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The COSC-2 drill core and its well-preserved lower Palaeozoic sedimentary succession – an unexpected treasure beneath the Caledonian nappes

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ABSTRACT

The Collisional Orogeny in the Scandinavian Caledonides (COSC) project focuses on processes related to the closure of the Iapetus Ocean, causing the Ordovician–Silurian continent–continent collision between Baltica and Laurentia. The rock succession in the second drill core (COSC-2) from the Jämtland County, central Sweden, provides the base for detailed sedimentological, stratigraphic, geophysical, geochemical, geothermal and structural studies. The basement, comprising 1.66–1.65 Ga Transscandinavian Igneous Belt porphyries intruded by 1.47 Ga and 1.27–1.26 Ga mafic dykes and sills, is heavily weathered towards the top. Here it grades into typical saprock and saprolite (including immature soil reflecting the sub-Cambrian peneplain). The overlying sedimentary sequence starts with basal conglomerates and heterogeneous sediments with shell fragments, indicating an early Cambrian rather than a Neoproterozoic age for the marine transgression in the area. The developing early Cambrian basin was rapidly filled, initially by mostly coarse-grained sediment gravity flows. These strata are covered by sandstone turbidites that show an upward transition into the Alum Shale Formation, representing a tectonically quieter period (mid-Cambrian/Maolingian to Early Ordovician/Tremadocian). The upper part of the Alum Shale Formation is overlain by a late Early Ordovician turbidite succession. Local sources of sediments below the Alum Shale Formation and the extended deposition period may indicate continuous sedimentation in a pull-apart basin preserved in a window beneath the Caledonian thrust sheets.

Introduction

The Collisional Orogeny in the Scandinavian Caledonides (COSC) project is supported by the International Continental Scientific Drilling Program (ICDP) and linked to the Swedish Scientific Drilling Program (SSDP). Its main goal is to characterise orogenic processes involving structures, basement and sedimentary successions, through the collaboration of an international, multidisciplinary team of geoscientists. COSC studies the processes related to the closure of the Iapetus Ocean and the corresponding Scandian continent–continent collision between Baltica and Laurentia during early Palaeozoic times (Fig. 1). During this time interval the Baltoscandian margin was partially subducted beneath Laurentia, forming a Himalayan-type collisional mountain belt along the northern segment of the Caledonian Orogen (e.g. Labrousse et al. 2010; Gee et al. 2010), within which an external nappe system was thrust eastwards over the continental foreland of Baltica (e.g. Gee et al. 2008).

Part of the external zone of this orogenic belt, now deeply eroded, outcrops in the western parts of central Sweden. From this area (Fig. 1), two deep drill cores, ~2.5 and ~2.27 km in depth, have been retrieved from the Jämtland County. At the COSC-1 site, the subduction-related allochthon and its associated thrust zone were cored in 2014. The COSC-2 drilling took place near Järpen in 2020, aimed to extend drilling further down through the underlying nappes (Lower Allochthon) and into the Caledonian basement.

The goal, based on available seismic interpretations and geophysical models (e.g. Hedin et al. 2012; Juhlin et al. 2016), is to study a continuous lower Palaeozoic sedimentary succession, the main Caledonian décollement in the Cambrian Alum Shale Formation (Fm), and a Fennoscandian granitic basement (Fig. 2, left). However, the COSC-2 record displays perfectly why deep continental drilling is crucial. Logging and initial studies showed that our first model was incorrect in several key respects. First, the drill cores revealed an unexpected succession of an undeformed and unmetamorphosed thick porphyry sequence, intruded by dolerite dykes, instead of the assumed Palaeoproterozoic granitic basement (Lorenz et al. 2022; Fig. 2, right). Second, the initial interpretation was that an imbricate zone with Proterozoic and Cambrian sandstones originating from different settings (interpreted as Neoproterozoic tuffs by Lescoutre et al. 2022b) covers this basement, and in turn is overlain by a deformed Alum Shale Fm, comprising the main décollement, followed by a lower Palaeozoic siliciclastic succession formed in deeper, more outboard environments (Lescoutre et al. 2022b). Based on the drill core, the suggested imbricate zone and décollement within the Alum Shale Fm actually represent a stratigraphically continuous succession of early Cambrian conglomerates and sandstones, overlain by the Alum Shale Fm, which features a strong deformation zone in its predominantly shaly middle part.

