. 2006); Silurian intrusives are in white text on gray background: ***B*** = Bakfjord granite, ***E*** = Engesfjellet granite (Kirkland et al. 2005b), ***F*** = Finnvik granite, ***Ho*** = Honningsvåg igneous complex, and ***Sv*** = Skarsvåg granite (Corfu et al. 2006).

erites within the KNC has prompted correlation (Zachrisson 1986) with the Seve Nappes, that is, the lower part of the Upper Allochthon, whose rocks were considered to represent the Iapetus margin of Baltica. This correlation is denoted by the term Seve-Kalak Superterrane (Andréasson et al. 1998).

The KNC is made up of a series of thrust sheets and imbricate stacks formed by repetition of the metasediments and underlying, presumably basement, gneisses (Ramsay et al. 1985; Rice 1987). West of Porsangerfjorden, numerous thrusts have been mapped in detail, and the nappe boundaries are well established (Gayer et al. 1985; fig. 1). East of Porsangerfjorden, few thrusts have been mapped (Rice et al. 1989; fig. 1), and regional correlation of individual nappes is difficult (Rhodes and Gayer 1977; Gayer et al. 1984; Rice 1984). Following Gayer et al. (1987), Daly et al. (1991), and Kirkland et al. (2005b, 2006) and incorporating new information arising from this study, the KNC is divided into five allochthonous units, broadly grouped into "upper" and "lower" nappes. In terms of tectonostratigraphic order, the Sørøy-Seiland Nappe and the underlying Havvatnet Imbricate Stack comprise the upper nappes, while the Kolvik and Olderfjord nappes occupy lower levels. The Veines Nappe, a new structural member of the upper nappes, is proposed, which lies structurally above the Kolvik Nappe on Svaerholthavøya (fig. 1).

Zircon Geochronology

This article presents a detailed detrital zircon geochronology study of the KNC metasediments in the context of well-constrained deformational and magmatic history (Daly et al. 1991; Corfu et al. 2005; Kirkland et al. 2005a, 2006). These data are used to test and refine a model of episodic terrane accretion (Kirkland et al. 2006) and to constrain the age of sedimentation. The results reveal that the KNC metasediments comprise two distinct sequences interpreted as deposited in successor basins to an accretionary orogenic belt on the indented Rodinia margin during the Tonian (1000–850 Ma) and Cryogenian (850–630 Ma).

Analytical data are presented in table B1 (available in the online edition or from the *Journal of Geology* office) and are discussed below in tectonostratigraphic order, with three samples from the lower nappes (CK006c, CK267, and CK005a), four from the upper nappes (CK099, CK001, CK240, and CK031), and two samples (CK003b and CK012) of Eidvågeid Paragneiss (fig. 1). The sample preparation and U-Th-Pb ion microprobe methods are de-

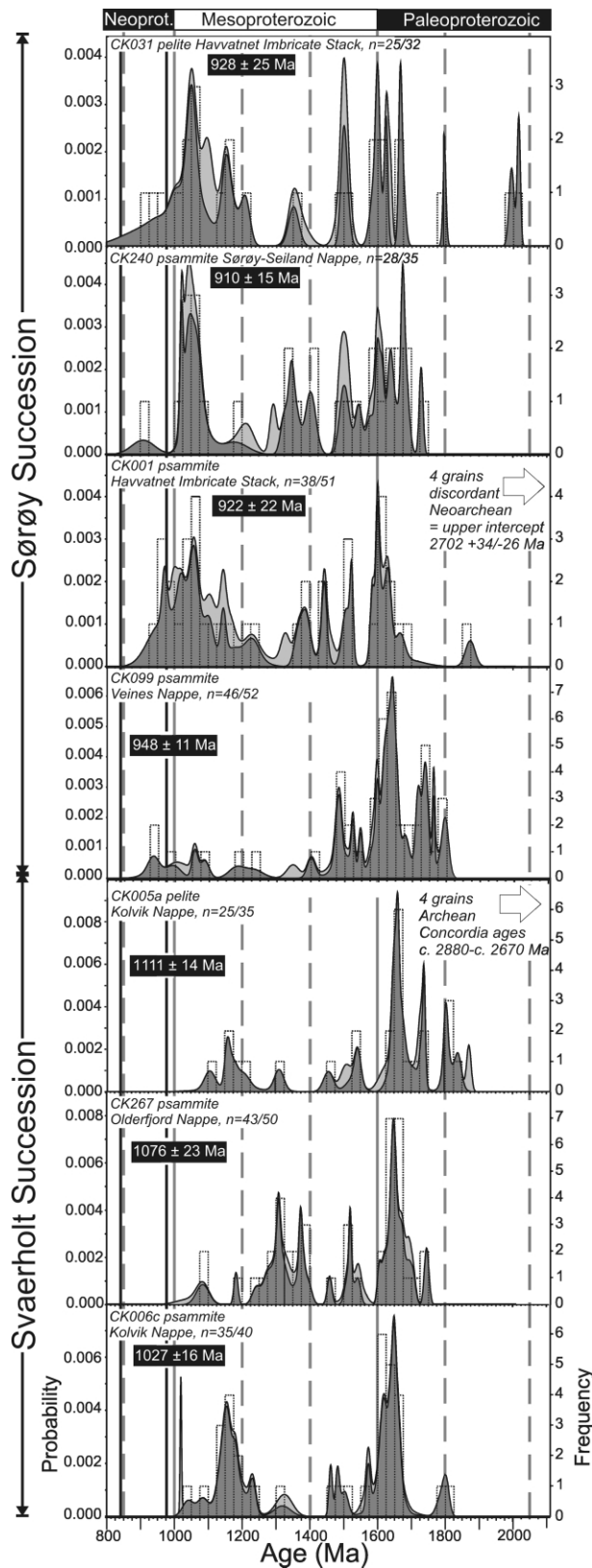
tailed in appendix C, available in the online edition or from the *Journal of Geology* office. Concordia ages (Ludwig 1998) are quoted for the youngest detrital grains, while the probability plots (figs. 2, 3) use $^{207}\text{Pb}/^{206}\text{Pb}$ ages.

Lower Nappes

CK006c: Psammite, Kolvik Nappe. The vast majority of the 40 analyses from CK006c are concordant, with only five being >5% discordant. The two oldest grains together yield a concordia age of 1809 ± 9 Ma (fig. 4). There is a well-defined peak at ca. 1650 Ma, corresponding to ca. 40% of the total population. A younger peak at ca. 1575 Ma is defined by two grains, while three grains have ages between ca. 1450 and 1525 Ma (fig. 2). Between ca. 1450 and ca. 1250, there is one grain at ca. 1325 Ma. The youngest peak reflects a spread of ages between ca. 1000 and 1250 Ma, with a maximum at ca. 1150 Ma (fig. 2). The youngest concordant grain has a concordia age of 1027 ± 16 Ma and a moderate Th/U ratio of 0.16. The analytical spot was on a cathodoluminescence (CL)-bright idiomorphically zoned overgrowth that surrounds a CL-dark core (fig. 5C), which has a concordia age of 1648 ± 9 Ma. One spot, on a brown, CL-dark, U-rich (8028 ppm) grain (5a, table B1) shows a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1019 ± 4 Ma but is strongly reversely discordant.

CK267: Psammite, Olderfjord Nappe. Forty-three out of 50 grains from CK267 are <5% discordant (table B1; fig. 4). Most grains are clear and euhedral, with aspect ratios of ca. 4–5 and with few showing any indication of surface pitting or frosting. The oldest grain has a concordia age of 1748 ± 12 Ma. The next youngest grains have greater discordance but may belong to a single population with an upper intercept of ca. 1748 Ma, subject to lead loss at ca. 440 Ma, a time of known thermal perturbation during initial Caledonian deformation within the KNC (Dangla et al. 1978; Corfu et al. 2004; Kirkland et al. 2005a, 2006). Fourteen grains have ages around 1650 Ma (fig. 2). The next youngest peak is at ca. 1510 Ma. Only one grain, with a concordia age of 1461 ± 13 Ma, falls between 1400 and 1500 Ma. A spread of ages occurs between 1200 and 1400 Ma, with a maximum at ca. 1310 Ma. Five grains have concordia ages between ca. 1310 and 1330 Ma. The youngest grain (fig. 5c) has a concordia age of 1076 ± 23 Ma.

CK005a: Pelite, Kolvik Nappe. Sample CK005a contains small detrital zircons (<150 μm), of which only five from 35 analyses are >5% discordant (table B1; fig. 4). The oldest grain has a Neoproterozoic

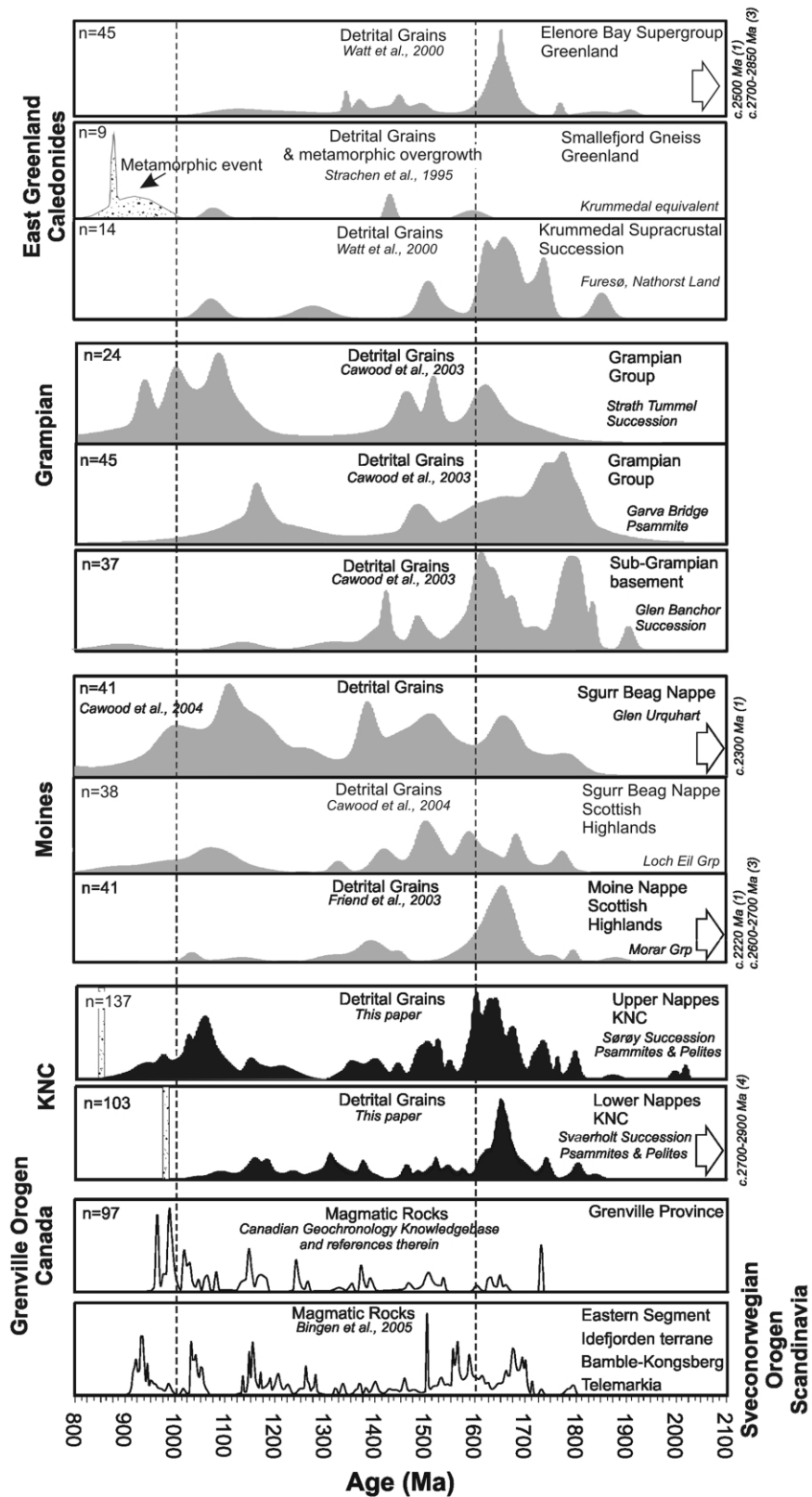


concordia age of 2882 ± 11 Ma, and another grain has an age of 2637 ± 31 Ma. The next peak on the probability density diagram is at ca. 1800 Ma, while another peak occurs at ca. 1720 Ma (fig. 2). Grains dated at ca. 1650 Ma account for about one-quarter of the total population. Several grains have $^{207}\text{Pb}/^{206}\text{Pb}$ ages between ca. 1450 and 1550 Ma. The youngest age peak occurs at ca. 1150 Ma, while the youngest detrital grain (fig. 5c) has a concordia age of 1111 ± 14 Ma and a Th/U ratio of 0.33. This spot is on a CL-dark core with an undated CL-brighter overgrowth. A younger concordia age of 737 ± 9 Ma, from a CL-dark overgrowth on grain 30 (fig. 5c) with a low Th/U ratio, is interpreted as metamorphic. This age is probably slightly too old for the metamorphic overgrowth, because the spot may have inadvertently sampled both the overgrowth and an older core. Metamorphism at ca. 710 Ma is known from a higher-level nappe (Havvatnet Imbricate Stack), and a synkinematic pegmatitic leucosome within the Sørøy-Seiland Nappe has yielded a U-Pb concordia age of 709 ± 4 Ma (Kirkland et al. 2006).

