A Silurian age for the metasedimentary rocks of the Ekne Group, Trøndelag, Mid-Norwegian Caledonides: and inferences for a peri-Laurentian provenance

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U–Pb analyses (LA–SF–ICP–MS) of detrital zircons from low-grade metasandstones, some tuffaceous, of the biostratigraphically-barren Ekne Group in the Støren Nappe of the Mid-Norwegian Caledonides have revealed that the sequence is almost entirely of Silurian age. The complete Ekne Group succession is about 2800 m thick and estimates of maximum depositional age based on the mean age of the youngest five zircon grains show an upward younging from 446.6 Ma at the base of the group to 432.9 – 427.2 Ma in the upper half. In the sample close to the very top of the succession, a small number of zircons yield latest Silurian to earliest Devonian ages. Considering the inferred staging, recycling and catastrophic release of sediments into the basin during deposition, it is possible that the younger ages reflect genuine Early Devonian sediment input. All samples are dominated by Early Palaeozoic and notably Late Ordovician (Sandbian–Katian) zircon ages, with some peaks suggesting derivation from Taconian plutons occurring in different parts of Mid Norway. Some 40% of zircons in the sample from the base of the Ekne Group range in age from Mesoproterozoic to Palaeoarchaeon. Bearing in mind the palaeogeography at the time, the Archaean grains are considered to have been recycled from older sandstones, with their original provenance most likely being the c. 3.65 Ga gneiss complexes in SW Greenland. As the Iapetus Ocean had closed by latest Ordovician time, by comparing the Ekne Group and other Silurian successions in Trøndelag with similar volcanosedimentary sequences in the northern Appalachians of USA and Canada, it is highly likely that the Ekne Group was deposited in a basin peripheral to the eastern margin of Laurentia during the Salinic orogenic cycle.

Keywords: Ekne Group, Silurian, detrital zircons, U–Pb analyses, Støren Nappe, Caledonides, Appalachians

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Introduction

Over the last few decades, provenance studies and tectonic analysis of siliciclastic sedimentary rock successions have relied heavily on U/Pb geochronology of detrital zircons. Such investigations, in many cases

supported by other provenance indicators such as whole-rock and heavy-mineral geochemistry, and palaeocurrent data, have provided valuable information on the likely sources and ages of the zircons contained within the sedimentary load (e.g., Hallsworth et al., 2000; Garzanti et al., 2016; Fleming et al., 2016). In successions devoid of fossils, determining the maximum

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Figure 1. (A) Location map. (B) Outline geological map of part of the western Trondheim Region. The red rectangle in the top-right corner shows the area enlarged in the main map. (C) Simplified geological map of the Ekne-Åsenfjord area showing the locations of the four samples, EK1 to EK4.

depositional age can be of enormous help in constraining the geological history of the area and the particular rock complex under scrutiny. Zircon age data can be used to constrain maximum depositional age because evidently a deposit can be no older than its youngest detrital mineral constituent.

In this short contribution we present and interpret detrital zircon analytical data from a thick, biostratigraphically-barren sequence of sandstones with a felsic-tuffaceous component situated at the top of a Lower Palaeozoic, back-arc basinal succession in one of the nappes of the Mid-Norwegian Caledonides.

Geological setting

The Caledonide orogen of central Norway, represented mostly by the extensive Trondheim Nappe Complex, part of the Upper Allochthon, is especially well known on two accounts; namely, its prolific fauna in one particular area southwest of Trondheim, and secondly for the fragmented and dismembered ophiolite assemblages that lie at or close to the base of the Støren Nappe (Fig. 1B). Several geochronological studies have shown that the ocean-floor magmatic rocks of the ophiolite(s) range in age from Furongian to Tremadocian, within the time-span c. 497 to 480 Ma (see references appended to table

1 in Slagstad et al., 2014). Shortly after their generation in a suprasubduction-zone setting in the Iapetus Ocean, the ophiolites were obducted, deformed, weakly metamorphosed, uplifted and eroded, with their detritus forming a basal conglomerate to a thick, back-arc or marginal-basin, volcanosedimentary succession which has been inferred, but not satisfactorily proven, to extend up into the Silurian period (Vogt, 1945; Henriksen et al., 2018). A depositional model for the succession in the Ekne–Frosta area involved repeated events of long-term staging and reworking of sediments in near-shore areas before sudden, catastrophic release into the basin (Henriksen et al., 2018).

