The use of detrital zircon data in terrane analysis: A nonunique answer to provenance and tectonostratigraphic position in the Scandinavian Caledonides

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ABSTRACT

The Scandinavian Caledonides are conventionally described as a stack of parautochthonous to allochthonous nappes with more exotic units residing at structurally higher levels, from Baltica derived at the base to Laurentia derived at the top. Detrital zircon geochronology has been increasingly used for determining provenance and, by implication, tectonostratigraphic position. We present detrital zircon U-Pb-Hf results from the structurally highest, inferred Laurentia-derived Uppermost Allochthon. The data from the Uppermost Allochthon are statistically indistinguishable from those of the Lower and Middle Allochthons, and from other Neoproterozoic and younger metasediments around the North Atlantic. Detrital zircon U-Pb ages and Lu-Hf compositions fail the test of paleogeographic uniqueness, which is a prerequisite for using this tool to distinguish Laurentian from Baltic provenance, and therefore it cannot be used to infer tectonostratigraphic position.

INTRODUCTION

Terrane analysis of accretionary and/or collisional orogens requires insight into the magmatic and metamorphic history of the various units, timing and kinematics of the tectonic contacts separating them, and their geographic origin. In nonfossiliferous units, determining geographic origin is inherently difficult. Nevertheless, the advent of quick and relatively affordable analysis by laser ablation–inductively coupled plasma–mass spectrometry has enabled detrital zircon geochronology to become an important method for shedding light on the origin of different terranes brought together by tectonic processes (e.g., Beranek et al., 2010; Li et al., 2015). Here we test if detrital zircon geochronology and Lu-Hf isotopic analysis can discriminate between exotic and indigenous units to Baltica within the Scandinavian Caledonian nappe stack. This test of detrital age uniqueness is performed by comparing new U-Pb age and Lu-Hf zircon data sets from the tectonostratigraphically highest units, where an exotic Laurentian ancestry has been established through several other independent methods, including faunal provinciality, Sr isotope stratigraphy, and structural considerations, with data from tectonostratigraphically lower nappes.

The late Silurian–Early Devonian Scandinavian Caledonides formed during closure of the Iapetus Ocean, separating Baltica and Laurentia (Fig. 1A, inset), resulting in deep subduction of the western margin of Baltica beneath Laurentia (e.g., Cuthbert et al., 2000) and southeastward-directed thrusting of the western Baltic margin along with outboard and exotic terranes (Gee, 1978). The Caledonian orogenic architecture is characterized by a series of nappes subdivided into allochthons (Gee et al., 1985) (Fig. 1A). Although originally a purely structural and lithologic framework, this subdivision has evolved to also provide inferred constraints on the paleogeographic origin of the allochthons (e.g., Roberts, 1988; Stephens and Gee, 1989). Structurally low Neoproterozoic to Ordovician metasediments of the Lower and Middle Allochthons are inferred to represent the telescoped cover of the Baltic margin, and the overlying ophiolite-bearing Upper Allochthon has been considered to represent obducted Iapetan oceanic crust, whereas the structurally highest Uppermost Allochthon is regarded as stranded vestiges of the overthrust Laurentian margin. Over the past few years, detrital zircon geochronology from structurally lower and middle parts of the orogen has been used to establish their Baltic provenance (e.g., Be’er-Shlevin et al., 2011; Gee et al., 2014). However, others have used similar data, augmented by the age of magmatic and deformation events, to argue for a much more outboard origin of units in similar structural positions (Kirkland et al., 2011, 2007) and so belonging to a higher tectonostratigraphic level. These contrasting interpretations have a bearing on our understanding of the pre-Caledonian evolution of the units in question, as well as on the architecture of the orogen. The goal of this study is to test the applicability of detrital zircon geochronology as a tool to assist in the assignment of tectonostratigraphic position in the Scandinavian Caledonides. This can be achieved either by providing information on a unit’s provenance and assuming that the provenance–tectonostratigraphic position relationship holds, or simply by recognizing consistent provenance differences between units at different tectonostratigraphic levels.