Upper Nappes

CK099: Psammite, Veines Nappe. All 52 analyses from CK099 (fig. 1) fall on or very near concordia, with only six being >5% discordant (table B1; fig. 4). The three oldest grains yield a concordia age of 1790 ± 10 Ma (fig. 4). Three younger grains have ages near ca. 1750 Ma; two yield concordia ages of 1762 ± 6 and 1740 ± 12 Ma. The next six youngest zircons produce a well-defined concordia age of 1728 ± 6 Ma (MSWD = 1.5), corresponding to the second largest peak on the probability density diagram (fig. 2). The next peak on the probability den-

Figure 2. Number/relative probability versus age plot for <5%-discordant U-Pb analyses (table B1) of detrital zircons from metasediments in the Kolvik, Olderfjord, Havvatnet, Sørøy-Seiland, and Veines nappes, arranged according to tectonostratigraphic position within the Kalak Nappe Complex. Concordia ages of the youngest detrital zircons are shown with 2σ errors in white lettering on black boxes. Dashed lines indicate period divisions at 850, 1200, 1400, 1800, and 2050 Ma (Gradstein et al. 2004). Dark solid lines indicate ages of granitic magmatism in lower nappes (ca. 980 Ma) and upper nappes (ca. 840 Ma). The probability distribution plots (light gray) include ages with >5% discordance. The number of grains that are <5% discordant and the total number of analyzed grains are indicated.



sity diagram is at ca. 1630 Ma and corresponds to a concordia age from five of these spots at 1631 ± 7 Ma (MSWD = 1.07). A subsidiary peak on the probability density diagram occurs at ca. 1600 Ma. There is more than one population of zircons between 1600 and 1300 Ma, with the main peak at ca. 1500 Ma. Several grains occur between ca. 1250 and ca. 900 Ma. The two youngest grains yield a concordia age of 948 ± 11 Ma. They display CL-bright oscillatory zoning (fig. 5a) and euhedral facets and have high Th/U ratios characteristic of magmatic zircon (Klötzli 1999; Rubatto 2002).

CK001: Psammite, Havvatnet Imbricate Stack. Data were obtained from 51 grains. The majority are morphologically similar to those from psammite CK267 in the underlying nappe, though with additional large stubby grains. Thirty-eight grains yielded concordant Paleoproterozoic to early Neoproterozoic ages between 1874 and 928 Ma (fig. 4). The oldest analysis is 12% discordant, with an age of 2626 ± 11 Ma, which, together with three younger and more discordant Neoproterozoic grains, defines an age of $2702 +34/-26$ Ma and a lower intercept of $988 +88/-84$ Ma. Spot 34a is from a CL-dark grain margin, whereas spot 34b is from a CL-bright core. Both these spots have Th/U ratios >0.2 . The core shows more discordance that is probably associated with lead loss facilitated by fractures within the core. This is consistent with the lower intercept reflecting Pb loss during a late Grenvillian metamorphic event. An inherited zircon component within a pegmatite cutting psammites and also within the Havvatnet Imbricate Stack has a Neoproterozoic concordant age of 2707 ± 21 Ma (Kirkland et al. 2006). The oldest concordant grain has an age of 1861 ± 24 Ma. On the probability density diagram, a pronounced peak is defined at ca. 1600 Ma, although older grains may be present within this peak up to ca. 1700 Ma (fig. 2). There is a well-defined peak at ca. 1500 Ma, and additional grains yield ages at ca. 1430 Ma and between ca. 1340 and 1400 Ma. A broad spread of grains has ages between ca. 1240 and 920 Ma, and within this spread a maximum occurs at ca. 1050 Ma. The youngest grain

(fig. 5a) has a concordia age of 922 ± 22 Ma from a spot in the core region of a CL-bright grain with a Th/U ratio of 0.47. Five other grains yield a concordia age of 967 ± 8 Ma, with MSWD = 1.09. All of these spots are on CL-bright grains, which have indications of idiomorphic zoning (fig. 5a).

CK240: Psammite, Sørøy-Seiland Nappe. The detrital zircons from CK240 display a range of morphologies. About half are colorless and predominantly prismatic. The remainder are more turbid, slightly orange in color, stubby, and have well-rounded terminations. The data display peaks at ca. 1700, ca. 1650, ca. 1600, and ca. 1500 Ma, together with a spread between 1300 and 1400 Ma and a significant peak at ca. 1050 Ma (fig. 2). The oldest grain has an age of 1729 ± 11 Ma and is slightly discordant. The youngest grain (fig. 5a) has a concordia age of 910 ± 15 Ma.

CK031: Pelite, Havvatnet Imbricate Stack. CK031 contains small ($<150 \mu\text{m}$) translucent zircons with a range of morphologies, from stubby rounded prisms to faceted equant grains. Data were obtained from 32 spots on 32 grains. Most of these have $^{207}\text{Pb}/^{206}\text{Pb}$ ages between ca. 900 and 1200 Ma, but older peaks are also present (fig. 2). The oldest grain has a concordia age of 2020 ± 9 Ma and shows idiomorphic zoning with a Th/U ratio of 0.13. Another slightly younger grain contributes to this peak, with a near-concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1999 ± 15 Ma. The next youngest peak on the population density diagram is at ca. 1800 Ma. There is a spread of ages between ca. 1590 and 1700 Ma, and a peak at ca. 1500 Ma (fig. 2). Two grains have a concordia age of 1498 ± 12 Ma, and another two grains show slightly younger ages and more discordance. This distribution of data may suggest a detrital component at $1502 +35/-14$ Ma that experienced Pb loss. Between ca. 1490 and 1200 Ma, there are comparatively few analyses except for two grains that have $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ca. 1350 Ma. There is a broad spread of detrital zircon ages between ca. 900 and 1200 Ma, including a prominent peak at ca. 1050 Ma. The youngest grain (30a, table B1) is one of the largest in the population and is

Figure 3. Cumulative frequency distribution plots comparing detrital zircon $>95\%$ concordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages in the range 800–2100 Ma from North Atlantic Neoproterozoic metasediments (including the Sørøy and Svaerholt successions) and potential source lands in the Grenville and Sveconorwegian orogens. Large open arrows indicate older detrital zircons, summarized on the side of the diagram. Stippled vertical bars in the Kalak Nappe Complex plots represent Rigolet (ca. 980 Ma) and Porsanger (ca. 840 Ma) magmatism in the lower and upper nappes, respectively. In bottom plot (Eastern Segment), $n = 204$. The age of Grenville magmatic rocks is from the Canadian Geochronology KnowledgeBase (2005).

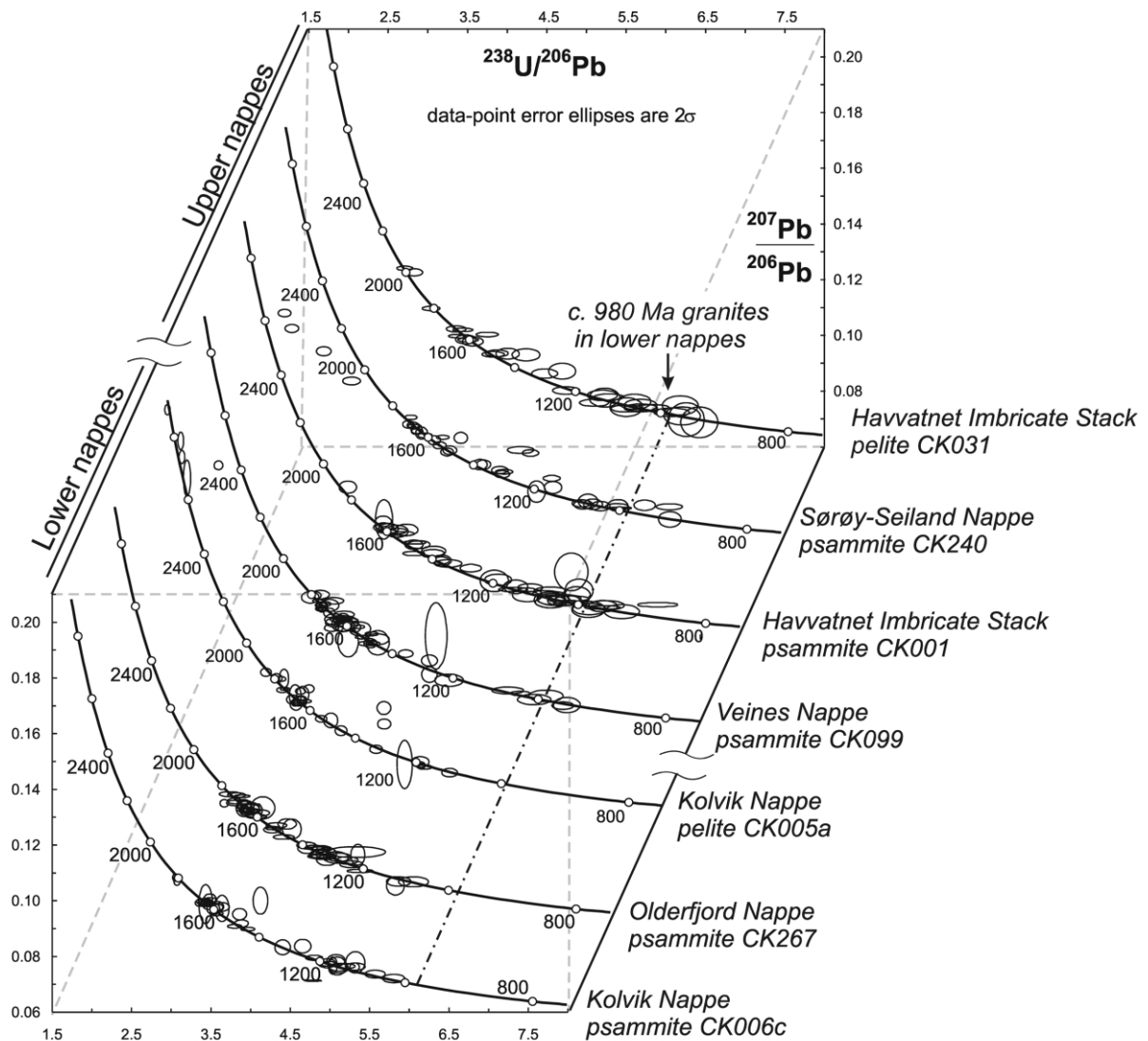


Figure 4. Tera-Wasserburg concordia diagrams for detrital zircons (shown as 2σ error ellipses) from metasedimentary rocks of the Kalak Nappe Complex (KNC). Note that the Sørøy Succession (upper nappes) contains detritus that is younger than the ca. 980-Ma granites (black dot-dashed line) cutting the Svaerholt Succession metasediments in the lower nappes. The KNC metasediments, therefore, must belong to two separate sequences.

distinctly limpid, prismatic, and idiomorphically zoned; it has a high Th/U ratio of 1.14 and a concordia age of 928 ± 25 Ma (fig. 5a).

