Geoscience Frontiers 16 (2025) 102077

Contents lists available at ScienceDirect

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

Detrital zircon geochronology of lower Palaeozoic sedimentary rocks from the COSC-2 borehole, Scandinavian Caledonides

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ARTICLE INFO

Article history:
Received 29 November 2024
Revised 7 April 2025
Accepted 8 May 2025
Available online 20 May 2025
Handling Editor: Mathew Domeier

Keywords:
Detrital zircon geochronology
COSC-2
Baltica
Cambrian
Ordovician

ABSTRACT

Detrital zircon geochronology is reported from the c. 1200 m thick Cambro-Ordovician sedimentary succession recovered in core from the COSC-2 continental drilling project in the Scandinavian Caledonides. Above a regolith marking the sub-Cambrian peneplain, a lower to middle Cambrian(?) succession comprises conglomerate, sandstone and shale overlain by gravity flows fining upwards into the Alum Shale Formation. First results of detrital zircon geochronology from the Cambrian(?) succession show that the basal section of the autochthonous cover is characterized by mainly late Paleoproterozoic – early Mesoproterozoic detrital grains. The middle part of the succession is dominated by late Paleoproterozoic detritus with minor Mesoproterozoic and Archean input. The upper part of lower Cambrian(?) succession is characterized by Archean to Cambrian detritus. The maximum depositional age is calculated to 530.5 ± 4 Ma for the upper part of the lower Cambrian succession. Two samples from the Lower Ordovician(?) succession above the Alum Shale Formation show predominantly Mesoproterozoic to early Neoproterozoic (1.5–0.9 Ga) ages.

The autochthonous lower Cambrian(?) passive margin succession in the lower section is dominated by local detritus, sourced exclusively from the Eastern Segment of the Sveconorwegian Orogen, which includes the basement studied in COSC-2. Up-section, the provenance shifts towards the Transscandinavian Igneous Belt and Svecofennian Orogen sources, with the youngest part of the succession showing a notable input of Neoproterozoic –Cambrian active margin detritus. The Ordovician(?) succession is characterized by populations, likely derived from the Sveconorwegian Orogen, and a minor cratonic contribution.

Statistical analysis of detrital zircon datasets across Baltica suggests that the Southern Baltica/Sandomirian Arc, rather than the Timanian Orogen, was a significant source of detrital material across the paleocontinent. The influence of Timanian Orogen grains is limited to northernmost Scandinavia, whereas Sandomirian detritus reached central Scandinavia in the lower to middle Cambrian and remained prevalent in southern Scandinavia into the Lower Ordovician.

1. Introduction

The Collisional Orogeny in Scandinavian Caledonides (COSC) drilling project of the International Continental Drilling Programme (ICDP) is focused on understanding the structures and geological processes that formed the Paleozoic Caledonian mountain belt of Scandinavia (Gee et al., 2010). Two deep boreholes have provided a unique opportunity to investigate continuous rock successions in Jämtland, central Sweden (Fig. 1). The material supplied for this study was acquired during the COSC-2 drilling project (Lorenz et al., 2021). The recovered drill core consists of a parautochthonous succession separated from an autochthonous cover and a pre-Sveconorwegian basement by a tectonized zone (Lorenz et al., 2022). The COSC-2 drill core offers an insight into

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https://doi.org/10.1016/j.gsf.2025.102077
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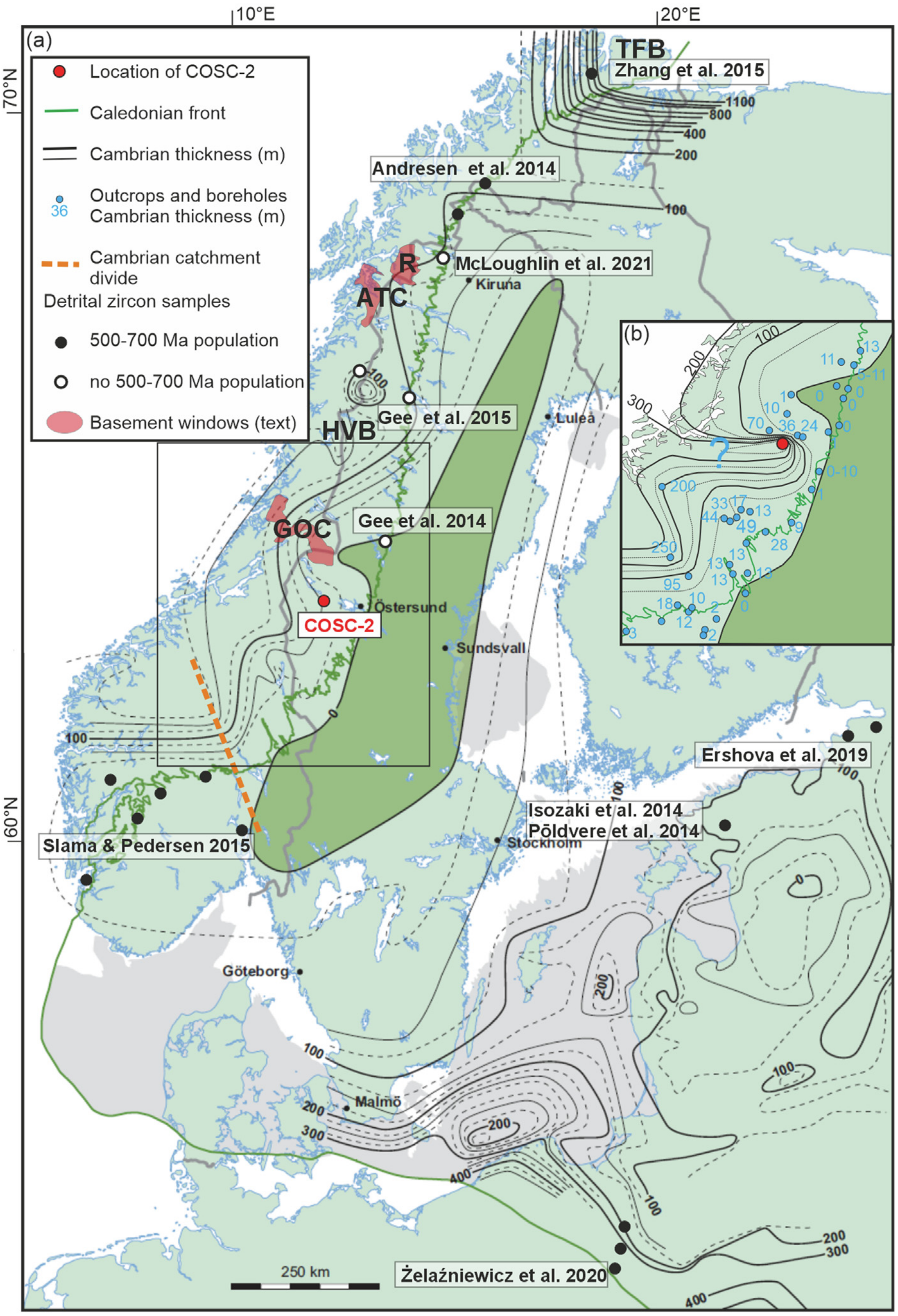

Fig. 1. Isochore maps showing the thickness of Cambrian sedimentary units in Scandinavia and northeastern Europe and the location of the COSC-2 borehole (63.3124° N, 13.5265° E). Area of inferred Cambrian subaerial exposure is marked with a darker green colour. (a) Locations of the detrital zircon samples discussed in this study are marked according to the presence of 0.75 – 0.52 Ga detrital zircon populations. The basement windows and basins mentioned in the text: R – Rombak window; ATC – Akkajaure–Tysfjord Culmination; HVB – Hornavan–Vattudal Basin; GOC – Grong–Olden Culmination, TFB – Timanian Foreland Basin. The Cambrian catchment divide is after Lorentzen et al. (2020). Map is after Nielsen and Schovsbo (2011) and Wickström Stephens (2020). Rectangle marks the area of Fig. 1b. (b) Reinterpretation of the Cambrian isochores based on the measured thickness of the Cambrian succession in COSC-2 borehole and data compilation from Nielsen and Schovsbo (2011). The extent of the pull-apart basin is unknown due to insufficient data to the west of the COSC-2 site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the detrital sources of the sediments deposited in a pull-apart basin formed during the Cambrian and Ordovician when Baltica entered a stage of major rotation (Torsvik et al., 1996; Meert, 2014).

One of the major questions that arose during similar studies across Baltica was related to the origin of late Neoproterozoic-Cambrian detrital zircon grains in Scandinavia that are commonly attributed to the Timanian Orogen (e.g. Andresen et al., 2014; Slama, 2016; McLoughlin et al., 2021). Recent studies in the southern part of the East European Craton provided another possibility for the origin of the aforementioned detritus. The Sandomirian Arc that developed on the southern Baltica margin (present-day coordinates, as further in the text) in the latest Neoproterozoic-early Cambrian is considered the main contributor of the late Neoproterozoic – Cambrian detritus there (Collett et al., 2022; Callegari et al., 2025). The question arises as to whether these two detrital sources can be differentiated and where the boundary between the possible depocenters sourced from the southern and the northern orogens was located?