Thus far, most detrital zircon studies have been carried out on rocks in the Lower and Middle Allochthons, with comparatively few studies in the...
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Regardless of the inferred provenance of the allochthons, there must be a contrast in the detrital zircon fingerprint for it to be a useful tectonostratigraphic assignment tool. This contrast could be either age or some other parameter carried within the detrital load, such as Lu-Hf isotopic composition. Here we present U-Pb ages and Lu-Hf isotopic compositions of detrital zircons from six samples from the Uppermost Allochthon and compare these with existing data throughout the orogen in order to assess the uniqueness, and therefore diagnostic potential, of such data.

UPPERMOST ALLOCHTHON

The Uppermost Allochthon is distinct from underlying nappes with respect to both depositional history and magmatic and metamorphic evolution (Roberts et al., 2007). Uppermost Allochthon supracrustal successions were deposited in platformal, shelf edge, and shelf slope environments during the late Neoproterozoic to early Silurian (Melezhik et al., 2002b) along with banded iron formations (Melezhik et al., 2015), and were intruded by voluminous Ordovician to early Silurian arc-type granitoid plutons and batholiths (Barnes et al., 2007; Nordgulen et al., 1993). Coeval voluminous magmatism is also recorded in the British-Irish and Greenland Caledonides (e.g., Flowerdew et al., 2005; Rehnström, 2010). In addition, early Caledonian (Taconic age), northwest-vergent thrusting (Yoshinobu et al., 2002) appears to be a unique feature in the Scandinavian Caledonides. These geological features of the Uppermost Allochthon are compatible with, and generally interpreted to reflect active-margin processes along the Laurentian margin of Iapetus, prior to continent-continent collision in the late Silurian (Roberts et al., 2007).

U-Pb AGES AND Lu-Hf COMPOSITIONS OF DETRITAL ZIRCONS FROM THE UPPERMOST ALLOCHTHON

The locations of the investigated samples are shown in Figure 1B, and lithological and tectonostratigraphic information is summarized in Table 1. Analytical methods are provided in Data Repository Supplement DR1. U-Pb and Lu-Hf isotopic data are shown in Figures 2–4, and given in Data Repository Supplements DR2 and DR3, respectively. The data are presented in order from the tectonostratigraphically lower Rödingsfjellet nappe complex (RNC) to the tectonostratigraphically higher Helgeland nappe complex (HNC). We specify that the purpose of this study is to determine if there are recognizable differences in either U-Pb age or Lu-Hf composition of detrital zircons from different tectonostratigraphic levels in the Scandinavian Caledonides. As is generally the case in the mainly nonfossiliferous, medium- to high-grade metasediments of the Scandinavian Caledonides, we do not have strict constraints on depositional age. For these reasons, any discussion on processes such as emerging or disappearing source regions that may be gleaned from

1 GSA Data Repository Item 2017392, DR1: Methods U-Pb zircon geochronology; DR2: U-Pb zircon geochronological data; DR3: Lu-Hf zircon isotopic data, is available at http://www.geosociety.org/datarepository/2017, or on request from editing@geosociety.org.
the presented data would be highly speculative, and is therefore avoided in this contribution.

In this work we use concordia ages for analyses within 10% analytical uncertainty of concordia, defined as the position of the closest approach of the 2σ error ellipse to the concordia curve. In some samples only small numbers of zircon grains were recovered from large samples, reflecting a relatively zircon-poor protolith or loss of zircon during transport and deposition. Nonetheless, for 30 recovered zircon grains, at 90% probability, such a data set should reflect anything greater than 13% of the total population (Vermeesch, 2004).

### MO082, Garnet Mica Schist, Plura Nappe, RNC

This sample is from the Plura nappe of the RNC, dominated by variably calcareous (garnet) mica schists and marbles (Marker et al., 2012). The marbles have C and Sr isotopic compositions comparable to those elsewhere in the Uppermost Allochthon and are considered to be exotic to Baltica, most likely with a Laurentian provenance (Melezhik et al., 2015).