Eidvågeid Paragneiss

The investigated samples are foliated, dark purple to rusty, weathered garnet-biotite-silimanite $\pm$ kyanite-K-feldspar-bearing migmatitic gneisses, that is, the type lithology of the Eidvågeid Paragneiss (Worthing 1971a, 1971b) from two localities within the Sørøy-Seiland Nappe (fig. 1).

CK003b: Paragneiss, Sørøy-Seiland Nappe. Data were obtained from 20 spots on 17 zircon grains from the mesosome of CK003b, the pegmatitic leucosome of the same rock has an age of 709 ± 4 Ma (Kirkland et al. 2006). Despite the small number of analyses, the data provide important age constraints. The youngest grain has a concordant age of 721 ± 20 Ma and is morphologically distinct from the rest of the population (fig. 5b). It is CL-bright, has a high aspect ratio, and is interpreted as migmatitic in origin (similar to grains of identical age, Th/U ratio, and petrography) in the leucosome

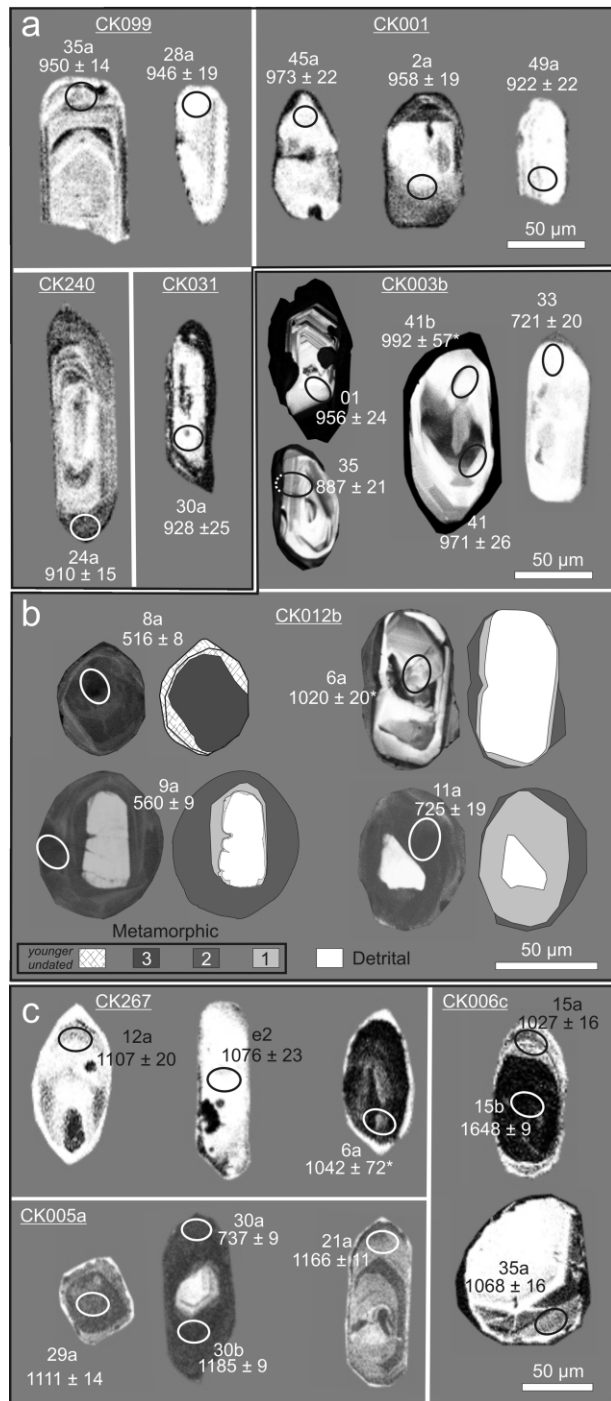


Figure 5. *a*, Scanning electron microscope (SEM) cathodoluminescence (CL) images of selected young zircon grains from the upper nappes of the Kalak Nappe Complex (KNC). *b*, Selected SEM CL images of zircon grains from Eidvågeid paragneiss. CK012b displays multiple generations of metamorphic zircon overgrowth. Interpretative sketch shown at right. Note that grain 33 from CK003b is interpreted as migmatitic in origin. *c*, Selected images of detrital zircons from lower nappes of KNC. Ellipses indicate analyzed regions, labeled with spot

in the same sample (Kirkland et al. 2006). The oldest detrital grain is discordant, and its $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2024 ± 14 Ma is therefore a minimum estimate. Three grains have ages from ca. 1800 to 1500 Ma, while a further three are close to ca. 1250 Ma (fig. 6A). Quite a large spread of ages occurs between ca. 1250 and 900 Ma. The youngest concordia age from a grain interpreted to be detrital is 887 ± 21 Ma (fig. 5b, grain 35, CK003b). However, this may be a mixed age because the spot is located on the rim of an idiomorphically zoned core surrounded by a CL-dark overgrowth (fig. 5a). A more conservative estimate of the youngest component is provided by three detrital grains (01, 41, 43; table B1), which together yield a concordia age of 966 ± 14 Ma (fig. 5a). This is within error of the 976 ± 3 Ma age of late Grenvillian magmatism in the lower nappes of the KNC (Kirkland et al. 2006).

CK012: Paragneiss, Sorøy-Seiland Nappe. Eighteen grains were dated from the mesosome of CK012, which contains subrounded (many nearly spherical) zircons, sometimes with crystal faces. All grains are at least partly mantled by CL-dark overgrowths (fig. 5b), which is interpreted as being metamorphic. The youngest spot in the center of a CL-dark spherical grain has a concordia age of 516 ± 8 Ma (fig. 6B) and a low Th/U ratio of 0.01 (table B1). Two other spots, on CL-dark overgrowths on CL-bright structureless cores (fig. 5b), define a concordia age of 563 ± 6 Ma (fig. 6B). Four CL-dark spherical grains, all with very low Th/U ratios of ca. 0.005, define a concordia age of 672 ± 7 Ma (fig. 6B). This age is identical to the 660 ± 10 -Ma age of a single analysis from the pegmatitic leucosome (CK003) in paragneiss CK003b reported by Kirkland et al. (2006). Another spot on a CL-dark grain (15a) has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 645 ± 30 Ma and may have suffered some lead loss (fig. 6B). Two older grains yield a concordia age of 710 ± 12 Ma (fig. 6B). Another spot (17a) has a moderate Th/U ratio of ca. 0.3 and yields a concordia age of 902 ± 13 Ma, though it is probably an inadvertent mixture between a detrital core and a metamorphic overgrowth. The youngest grain interpreted to be of detrital origin has a concordia age of 965 ± 15 Ma (fig. 6B). Three CL-bright discordant grains have $^{207}\text{Pb}/^{206}\text{Pb}$ ages between ca. 1020 and 1030 Ma and undated CL-darker rims (e.g., 6a, fig. 5b). The oldest detrital grain has a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1717 ± 11 Ma.

numbers and concordia ages with 2σ errors, except an asterisk represents $^{207}\text{Pb}/^{206}\text{Pb}$ ages.

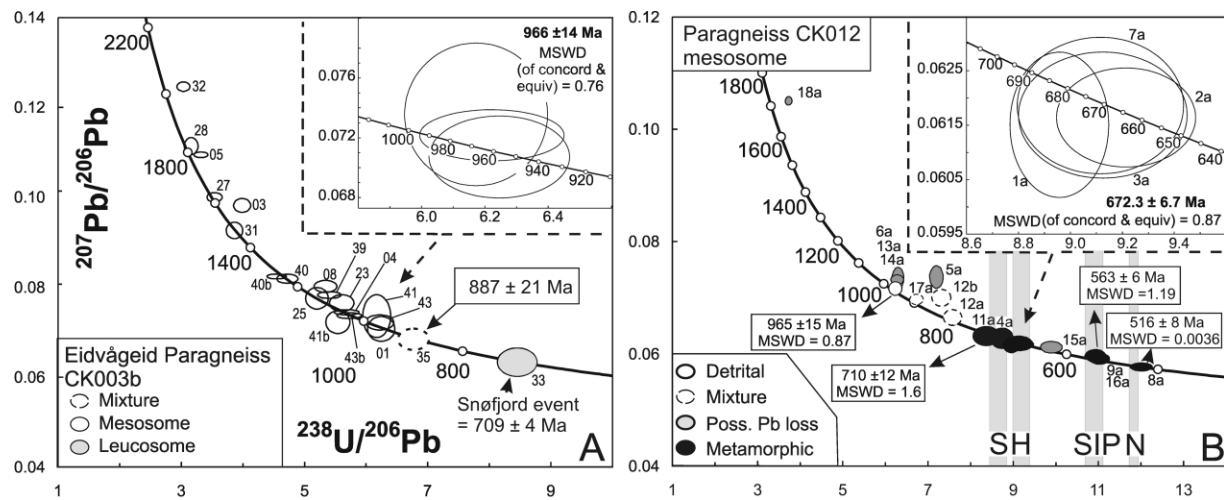


Figure 6. A, Tera-Wasserburg concordia diagram for zircon grains from Eidvågeid paragneiss mesosome (CK003b), with 2σ error ellipses. One analysis from a zircon (33) interpreted to be from a migmatitic leucosome is also shown. B, Tera-Wasserburg concordia diagram with 2σ error ellipses for zircons from Eidvågeid paragneiss (CK012). Gray bars indicate the ages (in terms of $^{238}\text{U}/^{206}\text{Pb}$) of known tectonometamorphic events in the Sørøy-Seiland Nappe. S = Snøfjord event (Kirkland et al. 2006); H = Hasvik gabbro (Aitchison 1989; Daly et al. 1991); SIP = Storvik gabbro, Hasvik gabbroic pegmatite, Kvalfjord gabbro (Mørk and Stabel 1990; Daly et al. 1991; Roberts et al. 2006); N = nepheline syenite pegmatites (Pedersen et al. 1989).

From the multiple CL-dark overgrowths (fig. 5b), low Th/U ratios, and large size and age range of the overgrowths, it is clear that the rock has experienced at least four phases of metamorphic zircon growth/overgrowth at ca. 710, ca. 670, ca. 560, and 520 Ma.

Discussion

Depositional Age of the KNC Metasediments. Metasediments from the lower nappes (Kolvik and Olderfjord) have similar detrital zircon populations but are distinctly different from those in the upper nappes (figs. 2, 4). The lower nappe metasediments are dominated by latest Paleoproterozoic and Mesoproterozoic grains (fig. 3), with peaks around 1680–1590, 1510–1490, and 1350–1150 Ma. Based on the youngest detrital zircon and the oldest intrusive (Kirkland et al. 2006), sedimentation occurred within the Kolvik Nappe after 1027 ± 16 Ma and before 978 ± 9 Ma and in the Olderfjord Nappe after 1076 ± 23 Ma and before 981 ± 7 Ma. Combining these constraints yields an age range between ca. 980 and 1030 Ma.