The main goal of this paper is to characterize the provenance of the Cambro-Ordovician succession of the COSC-2 borehole and try to pinpoint the sources of the Neoproterozoic-Cambrian detritus. To address these issues we undertook a geochronological study of detrital zircons in parautochthonous to autochthonous rocks using laser ablation – inductively coupled plasma mass spectrometry (LA-ICPMS) analysis. The results represent a complementary view on provenance shifts across Cambrian-Ordovician sediments of the central-western Baltican cover sequence. The outcome also contributes an important missing link between the previous provenance studies in northern (Andresen et al., 2014) and southern Scandinavia (Slama and Pedersen, 2015; Slama, 2016). Through the statistical comparison of the detrital zircon populations of the Cambrian-Ordovician successions across Baltica we provide a new insight into the currently established boundaries of the Timanian/Sandomirian depositional domains.

2. Geological background

2.1. Cambrian-Lower Ordovician sequences of the Baltoscandian margin

Neoproterozoic to Lower Paleozoic sedimentary basins, to various extents involved in the collisional orogeny of the Scandinavian Caledonides, developed during the opening of the Iapetus Ocean and the subsequent drift of Baltica (e.g. Bingen et al., 2011, Slama, 2016). The Iapetus Ocean reached its maximum extent in Cambro-Ordovician times, immediately prior to the onset of subduction that led to its closure in the Silurian period (e.g. Cocks and Torsvik, 2005; Corfu et al., 2014). Neoproterozoic Sparagmite basins developed during the rifting stage and in some parts were subsequently covered by drift stage sediments in Cambrian to Ordovician times (Nystuen et al., 2008; Wickström and Stephens, 2020). The Cambrian to Lower Ordovician sedimentation in Scandinavia was a result of early Cambrian transgression and, locally, activation or reactivation of faults bounding the sedimentary basins (Cocks and Torsvik, 2005; Wickström and Stephens, 2020). Sedimentation along the Baltoscandian margin continued from Neoproterozoic into Cambrian time (e.g. Saintilan et al., 2016), whereas a sub-Cambrian peneplain developed on inner Baltica and was covered by a lower to middle Cambrian siliciclastic succession (Nielsen and Schovsbo, 2011).

Deposition of early Cambrian to Ordovician sediments on the proximal Baltoscandian margin was controlled by two major structures that divided the margin into three potentially separate deposition centers. The Timanian Foreland Basin (TFB) and the Gaissa Basin are divided from the Hornavan-Vattudal Basin (HVB) to the south by the Rombak Window and the Akkajaure–Tysfjord Culmination (ATC; e.g. Björklund, 1989; Greiling et al., 2024). The HVB is separated from the Hedmark and related basins in the south by the Grong–Olden Culmination (GOC; Gee, 1977; Greiling et al., 2024). These basins are differently sourced with respect to their Neoproterozoic-Cambrian detritus. The Hedmark and related basins, as well as the TFB and Gaissa Basin, frequently have a significant population of late Neoproterozoic-Cambrian zircon grains, while the HVB is devoid of Neoproterozoic–Cambrian-sourced detritus (Andresen et al., 2014; Slama and Pedersen, 2015; Greiling et al., 2024).

Lower Ordovician sedimentary strata are widespread on Baltica along the modern Caledonian erosional front as well as in the Lower Allochthon (e.g. Wickström and Stephens, 2020). They consist mainly of the upper part of the Alum Shale Formation and the overlying clastic succession dominated by greywacke (e.g. Andersson et al., 1985). Geochronological studies are very limited but data are available mainly for locations south of Jämtland (e.g. Gee et al., 2014; Slama and Pedersen, 2015; Fig. 1). Lower Ordovician sedimentary units in southern Norway still show late Neoproterozoic-Cambrian detrital zircon signatures (Slama and Pedersen, 2015).

2.2. Sources of late Neoproterozoic-Cambrian detritus

While the Baltoscandian margin from Neoproterozoic to Lower Ordovician times was in a rift-to-drift stage basin system, the remaining margins of Baltica were in a convergent regime. The northern and eastern margins (present coordinates) experienced collision (Kuznetsov et al., 2007) or accretion (Pease, 2011) of a series of volcanic arcs and microcontinents to construct the Timanian Orogen. The TFB developed in the late Ediacaran to early Cambrian along the northeastern margin of Baltica (Pease, 2011). The corresponding detrital zircon signal spans from ca. 0.75 Ga to ca. 0.52 Ga (Kuznetsov et al., 2007; Corfu et al., 2010).

Southern Baltica developed a convergent margin in the late Ediacaran – earliest Cambrian as well. The first interpretation of this tectonic scenario suggested that the Baltican margin was overridden by a group of terranes that resulted in the development of the Scythides and Santacrucides with a foreland basin preserved in modern southern Ukraine (Żelaźniewicz et al., 2020; Paszkowski et al., 2021). However, more recent studies suggest that Baltica developed an active margin in an upper plate position relative to subducting lithosphere of the Mirovoi Ocean (Collett et al., 2022; Callegari et al., 2025). This active margin was called either the Southern Baltica (Collett et al., 2022) or the Sandomirian Arc (Callegari et al., 2025) and most of it is posited to have subsequently rifted from Baltica (Collett et al., 2022; Soejono et al., 2022). The related detrital signatures are rich in 0.75 – 0.52 Ga zircon grains and common in Ukraine, Belarus and eastern Poland (Paszkowski et al., 2019, 2021; Żelaźniewicz et al., 2020).

2.3. COSC-2 core profile

The COSC-2 drill site is located in Jämtland in the vicinity of the towns Järpen and Mörsil on the southern side of the lake Liten (Fig. 1, 63.3124° N, 13.5265° E). The COSC-2 borehole reached 2276 m depth with the lowermost core derived from the Baltican basement (Lorenz et al., 2022). The basement penetrated between 1220 m and 2276 m consists of porphyries and porphyritic tuffs intruded by diabase and dolerite dykes (Fig. 2). The porphyries are dated to ca. 1.66–1.65 Ga (Andersson et al., 2022), while two generations of flat-lying mafic intrusions display ages of ca. 1.47 Ga and 1.27 Ga (Lescoutre et al., 2022a, 2022b). The basement is covered by an immature palaeosol marking a sub-Cambrian(?) peneplain. This surface is overlain by conglomerate, sandstone, carbonate and shale of the upper Sjoutälven Group (Fig. 3). The overlying coarse-grained turbidites of the Sjoutälven Group fine upwards and transition into the tectonized Alum Shale Formation at ~ 845 m depth.

The Alum Shale Formation is divided into lower (~12 m), middle (~45 m) and upper (~25 m) parts that are transitional into the 'regular' turbidites beneath and above (Lehnert et al., 2024). These transitions are well preserved, totally undisturbed. Even within the tectonized part, where there are zones showing horizontal shearing such thrust zones do not cause any thrust complications or stratigraphic repetitions. The shear zones in the 45 m thick, middle and shale-dominated part of the Alum Shale Formation were regarded as the 'décollement' in former seismic interpretations (see Lorenz et al., 2022), but there is no evidence for any major dis-

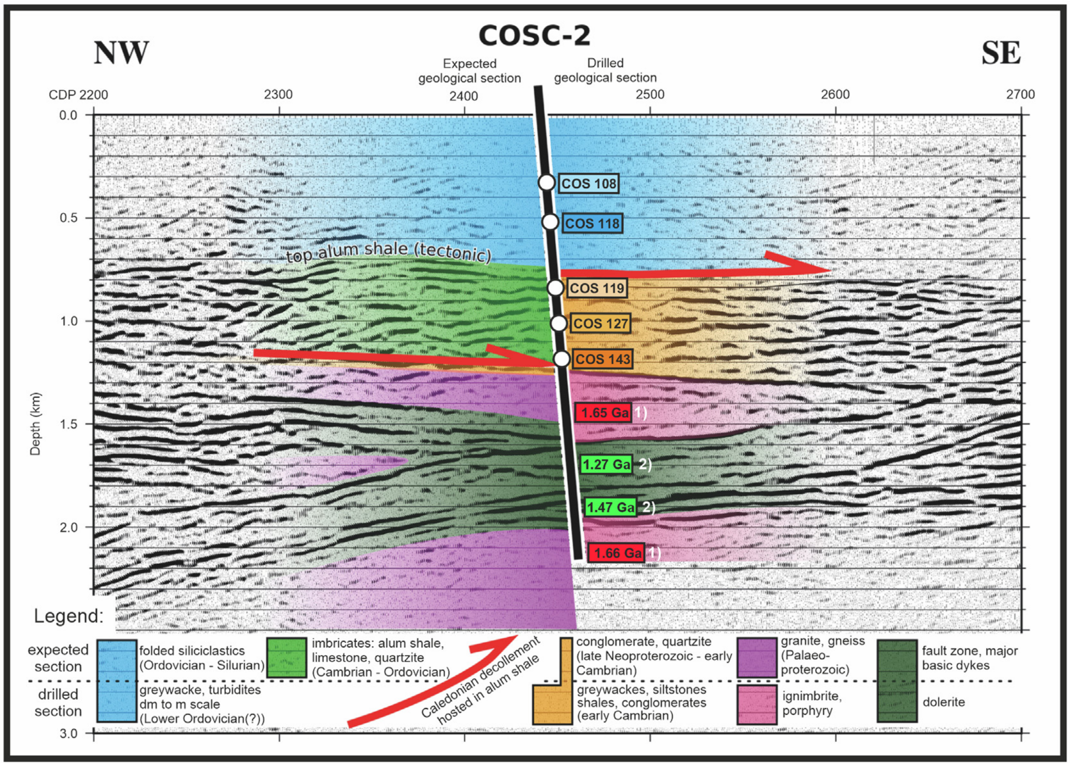

Fig. 2. The COSC-2 anticipated geology (left) and the drilled geology (right) superimposed on the depth-converted seismic section that represents the rocks surrounding the COSC-2 drill site (Lehnert et al., 2024; modified from Lorenz et al., 2022 and Hedin et al., 2012). The age data is from Andersson et al. (2022) and Lescoutre et al. (2022).