The changes in interpretation are illustrated in Fig. 2, which contrasts the initial geological model (left) with the results from the core investigation (right). The previously suggested décollement within the Alum Shale Fm (red arrow, left), now recognised as the middle part of a stratigraphically continuous succession of the Alum Shale Fm, clearly represents a deformation zone between ~775 and ~820 m depth within the shale (green arrow, right). In addition, the structural dips, which incline slightly towards the ESE to E instead of moderately to the W, are in contradiction to the dip angles, as

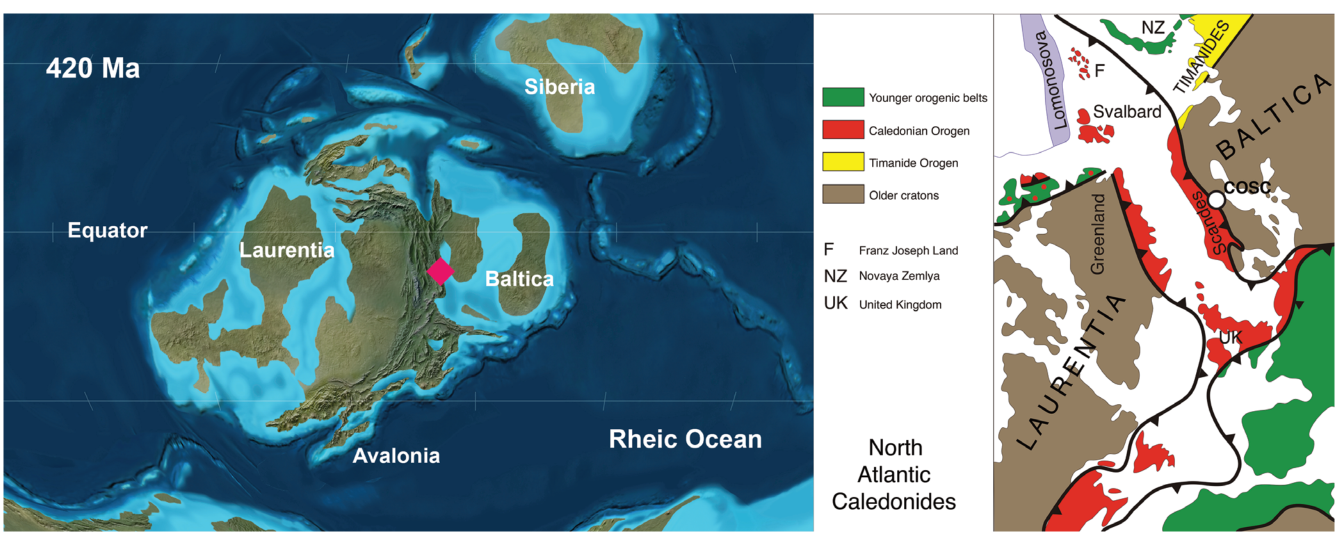

Fig. 1. Silurian palaeogeography (left), showing the equatorial position of Baltica during the interval of its amalgamation with Laurentia and Avalonia (source map © 2016 Colorado Plateau Geosystems Inc.). The pink diamond marks the position of the COSC drill sites. The palaeogeographic map (right; Gee et al. 2010; ~140 Ma) shows the relevant part of the Caledonian Orogen about 60 million years before the opening of the North Atlantic between North America and Europe.