Metasediments from the upper nappes (Sørøy-Seiland, Havvatnet, and Veines) have similar detrital zircons, dominated by late Mesoproterozoic detritus with a significant component of latest Paleoproterozoic grains. Archean and Paleoproterozoic grains older than 1800 Ma are rare (fig. 3). The upper nappes also contain significant Neoproterozoic detritus that is absent in the lower nappes (figs. 2, 4). Importantly, this includes material younger than the ca. 980-Ma granites that cut the metasediments in the lower nappes (Kirkland et al. 2006). The Havvatnet Imbricate Stack and Sørøy-Seiland Nappe have similar youngest zircon components dated at ca. 910–920 Ma, while the youngest grains in the Veines Nappe are dated at ca. 950 Ma. Assuming that the metasediments correlate between the three nappes, the younger age constraint is provided by the ca. 840-Ma granites in the Havvatnet Imbricate Stack (Kirkland et al. 2006). Thus sedimentation in the upper nappes is bracketed between ca. 910 and 840 Ma. Given the above age constraints on the timing of deposition, it is clear that the KNC metasedimentary rocks cannot have been deposited at the same time and thus cannot belong to a single conformable stratigraphic sequence.

Revisions to the Tectonostratigraphy of the KNC. The term “Sørøy Succession” has been used to refer to all the KNC metasediments under the assumption that they represented a single conformable succession that was correlated regionally (Ramsay et al. 1985; Siedlecka and Roberts 1996; Siedlecka et al. 2004; fig. A1). Kirkland et al. (2005b) showed that the uppermost unit, the Hellefjord Schist, was

deposited in the Llandovery (ca. 438 Ma) and could not be part of the same sequence. Slagstad et al. (2006) used Sr isotopic evidence to conclude that the Falkenes Limestone was deposited between 760 and 710 Ma. Hence, the Sørøy Succession was redefined to include only the lower psammitic and pelitic units (i.e., Klubben Psammite and Storelv Schist and the equivalent Kokelv Schist), between which a transitional contact occurs on Sørøy (Ramsey 1971). Based on the evidence then available (petrography and limited Sm-Nd data), the tacit assumption was made that these units were present throughout the KNC. However, that view is inconsistent with the data presented in this article, that is, the detrital zircon populations and the age constraints on deformation (Kirkland et al. 2006).

Therefore, we propose to restrict the use of the term "Sørøy Succession," comprising Klubben Psammite and Storelv (including Kokelv) Schist, to the upper nappes of the KNC (i.e., Sørøy-Seiland, Havvatnet, and Veines). As discussed above, deposition of the Sørøy Succession took place between ca. 910 and 840 Ma (figs. 2, A1).

The metasediments in the lower nappes belong to a separate succession, deposited between ca. 980 and 1030 Ma, for which we suggest the term "Svaerholt Succession" (fig. A1). The Svaerholt Succession is made up of the Smørfjord Psammite, defined in the Brennelva valley (fig. 1) within the Olderfjord Nappe, and the Hårvikneset Schist, named from its type locality west of the Hårvika granite, within the Kolvik Nappe (fig. 1). The contact between these units is uncertain but may be conformable, based on field mapping and detrital zircon data.

Depositional Constraint on the Eidvågeid Paragneiss. In contrast to the traditional view that the Eidvågeid Paragneiss is the basement to the KNC metasediments, Kirkland et al. (2006) pointed out that it may instead be a high-grade correlative of the metasediments within the upper nappes. This view is supported by the new detrital zircon data; for example, both contain ca. 980-Ma detritus. Nevertheless, the data permit the paragneiss to be the basement to Sørøy Succession since both were deposited before ca. 840 Ma (C. L. Kirkland, J. S. Daly, and M. J. Whitehouse, unpublished results) and after ca. 980 Ma.

It is clear, however, that the Eidvågeid Paragneiss must be younger than the Svaerholt Succession, which was both deposited and deformed before ca. 980 Ma. In paragneiss, CK012, the youngest zircon grain that can be confidently identified as detrital, has an age of 965 ± 15 Ma, while in sample CK003b, three grains yield an identical age of

966 ± 14 Ma. Together these define a weighted mean age of 966 ± 10 Ma, which provides a maximum depositional age for the sedimentary protolith of the Eidvågeid Paragneiss.

Neoproterozoic Tectonic Events and the Exotic Origin of the KNC. The youngest detrital zircons provide new constraints on the tectonic evolution of the KNC. Within the lower nappes, the first deformation events (D1 and D2) occurred between ca. 980 and 1030 Ma, confirming a general correlation with the Grenville Orogeny (Kirkland et al. 2006) but aligning more precisely with the Rigolet phase (Rivers et al. 2002; fig. A2). Within the upper nappes, D1 and D2 deformation occurred between ca. 910 and ca. 840 Ma, that is, in the Porsanger Orogeny (fig. A2), assuming that the same meta-sediments occur in the Sørøy-Seiland Nappe and Havvatnet Imbricate Stack, consistent with their detrital zircon populations (see "Upper Knappes").

The ca. 710-Ma Snøfjord event (Kirkland et al. 2006; fig. A2) was based on the age of a synkinematic leucosome in the Eidvågeid Paragneiss in the Sørøy-Seiland Nappe at Snøfjord (fig. 1) and on a coeval metamorphic zircon overgrowth in the underlying Havvatnet Imbricate Stack. This event has also been recognized in two additional localities, in the Sørøy-Seiland Nappe on Kvaløy (paragneiss CK012, fig. 6B) and in the Kolvik Nappe near Olderfjord (pelite CK005a), indicating that the thermal effects of the Snøfjord event were widespread (fig. 1).

Several later metamorphic events are also recorded by overgrowths on detrital zircon crystals within the paragneiss on Kvaløy (CK012; see above). These correspond to magmatic episodes recorded within the Sm-Nd system (Daly et al. 1991) in the Seiland Igneous Province (SIP). The ca. 710-Ma Snøfjord event corresponds to the older of two Sm-Nd mineral isochrons from the Hasvik Gabbro (Daly et al. 1991). Zircon overgrowths in CK012 at 672 ± 7 Ma (fig. 6B) are identical, within error, to the younger Sm-Nd isochron at 668 ± 68 Ma (Daly et al. 1991). These Sm-Nd ages have been questioned by Roberts et al. (2006), who considered them to reflect mixing with an nonradiogenic source, that is, crustal contamination. Roberts et al. (2006) obtained a U-Pb TIMS zircon age of 562 ± 6 Ma for an eponymous gabbro pegmatite, which they interpreted to reflect crystallization of the entire Hasvik body. Roberts et al. (2006) also dated several other gabbroic bodies between ca. 580 and 560 Ma. Another generation of metamorphic zircon from the Kvaløy paragneiss is dated at 563 ± 6 Ma, identical to the age of the main SIP magmatism. The latest magmatism within the Sei-

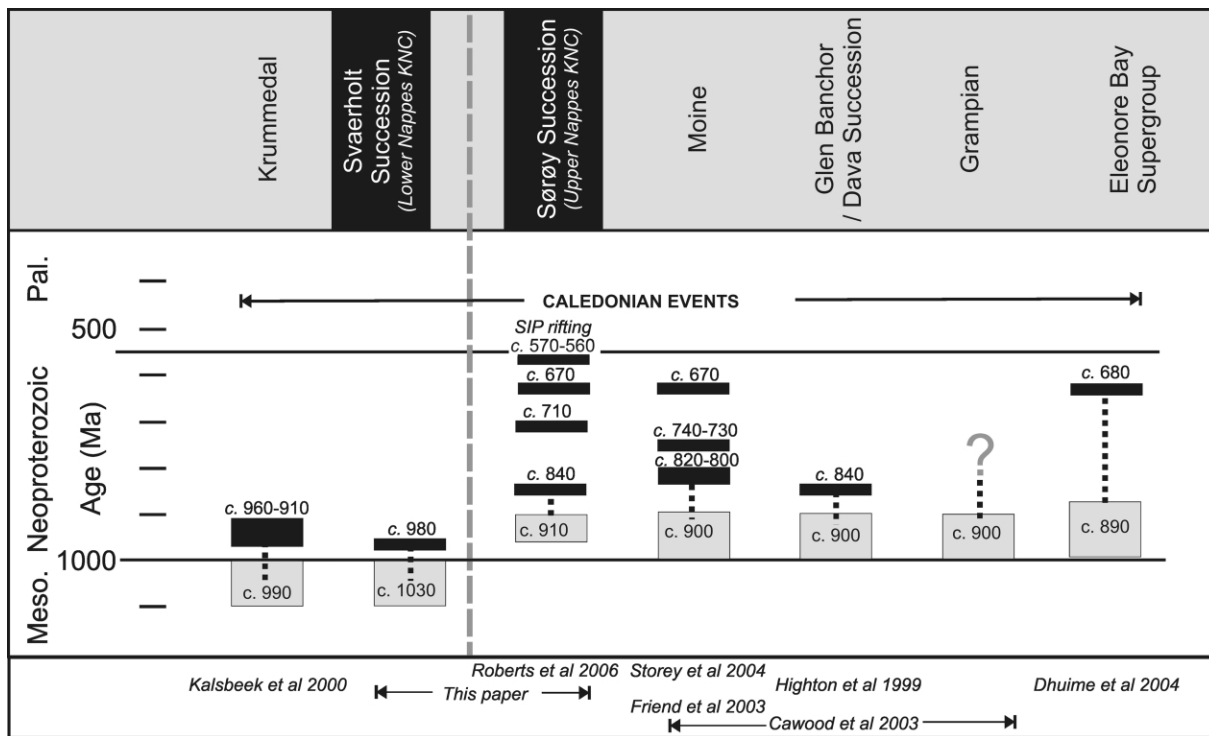


Figure 7. Comparison of the depositional age ranges (gray rectangles) and timing of tectonothermal events (black rectangles) for the Svaerholt and Sørøy successions and other Neoproterozoic metasediments in the North Atlantic region. References to the data sources are shown below their corresponding rectangles.

land Igneous Province is represented by the Melkvann Ultramafic Complex, which has yielded Sm-Nd internal isochron ages of 559 ± 36 and 513 ± 24 Ma (Snow et al. 1986) and nepheline syenite pegmatites with U-Pb zircon ages of 531 ± 2 and 523 ± 2 Ma (Pedersen et al. 1989). These probably correspond to the youngest metamorphic zircon overgrowth within the paragneiss, at 516 ± 8 Ma.

The traditional depositional setting envisaged for the KNC metasediments on the Iapetus margin of Baltica is inconsistent with the multiple phases of magmatism, deformation, and/or metamorphism at ca. 980, ca. 840, ca. 710, and ca. 670 Ma and the emplacement of the SIP at ca. 560 and ca. 520 Ma. These events (fig. 7) have no correlatives in the northern Baltic Shield, which, in particular, contains no collision-related Neoproterozoic rocks. Although several of the magmatic events may be related to rifting, the ca. 840-Ma Porsanger Orogeny is clearly a compressional event, which resulted in the juxtaposition of two disparate terranes, that is, the upper and lower nappes. This event is unknown on the Baltic Shield, emphasizing the exotic nature of the KNC, and hence, in keeping with the findings

of Kirkland et al. (2006), an exotic terrane accretion model is favored.

Provenance and Paleogeography. When the KNC metasediments were deposited, Baltica, Laurentia, and Amazonia were probably linked (e.g., Weil et al. 1998) by the Grenville/Sveconorwegian orogenic belts within the Rodinia supercontinent (Dalziel 1991; Hoffman 1991; Torsvik et al. 1996; Torsvik 2003). Within this reconstruction, sediments of the North Atlantic region accumulated near the junction between these three large continental landmasses (Weil et al. 1998; Cawood et al. 2003). The Grenville/Sveconorwegian orogens were assembled from a complex array of lithotectonic and magmatic units, each capable of providing a range of detrital zircons. The main tectonothermal events in the Grenville Province include Labradorian, ca. 1710–1620 Ma; Pinwarian, ca. 1500–1445 Ma; accretion of the Montauban arc, ca. 1390 Ma; Elzevirian, ca. 1250–1190 Ma; Shawinigan, ca. 1190–1140 Ma; Ottawan, ca. 1080–1020 Ma; and a Rigolet phase, ca. 1000–980 Ma (McLelland et al. 1996; Rivers 1997; Gower and Krogh 2002; Rivers et al. 2002; Tollo et al. 2004). In Scandinavia, the

Sveconorwegian orogeny involved imbrication of terranes between 1130 and 970 Ma, broadly overlapping with younger events in the Grenville Province (Bingen et al. 2005).