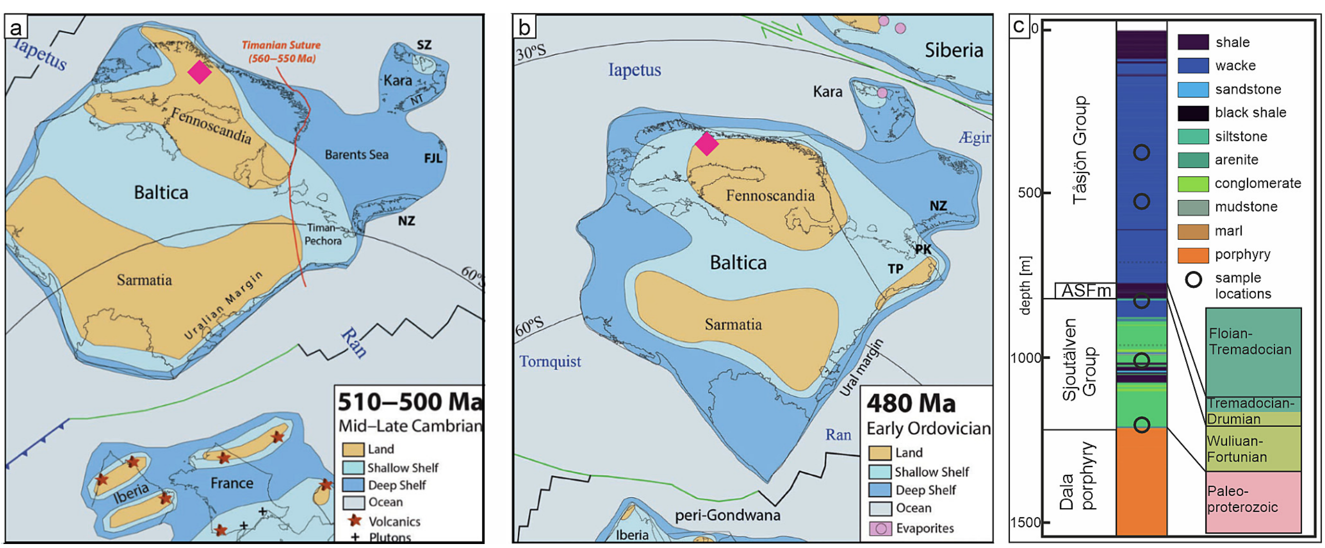

Fig. 3. Sketch maps of palaeogeographic reconstructions by Torsvik and Cocks (2017) for the (a) middle/upper Cambrian (ca. 505 Ma) and (b) Early Ordovician (ca. 480 Ma); purple diamonds in the palaeogeographic sketches indicate the COSC-2 drill site. Note the discrepancy between COSC-2 marine succession and position of the borehole on landmass at the time (c) Simplified log of the COSC-2 succession, illustrating the main lithologies of the Palaeozoic basement cover and their chronostratigraphic position (Lehnert et al. 2024, modified); ASFm – Alum Shale Formation, FJL – Franz Joseph Land, NT – North Taimyr, NZ – Novaya Zemlya, PK – Pai-Khoi, TP – Tajmyr Peninsula, SZ – Severnaya Zemlya. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

placement (Lehnert et al., 2024). The middle section of Lower Cambrian through the middle (–upper?) Cambrian Alum Shale marks a transition into the parautochthonous (middle?) upper Cambrian part of the Alum Shale Formation and overlying Lower Ordovician (Tremadoc-Floian?) turbidites representing the upper part of the Tåsjön Group (Fig. 3), (Heuwinkel et al., 2007). The whole Early Palaeozoic succession above the sub-Cambrian(?) peneplain is considered to have been deposited in a local, long-lived pull-apart basin (Lehnert et al., 2024).

3. Methods

Detrital zircon samples were collected from the COSC-2 core repository in the Federal Institute for Geosciences and Natural Resources (BGR) in Berlin-Spandau, Germany. All the depths given for the samples are calculated and corrected to the top depth of the section unit (meters composite depth – MCD). The half-cores ranging in length from 42.5 to 99 cm were processed using standard zircon separation techniques involving crushing, grinding, water table concentration of high-density components, magnetic separation, and heavy liquid density separation at the Polish Academy of Sciences, Kraków and AGH University of Krakow, Poland. A small part of the half-cores was cut to make standard polished thin sections. The short description of the sampled material can be found in Table 1. Concentrated zircon separates were co-mounted in 2.54 cm epoxy rings with natural zircon reference materials and polished to expose the grain interiors at the University of Iowa, USA. Zircon from each mount was characterized using a scanning electron microscope (SEM) equipped with cathodoluminescence (CL) imaging. Detrital zircon U-Pb analyses of five samples were conducted by LA-ICPMS at the Arizona LaserChron facility (Tucson, USA). The U-Th-Pb concentrations in the unknown zircons were calibrated using natural reference material FC (1099 Ma, Schmitz and Bowring, 2001) as the primary reference material and R33 (419 Ma, Mattinson, 2010) and TEM (417 Ma, Black et al., 2003) as secondary reference materials. Complete descriptions of the U-Th-Pb analytical protocol are reported in Gehrels et al. (2006, 2008) and Gehrels and Pecha (2014).

During filtering of acquired LA-ICPMS U-Pb data, the $^{206}Pb/^{238}U$ dates were used for analyses younger than 1200 Ma and the $^{207}Pb/^{206}Pb$ dates for analyses older than 1200 Ma (Supplementary Data Table S1). Analyses with > 10% uncertainty in $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ dates > 10% discordance or > 5% reverse discordance have been excluded. Detrital zircon U-Pb age results are presented with 2σ uncertainties in probability density plots with stacked histograms made with the Isoplot 4.15 Excel macro of Ludwig (2003; Fig. 4). All single grain ages in the text and tables are given with 2σ uncertainties. The value "n" corresponds to the number of analyses matching the criteria out of the total number of analyses for each sample. The geochronological datasets were evaluated by statistical analysis using Kołmogorov – Smirnov (K – S) tests and cumulative density functions calculated using the Excel macro of Arizona LaserChron Center (Guynn and Gehrels, 2010). Non-Metric Multidimensional Scaling was performed following the method of the Kuiper test V value using the DZmds software of Saylor et al. (2018). The maximum depositional ages (MDA) of the studied samples were calculated based on the maximum likelihood age (MLA) following the routine of Vermeesch (2021) where a population of youngest detrital ages overlapping within error is present.

4. Results

4.1. The autochthonous lower to middle Cambrian(?) succession

The samples of lower to middle Cambrian(?) sandstones (Lehnert et al., 2024) were taken from the three positions in the profile, described here in order of decreasing depth. COS-143 (IGSN ICDP5054EX4N001) is a weakly metamorphosed arkose of the Sjoutälven Group sampled at 1180 m depth, ~40 m above the basal conglomerate. The sample is composed mainly of medium to coarse clasts of monocrystalline quartz, microcline and plagioclase. A total of 269 out of 292 grains gave results that met the filtering criteria. The detrital zircon spectrum is dominated by late Paleoproterozoic (47%) to Mesoproterozoic (52%) ages (Fig. 4e). The age signature is characterised by peaks at ca. 1.77 Ga, 1.67 Ga, 1.56 Ga and 1.44 Ga with a subordinate population at 1.25 Ga. The youngest grain is 737 ± 4 Ma.

Sample COS-127 (IGSN ICDP5054EXWM001) was collected from metagreywacke of the Sjoutälven Group in the middle part of the profile at 1018 m depth. The detrital composition is dominated by monocrystalline quartz, sericitized potassium feldspar and plagioclase with minor muscovite. The matrix has been recrystallized into sericite. A total of 247 out of 292 grains analysed gave meaningful detrital ages. The detrital zircon spectrum displays late Paleoproterozoic (62%), Mesoproterozoic (21%) and Archean (11%) ages (Fig. 4d). The dominant populations are ca. 1.87 Ga and 1.79 Ga with subordinate populations at 2.71 Ga, 1.97 Ga, 1.70 Ga and 1.45 Ga. The single youngest grain is 604 ± 4 Ma.

The sample COS-119A (IGSN ICDP5054EXEM001) is a greywacke of the Sjoutälven Group sampled at 847 m depth, two meters below the base of the tectonized Alum Shale. A total of 262 out of 300 grains analysed gave meaningful detrital ages. The detrital zircon age spectrum spans Archean to Cambrian ages. The Archean grains (12%) are dominated by a ca. 2.67 Ga population (Fig. 4c). The Paleoproterozoic (25%) population is dominated by ca. 2.12 Ga, 1.80 Ga, 1.76 Ga and 1.64 Ga age peaks. Mesoproterozoic grains (41%) show two dominant populations at ca. 1.53 Ga and 1.20 Ga. The Cryogenian-Ediacaran grains (16%) display 0.72 Ga, 0.60 Ga and 0.53 Ga age peaks. The youngest age peak is lower Cambrian and the maximum age of deposition calculated via the maximum likelihood age algorithm is 530.5 ± 4 Ma.