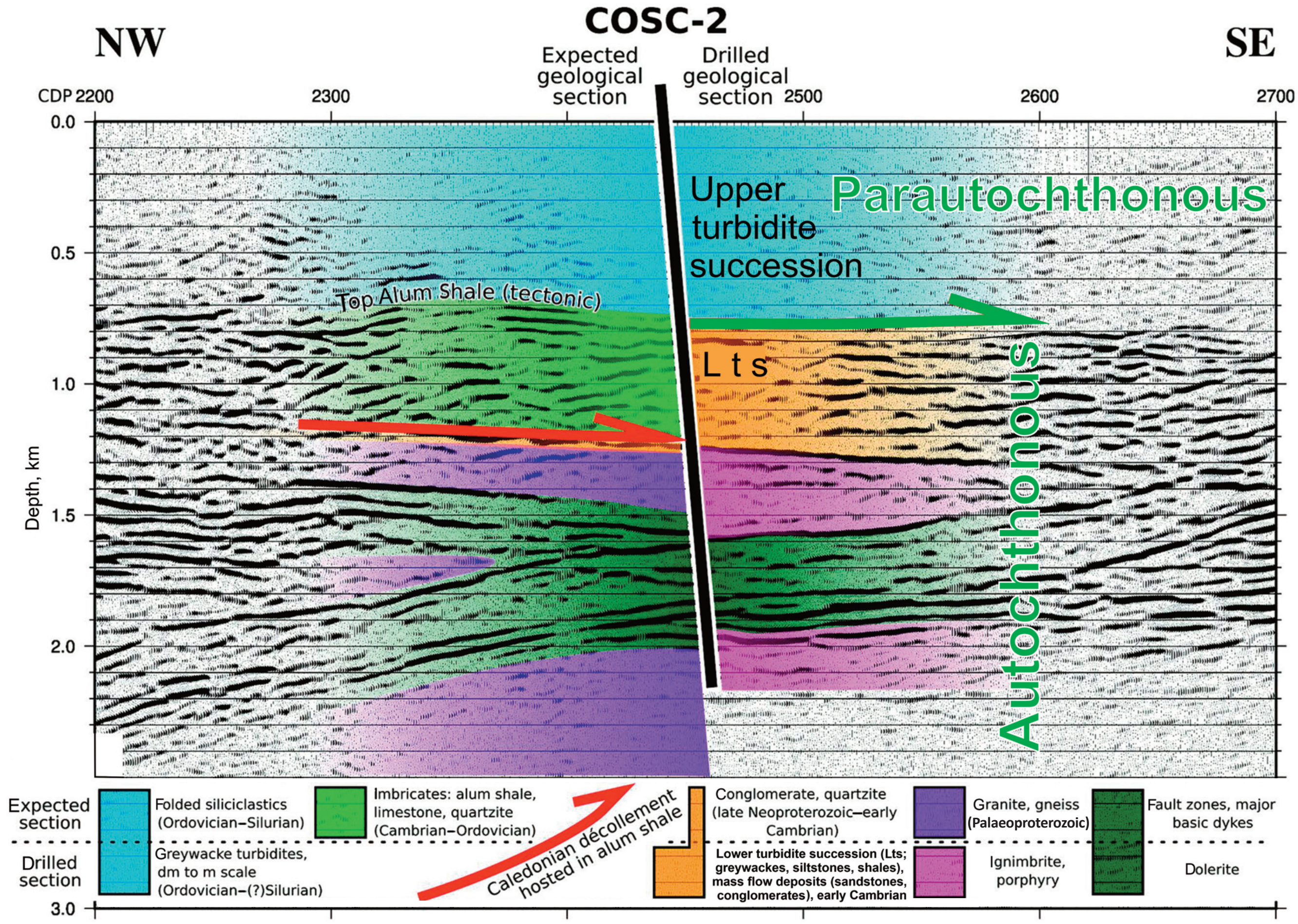

Fig. 2. The expected geological succession at the COSC-2 drill site (left; after Hedin et al. 2012; Juhlin et al. 2016) and the geology interpreted while drilling (right), superimposed on a depth-converted seismic section representing the bedrock in the vicinity of the COSC-2 drill site (modified from Lorenz et al. 2022).

would be expected for the décollement in this part of the Caledonides (Schweizer et al. 2023).

The goal of this study is to present the current state of knowledge regarding the COSC-2 drill core succession, which after its logging changed previously published subsurface models as well as some early onsite interpretations. Another aim of the article is to clearly demonstrate the importance of scientific drilling projects.

The COSC-2 succession

The basement (from ~1215 m to the base of the core at 2276 m) is represented by a volcanic succession (1.66–1.65 Ga felsic porphyry; Andersson et al. 2022) that is intruded by dolerite dykes (mainly at 1590 to 1850 m, dolerites to gabbros). Two dolerite dyke generations, 1.47 Ga and 1.27–1.26 Ga in age (Lescoutre et al. 2022a), are recognised and further dating may show if an even younger generation, such as the Blekinge–Dalarna Dolerite suite (~0.98–0.95 Ga; Söderlund et al. 2006), is also present. It has previously been proposed that these intrusions are part of the Central Scandinavian Dolerite Group (~1.27–1.25 Ga; Lescoutre et al. 2022b) based on their geometries and widespread occurrence in the autochthonous basement east of the Caledonides (Söderlund et al. 2006).