The detrital age peaks at ca. 1650 and ca. 1500 Ma within both KNC successions correspond closely to the Labradorian and Pinwarian magmatic events in NE Laurentia and Baltica (fig. 3), while detrital age peaks of late Mesoproterozoic age and the lack of Archean detritus also correspond well to the geological history of the Laurentia-Baltica region (Watt and Thrane 2001; Friend et al. 2003; Cawood et al. 2004). The lack of Archean detritus may indicate that the topographic high ground of the Grenville Orogen shielded the successor basins from material derived from the cratonic interior of Rodinia, where Archean ages are more prevalent.

The Sørøy Succession detritus (samples CK099, CK001, CK240, and CK031; see fig. 1 legend) was derived at least partly from the Grenville Orogen. After ca. 980 Ma, the granites cutting the Svaerholt Succession may have provided a local source for some of the Sørøy Succession detritus. In addition, the psammite (CK001) from the Havvatnet Imbricate Stack indicates a ca. 990-Ma lead loss event within its detritus (fig. 4), providing further evidence for a source with a late Grenvillian history. This must reflect a predepositional event because these rocks were not deposited until after ca. 910 Ma.

The ca. 980-Ma granites cutting the Svaerholt Succession are synchronous with magmatism elsewhere along the Rodinia margin as far apart as eastern Mexico and the Sveconorwegian domain (Keppie et al. 2001). This magmatism and the deformation preceding it may correspond to the Rigolet phase of the Grenvillian Orogeny (~1000–980 Ma). In the Sveconorwegian Orogen, syn- to late-kinematic granites range in age between 1060 and 986 Ma (Romer 1996) and so may span the Ottawan and Rigolet events (Tollo et al. 2004). In eastern Mexico, the northern Oaxacan Complex, interpreted to be a Grenvillian arc on the margin of Amazonia, is dated at ca. 980 Ma (Solari et al. 1998; Keppie et al. 2001). In Colombia, a 981 ± 85 -Ma U-Pb age of the Santander massif is also correlated with the Rigolet phase (Restrepo-Pace et al. 1997; Keppie et al. 2001). Furthermore, ages between 1050 and 950 Ma are common for syn- to posttectonic granites in the Sunsas belt of Bolivia (Tohver et al. 2005). Collectively, these data suggest that the Rigolet event is recorded mainly along the margins of the Grenville, Sveconorwegian, and Sunsas orogens. In this context, the Svaerholt Succession

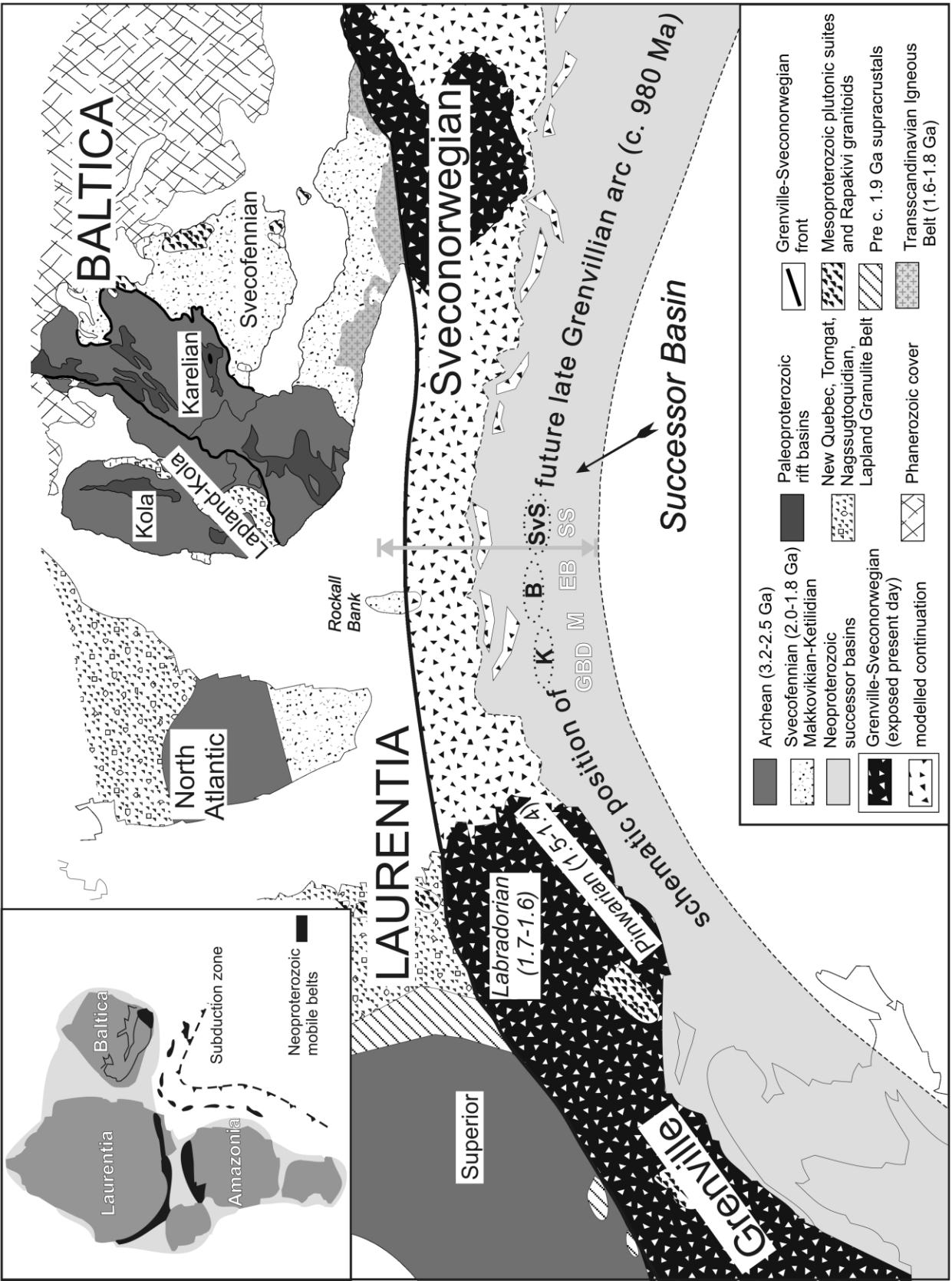
is envisaged as a successor basin that was cut by a late Grenvillian arc complex that stretched along the embayed southern and eastern margin of Rodinia (fig. 8).

Comparison with Other Successions in the North Atlantic Region. With a view to Neoproterozoic paleogeography, geochronological constraints on sedimentation and deformation permit comparison between the KNC successions and other sequences in the North Atlantic region. These include the Moine Supergroup and the Glen Banchor/Dava Successions of Scotland, the Grampian Group within the Dalradian of Scotland and Ireland, the Krummedal supracrustal sequence, and some of the lower Eleonore Bay Supergroup of Greenland.

The strong similarity in detrital zircon population and the timing of Neoproterozoic tectonics (figs. 3, 7) suggest that the Sørøy Succession may be equivalent to the Moine Supergroup. The Moine rocks were deposited between ca. 950 Ma, the youngest detrital age (Cawood et al. 2003), and ca. 870 Ma, the age of the intrusive West Highland granite gneiss (Friend et al. 2003) and coeval gabbros (Millar 1999). A U-Pb titanite age of 669 ± 31 Ma, which has been interpreted to date a metamorphic event in the Moine Supergroup (Storey et al. 2004), is identical, within error, to the age of metamorphic zircon overgrowth in the Eidvågeid Paragneiss at 672 ± 7 Ma (fig. 6B).

The Eleonore Bay Supergroup in Greenland has a similar detrital zircon population (Watt et al. 2000; figs. 3, 7) and age constraints inviting correlation with the Sørøy Succession. Deposition of the Eleonore Bay Supergroup occurred after 889 ± 44 Ma, the age of the youngest detrital zircon in the Nathorst Land Group, and before ca. 680 Ma, the Pb-Pb age of a stratiform Cu deposit within the overlying Ymer Ø group (Dhuime et al. 2004). This age bracket is consistent with its Neoproterozoic acritarch fauna (Vidal and Moczydlowska 1993).

The detrital zircon population of the Grampian Group (deposited after ca. 890 Ma; Cawood et al. 2003) is similar to that of the Moine Supergroup, lacking significant Archean detritus but with a considerable Mesoproterozoic component. Moreover, in western Ireland, the Grampian Group was probably deposited unconformably on Grenvillian basement of the Annagh Gneiss Complex (Daly 2001). The sub-Grampian basement in the Central Highlands (Glen Banchor/Dava Succession) is also similar to the Moines (Cawood et al. 2003). This could be taken to indicate a similar depositional age and setting for all of these units (Cawood et al. 2003). Various studies have suggested an event around ca.



800 Ma within the sub-Grampian basement, that is, the Glen Banchor/Dava Succession (Noble et al. 1996; Highton et al. 1999; Hyslop and Piasecki 1999), with possible correlatives (Knøydartian) within the Moine (Rogers et al. 1998; Kinny et al. 2003; Tanner and Evans 2003) and the upper nappes of the KNC (Kirkland et al. 2006; fig. 7). The Glen Banchor/Dava Succession was deposited between ca. 900 (Cawood et al. 2003) and ca. 840 Ma (Highton et al. 1999; fig. 3). These age constraints are similar to those for the Sørøy Succession, that is, between 840 and 910 Ma.

The KNC has been correlated with the Seve Nappe Complex of northern Sweden by Andréasson et al. (1998), who suggested that these rocks were derived from the infill of a Baltoscandian rift basin. The Seve Nappe Complex consists of a succession of psammites, quartzites, and schists, with occasional thin marbles and graphitic pelites (Zwaan and Van Roermund 1990; Svenningsen 2001). A minimum age for the Seve rocks and an inferred time of rifting is provided by a 608 ± 1 -Ma mafic dike (Svenningsen 2001), while a maximum age of ca. 1000 Ma is provided by the youngest detrital zircon (Williams and Claesson 1987). The Seve metasedimentary rocks have a detrital zircon population similar to that of the Svaerholt Succession, being dominated by 1400- to 1730-Ma grains, with minor components at ca. 1250 and 1000 Ma.

Paulsson and Andréasson (2002) suggested an earlier age of rifting, based on the intrusion of the Vistas Granite and associated gabbro into the Seve Nappe Complex at ca. 840 Ma. This age is identical to the Porsanger intrusives within the Havvatnet Imbricate Stack in the KNC (Kirkland et al. 2006). Paulsson and Andréasson (2002) considered that the protoliths of the Seve-Kalak Superterrane developed on the rifted margin of Baltica and related the ca. 840-Ma magmatism to the breakup of Rodinia. Siedlecka et al. (2004) also correlated the mafic magmatism and sedimentation in the Seve Nappe Complex, with the deposition of the KNC metasediments and SIP intrusion. However, the KNC metasedimentary rocks cannot be related to

the SIP because they were deposited considerably earlier (Pedersen et al. 1989; Roberts et al. 2006), that is, before ca. 840 Ma for the Sørøy Succession and before ca. 980 Ma for the Svaerholt Succession. However, a similar paleogeography and depositional setting for the sediments of the Seve Nappe Complex and the KNC is possible, based on their similar lithofacies, age of intrusive magmatism, and detrital zircon signatures.