4.2. The parautochthonous middle Cambrian to lower Ordovician(?) succession

Two samples of the parautochthonous Lower Ordovician (Tremadocian – Floian?) turbidites of the Tåsjön Group were collected 225 and 396 m above the basal contact with the Alum Shale Formation. Sample COS-118 (IGSN ICDP5054EXYL001) is a feldspathic metagreywacke from a depth of 530 m. The rock is fine-grained sandstone with siltstone laminae and is composed mainly of monocrystalline quartz, sericitized feldspar, and minor white mica and biotite. A total of 274 out of 300 grains analysed gave meaningful detrital ages. The detrital zircon spectrum displays mainly Mesoproterozoic to Early Neoproterozoic (77%) ages (Fig. 4b) with dominant populations at ca. 1.47 Ga, 1.15 Ga, 1.02 Ga and 0.95 Ga and subordinate populations at 2.72 Ga, 1.79 Ga and 1.38 Ga. The youngest age peak is early Neoproterozoic and the maximum age of deposition calculated via the maximum likelihood age algorithm is 912.3 ± 7.2 Ma.

The metagreywacke sample COS-108 (IGSN ICDP5054EXPL001) collected at 359 m depth is petrographically similar to sample COS-118. A total of 234 out of 315 grains analysed met the filtering criteria for meaningful detrital ages. The detrital zircon spectrum is dominated by Mesoproterozoic to Early Neoproterozoic (76%) ages with significant early Mesoproterozoic groups at ca. 1.60 Ga, 1.56 Ga, 1.47 Ga and late Mesoproterozoic – early Neoproterozoic groups at ca. 1.15 Ga, 1.10 Ga, 1.05 Ga and 0.97 Ga (Fig. 4a). The youngest zircon grain is 642 ± 5 Ma.

Table 1
Summary of the sample numbers, position in the borehole, possible age and short microscopic and macroscopic description. MCD – meters composite depth.

Sample name	Depth [MCD]	Possible Age	Dominant lithology	Thickness of the Bouma sequences
COS-108	359	Floian – Tremadocian	fine grained metagreywackewith siltstone laminae	20–50 cm
COS-118	530	Floian – Tremadocian	fine grained metagreywackewith siltstone laminae	20–30 cm
COS-119A	847	Wuliuan – Fortunian	very-fine grained metagreywackewith siltstone laminae	0.5–3 cm
COS-127	1018	Wuliuan – Fortunian	fine grained metagreywacke	40–50 cm
COS-143	1180	Wuliuan – Fortunian	Coarse grained metaarcose	–

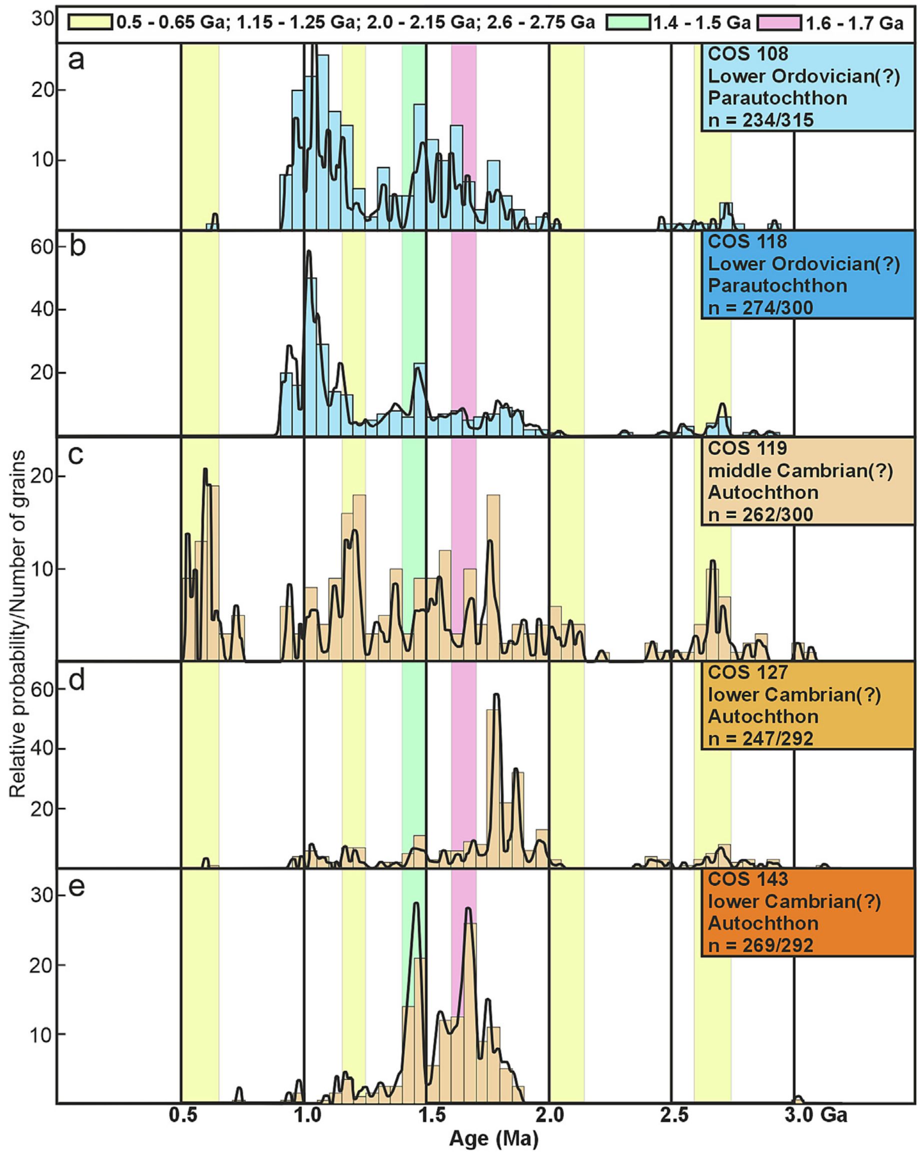

Fig. 4. Comparison of probability density plots of detrital zircon age signatures for Cambrian-Ordovician sediments from the COSC-2 borehole (a–e). All zircon ages for the samples were obtained using LA-ICPMS at the Arizona LaserChron Center, Tucson, USA. The displayed ages are 10% or less discordant and 5% or less reverse discordant. The $^{207}Pb/^{206}Pb$ age cut off is 1.2 Ga.

5. Discussion

5.1. Detrital zircon geochronology of COSC-2 samples

The lower to middle Cambrian(?) succession of the COSC-2 drill core displays progressive shifts in the zircon age spectrum of the sampled detrital material. The lowermost part of the succession shows detrital age signatures that are similar to the ages of the underlying basement units (Fig. 4e) and those of the Eastern Segment of the Sveconorwegian Orogen in general (Bingen et al., 2009). Up section, the locally sourced material is replaced by input from predominantly older, Paleoproterozoic (Fig. 4d) sources that resemble the older parts of the Transscandivian Igneous Belt (TIB) and the Svecofennian basement (Bingen et al., 2009). A major provenance shift is noted within a sandstone unit (sample COS-119A) representing proximal turbidites from the upper part of the lower turbidite section below the Alum Shale Formation (Fig. 4c; Lehnert et al., 2024). The sampled level is 2 m below the transition into the turbiditic lower part of the Alum Shale Formation, which is characterized by highly organic-rich black shale intercalations and increased U/Th contents. Deposition of the Alum shale generally started in the Baltoscandian Basin in the Guzhangian Stage of the upper Miaolingian (Zhao et al., 2022), suggesting that the sampled unit likely represents the Drumian Stage in the lower part of the upper Miaolingian, if there was no significant depositional gap in the turbiditic succession (Lehnert et al., 2024). Detrital zircons from sample COS-119A display Cryogenian to Cambrian age populations and a significant Mesoproterozoic age peak at ca. 1.2 Ga that is not a dominant population observed in units down section. Additionally, there is a notably higher contribution of Archean grains than observed in other samples, and the 2.15–2.00 Ga populations do not appear in any other sample. Although some of these populations appear in samples with Baltican signatures, the dominance of younger ages suggests significant input of late Neoproterozoic – early Cambrian detritus. Therefore, the younger populations are likely to represent a signature of far travelled material from sources external to western Baltica. Overall, the maximum depositional age of the lower turbidite succession is constrained in its upper part to a Lower Cambrian age (530.5 ± 4 Ma) via the maximum likelihood age algorithm.

The Lower Ordovician(?) turbidite succession from 530 to 359 m displays another change in detrital age pattern. Both samples are dominated by late Mesoproterozoic – early Neoproterozoic zircons characteristic of source areas exposed in the main segments of the Sveconorwegian Orogen (Fig. 4a, b; Bingen et al., 2011). Only a single detrital zircon yields Cryogenian age in contrast to the uppermost part of the lower to middle Cambrian(?) succession that is rich in Cryogenian – Cambrian detritus. In the Cambro-Ordovician, the Baltoscandian margin depocenters are separated into two types due to the large distance between its distal and proximal domains or possibly also the late Neoproterozoic hyperextension (e.g. Andersen et al., 2012; Jakob et al., 2019). The most distal portion of the rifted margin evolved in an active subducting setting and related arc basins, but the proximal margin remains in rifted or passive mode up to Late Ordovician – Silurian times (Gee et al., 2015). Consequently, the proximal margin with the whole sedimentary COSC-2 succession represents a rifted to passive margin that was temporarily fluxed by detritus from a convergent setting developed on the other Baltican margins i.e. Timanian or Southern Baltica/Sandomirian.