Detailed geological core description shows that the unaltered basement is capped at about 1215 m by a weathered horizon of saprock and saprolith, which is covered by regolith, likely corresponding to the sub-Cambrian peneplain. This ~3 m weathered zone is overlain by a basal conglomerate and a few metres of heterogeneously composed sediments (lower Cambrian?), revealing the unusual development of a basin that was initially filled by mostly coarse-grained sediment gravity flows grading into fine-grained turbidites (Lehnert et al. 2023b). Thus, there is no imbricate zone overlying the basement, but a continuous sedimentary succession (Fig. 2).

Finer-grained siliciclastics a few metres above the basement, as well as the shales within the middle part of the Alum Shale Fm (780 to 825 m depth), are highly sheared and deformed, but the structures in this formation and the continuity of the succession do not support the presence of a main décollement. The sedimentary succession appears continuous, and although there is some internal deformation and thrust translation, it does not seem sufficient to support the presence of a major décollement at the base of a large nappe. The dip angles are towards the ESE, rather than to the W, as would be expected for the main décollement (Schweizer et al. 2023).

Coarse conglomerates and coarse-grained sandstone units constitute most of the sediments beneath the Alum Shale Fm.

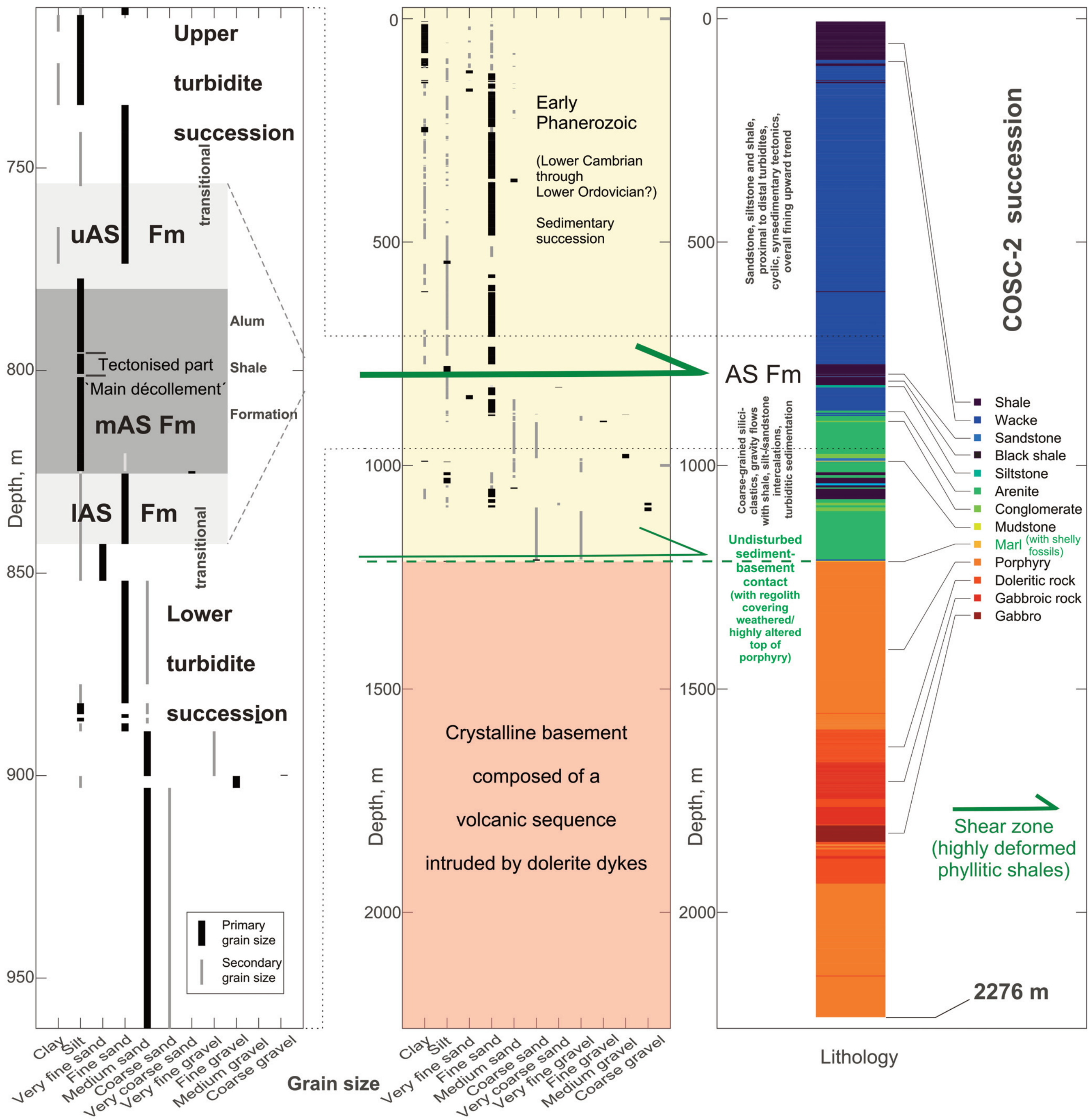

Fig. 3. Simplified log of the COSC-2 succession, illustrating the main subdivision into a substantial basement succession covered by a thick and continuous lower Palaeozoic sedimentary succession. The level of the Alum Shale Fm is highlighted with grey bars (AS – Alum Shale; lAS – lower, mAS – middle, uAS – upper Alum Shale). The left side shows details of the sedimentary transitions of the Alum Shale Fm into the under- and overlying turbidites, including its shaly middle part (dark grey), where the structural zone was previously suggested to represent the main décollement.

Above these units, a lower turbidite unit passes upwards into interbedded shale and turbidites of the lower Alum Shale Fm (~825 to 827 m depth), distinguished from the lower turbidites by higher organic content, increasing gamma-ray values and a rather high U/Th ratio. The Alum Shale Fm consists of relatively homogeneous, organic-rich shale (source rocks with maximum total organic carbon values of 28 wt%), containing high concentrations of redox-sensitive metals (Mo, U, V; Bian et al. 2021), which indicate a deeper water depositional setting. Correlations of U/Th and gamma-ray log signatures in Scandinavian drill cores allow reliable comparisons of this part of the COSC-2 succession with cores representing deeper marine settings in other parts of Baltoscandia (Nielsen et al. 2018).