This largely Ordovician, greenschist-facies succession is rich in body fossils of Mid Ordovician (Dapingian to Darriwilian) age, notably in the Hølanda area just southwest of Trondheim (Fig. 1B). Thereafter, the faunal assemblages, which are of warm-water North American affinity, diminish in number and taxa during Sandbian and early Katian time. To the north of Trondheim, in the Frosta–Åsenfjord district (Fig. 1C), Early to Mid Katian fossils are recorded (Spjeldnæs, 1985; Tolmacheva & Roberts, 2007), but no younger fauna has yet been found. Vogt (1945) suggested that the Upper Hovin and Horg groups of the Hølanda area could possibly be of Llandoveryan age, based on finds of the graptolites *Monograptus* and *Rastrites* (Getz, 1890) in shales in the youngest sequence in another nappe in the easternmost part of the Trondheim Nappe Complex. Since the time of Vogt's (1945) classical work, the question of the age of the youngest rocks in the Hølanda area had remained unresolved. However, a provenance study by Gasser et al. (2016) in conjunction with U–Pb TIMS analyses of volcanic units has shown that sediments of the Horg Group extend up into the Wenlock epoch. Further U–Pb zircon dating work, in an area c. 50 km south of Hølanda, has shown that the youngest volcanosedimentary succession there is of Late Silurian age and possibly extending up into earliest Devonian time (Stokke et al., 2018).

The present contribution concerns the youngest Ekne Group in the Åsenfjord–Ekne area (Fig. 1C). This is a biostratigraphically-barren succession of greenschist-facies shales, siltstones, turbiditic graded-bedded sandstones and intercalated conglomerates with tuffaceous sandstones higher up. The base of the group is marked by the polymict Hopla conglomerate. The total thickness of the Ekne Group is estimated at 2800 m (Henriksen et al., 2018). In the Åsenfjord district, fragments of gastropods and corals of imprecise Mid to Late Ordovician age occur in metalimestones in higher parts of the subjacent Vuddudalen Group, which is otherwise characterised by deep-marine *Nereites* trace fossils (Roberts, 1969, 1984; Uchman et al., 2005). Details of the sedimentology and facies associations are given in Henriksen et al. (2018). In the present contribution, detrital zircons have been separated from

four samples from the Ekne Group, from the basal Hopla conglomerate up to one of the youngest sandstones in the informally named Liahøgda formation (Figs. 1C & 2), in an attempt to determine the maximum depositional age of the succession.