The Cambrian section drilled in the COSC-2 borehole shows a markedly different thickness relative to the surrounding Cambrian strata in central Scandinavia. The estimated thickness of Cambrian units in the Östersund – Åre area does not exceed 100 m (Nielsen and Schovsbo, 2011), while the maximum thickness of the HVB sediments north of the GOC is estimated to exceed 300 m (Greiling et al., 2024). The Cambrian section of the COSC-2 borehole is separated from the HVB by the GOC and is > 350 m thick, which indicates that it is most likely a tectonically bounded basin forming at the edge of the Baltican shelf. Baltica was already at the rift-to-drift stage at the time, which typically does not allow for the formation of pull-apart basins. The remaining margins, however, were in a contractional mode, which may have caused a far-field transtensional effect that resulted in the formation of the deeper basin near the present-day COSC-2 site.

5.2. Early-middle Cambrian detrital zircon signatures of Baltica

Most samples analyzed during this study revealed signatures typical for the underlying Baltica basement units as well as more diverse age spectra suggesting additional input from more distal sources up-section. For example, multiple populations of apparent exotic origin appear in addition to locally sourced material in the middle Cambrian interval (Fig. 4). This group consists of ca. 0.75 – 0.52 Ga and 2.15 – 2.0 Ga populations that are atypical for Baltoscandian margin sediments (e.g. Gee et al., 2015) as well as an increased number of grains in the 1.25 – 1.15 Ga and 2.7 – 2.6 Ga intervals. When comparing contemporaneous sediments across Baltica, it is apparent that most of the lower to middle Cambrian sediments display similar patterns across the paleocontinent (Fig. 5). The only exception is the TFB in northern Scandinavia, where the sedimentary units do not show significant populations at ca. 1.2 Ga and 2.1 Ga, and Archean input does not differ or is even lower in slightly older samples in the area (Andresen et al., 2014; Zhang et al., 2015). Such a difference is also apparent when comparing TFB signatures with populations of Lower Ordovician detrital zircon spectra from Baltica (Fig. 5g–l). The samples rich in late Neoproterozoic – Lower Cambrian detritus also display prominent 1.2 Ga and 2.1 Ga populations. Comparison of the late Neoproterozoic – early Cambrian detrital signatures across the lower to middle Cambrian in COSC-2 also shows the discrepancy between the samples from northern Scandinavia and those from remaining areas of Baltica (Fig. 6). The northern Scandinavian samples display a bimodal pattern with a dominant peak at ca. 0.56 Ga and an additional population at ca. 0.65 Ga. Most other Baltican samples show an additional age peak at ca. 0.62–0.6 Ga or at ca. 0.53 Ga.

Large-scale statistical dataset comparison of the Baltican, Avalonian, and Cadomian detrital zircon signatures shows a persistent trend across the samples (Fig. 7). Cadomian and Avalonian samples are dominated by Neoproterozoic ages, whereas those from Baltica show variable input of older components both for lower to middle Cambrian (Fig. 7a; Albert et al., 2015a, 2015b) and Lower Ordovician sediments (Fig. 7b). This pattern is consistent with a transition from the active margin signature typical for the Cadomides (left side of the plot in Fig. 7) through foreland basin, hybrid basin (foreland to passive margin) and passive margin settings (right side of the plot in Fig. 7) that reflect increasing amounts of 1.8–0.9 Ga grains from the Baltican and Avalonian basement. Samples of foreland to hybrid margins of Baltica share fairly similar signatures with contemporaneous Avalonian samples that also tend to contain more Mesoproterozoic detritus than Cadomian ones. In particular, samples with East Avalonian signatures show strong links to Baltican samples, which occurs due to a similar amount of late Neoproterozoic – early Cambrian detritus as well as ca. 2.1 Ga, 1.5 Ga and 1.2 Ga populations common to both (e.g. Linnemann et al., 2012; Waldron et al., 2019).

5.3. Tectonic implications

Although the Baltoscandian margin in early Cambrian time was in a passive regime (e.g. Gee et al., 2015), the remaining margins of Baltica were variably subjected to volcanic and tectonic activity (e.g. Kuznetsov et al., 2007; Collett et al., 2022). This is reflected in the detrital zircon spectra of the Cambrian sediments of Baltica, notably including the Baltoscandian margin (Fig. 5). Late Neoproterozoic – Cambrian detrital zircon populations are common both in the foreland basin of the Timanian orogen (e.g. Kuznetsov et al., 2007; Andresen et al., 2014) as well as in the southern Baltican active margin of the Sandomirian Arc (Żelaźniewicz et al., 2020; Paszkowski et al., 2021; Collett et al., 2022; Callegari et al., 2025). The influx of late Neoproterozoic – Cambrian grains observed on the Baltoscandian passive margin is interpreted to reflect distant tectonic processes rather than being directly tied to the Iapetus opening (e.g. Slama, 2016). However, the Baltoscandian margin sediments of the HVB (Fig. 1) are devoid of this material, suggesting that they were sheltered from potential sources of late Neoproterozoic – Cambrian detritus to both the south and north (Greiling et al., 2024).

The subsequent euxinic deposition of the Alum Shale Formation along the western margin of Baltica records a tectonically quiet time interval with low deposition rates (around 4 cm/Ma) that continued for more than 20 million years from the middle Cambrian to the lower Ordovician (Miaolingian through Tremadocian; Nielsen and Schovsbo, 2011; Zhao et al., 2022). The COSC-2 succession shows that the main phase of shale sedimentation was preceded by a clear transition into a turbiditic lower Alum Shale Formation with highly organic black shales and high U/Th contents comparable to the gamma ray logs and Uranium contents in the lower Alum Shale Formation in the epicontinental Baltoscandian Basin (e.g. Nielssen et al., 2018). The upper part of the Alum Shale Formation became turbiditic again, slowly grading into the overlying turbidites, which lack the very dark colour of the Alum shales and their high U contents. The succession is (authochthonous?) to parautochtonous; it had been previously assumed that there was a major décollement within its exclusively black shale middle part, but there is no evidence for long-range tectonic transport along this horizon. Subsequent Lower Ordovician (Tremadocian – Floian?) turbidites sampled in the COSC-2 borehole display detrital

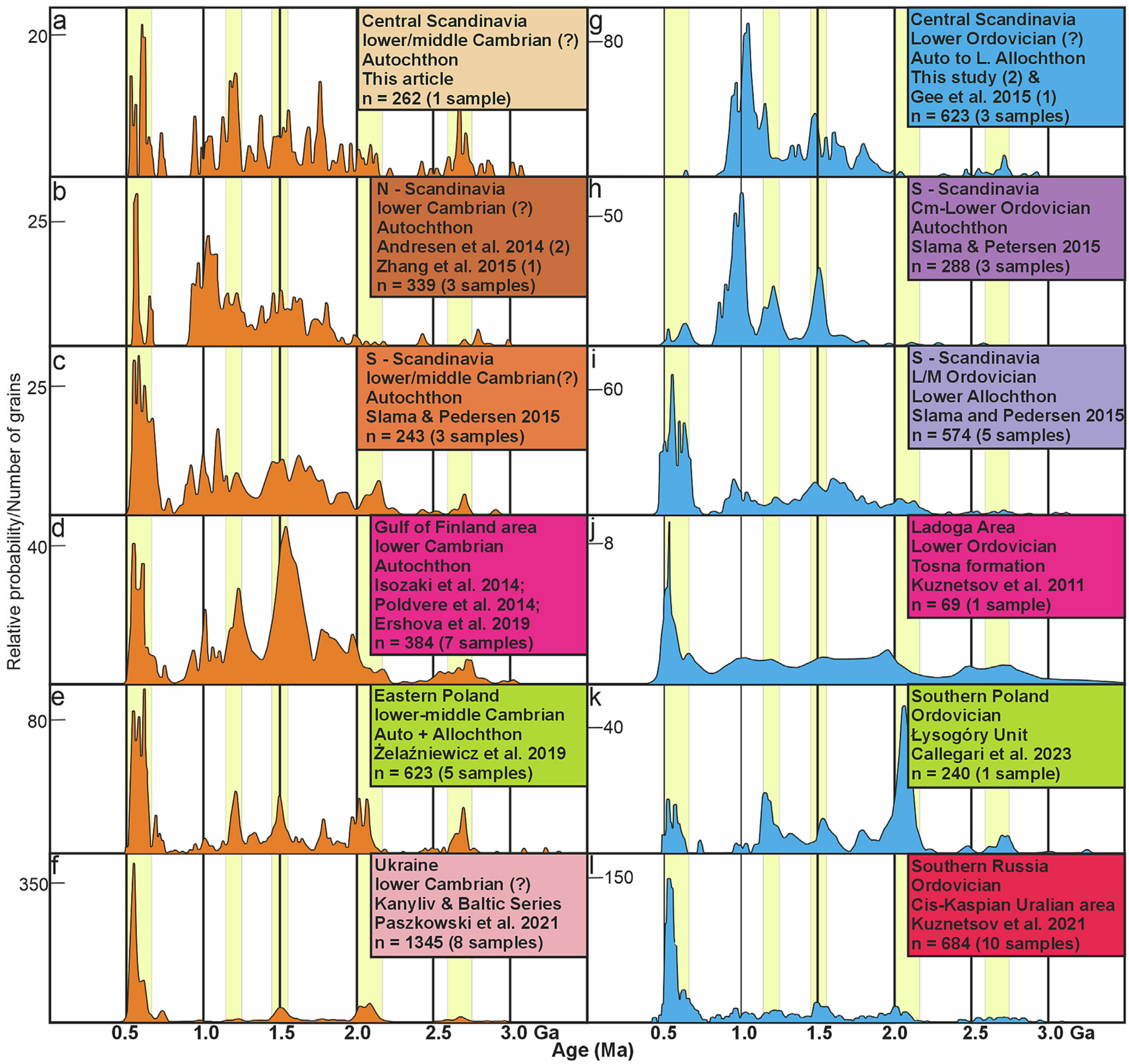

Fig. 5. Comparison of probability density plots of detrital zircon age signatures for lower Cambrian and Lower Ordovician rocks across Eastern European Platform (a–f). Discrimination criteria follow the ones on Fig. 4. Yellow bars mark the characteristic populations of 2.7 – 2.6 Ga, 2.15–2.0 Ga, ca. 1.5 Ga, ca. 1.2 Ga and 0.7 – 0.55 Ga. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