In the lower turbidite unit beneath the Alum Shale Fm, as well as in the upper turbidite unit above this formation (Fig. 3, blue units to the right), stratal cyclicity is observed on seemingly different orders, e.g. turbidites ranging from thick proximal beds to intermediate and thin layers of deeper water turbidites. It is uncertain whether these cycles represent changes in relative sea level (tectonics) or orbital cycles, making this an important subject for further research. Seismogenic features are mainly observed in the lower turbidite unit, possibly triggered by strike-slip fault movements corresponding to the rotational movements of Baltica. Stronger events are indicated by the wholesale destruction of bedding in the thick and cyclic turbidite packages destroying the visual record of the cycles. In addition, earthquakes and seimic tremors are also revealed by structures reflecting synsedimentary tectonics (slumping structures of different scales and synsedimentary faulting), resulting in injections of coarser sands into younger strata (liquefaction structures, sand diapirs/dykes with coarser sands).

This sedimentation was interrupted by a longer period of sediment starvation and enrichment of organic materials, as evidenced by the Alum Shale Fm (middle Cambrian through Tremadocian). The turbiditic upper Alum Shale Fm (~755 to 780 m depth) transitions into the overlying second turbidite succession (Tremadocian and younger), which shows an overall fining upward trend in grain size, indicating a general deepening of the depositional environment. These strata were previously erroneously regarded as a much younger foreland basin fill, the Föllinge greywackes (Middle–Upper Ordovician), along with their sedimentary cover (Upper Ordovician and Silurian shales).

Regional implications and future perspectives

The geological logging of the COSC-2 core succession revealed a mostly continuous sedimentary succession deposited on top of a deeply weathered porphyry sequence, with no abrupt transition from autochthonous to allochthonous units. Based on observations by Schweizer et al. (2023) and our interpretation of the recovered Palaeozoic succession, we suggest that the upper part of the core, above the heavily deformed and sheared central part of the Alum Shale Fm, is parautochthonous (Fig. 2). We do not regard the upper turbidite succession as an equivalent of the younger Föllinge Fm. Instead, we interpret the core as a conformable transition from the turbiditic upper Alum Shale Fm into the thick upper turbiditic unit. This transition is marked by a reduction in the organic matter content (evidenced by a colour change from blackish to greyish-greenish shale/layers) and a significant decrease in the characteristically high U/Th contents, corresponding to a significant drop in the gamma-ray values.