U–Pb zircon age determination

U–Pb age data were obtained by laser ablation, single collector, magnetic sectorfield, inductively coupled plasma mass spectrometry (LA–SF–ICP–MS) at the Central Analytical Facility of Stellenbosch University (South Africa), employing a Thermo Finnigan Element2 mass spectrometer coupled to an Australia Scientific Instruments Resolution S155 excimer laser ablation system. The zircon age data presented here were obtained by single spot analyses with a spot diameter of 30 µm and a crater depth of approximately 15–20 µm, corresponding to an ablated zircon mass of approximately 150–200 ng. The zircon GJ–1 (Jackson et al., 2004) was used as primary calibration material to correct for instrumental mass bias and instrument drift. The laser induced element fractionation (LIEF) on $^{206}\text{Pb}/^{238}\text{U}$ ratios was corrected using the intercept method. Common Pb was corrected using the background and ^{202}Hg interference corrected ^{204}Pb signal and a model Pb composition (Stacey & Kramers, 1975) at the projected age of the zircons. Gold traps are used in both He and Ar gas lines to reduce the Hg interference on ^{204}Pb . The methods employed for analysis and data processing are described in detail by Gerdes & Zeh (2006) and Cornell et al. (2016). For quality control, the Plešovice (Sláma et al., 2008) and M127 (Nasdala et al., 2008; Mattinson, 2010) zircon reference materials were analysed, and the results were consistently in excellent agreement with the published ID–TIMS ages. Full analytical details and the results for all quality control materials analysed are reported in Table 1. Plotting of concordia diagrams (Fig. 3) was performed using Isoplot/Ex 3.0 (Ludwig, 2003), with probability density distribution (PDD) and histogram diagrams (Figs. 4 & 5) being generated by AgeDisplay (Sircombe, 2004). The threshold for using $^{206}\text{Pb}/^{238}\text{U}$ vs $^{207}\text{Pb}/^{206}\text{Pb}$ ages plotted in PDD and histogram diagrams is 800 Ma. A concordance filter of 90 to 110% was applied to differentiate between concordant and discordant grains for display in the probability-density plots. Maximum depositional age determinations were made using the $^{206}\text{Pb}/^{238}\text{U}$ ratios and ages.

Dickinson & Gehrels (2009) proposed several criteria for constraining maximum depositional age using detrital zircon U–Pb data. These include the youngest single grain age, the mean age of the youngest two or more grains that overlap in age at 1σ , and the mean age of the youngest three or more grains that overlap in age at 2σ . Of these, the most reliable is the mean age of the youngest three or more grains that overlap in age at 2σ

Figure 2. Field photos from the outcrops where the samples were collected. (A) Locality EK1. (B) Locality EK2. (C) Locality EK3. (D) Locality EK4.

(Dickinson & Gehrels, 2009). We discuss all three criteria in this contribution, with the additional provisos that only zircons with 95–105% concordance are considered, thus eliminating grains nearest to discordance and making the assessment of maximum depositional ages more robust. We also take the mean age of the youngest five zircons that overlap in age at 2σ in order to be consistent with the equivalent study on the succession discussed by Stokke et al. (2018).

Sample locations and descriptions

The zircons analysed in this study come from four samples of sandstones collected from different parts of the Ekne Group succession. The numbering of the samples starts in what is adjudged to be a unit close to the very top of the Liahøgda Formation succession (EK1) near the core of a late-stage open syncline (Roberts, 1985). Samples EK2 and EK3 were taken approximately midway through the thick succession, whilst sample EK4 comes from a sandstone bed within the basal Hopla conglomerate formation (Fig. 1C). The samples were

Figure 3. U–Pb isotopic compositions of zircons in samples EK1–4 plotted on Tera–Wasserburg concordia diagrams.

all of roughly double-fist size. All the sampling sites are situated on the 1:50,000 topographic map-sheet 'Frosta' 1622–2, UTM zone 32V, blue grid WGS84, and the given map coordinates for each site thus follow this system.

EK1. Grid reference 59570 706410. Locality in a road-cut along a minor road c. 7 km west of Ekne, at about 500 m northeast of Kristivika (Fig. 2A).

EK2. Grid reference 59340 705920. Locality in a long road-cut c. 200 m east of the small lake Skardtjønna (Fig. 2B).

EK3. Grid reference 59295 706090. Outcrop along a gravel road c. 100 m south of the reception office to the 'Åsholmen camping' site (Fig. 2C).

EK4. Grid reference 59475 704940. Locality at the rocky promontory Blekkpynten, just a couple of metres west of small concrete steps leading along the shoreline (Fig. 2D).