zircon age spectra that lack the late Neoproterozoic – Cambrian detritus (Fig. 4). This is in contrast with other (albeit very limited) data from Lower Ordovician samples of Baltica, including the Ladoga, southern Ural and southern Scandinavian regions (Fig. 5g–l; Kuznetsov et al., 2007, 2010, 2014b; Slama and Pedersen, 2015; Ershova et al., 2019). The Lower Ordovician COSC-2 samples are dominated by late Mesoproterozoic detritus characteristic of source areas in the Sveconorwegian Orogen (Bingen et al., 2011). The most similar detritus characterizes the southern Scandinavian samples of parautochtonous successions (Slama and Pedersen, 2015), while the Lower Allochthon is more enriched in late Neoproterozoic – Cambrian detritus (Fig. 5).

The documented thickness of the lower to middle Cambrian succession drilled in the COSC-2 borehole reaches about 350 m, which is much more than expected from neighbouring outcrops and boreholes (Nielsen and Schovsbo, 2011; Fig. 1). This, together with the recent results from the HVB (Greiling et al., 2024) that also reaches more than 300 m but is separated from COSC-2 by the GOC, suggests that the models for the Cambrian sedimentation in Scandinavia require local revision to account for existence of a probable pull-apart basin south of the GOC.

The sediments from the COSC-2 borehole show a progressive change of detritus from the local Eastern Segment source areas through the TIB and Svecofennian sources to long-transported material in the lower Cambrian. This is in agreement with the early Cambrian marine regression and later transgression that provided new detrital source areas (Nielsen and Schovsbo, 2011) and allowed expansion of the source area through new pathways that provided the detritus for the drilled lower Cambrian sediments. The Lower Ordovician section shows detritus similar to coeval samples from southern Scandinavia (Figs. 4 and 5). However, late Neoproterozoic – Cambrian-sourced detritus is still a major com-

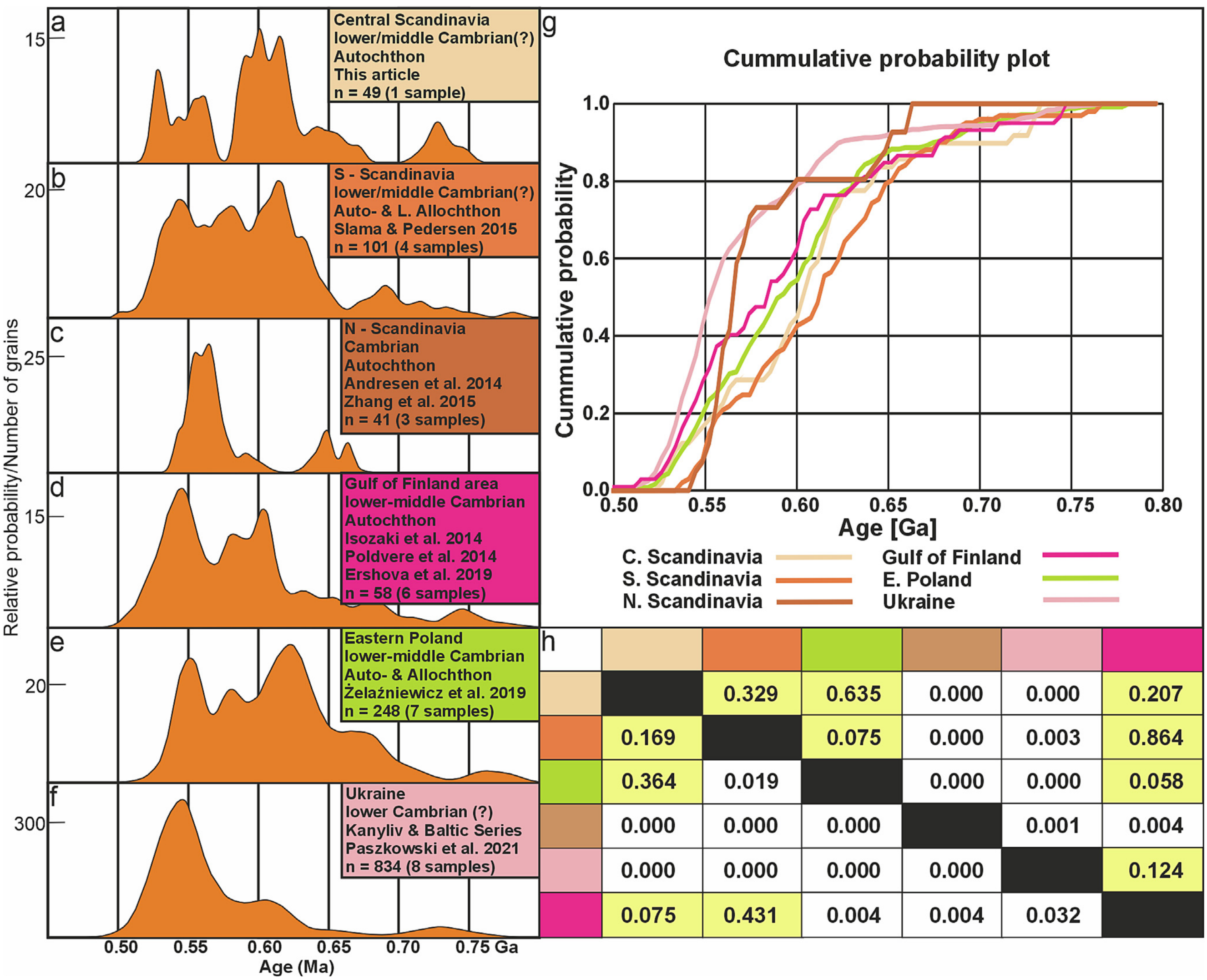

Fig. 6. (a–f) Comparison of probability density plots of detrital zircon age signatures between 0.8 Ga and 0.5 Ga for lower to middle Cambrian sediments of Baltica. (g) Cumulative density function for the same lower to middle Cambrian sediments. Note the characteristic increase of the ca. 0.57 – 0.56 Ga population that occurs only in the northern Scandinavian samples that belong to the Timanian foreland basin. In contrast, remaining samples have significant populations at ca. 0.61 – 0.60 Ga. (h) Results of the Kołmogorov-Smirnov test for the analyzed sample intervals. In the upper right, results are presented with a 1σ confidence level, in the lower left, without a 1σ confidence level. The sample pairs with $p > 0.05$ are highlighted in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ponent in southern Scandinavia (Slama and Pedersen, 2015), suggesting that southern Scandinavia was still receiving late Neoproterozoic – early Cambrian detritus during Lower Ordovician times. Recycling detritus of this age from Cambrian strata is unlikely as the Baltoscandian margin was still in a passive margin regime but cannot be entirely precluded (Nielsen and Schovsbo, 2011). Likewise, the lack of coeval grains in central Scandinavia in Lower Ordovician turbidites is hard to explain if southern Scandinavia was still receiving detritus from the Timanian Orogen. Especially since both regions were mainly supplied by Sveconorwegian detritus at the time, indicating northward transport of material to central Scandinavia. Additionally, the HVB, which is located across the GOC from the drilled lower Cambrian section, lacks any record of late Neoproterozoic – Cambrian grains, which leads to the conclusion that the GOC and ATC were major uplifted structures in the lower Cambrian to Ordovician. Therefore, the catchment divide must have changed between the lower Cambrian and Lower Ordovician from the GOC to another barrier further south, possibly following the lower Cambrian catchment divide proposed by Lorentzen et al. (2020) (Fig. 8).