The Baltoscandian Alum Shale Fm is Miaolingian to Tremadocian in age (e.g. Zhao et al. 2022), showing that this rather thin unit corresponds to a long and, in this part of Baltica, tectonically quiet time interval (~20 Ma) without any rotation of the continent. There were probably no strike-slip movements during this possible quiescent drift period sufficient to cause large-magnitude earthquakes, large-scale extension or major mass flows. The transition from the upper turbiditic part of the Alum Shale Fm into the overlying turbidite succession indicates that the latter started deposition in late Tremadocian times, since there are no younger Alum Shale Fm strata known elsewhere in the Baltoscandian Basin, an area of around 100,000 km^2 (Zhao et al. 2022) extending across a large area of northern Europe (Norway, Sweden, Denmark, Poland, Estonia, and Russia; Bian et al. 2021). The proposed onset of deposition of the upper turbidite succession in the late Tremadocian predates the deposition of the Föllinge Fm greywacke that spans mainly a Middle through Upper Ordovician interval (lower Llanvirn to upper Caradoc in older literature; Karis 1988). However, local deposition starts already in Arenig times (Greiling et al. 2013), resting there with erosional contact on older beds (Strömberg 1998). In terms of international stages, the early foreland development started during the Floian with the Föllinge Fm and persisted until the mid-Katian. The thickness of the Föllinge Fm is regionally difficult to calculate, as the unit was initially suggested to represent a stack of imbricated nappes with vergences to the W. However, Karis (1998) estimated a thickness of ~500 m at Föllinge. Biostratigraphic data from the succession are notably scarce and based on a limited number of graptolite-bearing levels (Karis 1998; Heuwinkel and Lindström 2007).

It is possible that the upper turbidite succession could be comparable to the Föllinge Fm and may be interpreted as a continuous equivalent without tectonic imbrication. However, there is no erosional base (caused by a forebulge movement in sections to the E), and the sedimentation is instead transitional from the underlying upper turbiditic part of the Alum Shale Fm. Without reliable biostratigraphic data to date the top of this succession, it remains possible that it is of Early Ordovician age, as such a turbidite succession might have formed within a geologically short time interval.

Local sources of turbiditic sediments below the Alum Shale Fm (Ziemniak et al. 2023) and the extended time of deposition rather point to continuous sedimentation in a long-lived pull-apart basin preserved in a tectonic window beneath the Caledonian thrust sheet (Lehnert et al. 2023a). This pull-apart basin may have developed and opened in a dextral strike-slip regime when Baltica was drifting N and rotating to the W. Continuous tension, intervals of westward rotation and corresponding tectonic movements may have triggered strong seismic activity. A future detailed stratigraphic framework could provide age constraints for these active periods, distinguishing them from times when the turbidite successions were less disturbed. This may also help indirectly detect intervals with changes in the directions of plate motions. Baltica's movement from high southern latitudes towards the tropics (Fig. 4) and its eventual collision with Laurentia (Fig. 1) was not as simple as shown in most published models (e.g. Corfu et al. 2014). Studying the basin fill in the COSC-2 area will help understand the timing of Baltica's movements and rotations.

There are still many open questions regarding the regional development of a suggested pull-apart basin, which formed during Baltica's drift and rotational movements. Usually, such basins are short-lived, often lasting less than a few to ten million years (for references see Wijk et al. 2017). Resolving the history of this basin requires more detailed interdisciplinary studies. However, it is obvious that most of the deposition period of the Alum Shale Fm was a quiet interval during continental drift, presumably without much tectonic activity. After this tectonic quiescence, renewed movements and rotation retriggered turbiditic sedimentation in the upper part of the Alum Shale Fm. The overall deepening trend observed in the upper turbidite succession could reflect