Results

Sample EK4

The oldest sample in the study, EK4, comes from a sandstone bed within the basal Hopla conglomerate formation. A relatively high proportion of the zircons in this sample yielded discordant U–Pb ages, which might be due to either residual common Pb (undercorrection for common Pb contents) or Pb loss related to crystal damage caused by alpha-recoil or hydrothermal/thermal resetting. Most of the discordant grains in this sample plot in a near-linear array just above concordia on the Tera–Wasserburg diagram (Fig. 3) that resembles a discordia trend. Furthermore, zircons with similar low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios show a variable degree of concordance (from highly concordant to highly discordant). Additionally, the common Pb (cPb) correction for the secondary quality control standard Plešovice, which is known to contain significant amounts of

Table 1. LA-SF-ICP-MS U-Th-Pb dating methodology at CAF, Stellenbosch University

Laboratory & Sample Preparation	
Laboratory name	Central Analytical Facility, Stellenbosch University
Sample type / mineral	Detrital zircons
Sample preparation	Conventional mineral separation, 1 inch resin mount, 1 µm polish to finish
Imaging	CL, LEO 1430 VP, 10 nA, 15 mm working distance
Laser ablation system	
Make, Model & type	ESI/New Wave Research, UP213, Nd:YAG
Ablation cell & volume	Custom build low volume cell, volume c. 3 cm ³
Laser wavelength	213 nm
Pulse width	3 ns
Fluence	2.5 J/cm ²
Repetition rate	10 Hz
Spot size	30 µm
Sampling mode / pattern	30 µm single spot analyses
Carrier gas	100% He, Ar make-up gas combined using a T-connector close to sample cell
Pre-ablation laser warm-up (background collection)	40 seconds
Ablation duration	20 seconds
Wash-out delay	30 seconds
Cell carrier gas flow	0.3 l/min He
ICP-MS Instrument	
Make, Model & type	Thermo Finnigan Element2 single collector HR-SF-ICP-MS
Sample introduction	Via conventional tubing
RF power	1100 W
Make-up gas flow	1.0 l/min Ar
Detection system	Single collector secondary electron multiplier
Masses measured	202, 204, 206, 207, 208, 232, 233, 235, 238
Integration time per peak	4 ms
Total integration time per reading	Approx. 1 sec
Sensitivity	20000 cps/ppm Pb
Dead time	16 ns
Data Processing	
Gas blank	40 second on-peak
Calibration strategy	GJ-1 used as primary reference material, Plešovice and M127 used as secondary reference material (Quality Control)
Reference Material info	M127 (Nasdala et al., 2008; Mattinson, 2010); Plešovice (Slama et al., 2008); GJ-1 (Jackson et al., 2004)
Data processing package used / Correction for LIEF	In-house spreadsheet data processing using intercept method for laser induced elemental fractionation (LIEF) correction
Mass discrimination	Standard-sample bracketing with 207Pb/206Pb and 206Pb/238U normalised to reference material GJ-1
Common-Pb correction, composition and uncertainty	204-method, Stacey & Kramers (1975) composition at the projected age of the mineral, 5% uncertainty assigned
Uncertainty level & propagation	Ages are quoted at 2 sigma absolute, propagation is by quadratic addition. Reproducibility and age uncertainty of reference material and common-Pb composition uncertainty are propagated.
Quality control / Validation	Plešovice: Wtd ave 206Pb/238U age = 337 ± 4 (2SD, MSWD = 0.2) M127: Wtd ave 206Pb/238U age = 520 ± 5 (2SD, MSWD = 0.8)
Other information	Detailed method description reported by Frei and Gerdes (2009)

Figure 4. Detrital zircon ages in samples EK1–4 displayed as probability-density plots. 'n' = number of zircons with <10% discordance in the total zircon population. Dark blue areas are zircons with <10% discordance, pale blue areas are zircons with >10% discordance. Pie charts show relative abundance of Early Palaeozoic, Neoproterozoic, Meso- and Palaeoproterozoic and Archaean zircons.

cPb, yielded highly concordant analyses, which argues against undercorrection of cPb (e.g., due to insufficient interference correction of Hg in the carrier gas). We therefore argue that the observed discordance is mainly due to Pb loss.