The depositional age of the Svaerholt Succession (ca. 980–1030 Ma) is similar to that of the Krummedal supracrustal sequence in Greenland, which was deposited after ca. 1000 Ma (Kalsbeek et al. 2000) and before high-grade metamorphism at 955 ± 13 Ma (Strachan et al. 1995; fig. 3). On eastern Svalbard, the late Mesoproterozoic Brennevinsfjorden Group shares a similar depositional age and detrital zircon population with the Krummedal and Smallefjord sequences in Greenland (Johansson et al. 2005). The Brennevinsfjorden Group is intruded by ca. 930–960-Ma granites (Gee et al. 1995; Johansson et al. 2004, 2005). The overlying andesitic to rhyolitic Svartrabbane Formation and Kapp Hansteen Group volcanics are of similar age and have chemical and isotopic signatures indicative of an orogenic environment (Johansson et al. 2000). Granites intruding the lower nappes of the KNC are somewhat older (ca. 980 Ma) but have a similar arclike chemistry (Kirkland et al. 2006).

Successor Basin Model. The detrital zircon data and the timing of deformation and magmatism experienced by the KNC successions suggest close links with Neoproterozoic Laurentia-Baltica. During the depositional time frame for the KNC rocks, Laurentia and Baltica were bound together within the Rodinia Supercontinent. A number of similar basins within the north Atlantic region, currently dispersed as a result of Caledonian and later tectonics, share strong affinities with the KNC metasediments (fig. 7).

The arclike chemistry of the Neoproterozoic granites intruding the KNC (Kirkland et al. 2006) suggests a tectonic setting associated with subduction, presumably outboard the Grenville-Sveco-

Figure 8. Schematic tectonic reconstruction of the North Atlantic region at ca. 1030 Ma, during the deposition of the Svaerholt Succession (SvS) showing location and distribution of possible source regions and other coeval clastic sequences: *K* = Krummedal supracrustal sequence; *B* = Brennevinsfjord Group (with their positions shown schematically as dashed ellipses) and the future position of the ca. 980-Ma late Grenville arcs. The future locations of *M* = Moine Supergroup, *GBD* = Glen Banchor/Dava Succession, *EB* = Eleonore Bay Supergroup, and *SS* = Sørøy Succession are also indicated. Inset map shows a reconstruction for Rodinia during the same time frame, modified after Weil et al. (1998) and Torsvik (2003). The vertical gray line near the center shows the location of the cartoon sections displayed in figure A3.

norwegian Orogen. However, it is unlikely that the KNC successions were deposited in an active plate margin setting. No contemporaneous igneous activity is preserved, and the sedimentary rocks are not typical of a fore-arc basin. Instead it is suggested that they represent a pair of successor basins, located on top of the developing Grenville Orogen after successive cycles of accretionary orogenesis and erosion. Later these basins were intruded by arc complexes. This scenario accounts for the provenance data (this article), granite petrochemistry, and deformation history (Daly et al. 1991; Kirkland et al. 2006) of the KNC terranes.

Figure 8 depicts an early Neoproterozoic paleogeography in which the Sveconorwegian and Grenville belts are aligned along the embayed margin of Rodinia. Within Rodinia, Baltica is generally placed adjacent to northeastern Laurentia but in a variety of configurations (Dalziel 1997; Hartz and Torsvik 2002; Cawood et al. 2003; Pisarevsky et al. 2003). Cawood and Pisarevsky (2006) consider the most viable reconstruction to be the juxtaposition of the western Scandinavian margin of Baltica, in its classic right-way-up orientation, against the Rockall-Scotland-southeast-Greenland segment of Laurentia (fig. 8). The positioning of Amazonia relative to Baltica controls whether the North Atlantic Neoproterozoic sediments were deposited in an intracratonic setting (Cawood et al. 2004) or on a free oceanic margin. Geochronology and paleomagnetic data for late Mesoproterozoic rocks in Amazonia (Tohver et al. 2005) suggest that western Amazonia was adjacent to the Llano portion of the Laurentian margin, hence locating Amazonia at the southernmost portion of Laurentia's Grenvillian margin. This allows sufficient space for sedimentary basins to develop to the east of Amazonia, off Laurentia-Baltica (fig. 8). We consider that the Svaerholt Succession, together with the Krummedal and Brennevinsfjorden groups, developed in a successor basin to the Ottawan event, thus accumulating Labradorian, Pinwarian, and early Grenvillian detritus. The Svaerholt Succession was later deformed by the Rigolet phase at ca. 980 Ma (fig. A3) as a consequence of subsequent terrane accretion along the same margin. Magmatism at 980 Ma followed or may have accompanied Rigolet deformation and was caused by the development of a magmatic arc of similar age.

The Sørøy Succession and correlative units such as the Moine and Eleonore Bay supergroups (figs. 3, 7) are interpreted as the fill of a later successor basin unconformably overlying terranes accreted during the Rigolet phase. Some of its detritus may

have been locally derived from the already deformed Svaerholt Succession. This is in keeping with the presence of ca. 980-Ma detrital zircon grains and also with the record of Pb loss at a similar time in some of the Sørøy Succession detritus. The Sørøy Succession metasediments were themselves shortened and juxtaposed with the lower nappes during the Porsanger Orogeny, a further Neoproterozoic accretion event (fig. A3), accompanied by magmatism at ca. 840 Ma. This is consistent with the resetting of the Rb-Sr isotopic system of the ca. 980-Ma Repvåg granite in the lower nappes during the Porsanger Orogeny at ca. 840 Ma (Kirkland et al. 2006). Thus, a series of successor basins stretching along the Laurentia-Baltica margin (fig. 8), which was subject to later shortening, accounts for the various Neoproterozoic compressional events and the juxtaposition of terranes (fig. 8; fig. A3).

The traditional model for Rodinia (Dalziel 1991; Hoffman 1991; Moores 1991) envisages a Wilson-type (Wilson 1966) fit, inferring Neoproterozoic orthogonal rifting of northern Iapetus between Baltica and Laurentia. This would place the KNC within an intracratonic setting within Rodinia, in a location similar to that of the Moines (Cawood et al. 2004) and east Greenland Caledonides. However, the postdepositional Neoproterozoic history of the KNC is not consistent with an intraplate setting, which is difficult to reconcile with the development of an extensive orogenic belt and terrane accretion onto it. An intracratonic situation would require a very large rift system to accommodate all of the correlative siliciclastic rocks within the North Atlantic region, and it is unlikely that such a large system could operate without substantial coeval magmatism. We suggest that a location on the periphery of Rodinia is a more plausible paleogeographic situation, thereby providing a free oceanic margin allowing accretionary and arc processes to operate.

Conclusions

Detrital zircon U-Pb dating combined with field relationships and geochronology of intrusive granitoids show that the metasedimentary rocks of the KNC cannot belong to a common stratigraphy. At least two distinct metasedimentary sequences are present and have different provenances. The lower nappes of the KNC (Olderfjord and Kolvik) contain an older Svaerholt Succession comprising the Smørfjord Psammite and Hårvikneset Schist. These rocks were affected by late Grenville intrusion (Ri-

golet phase) and were deposited between ca. 980 and 1030 Ma.

The Sørøy Succession, redefined to refer only to the Klubben Psammite and Storelv (Kokelv) Schist, occurs within the upper nappes of the KNC, that is, Sørøy-Seiland Nappe, Havvatnet Imbricate Stack, and Veines Nappe. Based on intrusives cutting folds in the Havvatnet Imbricate Stack, it was affected by the Porsanger Orogeny at ca. 840 Ma and contains detrital zircons as young as 910 ± 15 Ma within the Sørøy-Seiland Nappe. Thus, its depositional age is constrained between ca. 840 and 910 Ma. Detrital zircon data are consistent with some sedimentary derivation from the underlying Svaerholt Succession.

Paragneisses in the KNC, previously interpreted as basement, were derived from a similar source region to the Sørøy Succession and were deposited after the Svaerholt Succession. The paragneiss records metamorphic zircon overgrowths that match and are evidence of metamorphism that accompanied pulses of magmatic activity in the Seiland Igneous Province. Earlier metamorphic events at 710 and 670 Ma are also recorded. Together with late Grenvillian (ca. 980 Ma), Porsanger (ca. 840 Ma), and Snøfjord (ca. 710 Ma) events, these magmatic and metamorphic ages are unknown on the northern Baltic Shield and indicate that the KNC evolved elsewhere.

The detrital zircon populations of both KNC successions are consistent with a Laurentia-Baltica affinity. Few Archean grains are present, and Paleoproterozoic grains older than 1800 Ma are very rare. The age peaks at around 1650 and 1500 Ma correspond closely to the Labradorian/Gothian and Pinwarian magmatic events. The younger age peaks correspond to phases of the Grenville/Sveconorwegian orogenies. The detrital age populations of the Sørøy Succession (upper nappes) bear strong similarity to those from the Moine Supergroup of Scotland, while the Svaerholt Succession (lower nappes) is comparable with the Krummedal supracrustal sequence in Greenland.

The two different depositional sequences (Sørøy and Svaerholt successions) and the different ages of magmatism and deformation within the upper and lower nappes are consistent with an allochthonous terrane accretion model for the KNC. Deposition of the Svaerholt Succession and its cor-

relatives in Greenland and Svalbard took place along the Laurentia-Baltic margin of the developing Grenville Orogen, in a successor basin after the Ottawan phase of the Grenville Orogeny. It was followed by deformation and magmatism associated with further accretion during the Rigolet phase at ca. 980 Ma. The Sørøy Succession and correlatives such as the Moine Supergroup occupied a younger successor basin on the same margin and were deformed and intruded during the ca. 840-Ma Porsanger Orogeny.

Neither of the KNC successions were deposited on the Baltica margin of the Iapetus Ocean. All of these rocks are distinctly older and have exotic affinities indicated by their deformation, magmatism, and provenance. Accepting a correlation between the KNC and the Seve Nappe Complex, this portion of the Scandinavian Caledonide tectonostratigraphy can no longer be considered simply as the telescoped Baltoscandian margin of Iapetus. Instead, it represents an exotic mobile belt sutured to the margin of Baltica.

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REFERENCES CITED

- Aitchison, S. J. 1989. Crustal evolution in the Seiland region of north Norway: a Nd-Sr-Pb isotopic study. PhD dissertation, University College Dublin, National University of Ireland.