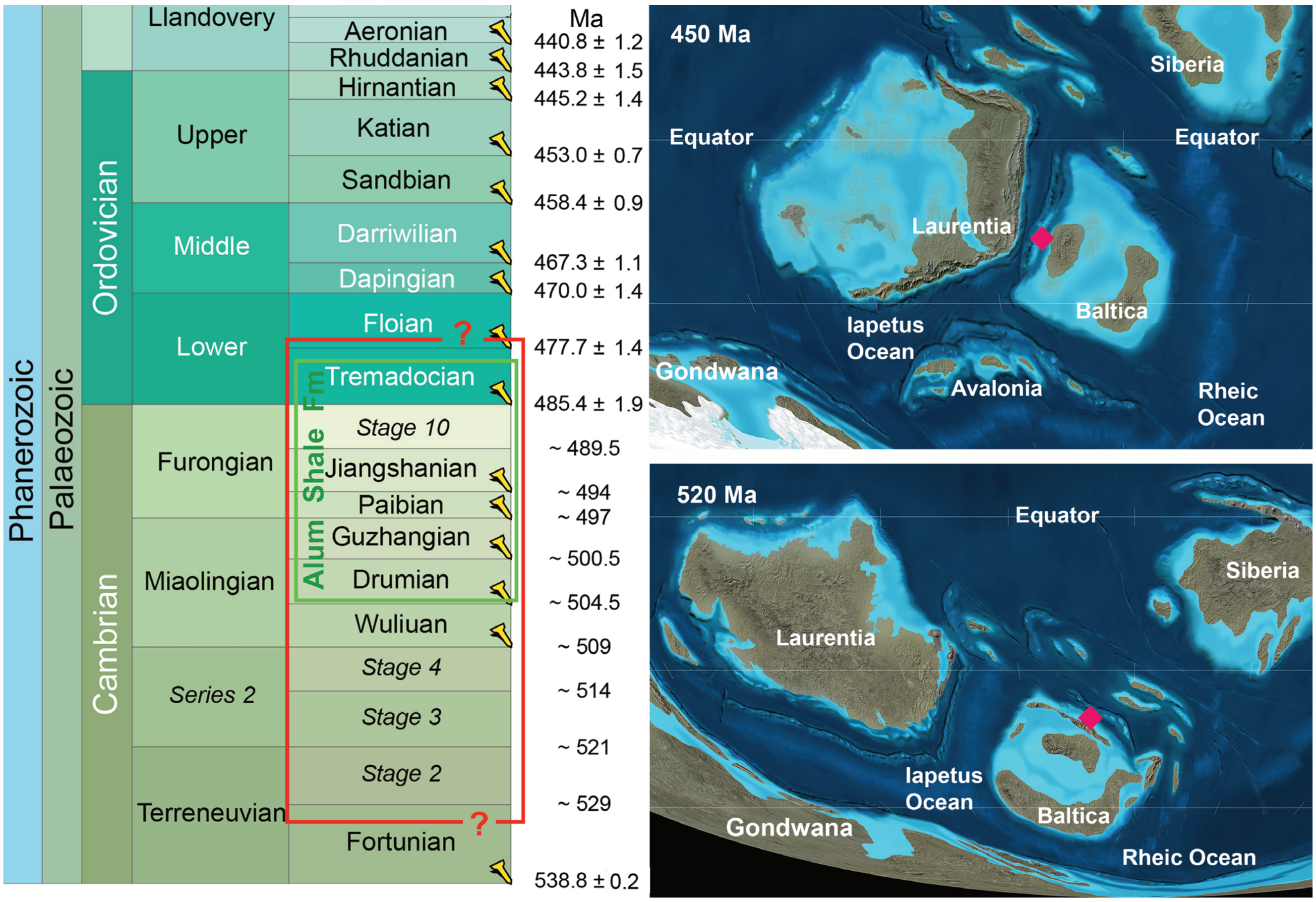

Fig. 4. **Left** – modified standard stratigraphic chart (GTS 2020 version). The red box shows the estimated range of the COSC-2 sedimentary succession, and the green box indicates the depositional time span of the Alum Shale Fm. **Right** – early Palaeozoic palaeogeography modified from maps used with permission by © 2016 Colorado Plateau Geosystems Inc., reflecting a counter-clockwise rotation of Baltica between early Cambrian (520 Ma) and Late Ordovician (450 Ma) times. The pink diamonds mark the project area of the COSC drill sites.

a regional transtensional setting, leading to greater subsidence. Nevertheless, this interval of turbidite sedimentation overlaps with the time of the earliest foreland basin formation, including the deposition of the Föllinge Fm. Therefore, more data are needed to better define the tectonic history of this whole portion of the Swedish Caledonides.

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