The majority of the zircons with <10% discordance (64 of the 112 analysed grains, 53% of the population) form a single peak in the Early Palaeozoic (Fig. 4). However, the spectrum also includes a relatively high proportion of Proterozoic and Archaean zircons. Palaeo-

to Mesoproterozoic zircons (1013–1982 Ma) comprise 31% of the near-concordant population, with Archaean zircons (2556–3486 Ma) forming a further 12%. The Proterozoic zircons are wide-ranging in age but appear to cluster mainly at c. 1000–1100 Ma and 1300–1500 Ma, whereas the Archaean component has no obvious age structure. There are also two late Neoproterozoic zircons (c. 629 Ma, c. 662 Ma).

The Palaeozoic zircons form a single relatively broad group between c. 434 Ma and c. 492 Ma (Fig. 5). There

Figure 5. Expansion of the Phanerozoic part of the zircon age spectra for samples EK1–4. Orange areas are zircons with <10% discordance, pale yellow areas are zircons with >10% discordance.

is a single younger zircon dated as c. 405 Ma, but this is only 91% concordant and the age is considered to be anomalously young, probably due to Pb-loss. Excluding this single outlier, the Palaeozoic zircons are dominated by a large group peaking at 462 Ma, with a minor subsidiary group peaking at 492 Ma.

Estimates of maximum depositional age using the Dickinson & Gehrels (2009) criteria are as follows: youngest single grain = 434.3 Ma, mean age of the youngest 2 zircons overlapping at 1σ = 438.2 Ma, and mean age of the youngest 5 zircons overlapping at 2σ = 446.6 Ma.

Sample EK3

Sample EK3, which is from a tuffaceous sandstone bed approximately midway through the succession, has a much higher proportion of zircons with near-concordant U–Pb ages compared with EK4 (Fig. 3). Virtually all the zircons with <10% discordance ($n = 92/114$, Fig. 3) yielded Early Palaeozoic ages, with only one near-concordant Proterozoic grain and a total absence of the Archaean. The Palaeozoic zircons are dominated by a large group peaking at 451 Ma, with a minor subsidiary group peaking at 489 Ma.

Estimates of maximum depositional age using the Dickinson & Gehrels (2009) criteria are as follows: youngest single grain = 434.8 Ma, mean age of the youngest 2 zircons overlapping at 1σ = 435.6 Ma, and mean age of the youngest 5 zircons overlapping at 2σ = 437.0 Ma.

Sample EK2

Sample EK2, a tuffaceous sandstone, is also from roughly midway through the succession though slightly higher up than sample EK3. Similarly to EK3, most of the zircon analyses are near-concordant (Fig. 3), with 84 of the 113 analysed grains having <10% discordance. Of the 84 near-concordant zircons, the great majority (92%) is Early Palaeozoic (Fig. 4), but there is one Neoproterozoic grain (664 Ma), four Mesoproterozoic grains (1588–1697 Ma) and two Neoarchaeal grains (2680 Ma, 2788 Ma).

The Early Palaeozoic zircon spectrum (Fig. 5) is dominated by a group peaking at 450 Ma (in EK4 at 460 Ma), with a subsidiary peak at 509 Ma. There is a suggestion of a younger peak at c. 430 Ma manifested by a shoulder on the 450 Ma peak (Fig. 5).

Estimates of maximum depositional age using the Dickinson & Gehrels (2009) criteria are as follows: youngest single grain = 424.5 Ma, mean age of the youngest 2 zircons overlapping at 1σ = 425.8 Ma, and mean age of the youngest 5 zircons overlapping at 2σ = 427.2 Ma.

Sample EK1

Sample EK1 is from a tuffaceous sandstone bed considered to be close to the top of the Liahøgda formation. A relatively high proportion of the zircons in this sample yielded discordant U–Pb ages, owing to the abundance of common Pb (as identified by low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios). Similar to sample EK4, most of the discordant grains in this sample plot in a near-linear array just above concordia on the Tera–Wasserburg diagram (Fig. 3), and zircons with similar low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios show a variable degree of concordance (from highly concordant to highly discordant). Again, we therefore argue that the observed discordance is most likely caused by Pb loss.