The zircons are generally small, <100 µm, round to prismatic, with well-developed oscillatory zoning, although some preserve complex magmatic and possibly metamorphic growth zones. The analyses targeted...
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The analyses (n = 56) yield significant age peaks at 1007 Ma (4 grains), 1052 Ma (5 grains), 1267 Ma (5 grains), 1400 Ma (7 grains), 1465 Ma (6 grains), and 1649 Ma (5 grains) (Fig. 3). The youngest analysis is 941 ± 6 Ma (1σ), interpreted as the maximum depositional age for the protolith of the garnet mica schist.

Figure 4. Hf evolution plot for samples analyzed in this study shown with a compilation of zircon Hf isotope data from the Grenville Province (late Mesoproterozoic margin of Laurentia) and the Sveconorwegian Province (late Mesoproterozoic margin of Baltica). Data are from Spencer et al. (2015), Petersson et al. (2015), and Lamminen (2011). Hf isotopic patterns for the Grenville orogen on Laurentia, a potential source region for detritus in the Caledonian nappes, on average becomes more radiogenic from ca. 2000 Ma with an inflection at ca. 1600 Ma toward slightly more evolved values. After ca. 1300 Ma, the Hf signature dominantly rises toward more radiogenic compositions as high as Hf = +10 at ca. 1200 Ma; thereafter there is a distinct progression to more evolved values. A broadly similar pattern is observed in the Sveconorwegian orogen, an alternative or additional possible source region for much of the detritus, although this isotopic signature is on average somewhat more radiogenic and after ca. 1200 Ma it has a less pronounced return to evolved values near CHUR (chondritic uniform reservoir).

85186, Garnet Mica Schist, Storstranda Unit, RNC

This sample is from the Storstranda unit of the Skamdal nappe (RNC), which consists of various gneisses and schists interlayered with marble (Qvale et al., 2012). The associated lithologies suggest an affinity with the Uppermost Allochthon, but there are no geochronological or other isotopic data from this area. An age of 481 ± 2 Ma from a microcline gneiss farther south in the RNC (Larsen et al., 1995) suggests an Uppermost–Upper Allochthon affinity.

The zircons range in size between 100 and 200 µm, and are morphologically similar to MO082, with round to prismatic shapes and well-developed oscillatory zoning with evidence of magmatic and/or metamorphic growth or resorption. The analyses are mostly concordant with a few showing minor degrees of discordance (Fig. 2). Three analyses are characterized by >10% discordance and are excluded from further discussion. Analyses (n = 27) yield significant age peaks at 463 Ma (3 grains), 1381 Ma (3 grains), and 1644 Ma (3 grains) (Fig. 3). The youngest analysis, located on an oscillatory-zoned core interpreted to be of primary magmatic origin, yields an age of 440 ± 4 Ma (1σ). The date of 440 Ma is interpreted as the maximum depositional age for the protolith of the garnet mica schist.

Lu-Hf isotopic data were not obtained from this sample.
the lowest being εHf ~−4 at 516 Ma. Most data are Mesoproterozoic to late Paleoproterozoic in age with εHf ~+5.

**85185, Mica Schist, Tustørvatnet Thrust Sheet, HNC**

The following four samples are all from the HNC and are, as shown in the map in Figure 1B, closely associated with the Orдовикий intrusion to early Silurian intrusions and/or marble that confirm their affinity to the Uppeermost Allochton and suggest a Laurentian heritage.

The zircons from this sample range in size from ~80 to 150 µm, are rounded prismatic, typically with well-developed oscillatory zoning. The analyses are predominantly concordant (Fig. 2); 6 analyses are characterized by >10% discordance and 45 analyses yield significant age peaks at 1130 Ma (5 grains), 1155 Ma (4 grains), 1198 Ma (3 grains), 1276 Ma (3 grains), 1348 Ma (3 grains), 1362 Ma (3 grains), 1435 Ma (3 grains), 1621 Ma (8 grains), and 1631 Ma (7 grains) (Fig. 3). The most significant age component is 1072–1001 Ma (6 grains), 1037 Ma (6 grains), and 1582 Ma (4 grains) (Fig. 3). The most significant age component is 1053 ± 16 Ma (1σ). It is possible that this youngest analysis is of an unmodified detrital zircon grain, in which case the date of 1053 Ma represents the maximum depositional age for the protolith of the mica schist.