- . 1990. Nd isotopic evidence for exotic detritus in the Kalak Nappe Complex, north Norwegian Caledonides. *J. Geol. Soc. Lond.* 147:923–926.
- Akselsen, J. 1982. Precambrian and Caledonian tectono-metamorphic evolution of north-eastern Seiland, Finnmark, north Norway. *Nor. Geol. Unders. Bull.* 373:45–61.
- 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* 120:159–172.
- Bingen, B.; Skår, Ø.; Marker, M.; Sigmond, E. M. O.; Nordgulen, Ø.; Ragnhildstveit, J.; Mansfeld, J.; Tucker, R. D.; and Liégeois, J.-P. 2005. Timing of continental building in the Sveconorwegian orogen, SW Scandinavia. *Norw. J. Geol.* 85:87–116.
- Canadian Geochronology KnowledgeBase, Geochronology Laboratory, Geological Survey of Canada, Earth Sciences Sector, Natural Resources Canada. 2005. http://gsc-cgd.nrcan.gc.ca/cgd/geochron/index_e.html.
- Cawood, P. A.; Nemchin, A. A.; Smith, M.; and Loewy, S. 2003. Source of the Dalradian Supergroup constrained by U-Pb dating of detrital zircon and implications for the East Laurentian margin. *J. Geol. Soc. Lond.* 160:231–246.
- 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. *J. Geol. Soc. Lond.* 161:861–874.
- Cawood, P. A., and Pisarevsky, P. A. 2006. Was Baltica right-way-up or upside-down in the Neoproterozoic? *J. Geol. Soc. Lond.* 163:753–759.
- Corfu, F.; Roberts, R. J.; Gerber, M.; Torsvik, T. H.; Andersen, A.; Ramsay, D. M.; and Ashwal, L. D. 2005. Exotic terranes in the Finnmark Caledonides: U-Pb evidence for Peri-Gondwanan and Laurentian elements. Norwegian Geological Society winter meeting (Røros, 2005), abstract and proceedings, 1:22.
- Corfu, F.; Roberts, R. J.; Torsvik, T. H.; Andersen, T. B.; Ramsay, D. M.; and Ashwal, L. D. 2004. Crustal processing: the Finnmarkian orogen reassessed. *Geochim. Cosmochim. Acta* 68:A624.
- Corfu, F.; Torsvik, T. H.; Andersen, A.; 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. *J. Geol. Soc. Lond.* 163:291–301.
- Daly, J. S. 2001. The Precambrian. In Holland, C. H., ed. *The geology of Ireland*. Edinburgh, Dunedin Academic, p. 7–45.
- Daly, J. S.; Aitchison, 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. *J. Geol. Soc. Lond.* 148:29–40.
- Daly, J. S., and Flowerdew, M. J. 2005. Grampian and late Grenville events recorded by mineral geochronology near a basement-cover contact in north Mayo, Ireland. *J. Geol. Soc. Lond.* 162:163–174.
- Dalziel, I. W. D. 1991. Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. *Geology* 19:598–601.
- . 1997. Neoproterozoic-Paleozoic geography and tectonics: review, hypothesis, environmental speculation. *Geol. Soc. Am. Bull.* 109:16–42.
- Dangla, P.; Demange, A. P.; Quenardel, J.-M.; and Sonet, J. 1978. Données géochronologiques sur les Calédonides scandinaves septentrionales (Troms, Norvège du Nord). *C. R. Acad. Sci. Ser. D* 286:1653–1656 (in French).
- Dhuime, B.; Bruguier, O.; and Caby, R. 2004. Age (LA-ICP-MS and SIMS) and provenance of detrital zircons from the metasedimentary sequence of the Nathorst land group (Eleonore Bay Supergroup, NE Greenland). *Geophys. Res. Abstr.* 6:04144.
- Friend, C. R. L.; Strachan, R. A.; Kinny, P. D.; and Watt, G. R. 2003. Provenance of the Moine Supergroup of NW Scotland; evidence from the geochronology of detrital and inherited zircons from (meta)sedimentary rocks, granites and migmatites. *J. Geol. Soc. Lond.* 160:247–257.
- 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. *Nor. Geol. Unders. Bull.* 400:67–87.
- Gayer, R. A.; Humphreys, R. J.; Binns, R. E.; and Chapman, T. J. 1984. Tectonic modelling of the Finnmark and Troms Caledonides based on high level igneous rock geochemistry. In Gee, D. G., and Sturt, B. A., eds. *The Caledonide Orogen: Scandinavia and related areas*. Chichester, Wiley, p. 931–951.
- 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 problems of excess continental crust. *Trans. R. Soc. Edinb.* 78:197–217.
- Gee, D. G. 1975. A tectonic model for the central part of the Scandinavian Caledonides. *Am. J. Sci.* 275:468–515.
- Gee, D. G.; Johansson, A.; Ohta, Y.; Tebenkov, A. M.; Krasil'shnikov, A. A.; Balashov, Y. A.; Larionov, A. N.; Gannibal, L. F.; and Ryungenen, G. I. 1995. Grenvillian basement and a major unconformity within the Caledonides of Nordaustlandet, Svalbard. *Precambrian Res.* 70:215–234.
- Gower, C. F., and Krogh, T. E. 2002. A U-Pb geochronological review of the Proterozoic history of the eastern Grenville Province. *Can. J. Earth Sci.* 39:795–829.
- Gradstein, F. M.; Ogg, J. G.; Smith, A. G.; Agterberg, F. P.; Bleeker, W.; Cooper, R. A.; Davydov, V.; et al. 2004. *A geologic time scale 2004*. Cambridge, Cambridge University Press, 610 p.
- Grotzinger, J. P.; Bowring, S. A.; Saylor, B. Z.; and Kaufman, A. J. 1995. Biostratigraphic and geochronologic

- constraints on early animal evolution. *Science* 270: 598–604.
- Hartz, E. H., and Torsvik, T. H. 2002. Baltica upside down: a new plate tectonic model for Rodinia and the Iapetus Ocean. *Geology* 30:255–258.
- 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. *J. Geol. Soc. Lond.* 156: 1195–1204.
- Hoffman, P. F. 1991. Did the breakout of Laurentia turn Gondwanaland inside-out? *Science* 252:1409–1412.
- Hoffman, P. F.; Kaufman, A. J.; Halverson, G. P.; and Schrag, D. P. 1998. A Neoproterozoic snowball earth. *Science* 281:1342–1346.
- Hyslop, E. K., and Piasecki, M. A. J. 1999. Mineralogy, geochemistry and the development of ductile shear zones in the Grampian Slide zone of the Scottish Central Highlands. *J. Geol. Soc. Lond.* 156:577–589.
- Johansson, Å.; Gee, D. G.; Larionov, A. N.; Ohta, Y.; and Tebenkov, A. M. 2005. Grenvillian and Caledonian evolution of eastern Svalbard: a tale of two orogenies. *Terra Nova* 17:317–325.
- Johansson, Å.; Larionov, A. N.; Gee, D. G.; Ohta, Y.; Tebenkov, A. M.; and Sandelin, S. 2004. Grenvillian and Caledonian tectono-magmatic activity in northeasternmost Svalbard. In Gee, D. G., and Pease, V., eds. *The Neoproterozoic Timanide Orogen of eastern Baltica*. *Geol. Soc. Lond. Mem.* 30:207–232.
- Johansson, Å.; Larionov, A. N.; Tebenkov, A. M.; Gee, D. G.; Whitehouse, M.; and Vestin, J. 2000. Grenvillian magmatism of western and central Nordaustlandet, north-eastern Svalbard. *Can. J. Earth. Sci.* 90:221–254.
- 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 Grenvillian orogenesis? *J. Geol. Soc. Lond.* 157: 1215–1225.
- Karlstrom, K. E.; Bowring, S. A.; Dehler, C. M.; Knoll, A. H.; Porter, S. M.; Marais, D. J. D.; Weil, A. B.; et al. 2000. Chuar Group of the Grand Canyon: record of break-up of Rodinia, associated change in the global carbon cycle, and ecosystem expansion by 740 Ma. *Geology* 28:619–622.
- Kaufman, A. J.; Knoll, A. H.; and Narbonne, G. M. 1997. Isotopes, ice ages, and terminal Proterozoic Earth history. *Proc. Natl. Acad. Sci. USA* 94:6600–6605.
- Keppie, D. J.; Dostal, J.; Ortega-Gutiérrez, F.; and Lopez, R. 2001. A Grenvillian arc on the margin of Amazonia: evidence from the southern Oaxacan Complex, southern Mexico. *Precambrian Res.* 112:165–181.
- Kinny, P. D.; Strachan, R. A.; Friend, C. R. L.; Knocks, H.; Rodgers, G.; and Paterson, B. A. 2003. U-Pb geochronology of deformed metagranites in central Sutherland, Scotland: evidence for widespread late Silurian metamorphism and ductile deformation of the Moine Supergroup during the Caledonian orogeny. *J. Geol. Soc. Lond.* 160:259–269.
- Kirkland, C. L., and Daly, J. S. 2004. Evidence for the Neoproterozoic Porsanger Orogeny in the Caledonides of arctic Norway. *GFF* 126:81–82.
- Kirkland, C. L.; Daly, J. S.; Eide, E.; and Whitehouse, M. J. 2005a. Tectonic events in the Kalak Nappe Complex, arctic Caledonides redefined through a linked structural and geochronological approach. *Geophys. Res. Abstr.* 7:10,097.
- Kirkland, C. L.; Daly, J. S.; and Whitehouse, M. J. 2005b. Early Silurian magmatism and the Scandian evolution of the Kalak Nappe Complex Finnmark, arctic Norway. *J. Geol. Soc. Lond.* 162:985–1003.
- . 2006. Granitic magmatism of Grenvillian and late Neoproterozoic age in Finnmark, arctic Norway: constraining pre-Scandian deformation in the Kalak Nappe Complex. *Precambrian Res.* 145:24–52.
- Klötzli, U. S. 1999. Th/U zonation in zircon derived from evaporation analysis: a model and its implications. *Chem. Geol.* 158:325–333.
- Ludwig, K. R. 1998. On the treatment of concordant uranium-lead ages. *Geochim. Cosmochim. Acta* 62: 665–676.
- . 2003. User's manual for Isoplot 3.00: a geochronological toolkit for Microsoft Excel. Spec. Publ. No. 4. Berkeley, CA, Berkeley Geochronology Center.
- Lund, K.; Aleinikoff, J. N.; Evans, K. V.; and Fanning, C. M. 2003. SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central Idaho: implications for rifting of western Laurentia and synchronicity of Sturtian glacial deposits. *GSA Bull.* 115:349–372.
- McLelland, J.; Daly, J. S.; and McLelland, J. M. 1996. The Grenville orogenic cycle (ca. 1350–1000 Ma): an Adirondack perspective. *Tectonophysics* 265:1–28.
- Millar, I. L. 1999. Neoproterozoic extensional basic magmatism associated with the West Highland granite gneiss in the Moine Supergroup of NW Scotland. *J. Geol. Soc. Lond.* 156:1153–1162.
- Moore, E. M. 1991. Southwest U.S.–East Antarctica (SWEAT) connection: a hypothesis. *Geology* 19:425–428.
- Mørk, M. B. E., and Stabel, A. 1990. Cambrian Sm-Nd dates for an ultramafic intrusion and for high-grade metamorphism on the Oksfjord Peninsula, Finnmark, north Norway. *Norsk. Geol. Tidsskr.* 70:275–291.
- Murphy, J. B.; Fernandez-Suarez, J.; and Jeffries, T. E. 2004. Lithogeochemical and Sm-Nd and U-Pb isotope data from the Silurian-Lower Devonian Arisaig Group clastic rocks, Avalon terrane, Nova Scotia: a record of terrane accretion in the Appalachian-Caledonide orogen. *Geol. Soc. Am. Bull.* 116:1183–1201.
- Noble, S. R.; Hyslop, E. K.; and Highton, A. J. 1996. High-precision U-Pb monazite geochronology of the c. 806 Ma Grampian shear zone and the implications for the evolution of the Central Highlands of Scotland. *J. Geol. Soc. Lond.* 153:511–514.
- Paulsson, O., and Andréasson, P. 2002. Attempted break-up of Rodinia at 850 Ma: geochronological evidence from the Seve-Kalak superterrane, Scandinavian Caledonides. *J. Geol. Soc. Lond.* 159:751–761.