Most of the zircons with <10% discordance (64 of the 100 analysed grains) form a single peak in the Early Palaeozoic, which forms 95% of the near-concordant population (Fig. 3). In addition, there is minor representation of the Proterozoic (1049 Ma, 1485 Ma) and Archaeal (2711 Ma). The Early Palaeozoic zircons form a bimodal population with peaks at 447 Ma and 464 Ma (Fig. 4), together with four zircons that yielded younger apparent ages. The ages of these grains are 402.0

± 4.7 Ma, 406.9 ± 4.6 Ma, 411.7 ± 4.7 Ma and 418.1 ± 5.1 Ma. The youngest of these can be rejected on the basis of a concordance measurement of only 90.7%, but the other three are closer to concordia (97.5–101.5% concordant). Using the Dickinson & Gehrels (2009) criteria, therefore, gives the youngest single grain = 406.9 Ma, and mean age of the youngest 2 zircons overlapping at 1σ = 409.3 Ma. However, the more reliable criterion (mean age of the youngest 5 zircons overlapping at 2σ) gives a significantly older maximum depositional age of 432.9 Ma.

Discussion

On the basis of the most reliable of the criteria proposed by Dickinson & Gehrels (2009), maximum depositional ages determined for the Ekne Group succession show an upward younging, from 446.6 Ma (Late Ordovician) at the base (sample EK4), to 437.0 Ma (Llandovery, Early Silurian) and 427.2 Ma (Wenlock, Mid Silurian) in the middle parts of the succession (samples EK3 and EK2, respectively). The sample from near the top of the succession (EK1) has a conservative maximum depositional age of 432.9 Ma (Wenlock, Mid Silurian). The youngest of these ages (427.2 Ma) is closely comparable to the maximum depositional age of c. 430 Ma inferred for the Horg Group in the Hølanda area (Gasser et al., 2016), and that of c. 427 Ma for the sandstone succession at Dugurdsknappen c. 50 km south of Hølanda (Stokke et al., 2018). Although there are a small number of zircons yielding latest Silurian and earliest Devonian ages in sample EK1, additional confirmatory analyses would be required before proposing that deposition of the Ekne Group genuinely extended into the earliest Devonian. Nevertheless, considering the inferred multiple pulses of staging and recycling of sediments in this tectonically active basin then a Devonian input cannot be discounted.

Three of the four analysed samples are overwhelmingly dominated by Early Palaeozoic (Mid to Late Ordovician) zircon ages, but over 40% of the zircons in the basal sample (EK4) are much older (Proterozoic and Archaeal) (Fig. 4). Given the wide diversity of ages concerned, these zircons are interpreted as being recycled from pre-existing sandstones. Their most likely origin would be sediments from older successions in the Caledonian nappes, but the abundance of Archaeal zircons is somewhat surprising. Current information suggests that zircons of this age are comparatively scarce throughout the Lower, Middle, Upper and Uppermost allochthons (Bingen & Solli, 2009; Slagstad & Kirkland, 2017 and references therein). However, relatively few data have been published from the nappes of the Upper Allochthon, to which the Ekne Group succession belongs. We also note that Archaeal zircons are relatively common in metasandstones in the Lower Nappe of the

Helgeland Nappe Complex (Uppermost Allochthon) in the Bindal area, Nordland county, as are Meso- and Palaeoproterozoic zircons between c. 1000 Ma and c. 1900 Ma (Barnes et al., 2007). Recycling of zircons from sandstones with similar age spectra could account for the Precambrian component of the detrital zircon population found in the basal Ekne Group.