The εHf isotopic values range from superchondritic and as high as εHf ~+14 at 1579 Ma to subchondritic εHf ~−12 at 1292 Ma (Fig. 4). Most data are Mesoproterozoic to late Paleoproterozoic and cluster around εHf ~+5.

**85187, Garnet Mica Schist, HNC**

The zircons from this sample are between 100 and 150 µm, stubby to rounded prismatic and, in some cases, irregular, typically with well-developed oscillatory or sector zoning. Some grains are overgrown by thick, U-poor (CL bright) mantles. The analyses range from concordant to normally discordant, with the distribution of data in the Tera-Wasserburg plot consistent with principally recent radiogenic Pb loss (Fig. 2). Some analyses (n = 27) are characterized by >10% discordance; 31 analyses yield significant age peaks at 922 Ma (3 grains), 1020 Ma (6 grains), 1037 Ma (6 grains), 1066 Ma (3 grains), and 1582 Ma (4 grains) (Fig. 3). The most significant age component is 1072–1001 Ma with contributions from 7 analyses. The youngest analysis, located on a CL bright, internally featureless grain, yields an age of 820 ± 10 Ma (1σ), interpreted as a maximum depositional age for the protolith of the garnet mica schist.

Hf isotopic values range from superchondritic values as high as εHf ~+13 at 1626 Ma to subchondritic values as low as εHf ~−11 at 820 Ma (Fig. 4). Most data of Mesoproterozoic to late Paleoproterozoic age cluster around εHf ~+5.

**85190, Mica Schist, HNC**

The zircons from this sample range in size between ~80 and 150 µm, are round to rounded prismatic, with well-developed oscillatory and sector zoning. Some grains have small cores. Some analyses (n = 26) (Fig. 2) are characterized by >10% discordance and one analysis has a large analytical uncertainty due to through-ablation change in isotope ratios; a consequence of sampling fine-scale multiple age domains. Some analyses (n = 36) yield significant age peaks at 1114 Ma (3 grains), 1133 Ma (4 grains), 1568 Ma (8 grains), 1596 Ma (6 grains), and 1636 Ma (5 grains) (Fig. 3). The most significant age component is 1613–1534 Ma, with contributions from 11 analyses. The youngest analysis, located on a sector zoned grain, yields an age of 1053 ± 16 Ma (1σ), interpreted as the maximum depositional age for the protolith of the mica schist.

Hf isotopic values range from superchondritic values as high as εHf ~+13 at 1313 Ma to subchondritic values as low as εHf ~−3 at 1566 Ma (Fig. 4). Most data of Mesoproterozoic to late Paleoproterozoic age cluster around εHf ~−2 to +10.

**85189, Mica Schist, HNC**

The zircons from this sample are typically <100 µm with well-developed oscillatory and sector zoning. Some grains show complex core-mantle relationships suggesting periods of growth and resorption. The analyses range from concordant to strongly normally discordant, with the distribution of data in the Tera-Wasserburg plot implying some degree of ancient radiogenic-Pb loss (Fig. 2). A high proportion of the data set has disturbed U-Pb systematics. Some analyses (38) are characterized by >10% discordance; 12 analyses within our defined concordance limits yield significant age peaks at 843 Ma (4 grains) and 1031 Ma (3 grains) (Fig. 3). The most significant age component is 928–782 Ma, with contributions from 4 analyses. The youngest analysis, located on a CL bright, sector zoned grain, yields an age of 635 ± 35 Ma (1σ), interpreted as a maximum depositional age for the protolith of the mica schist. At least 25% of the detrital population must be of Archean age.

A single Hf isotopic value was obtained from this sample; an 1889 Ma zircon crystal yields an εHf of ~−1.1 (Fig. 4).

**DISCUSSION**

**Nonuniqueness of Detrital Zircon U-Pb Ages**

All detrital zircon dates are interpreted as the ages of zircon-crystallizing rocks in the detrital source regions, or as the ages of detrital components within sediments that have been reworked into the sampled rocks. Maximum depositional ages, estimated from the youngest detrital zircon in each sample, range from 1053 Ma (2 samples) to 440 Ma. Despite this range in maximum depositional age, all samples, apart from 85189, display very similar detrital zircon populations, with dominantly late Paleoproterozoic (ca. 1.8 Ga) through Mesoproterozoic ages (Fig. 3), corresponding to ages of potential Precambrian basement sources around the North Atlantic (see overview provided by Bingen et al., 2008; Höltta et al., 2008; Lahtinen et al., 2008). These similarities suggest that the source areas remained more or less unchanged over time, and/or that younger sediments reflect, at least in part, reworking from the older sedimentary protoliths.