The discrepancies that contradict Timanian source areas for the central Scandinavian sediments appear to occur in the detrital zircon record of samples more proximal to the Timanian Orogen. The TFB was being supplied with latest Neoproterozoic detritus by Neoproterozoic – Cambrian boundary time (Zhang et al., 2015) and into the early Cambrian (Andresen et al., 2014). That constrains the timing of onset of the Timanian Orogeny to late Neoproterozoic (Zhang et al., 2015; Francovischi et al., 2023). However, the late Neoproterozoic – early Cambrian populations are not present in the early Cambrian Torneträsk Formation (Lorentzen et al., 2020), which suggests that the Rombak window and the ATC might represent a TFB forebulge (Greiling et al., 2024). In northeastern Baltica, samples from latest Neoproterozoic and early Cambrian strata (Kuznetsov et al., 2014a, 2014b) do not contain the populations in question either, which constrains the timing of the onset of the Timanian Orogeny to the middle Cambrian (Kuznetsov et al., 2014a). However, the introduction of late Neoproterozoic detritus into the Ladoga Area was constrained to earlier, latest Neoproterozoic time (Ershova et al., 2019), which contradicts the findings in the samples more proximal to the Timan Orogen (Francovischi

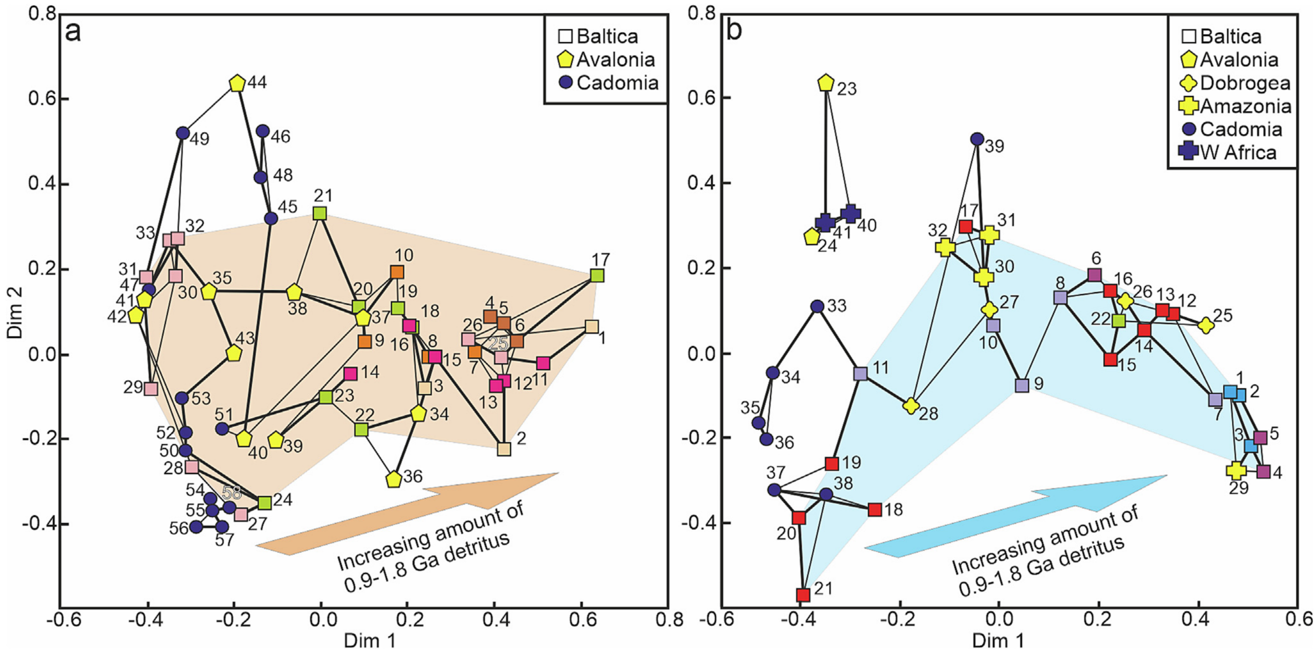

Fig. 7. Non-Metric multidimensional scaling (MDS) map using Kuiper statistics (after Vermeesch, 2013) for early-middle Cambrian (a) and Ordovician (b) sediments. Dim 1: Dimension 1, Dim 2: Dimension 2. Spatial proximity of points correlates with statistical similarity. Thick lines tie the most similar neighbours, thin lines tie the second most similar neighbours. Colours of Baltican samples indicate their area of origin according to Figs. 4 and 5. The coloured area surrounds the Baltican samples. In (a), 1–3: This study; 4–6: N Scandinavia (4: Zhang et al., 2015; 5, 6: Andresen et al., 2014); 7–10: S Scandinavia (Slama Pedersen 2015); 11–16: Finland Bay area (11–14: Ershova et al., 2019; 15: Isozaki et al., 2014; 16: Poldvere et al., 2014); 17–24: Poland (Żelaźniewicz et al., 2020); 25–33: Ukraine (Paszkowski et al., 2021); 34–35: British Isles (Waldron et al., 2019); 36: Nova Scotia (Willner et al., 2013); 37–38: Brabant Massif (Linnemann et al., 2012); 39–41: New Brunswick (Barr et al., 2012); 42: Silesian Block (Żelaźniewicz et al., 2020); 43: Serbo-Macedonian Massif (Meinhold et al., 2010); 44: Newfoundland (Pollock et al., 2009); 45–47: Morocco (Avigad et al., 2012); 48: Iberia (Fernandez-Suarez et al., 2014); 49–50: Iberia (Zimmermann et al., 2015); 51: Ossa Morena (Linnemann et al., 2008); 52–53: Orlica Śnieżnik Dome (Mazur et al., 2012); 54–58: NW Iberia (Albert et al., 2015a, 2015b). In (b), 1–3: Central Scandinavia (this study; Gee et al., 2015); 4–6: S Scandinavia autochthonous (Slama and Pedersen, 2015); 7–11: S Scandinavia allochthonous (Slama and Pedersen, 2015); 12–21: Ural (Kuznetsov and Romanyuk, 2021); 22: Holy Cross Mountains (Callegari et al., 2025); 23–24: Nova Scotia (Henderson et al., 2016); 25–28: Dobrogea (Balintoni et al., 2010); 29–32: Andes (Reimann et al., 2010); 33: Iberia (Henderson et al., 2016); 34–36: French Massif Central (Chelle-Michou et al., 2017); 37: Tepla-Barrandian (Drost et al., 2011); 38: Ossa Morena (Linnemann et al., 2008); 39: Saxo-Turingian zone (Linnemann et al., 2007); 40–41: Algeria (Linnemann et al., 2011).

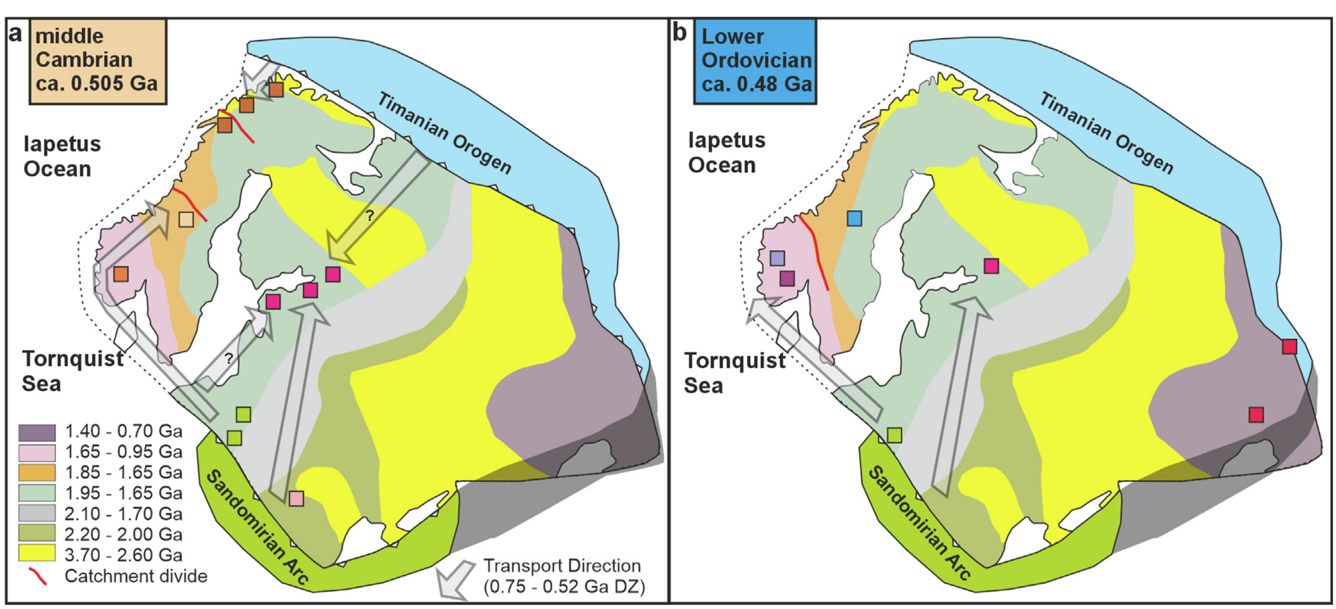

Fig. 8. Simplified geological sketch of Baltica in (a) lower to middle Cambrian and (b) Early Ordovician times after Bogdanova et al. (2008), Slama et al. (2016) and Żelaźniewicz et al. (2020). Position of Sandomirian Arc after Collett et al. (2022) and Callegari et al. (2025). (a) In the Early Cambrian period, central Scandinavian sediments are derived from local sources and supplied by material coming from a southern orogen as far north as the Grong–Olden Culmination catchment divide. In the north, the Timanian foreland basin with the addition of the late Neoproterozoic – early Cambrian detritus reaches approximately the Rombak Window – Akkajaure–Tysfjord Culmination. (b) In the Lower Ordovician times, the far southern source imprint is present only in southern Scandinavia, but no record of it is present in the central Scandinavian sediments. The Ordovician catchment divide does not reach as far north as the Grong–Olden Culmination, but likely as far as the early Cambrian catchment divide by Lorentzen et al. (2020); DZ – detrital zircon.

et al., 2023). Therefore, the source area of the TFB is firmly limited to have been very proximal to the Timanian Orogen and parts of Scandinavia north of the ATC.