The EK4 Hopla sample and also a sandstone from Hovin, near Hølanda, have yielded zircons of Eoarchaeon to Palaeoarchaeon age. The Hovin zircon (Forsknig, 2010) was considered to have been derived from SW Greenland, probably by recycling, where granitoid rocks in the Itsaq Gneiss Complex are of latest Eoarchaeon to Palaeoarchaeon (3.65 Ga) age (Nutman et al., 1999, 2000; Whitehouse et al., 1999). Here, it is important to remember that the prolific Mid to Late Ordovician body fossils in the Hølanda area are of North American provinciality, as are the few fossils found in the Vuddudalen Group, below the Ekne Group. Thus, sedimentation and volcanic activity at this time (Bruton & Bockelie, 1980; Grenne & Roberts, 1998) and in the succeeding Silurian period, in the nappes now exposed in Mid Norway, were occurring in a location peripheral to the eastern seaboard of Laurentia. The basin was conceivably close to southeasternmost palaeo-Greenland (Domeier & Torsvik, 2014; Domeier, 2016), possibly even involving the proximal margin of the Ganderian microcontinent which had already accreted to Laurentia by Mid Silurian time (van Staal et al., 2009, 2012; Fyffe et al., 2011; Wilson et al., 2017). Comparable arc-magmatic and basin-depositional activity at this time is recorded not only in the northern Appalachians and Newfoundland but also in the Irish Caledonides (Waldron et al., 2014).

The dominance of Early Palaeozoic zircon ages in the dataset is of interest with regard to possible sources for the various peaks. The weak 490–480 Ma signature registered in all samples is clearly denoting a derivation of these zircon grains from fairly local ophiolitic assemblages (Fig. 5). The source or sources for the peak of c.460 Ma in the oldest sample, EK4, is open to speculation, since we have no palaeocurrent flow indicators in the sandstones. Calc-alkaline arc plutons with ages of 465–459 Ma occur in the Gjersvik Nappe and Helgeland Nappe Complex some 150 km north of the Ekne area (Nordgulen et al., 1993; Meyer et al., 2003; Barnes et al., 2007). Similar plutons U–Pb-dated to 460 Ma also occur in the Smøla–Hitra Batholith on islands and the mainland in coastal Trøndelag, as well as on the northwestern side of Trondheimsfjorden c. 40 km northwest of Ekne (Tucker et al., 2004). All these plutons are considered to be parts of Taconian batholiths, akin in age and geochemistry to those in the northern Appalachians and southernmost East Greenland (Higgins et al., 2004; Roberts et al., 2007; Hollocher et al., 2016). In samples EK1–3, zircon grains spike predominantly at c. 450 Ma (Fig. 5) and may derive

from rhyolites in the Hovin–Hølanda district dated at around this age (D.Gasser, pers. comm. 2019). Subsidiary zircon peaks or shoulders at 430 Ma in some samples could signify a source from widespread, 438–430 Ma, pre-collisional plutons in the Gula Complex (Dunning & Grenne, 2000; Nilsen et al., 2003, 2007).

Following from the above considerations, the lithological successions of the Vuddudalen and Ekne groups should be compared with volcanosedimentary successions of the northern Appalachians and Irish Caledonides, where there are several reports of Silurian, calc-alkaline, bimodal volcanic and felsic-tuffaceous metasedimentary rocks (Whalen et al., 2006; Fyffe et al., 2011; Pinán Llamas & Hepburn, 2013; Wilson et al., 2015, 2017; Kay et al., 2017). Such a comparison may be significant and lead to a better understanding of how Iapetus closure-related tectonic elements can be correlated along the length of the orogen. While it is not a topic of the current publication, it is one that will generate much interesting research among future generations of Caledonian–Appalachian geologists. One may speculate, for example, that the unconformity marking the ‘Ekne Disturbance’ of Vogt (1936), i.e., at the base of the Ekne Group, may equate with the unconformity marking the inception of the Salinic orogenic cycle, in Katian time, in the northern Appalachians (e.g., Wilson et al., 2017). This is a distinct possibility, timewise; but alternatively, it may relate to the third phase of the Taconian orogeny (van Staal et al., 2009). In the Dugurdsknappen area, Stokke et al. (2018) have described isoclinal folding and an associated metamorphic phase that preceded an unconformity at the base of a post-427 Ma (Ludlow) volcanosedimentary succession. This tectonometamorphic episode, which has yet to be dated, may be equivalent to the main collisional phase of regional orogenesis in the northern Appalachians (van Staal et al., 2009, 2012; Wilson et al., 2017). The fact that this pre-427 Ma folding and metamorphism is not recognised in the Ekne Group succession may well indicate that the basinal successions in the Ekne, Hølanda–Støren and Dugurdsknappen districts are possibly derived from separate areas, sub-basins or even disparate terranes in the Appalachian–Caledonian collage, each with their own depositional, volcanic and deformational histories. The Ekne Group succession is thus in some ways reminiscent of deposition in a successor basin, in this case syn-Scandian and located at a high level in the Støren Nappe. Significant variations in basinal, volcanic and structural developments along the strike of the orogen have indeed been recorded in many of the publications cited above.