Sample 85189 stands out with dominantly Neoproterozoic ages; however, this sample has significant isotopic disturbance and loss of radiogenic Pb.

Figure 5 shows a nonmetric multidimensional scaling (Vermeesch, 2013) plot of detrital zircon ages obtained in this study, along with similar data from the Lower and Middle Allochthons, as well as data from the North Atlantic region. The basis for multidimensional scaling plots was discussed elsewhere (Spencer and Kirkland, 2016; Vermeesch, 2013); samples with similar detrital zircon age distributions will plot close together, whereas dissimilar samples will plot farther apart.

Metasedimentary units in the Lower and Middle Allochthons display mainly late Paleoproterozoic through Mesoproterozoic detrital zircon ages, similar to those presented here from the Uppermost Allochthon (Fig. 5). Few published data exist from the Upper Allochthon, but we note that the population older than 840 Ma from the Magerøy nappe in northern Finnmark (Kirkland et al., 2016), traditionally placed in the Upper Allochthon, is statistically similar to the Seve detrital zircon populations (Middle Allochthon).

Figure 5 also provides a comparison of detrital zircon age data from Caledonian (i.e., affected by late Silurian to Early Devonian
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Sørøy

Succes.

Gaissa

Napp e

Krossfjorden

Sværhol t

Succes.

Magerøy

Napp e

Central

Appalachian s

A

Seve

Napp e

Lower All.

Middle All.

Scandinavia autoch./paraut.

Laurentia autoch.

Figure 5. (A) Nonmetric multidimensional scaling (MDS) plots of the detrital zircon age spectra obtained in this study along with those of sedimentary successions elsewhere in the Scandinavian Caledonides and in the North Atlantic region. All.—allochthon. The following sources of U-Pb data are as compiled in Spencer and Kirkland (2016). Laurentia: Central Appalachians (Unicoi, Erwin, Hardyston Formations)—Eriksson et al. (2004); north-central Appalachians (Poughquag Quartzite)—McLennan et al. (2001); Bradore formation—Spencer et al. (2015); Battle Harbour—Kamo et al. (2011), Spencer et al. (2015); Siamarnekh formation—Wheeler (1964), Spencer et al. (2015); Double Mer formation—Spencer et al. (2015). Scotland: Banks et al. (2007), Cawood et al. (2003, 2004, 2007, 2015), P.A. Cawood et al. (unpublished, cited in Cawood et al., 2007), Cutts et al. (2009), Dhuime et al. (2007), Friend et al. (2003), Kinnaird et al. (2007), Lancaster et al. (2011), McAteer et al. (2010), Rainbird et al. (2001), Tucker et al. (1993), G.R. Watt and P.D. Kinny (unpublished, cited in Cawood et al., 2007), Watt et al. (2000). Svalbard: Pettersson et al. (2009). Norway: Gee et al. (2015), Spencer et al. (2014), Zhang et al. (2015). Greenland: Kalsbeek et al. (2000), Strachan et al. (1995), K. Thrane (unpublished, cited in Cawood et al., 2007), Slama et al. (2011). Allochthons: Barnes et al. (2007), Kirkland et al. (2007, 2008), Zhang et al. (2015), Bingen et al. (2011). Each data point reflects the incorporation of all published detrital zircon analyses (<10% discordant) from the unit in question. Gray curved arrow reflects progression toward a greater proportion of younger detritus within a sample. Linear arrows denote vector toward a detrital component of specified age. (B) Map of the Caledonides (Caledon.) and Appalachians around the North Atlantic showing the locations of samples plotted in A.
tectonometamorphic events) metasedimentary units around the North Atlantic. Deposition of these sedimentary units probably started at ca. 1030 Ma, and although there is little consensus as to the tectonic setting in which these sediments were deposited (cf. Cawood et al., 2010; Kirkland et al., 2007; Lorenz et al., 2012), most agree that deposition continued well into the Neoproterozoic and Cambrian on both Laurentia and Baltica. Considering the potential for intercontinental transport of detritus, it is hardly surprising that there are few, if any, diagnostic differences between metasedimentary units deposited prior to break-up of the two continents and opening of the Iapetus Ocean (Bingen et al., 1998). Furthermore, the similar Proterozoic basement evolution of the two continents (e.g., Karlstrom et al., 2001; Roberts and Slagstad, 2015) suggests that determining the provenance of sediments derived from this basement after break-up may be challenging. Such profound similarities in detrital zircon fingerprint can be observed across the entire North Atlantic region, for example, samples 85185, 85190, the Svarholt succession in Finnmark (variably interpreted as either Middle or Uppermost Allochthon), the Krossfjord Complex on Svalbard, the Battle Harbour on Laurentia, and autochthonous Sveconorwegian metasediments in Telemark, south Norway, all share statistically identical provenance.

