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Subduction and loss of continental crust during the Mesoproterozoic Sveconorwegian Orogeny

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ABSTRACT

The late Mesoproterozoic Sveconorwegian Orogeny in SW Fennoscandia is characterized by tectonically bound units that record different metamorphic, magmatic, and deformation histories, interpreted to indicate separation by some unknown distance prior to orogeny. New zircon U–Pb and Lu–Hf isotope data from a 1200 km-long NE–SW transect including Archean to 1450 Ma rocks constrain the likely age and isotopic architecture of western Fennoscandia prior to the late Mesoproterozoic Sveconorwegian Orogeny. Zircon age and Hf-isotope patterns indicate that the units comprising the Sveconorwegian Province are both younger and isotopically more juvenile than the surrounding autochthonous Fennoscandian crust, and thus most likely derived from west of the present-day Norwegian coastline. The Mylonite Zone defines a major tectonic structure separating allochthonous Sveconorwegian units in its hanging wall from autochthonous Fennoscandian crust in its footwall. New and compiled metamorphic age data demonstrate that the Mylonite Zone can be traced westward through the Western Gneiss Region, aligning with Nordfjord in western Norway, where it was reused during Caledonian deformation. The proposed westward continuation of the Mylonite Zone accommodated several hundred kilometers of sinistral strike-slip movement. Eastward translation of crust probably took place sometime between 1020 and 990 Ma, coinciding with a magmatic lull, followed by a shift to more evolved isotopic compositions in the hanging wall (Telemark) and high-pressure eclogite-facies metamorphism in the footwall (Eastern Segment) to the Mylonite Zone. Following this relatively short period of compression, the entire orogen and its foreland underwent extension lasting until at least 930 Ma. The nature and fate of the ca. 500 km of crust originally separating the autochthonous and allochthonous units remain elusive. There is no evidence of arc magmatism related to Benioff-style subduction of oceanic crust, and thus we propose an amagmatic Ampferer-style subduction comprising spontaneous subduction of thinned continental crust, as proposed for the Western Alps. Subduction of continental crust and associated radioactive heat-producing elements could also account for the anomalously high temperatures in the lithospheric mantle under the Sveconorwegian Province, which cannot easily be accounted for by other mechanisms. The Sveconorwegian Province may be an anomalous feature in an otherwise larger-scale orogen, the nature of which remains obscure.

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1. Introduction

The behavior of continental crust during orogeny is a key parameter for crustal growth and preservation, and its eventual recycling back into the mantle is critical to the evolution of crust and mantle compositions through time (Condie, 2013). Contrary to the long-held view that continental crust is too buoyant to subduct, a series of modeling- and geophysics-based studies focusing on the Alpine–Himalayan orogen have shown that not only is continental crust capable of subducting, it may also provide a driving force for convergence (Capitanio et al., 2010; Ingalls et al., 2016; Qi et al., 2022). However, identifying the former existence of subducted continental crust in ancient orogens is inherently challenging. Here, we show that this can be achieved by providing constraints on the pre-orogenic distribution of crustal units making up the orogen along with isotopic and geophysical data that argue for the existence of such crust in the deep lithosphere.

Tectonic processes on Earth have most likely changed significantly through time, as a function of decreasing mantle potential temperature (Sizova et al., 2014), and the Mesoproterozoic and early Neoproterozoic eras represent the transition to modern-day plate tectonics, characterized by cold subduction and horizontal movements of relatively strong tectonic plates. Divergence, accretion, and collision between the plates are reflected in the geological record by features such as ophiolites and low-temperature/high-pressure blueschist- and eclogite-facies metamorphism, which were largely absent before the Neoproterozoic (Hamilton, 2011; Piper, 2013; Stern et al., 2013). As discussed by Roberts et al. (2015), Mesoproterozoic orogens display a wide variety of tectonic processes, many of which resemble today's accretionary and collisional settings and some that do not. Identifying hitherto unrecognized tectonic processes in Mesoproterozoic orogens contributes to a framework within which a variety of geological data can be interpreted, and is of key importance for placing constraints on numerical models that attempt to recreate these processes. The late Mesoproterozoic Sveconorwegian Orogeny reworked the southwestern margin of the Fennoscandian Shield between ca. 1140 and 930 Ma. For this system, there are relatively tight constraints on the metamorphic and magmatic histories of individual tectonic units and the tectonic boundaries separating them (Fig. 1; Bingen et al., 2021; Slagstad et al., 2020). At present, the two prevalent models for the Sveconorwegian Orogeny are: (1) collision with an unknown continent to the west, involving crustal thickening and the development of an orogenic plateau, but with limited horizontal movement of Fennoscandian crust (Bingen et al., 2021), or (2) incremental accretion of crustal blocks derived from farther west on the margin, but with thickening limited to areas close to the orogenic foreland, in an active continental margin setting (Slagstad et al., 2020) (see summary of these models in Slagstad and Kulakov, 2024). Constraining the amount of horizontal movement associated with orogeny could, therefore, provide a test of the two models.