An alternative source of late Neoproterozoic – Cambrian detrital zircons might be a collisional (Paszkowski et al., 2021) or, in more recent interpretations, an active margin (Collett et al., 2022) of Baltica – the Sandomirian Arc (Callegari et al., 2025). The southern Baltica margin was in the early Cambrian an upper plate for the subducting Mirovoi Ocean and the forming Sandomirian Arc was at that time part of Baltica (Collet et al., 2022; Callegari et al., 2025). In the late Cambrian, a major part of the Sandomirian Arc was rifted off the southern Baltica margin as one of the Avalonian terranes (Collett et al., 2022; Landing et al., 2022). Therefore the information of the Sandomirian Arc is only preserved in the "Teisseyre Zone Terranes" and as a widespread detritus in the Cambrian sediments of southern Baltica (Collett et al., 2022).

Detrital zircon signatures of lower Cambrian strata in Poland and Ukraine bear a close similarity with the coeval central and southern Scandinavian signatures, including ca. 1.2 Ga and 2.0 – 2.1 Ga populations that are rather uncharacteristic for the Baltoscandian margin (Paszkowski et al., 2019, 2021; Żelaźniewicz et al., 2020; Fig. 5). The most prominent source of ca. 2.2 – 2.0 Ga detritus is present in the Ukrainian Shield of southern Baltica (Fig. 7 and references therein) as well as displaced and concealed terranes of Baltican-Avalonian origin along the southern Baltican margin. However, the origin of the ca. 1.2 Ga detritus is also puzzling for the lower to middle Cambrian samples in eastern Poland. This can be attributed to docking of terranes to southern Baltica (Żelaźniewicz et al., 2020) such as Brunovistulia (Soejono et al., 2022). Therefore, grains from the Sandomirian margin may have been transported along the southern Baltican shelf down to the shelf edge of Scandinavia (Fig. 8). The earlier timing of southerly detritus transport to Scandinavia is constrained to Cambrian Stage 3 by the samples from southern Scandinavia (Slama and Pedersen, 2015). This timing coincides with the Vergalian–Rausvian transgression, allowing a shorter shelf connection between the areas (Nielsen and Schovsbo, 2011). By Wuliuan times, an open seaway existed between the Tornquist margin and the present-day COSC-2 site (Nielsen and Schovsbo, 2015), which would allow the shelf currents to transport the material from the distant southerly source. The late Cambrian – Early Ordovician Sandomirian phase involved significant uplift in present-day southern Poland that could have resulted in an additional detrital pulse in the Lower Ordovician that reached the southern, but not the central Scandinavia and potentially supplied ca. 500 Ma grains in Scandinavia (e.g. Gągała, 2005; Slama and Pedersen, 2015; Callegari et al., 2025).

An additional dataset that can be considered for distinguishing northern and southern sources is provided by Hf isotopes of zircon, which differ between the Cambrian sediments of southern and northern Scandinavia (Slama and Pedersen, 2015). The late Neoproterozoic – Cambrian zircon of northern Scandinavian units and the Pechora and Uralian basins show a range of ε_{Hf} values of +15 to −5 (Kuznetsov et al., 2010; Andresen et al., 2014). In contrast, zircon of the same U-Pb age range from southern Scandinavian, Ukrainian, and Belarusian sediments display a wide range of ΔHf from +15 to −30, often with predominantly negative values (Slama and Pedersen, 2015; Paszkowski et al., 2019, 2021), which coincides also with the higher proportion of Paleoproterozoic and Archean grains in their detrital zircon spectra (Fig. 5). Overall, in Cambrian sediments of Scandinavia, detrital zircon age spectra and ε_{Hf} signatures of late Neoproterozoic – Cambrian grains, along with lack of such detritus in the lower Cambrian of the HVB and Lower Ordovician strata in central Scandinavia all suggest southerly, Sandomirian sources, not Timanian.

The detrital zircon age patterns together with the lack of Neoproterozoic-Cambrian detritus in the samples relatively proximal to the Timanian Orogen (Kuznetsov et al., 2014a; Lorentzen et al., 2020) might suggest that Estonian and Ladoga area samples were also sourced from the Southern Baltica/Sandomirian Arc, at least during the earliest stages of the Cambrian. The detrital zircon signatures of the Ladoga Area resemble those from Poland, Ukraine and southern-central Scandinavia (Figs. 5 and 6). The later input might be related to the Timanian Orogen, which cannot be resolved solely by detrital zircon patterns, but would require studies on the zircon Hf isotopes or paleocurrent directions. The early Cambrian reconstructions allow transport of the late Neoproterozoic – early Cambrian detritus from the south through the Volyn – Orsha aulacogen (Nielsen and Schovsbo, 2011).

An increasing amount of Late Neoproterozoic – Cambrian detritus is observed from central Scandinavia through Poland and the Ladoga area towards southern Ukraine, as shown on the MDS plots both for Cambrian and Ordovician samples (Fig. 7). This is in agreement with a southerly source for the detritus that was ultimately transported by currents along the shelf, as the shore of Baltica roughly resembled the present day southern-eastern coast of the Baltic Sea (Nielsen and Schovsbo, 2011, 2015). Evidence for long-distance transport of material offshore is common in the geological record, including examples of thousands of kilometres as in Alaska (Malkowski et al., 2022) or present-day sediments along the Brazilian-Uruguayan margin (Junior et al., 2021). Notably, the greater amount of late Neoproterozoic – Cambrian-sourced detritus in the more distal sediments of allochthonous successions of southern Scandinavia than in the more proximal, autochthonous Lower Ordovician strata (Slama and Pedersen, 2015) supports long-distance clastic sediment transport.

The record of the southern Baltican active margin observed in the late Neoproterozoic – Cambrian detritus is likely preserved in the "Teisseyre Zone Terranes" like the Małopolska Block and the Brunovistulia Domain (Collett et al., 2022; Soejono et al., 2022). The detrital zircon record of these terranes resembles the cratonic signatures of Baltica and Amazonia with additional Sandomirian age detritus (e.g. Żelaźniewicz et al., 2020; Soejono et al., 2022) and is virtually indistinguishable from Avalonian signatures (Fig. 7). Thus, the detrital zircon age spectra observed in Cambro-Ordovician strata of southern-central Scandinavia resemble those observed in Eastern Avalonia and vary only in respect to the amount of local Mesoproterozoic detritus (Fig. 5). This is in agreement with the models of Collett et al. (2022) where eastern Avalonia, including the Brabant Massif (but not including the Góry Sowie Block), as well as concealed Baltican-Avalonian terranes to the south, were the sources of the exotic for the Baltoscandian margin detritus in the lower to middle Cambrian of central Scandinavia.

6. Conclusions

The following conclusions can be drawn from our study of the detrital zircon from the COSC-2 borehole:

(1) The lower to middle Cambrian succession retrieved from the COSC-2 borehole is much thicker than expected from the surrounding boreholes and outcrops, and as such requires a reinterpretation of the lower to middle Cambrian sedimentation in this part of Baltica.
(2) The lower Cambrian succession of Central Scandinavia shows progressive development of a basin sourced at first locally from the Eastern Segment of Sveconorwegian Orogen and later from Transscandinavian Igneous Belt / Svecofennian source areas.

(3) In the lower to middle Cambrian (possibly lower part of the upper Miaolingian Drumian Stage? Lehnert et al., 2024) succession the influence of Sandomirian or Timanian sources is highlighted by late Neoproterozoic – Cambrian detritus with additional ca. 1.2 Ga and 2.0 – 2.15 Ga populations.
(4) A potential source of late Neoproterozoic – Cambrian detritus is the Southern Baltica/Sandomirian Arc in present-day southern Ukraine and Poland, recorded in the active margin or foreland basin successions there. The similarities observed between the detrital zircon signatures of coeval East Avalonian and Baltican successions point towards early Cambrian interactions between the two regions, which are recorded in the majority of contemporaneous Baltican sediments.
(5) The Ordovician (Tremadocian-Floian? Lehnert et al., 2024) section is sourced mainly from the Sveconorwegian Orogen and lacks Sandomirian grains, which contrasts with the southern Scandinavian autochthonous and allochthonous successions. This observation suggests that a southern source of late Neoproterozoic – Cambrian detritus is more likely than a Timanian origin.

CRediT authorship contribution statement

Grzegorz Ziemniak: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Iwona Klonowska:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **William C. McClelland:** Writing – review & editing, Supervision, Software, Resources, Methodology, Funding acquisition, Data curation. **Oliver Lehnert:** Writing – review & editing, Visualization, Resources, Investigation. **Simon Cuthbert:** Writing – review & editing, Investigation, Data curation. **Isabel Carter:** Writing – review & editing, Investigation. **Riccardo Callegari:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Data curation. **Katarzyna Walczak:** Writing – review & editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The COSC-2 borehole was drilled with the Swedish national research infrastructure for scientific drilling, "Riksriggen". We are thankful to the entire COSC drilling and scientific teams led by Henning Lorenz. This work was funded by the National Science Centre (NCN, Poland) project nos. 2018/29/B/ST10/02315 and 2019/33/B/ST10/01728 and the Swedish Research Council (Vetenskapsrådet) grant no. 2019-03688. OL is grateful to the Deutsche Forschunggemeinschaft for the support of his COSC-2 research (DFG 867/12-1,13-1, and 13-2). The Arizona Laserchron Facility is supported by a National Science Foundation (USA) grant EAR2050246. We thank Bernard Bingen and an anonymous reviewer for constructive reviews and Mathew Domeier for editorial handling.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2025.102077.

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