- Pedersen, R. B.; Dunning, G. R.; and Robins, B. 1989. U-Pb ages of nepheline syenite pegmatites from the Seiland Magmatic Province, north Norway. *In* Gayer, R. A., ed. *The Caledonide geology of Scandinavia*. London, Graham & Trotman, p. 3–8.
- Pisarevsky, S. A.; Wingate, M. T. D.; Powell, C. M.; Johnson, S.; and Evans, D. A. D. 2003. Models of Rodinia assembly and fragmentation. *In* Yoshida, M.; Windley, B. F.; and Dasgupta, S., eds. *Proterozoic East Gondwana: supercontinent assembly and breakup*. Geol. Soc. Lond. Spec. Publ. 206:35–55.
- Rainbird, R. H.; Hamilton, M. A.; and Young, G. M. 2001. Detrital zircon geochronology and provenance of the Torridonian, NW Scotland. *J. Geol. Soc. Lond.* 158:15–27.
- Rainbird, R. H.; Jefferson, C. W.; and Young, G. M. 1996. The early Neoproterozoic sedimentary Succession B of northwestern Laurentia; correlations and paleogeographic significance. *Geol. Soc. Am. Bull.* 108:454–470.
- Ramsay, D. M. 1971. Stratigraphy of Sørøy: in the Caledonian geology of northern Norway. *Nor. Geol. Unders. Bull.* 269:314–317.
- Ramsay, D. M.; Jansen, O. J.; Andersen, T. B.; and Sinharoy, S. 1985. The tectonostratigraphy of western Porsangerhalvøya, Finnmark, north Norway. *In* Gee, D. G., and Sturt, B. A., eds. *The Caledonide Orogen: Scandinavia and related areas*. Chichester, Wiley, p. 163–184.
- Ramsay, D. M., and Sturt, B. A. 1977. A sub-Caledonian sunconformity within the Finnmarkian Nappe Sequence and its regional significance. *Nor. Geol. Unders. Bull.* 334:107–116.
- . 1986. The contribution of the Finnmarkian orogeny to the framework of the Scandinavian Caledonides. *In* Fettes, D. J., and Harris, A. L., eds. *Synthesis of the Caledonian rocks of Britain*. Dordrecht, Reidel, p. 221–246.
- Ramsay, D. M.; Sturt, B. A.; and Andersen, T. B. 1979. A sub-Caledonian unconformity on Hjelmsøy: new evidence of primary basement/cover relationship in the Finnmarkian nappe sequence. *Nor. Geol. Unders. Bull.* 351:1–12.
- Restrepo-Pace, P. A.; Ruiz, J.; Gehrels, G. E.; and Cosca, M. 1997. Geochronology and Nd isotopic data of Grenville-age rocks in the Colombian Andes: new constraints for Late Proterozoic–Early Paleozoic paleocontinental reconstructions of the Americas. *Earth Planet. Sci. Lett.* 150:427–441.
- Rhodes, S., and Gayer, R. A. 1977. Non-cylindrical folds, linear structures in the X direction and mylonite developed during the translation of the Caledonian Kalak Nappe Complex of Finnmark, Norway. *Geol. Mag.* 114:329–340.
- Rice, A. H. N. 1984. Metamorphic and structural diachronicity in the Finnmarkian Nappes of north Norway. *J. Metamorph. Geol.* 2:219–236.
- . 1987. A tectonic model for the evolution of the Finnmarkian Caledonides of north Norway. *Can. J. Earth Sci.* 24:602–616.
- Rice, A. H. N.; Gayer, R. A.; Robinson, D.; and Bevins, R. E. 1989. Strike-slip restoration of the Barents Sea Caledonides Terrane, Finnmark, north Norway. *Tectonics* 8:247–264.
- Rivers, T. 1997. Lithotectonic elements of the Grenville Province: review and tectonic implications. *Precambrian Res.* 86:117–154.
- Rivers, T.; Ketchum, J.; Indares, A.; and Hynes, A. 2002. The high pressure belt in the Grenville Province: architecture, timing, and exhumation. *Can. J. Earth Sci.* 39:867–893.
- Roberts, D. 1968a. Hellefjord Schist Group: a probable turbidite formation from the Cambrian of Sørøy, West Finnmark. *Nor. Geol. Unders. Bull.* 48:231–244.
- . 1968b. The structural and metamorphic history of the Langstrand-Finfjord area, Sørøy, northern Norway. *Nor. Geol. Unders. Bull.* 253:1–160.
- . 1971. A conspectus of Eocambrian-Lower Palaeozoic sedimentation on Sørøy. *Nor. Geol. Unders. Bull.* 269:242–245.
- . 1985. The Caledonian fold belt in Finnmark: a synopsis. *Nor. Geol. Unders. Bull.* 403:161–178.
- Roberts, D., and Gee, D. G. 1985. An introduction to the structure of the Scandinavian Caledonides. *In* Gee, D. G., and Sturt, B. A., eds. *The Caledonide Orogen: Scandinavia and related areas*. Chichester, Wiley, p. 55–68.
- Roberts, R. J.; Corfu, F.; Torsvik, T. H.; Ashwal, L. D.; and Ramsay, D. M. 2006. Short-lived mafic magmatism at 570 Ma in the northern Norwegian Caledonides: U/Pb zircon ages from the Seiland Igneous Province. *Geol. Mag.*, forthcoming.
- Rogers, G.; Hyslop, E. K.; Strachan, R. A.; Peterson, B. A.; and Holdsworth, R. E. 1998. The structural setting and U-Pb geochronology of Knoydartian pegmatites in W Inverness-shire: evidence for Neoproterozoic tectonothermal events in the Moine of NW Scotland. *J. Geol. Soc. Lond.* 155:685–696.
- Romer, R. L. 1996. Contiguous Laurentia and Baltica before the Grenvillian-Sveconorwegian orogeny? *Terra Nova* 8:173–181.
- Rubatto, D. 2002. Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb ages and metamorphism. *Chem. Geol.* 184:123–138.
- Siedlecka, A., and Roberts, D. 1996. Finnmark Fylke Berggrunnsgeologi. *Nor. Geol. Unders. Map*, scale 1 : 500,000.
- Siedlecka, A.; Roberts, D.; Nystuen, J. P.; and Olovyanishnikov, V. G. 2004. North-eastern and north-western margins of Baltica in the Neoproterozoic time: evidence from the Timanian and Caledonian Orogens. *In* Gee, D. G., and Pease, V., eds. *The Neoproterozoic Timanide Orogen of Eastern Baltica*. *Geol. Soc. Lond. Mem.* 30:169–190.
- 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, north Norway. *J. Geol. Soc. Lond.* 163:277–289.

- Snow, J.; Bennett, M.; Basu, A.; Tatsumoto, M.; and Yeo, W. 1986. The Melkvann complex, N. Norway: Nd and Sr isotopic evidence for the origin of Alaskan-type ultramafic complexes. *Terra Cognita* 6:184.
- Solari, L. A.; Lopez, R.; Cameron, K. L.; Ortega-Gutierrez, F.; and Keppie, J. D. 1998. Reconnaissance U/Pb geochronology and common Pb isotopes of the northern part of the ~1 Ga Oaxacan Complex, southern Mexico. *EOS Trans. Am. Geophys. Union. Fall meeting* 79:F931.
- Stacey, J. S., and Kramers, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth Planet. Sci. Lett.* 26:207–221.
- Steiger, R. H., and Jäger, E. 1977. Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmochemistry. *Earth and Planet. Sci. Lett.* 36:359–362.
- Storey, C. D.; Brewer, T. S.; and Parrish, R. R. 2004. Late-Proterozoic tectonics in northwest Scotland: one contractional orogeny or several? *Precambrian Res.* 134: 227–247.
- Strachan, R. A.; Nutman, A. P.; and Friederichsen, J. D. 1995. SHRIMP U-Pb geochronology and metamorphic history of the Smøllefjord sequence, northeast Greenland Caledonides. *J. Geol. Soc. Lond.* 152:779–784.
- Sturt, B. A.; Pringle, I. R.; and Ramsay, D. M. 1978. The Finnmarkian phase of the Caledonian orogeny. *J. Geol. Soc. Lond.* 135:597–610.
- Svenningsen, O. M. 2001. Onset of seafloor spreading in the Iapetus Ocean at 608 Ma: precise age of the Sarek Dyke Swarm, northern Swedish Caledonides. *Precambrian Res.* 110:241–254.
- Tanner, P. W. G., and Evans, J. A. 2003. Late Precambrian U-Pb titanite age for peak regional metamorphism and deformation (Knaydartian orogeny) in the western Moine, Scotland. *J. Geol. Soc. Lond.* 160:555–564.
- Thomas, W. A. 1991. The Appalachian-Ouachita rifted margin of south-eastern North America. *Geol. Soc. Am. Bull.* 103:415–431.
- Tohver, E.; van der Pluijm, B. A.; Mezger, K.; Scandolara, J. E.; and Essene, E. J. 2005. Two stage tectonic history of the SW Amazon craton in the late Mesoproterozoic: identifying a cryptic suture zone. *Precambrian Res.* 137:35–59.
- Tollo, R. P.; Corriveau, L.; McLelland, J.; and Bartholomew, M. J. 2004. Proterozoic tectonic evolution of the Grenville orogen in North America: an introduction. *In* Tollo, R. P.; Corriveau, L.; McLelland, J.; and Bartholomew, M. J., eds. *Proterozoic tectonic evolution of the Grenville Orogen in North America*. *Geol. Soc. Am. Mem.* 197:1–18.
- Torsvik, T. H. 2003. The Rodinia jigsaw puzzle. *Science* 300:1379–1381.
- Torsvik, T. H.; Smethurst, M. A.; Meert, J. G.; Van der Voo, R.; McKerrow, W. S.; Brasier, M. D.; Sturt, B. A.; and Walderhaug, H. J. 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic: a tale of Baltica and Laurentia. *Earth Sci. Rev.* 40:229–258.
- Vidal, G., and Moczydlowska, M. 1993. The Neoproterozoic of Baltica-stratigraphy, palaeobiology and general geological evolution. *Precambrian Res.* 73:197–216.
- Watt, G. R.; Kinny, P. D.; and Friderichsen, J. D. 2000. U-Pb geochronology of Neoproterozoic and Caledonian tectonothermal events in the East Greenland Caledonides. *J. Geol. Soc. Lond.* 157:1031–1048.
- Watt, G. R., and Thrane, K. 2001. Early Neoproterozoic events in east Greenland. *Precambrian Res.* 110:165–184.
- Weil, A. B.; Van der Voo, R.; Mac Niocaill, C.; and Meert, J. G. 1998. The Proterozoic supercontinent Rodinia: paleomagnetically derived reconstructions for 1100 to 800 Ma. *Earth Planet. Sci. Lett.* 154:13–24.
- Whitehouse, M. J.; Claesson, S.; Sunde, T.; and Vestin, J. 1997. Ion microprobe U-Pb zircon geochronology and correlation of Archaean gneisses from the Lewisian Complex of Gruinard Bay, northwestern Scotland. *Geochim. Cosmochim. Acta* 61:4429–4437.
- Whitehouse, M. J.; Kamber, B. S.; and Moorbath, S. 1999. Age significance of U-Th-Pb zircon data from Early Archaean rocks of west Greenland: a reassessment based on combined ion-microprobe and imaging studies. *Chem. Geol.* 160:201–224.
- Wiedenbeck, M.; Allé, P.; Corfu, F.; Griffin, W.; Meier, M.; Oberli, F.; von Quadt, A.; Roddick, J. C.; and Spiegel, W. 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analysis. *Geostand. Newsl.* 19:1–23.
- 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. *Contrib. Mineral. Petrol.* 97:205–217.
- Wilson, T. J. 1966. Did the Atlantic close and then reopen? *Nature* 211:676–681.
- Worthing, M. A. 1971a. The stratigraphy of part of eastern Seiland, West Finnmark. *Nor. Geol. Unders. Bull.* 269:323–327.
- . 1971b. Studies in the structure and metamorphic petrology of the Eocambrian rocks of eastern Seiland, north Norway. PhD dissertation, University of London.
- Young, G. 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents? *Geology* 23:153–156.
- Zachrisson, E. 1986. Scandinavian Caledonides: strata-bound sulphides. *Sver. Geol. Unders. Ser.* 60, 68 p.
- Zeck, H. P., and Whitehouse, M. J. 1999. Hercynian, Pan-African, Proterozoic and Archean ion microprobe zircon ages for a Betic-Rif core complex, Alpine belt, W Mediterranean consequences for its P-T-t path. *Contrib. Mineral. Petrol.* 134:134–149.
- Zwaan, B., and Van Roermund, H. L. M. 1990. A rift-related mafic dyke swarm in the Corrovarre Nappe of the Caledonian Middle Allochthon Troms, north Norway, and its tectonometamorphic evolution. *Nor. Geol. Unders. Bull.* 419:25–44.