Here, we present whole-rock geochemical and zircon U–Pb and Lu–Hf analyses from more than 90 samples from a > 1200 km-long transect from Archean (ca. 2800 Ma) rocks in northern Norway to ca. 1450 Ma rocks in SW Norway, along with compilations of published zircon U–Pb (magmatic and metamorphic) and Lu–Hf data from Fennoscandia, and geophysical (magnetic, gravity, seismic) data (Fig. 1). The data provide insight into the pre-orogenic distribution of continental crust at the southwestern margin of Fennoscandia and the geologic histories recorded by these units, thus providing a test of the aforementioned tectonic models by placing some constraints on horizontal transport distances. Based on these data, we show that Sveconorwegian tectonic units located structurally above the Mylonite Zone – a major Sveconorwegian shear zone – are most likely allochthonous, but not exotic to Fennoscandia, and formed west of the present-day coastline of Norway, at least 500 km west of their current position. We also discuss the possibility that the ca. 500 x 500 km Sveconorwegian Province represents only a minor portion of a much larger orogenic system that may display highly variable tectonic settings and processes along strike (see also Slagstad et al., 2017). Considering the complexity of many present-day orogenic systems, such as the SW Pacific or Mediterranean Alpine system, that contain distinct tectonic domains within which the Sveconorwegian Province *sensu stricto* would fit, great care is warranted when discussing the broader tectonic significance of the Sveconorwegian Orogeny based solely on data from the extant Sveconorwegian Province.

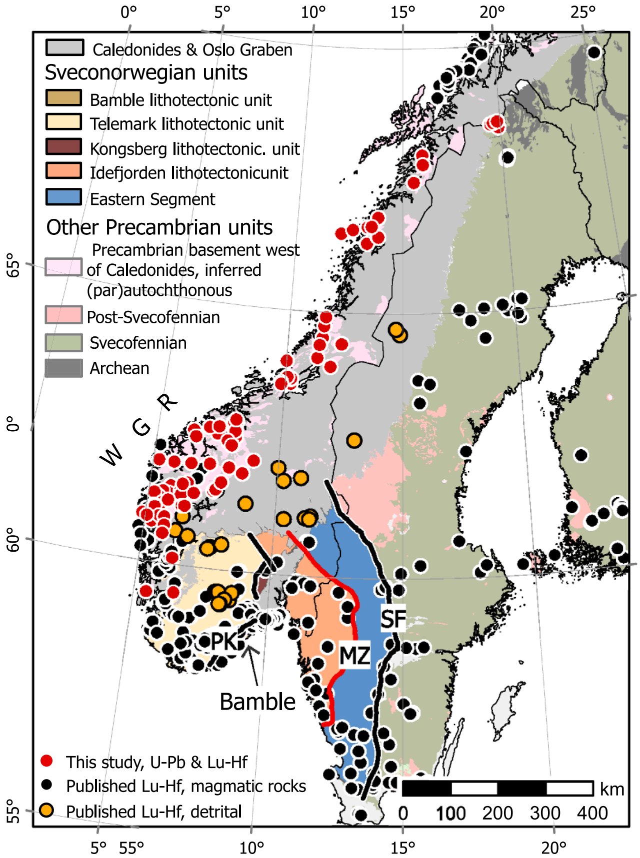

Fig. 1. (A) Simplified geologic map of western Fennoscandia and the Sveconorwegian Province with new samples in red and previously published Lu–Hf isotopic data in black and orange. Thick, black lines are Sveconorwegian shear zones. MZ–Mylonite Zone, PK–Porsgrunn–Kristiansand Shear Zone; SF–Sveconorwegian Front, WGR–Western Gneiss Region.

2. Geological background

2.1. Pre-Sveconorwegian evolution (1900–1140 Ma)

Following ca. 1900–1800 Ma amalgamation of Archean crustal blocks and juvenile arcs during the Svecofennian Orogeny (Fig. 1), westward growth of the Fennoscandian Shield commenced with emplacement of the ca. 1860–1660 Ma Transscandinavian Igneous Belt (TIB; Högdahl et al., 2004), followed by ca. 1660–1480 Ma Gothian and Telemarkian orogeny, typically interpreted to represent juvenile arc magmatism at or outboard of the western Fennoscandian margin (Åhäll and Connelly, 2008; Andersen et al., 2002; Bingen et al., 2005; Högdahl et al., 2004; Roberts et al., 2013).