Although detrital zircon geochronology may be a useful tool for comparing and contrasting sedimentary units within the Caledonides, for example, for the purpose of identifying otherwise cryptic tectonic contacts, our data show that such studies do not provide information suitable for uniquely ascribing a particular unit’s provenance to either Baltica or Laurentia, or a unit’s tectonostratigraphic position within the Caledonian nappe stack. These detrital zircon age similarities are reflected in the complete overlap in the multidimensional scaling plot for units conventionally interpreted to belong to disparate tectonostratigraphic levels.

Nonuniqueness of Detrital Zircon Lu-Hf Isotopic Compositions

Available Lu-Hf data from late Paleoproterozoic through Mesoproterozoic Laurentia and Baltica, including the Lower and Middle Allochthons, show significant scatter, but many analyses define a crude n-shaped evolutionary array trending toward the most radiogenic values at ca. 1500 Ma, with more evolved values both before and after this time period (see Fig. 4 caption for more details). The zircon Lu-Hf isotopic data from the Uppermost Allochthon presented here display a similar variation (Fig. 4), which implies that such data may also be nonunique with respect to tectonostratigraphic level. Thus, augmenting U-Pb ages with Lu-Hf isotopes may not uniquely distinguish the original crustal entity.

Implications for the Caledonian Allochthon Concept

Although the Caledonian tectonostratigraphic framework works extremely well at the introductory level, its dual significance, implying both structural position and heritage, has inherent weaknesses (e.g., Corfu et al., 2014). For example, out-of-sequence thrusting, piggyback transport of earlier structures, and normal faults cutting down across older thrust sheets may be inherently problematic to reconcile within such a framework (Fig. 6), and result in complexities going undetected.

There is also an inherent risk of circular arguments when nondiagnostic features are employed. For example, Agyei-Dwarko et al. (2012) argued that the Heggmoyvatn terrane in Troms is an exotic terrane located in the Uppermost Allochthon, rather than a Baltic basement fold nappe overlying the RNC (i.e., an out-of-sequence thrust; Rutland and Nicholson, 1965). This revision was suggested primarily based on the recognition that this terrane does not comprise ca. 1800 Ma orthogneisses, as would be expected if this was Baltic basement, but rather a late Mesoproterozoic
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CONCLUSIONS

Detrital zircon U-Pb and Lu-Hf isotopic data do not yield information that is conclusively diagnostic of Baltic versus Laurentian provenance. The most likely reason for this nonunique result is that the sources for sediments, subsequently deposited on contiguous pre–Iapetus opening Laurentia and Baltic, were the same. Therefore, detrital zircon ages cannot distinguish between sediments that were on one or the other continent following Iapetus opening. Using the concept of Caledonian allochthons to derive diagnostic features (e.g., detrital zircon distributions, ages of magmatism) for these allochthons and then using the same features to assign tectonostratigraphic position is an inherently circular argument (cf. Lorenz et al., 2012; Zhang et al., 2015). Attempts at strict adherence to the concept of Caledonian allochthons, with associated paleogeographic assignment, obscures architectural complexities in this orogen.

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