Broadly speaking, the main phase of the Salinic orogeny in the Appalachians is temporally equivalent to the Scandian orogeny in the Scandinavian Caledonides. In both regions, the later stages of these orogenies are characterised by extensional faulting and fairly flat-lying foliations resulting from vertical shortening concomitant with orogenic collapse during the Early Devonian period

(e.g., Roberts, 1967, 1968; Hossack, 1984; van Staal & de Roo, 1995; Fossen, 2010; Wilson et al., 2017; Stokke et al., 2018).

Volcanosedimentary successions of Silurian age, specifically in the Upper Allochthon, are known from western and southwestern Norway, based on finds of body fossils (Skjerlie, 1974; Thon, 1985). In central Norway, graptolites of Llandovery age have been described from the eastern part of the Trondheim Region (Getz, 1890). Thus, the recently documented geochronological proof of the existence of Silurian sedimentary rocks in the Hølanda (Gasser et al., 2016) and Dugurdsknappen (Stokke et al., 2018) areas, together with the results from our own study, adds to the fact that sedimentation in certain basins extended up into Mid or Late Silurian times, and conceivably into the Early Devonian period.

Conclusions

U–Pb age data from detrital zircons obtained by LA–SF–ICP mass spectrometry on four samples of sandstones from the barren Ekne Group in the Caledonides of Mid Norway include the following main results:

- 1 Estimates of maximum depositional age—based on the mean age of the five youngest grains—range from 446.6 Ma in a sandstone bed (sample EK4) in the basal Hopla conglomerate to 432.9 to 427.2 Ma in variably tuffaceous sandstones (EK1–3) in the upper half of the group. The bulk of the c. 2.8 km thick Ekne Group is thus of Silurian age.
- 2 Early Paleozoic zircons dominate all four samples. These comprise 92–99% of the <10% discordant zircons in the three stratigraphically highest samples (EK1–3), with the lowest sample (EK4) containing 53%. The majority of the Early Palaeozoic zircons are Late Ordovician (Sandbian–Katian), but in sample EK4, the population peak is at 462 Ma (Darriwilian), with a subsidiary group at 492 Ma (Late Cambrian), the latter likely to have derived from ophiolites. Sample EK2 also contains a few Cambrian grains. Sources for the c. 460 Ma zircons are thought to be plutons from Taconian batholiths exposed in different parts of Mid Norway.
- 3 About 40% of zircons in EK4 at the base of the Ekne Group range in age from Mesoproterozoic to Palaeoarchaeon. The Archaeon grains (oldest at 3486 Ma) are considered to have been recycled from older sediments, and to have originally been sourced from known Palaeoarchaeon gneiss complexes in Southwest Greenland.
- 4 The basin hosting the Ekne Group was evidently located in a terrane peripheral to the eastern seaboard of Laurentia, with deposition involving a volcanic arc source likely to have occurred during the protracted Salinic orogenic cycle that is recognised in many parts of the northern Appalachians and its Caledonian equivalent in the British Isles.

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