The 1450–1290 Ma period is poorly preserved in the rock record and hence ill-defined. The Hallandian orogeny in southern Sweden involved arc magmatism and associated high-grade metamorphism at ca. 1450 Ma and is typically ascribed to convergent active-margin processes (Brander and Söderlund, 2009; Johansson et al., 2016). Following a period of aerially restricted bimodal magmatism between 1340 and 1290 Ma, dominantly within the Idefjorden lithotectonic unit, widespread emplacement of mafic dikes throughout central and SW Fennoscandia between 1290 and 1230 Ma (Central Scandinavian Dolerite Group) has been ascribed to a large back-arc extensional regime at that time (Brander et al., 2012; Brewer et al., 2004; Söderlund et al., 2006). From 1180 Ma, magmatism was localized in future Sveconorwegian units, mainly in the Telemark lithotectonic unit, and largely dominated by felsic compositions, although chemical and Hf isotopic data suggest that the mantle contributed both heat and material (Andersen et al., 2009; Granseth et al., 2020; Granseth et al., 2021). In contrast, magmatism after 1180 Ma is absent in the future Sveconorwegian foreland.

The magmatic record, particularly from the Telemark unit, shows that extension became increasingly localized in crust that would later develop into the Sveconorwegian Orogen and that temperatures in the lower crust were high enough to sustain long-lived, voluminous melting (Granseth et al., 2020). These conditions were maintained from at least 1280 Ma and appear to have persisted more or less unperturbed throughout orogeny until ca. 930 Ma (Slagstad and Kulakov, 2024), consistent with a long-lived, wide and hot continental back arc (Hyndman, 2019; Roberts et al., 2023) in an overall extensional tectonic regime.

2.2. *Sveconorwegian Orogeny (1140–930 Ma)*

The Sveconorwegian Orogeny initiated at 1140 Ma, marked by high-grade, granulite-facies metamorphism (ranging from 7 kbar/800 °C to 11.5 kbar/>850 °C) in the Kongsberg and Bamble lithotectonic units situated in the central parts of the orogen (Fig. 1; Bingen et al., 2008; Engvik et al., 2016; Harlov, 2000; Slagstad et al., 2020). The adjacent Telemark lithotectonic unit, however, records continued extension and sedimentation until approximately 1100 Ma (Spencer et al., 2014), suggesting significant but unconstrained separation between Telemark and Bamble–Kongsberg (Fig. 1) prior to 1100 Ma. Sedimentation in the Telemark unit came to a halt concurrently with westward thrusting of the Bamble unit onto Telemark at 1100 Ma, indicated by rapid cooling of the former (Slagstad et al., 2020); however, the amount of pre-1100 Ma separation is unconstrained.

Between approximately 1080 and 930 Ma there was extensive, voluminous granitic magmatism accompanied by minor mafic magmatism in the Telemark unit, forming the orogenic hinterland. Voluminous granitic magmatism in the Telemark unit coincided with high- to ultrahigh-temperature (HT/UHT) metamorphism in the southwestern part of the unit, with temperatures exceeding 900–1000 °C under relatively low to moderate pressure (6–8 kbar) (Blereau et al., 2017; Drüppel et al., 2013; Laurent et al., 2018). The HT/UHT metamorphism is geographically associated with the Rogaland Anorthosite Province (RAP) and nearby Bjerkreim–Sokndal (BKSK) layered intrusion (Marker et al. 2003) and has been ascribed to short-lived emplacement of the RAP and BKSK at 930 Ma, leading to the development of contact-metamorphic isograds concentrically around the RAP and BKSK (Laurent et al., 2018; Schärer et al., 1996; Tobi et al., 1985; Westphal et al., 2003). However, recent research has shown that these contact-metamorphic "isograds" reflect HT/UHT conditions that persisted over an extended period of time from ca. 1090 Ma (Blereau et al. 2019), and it now appears that the distribution of HT/UHT rocks is primarily tectonically controlled and related to differential exhumation during widespread orogenic extension between 980 and 930 Ma (Slagstad et al., 2022). As such, the HT/UHT rocks in the southwestern Telemark unit are probably representative of the PT conditions that sustained lower-crustal melting as a result of long-lived mafic underplating rather than crustal thickening (Granseth et al., 2020; Slagstad et al., 2018b), consistent with the lack of high-pressure metamorphism and garnet in the lower-crustal residues to the granitic magmas.

A compilation of whole-rock chemical and zircon isotope data from granitic rocks in the Telemark unit shows only small changes in chemical composition, crystallization temperatures, and isotopic composition beyond that accounted for by secular decay between ca. 1280 and 950 Ma (Slagstad and Kulakov, 2024). These data do not appear to record a major change in sources or melting conditions, suggesting that the Telemark unit remained in a continental back-arc setting throughout that period, albeit affected by periodic compression and extension.

In contrast to the high-temperature/medium-pressure conditions that prevailed in the western orogenic hinterland, the tectonic style was very different towards the eastern foreland. High-pressure metamorphism (10–15 kbar/700–740 °C) is recorded in the Idefjorden lithotectonic unit at 1050 and 1030 Ma (Söderlund et al., 2008) and eclogite-facies metamorphism (16–19 kbar/850–900 °C) in the Eastern Segment at ca. 990 Ma was followed by migmatisation until ca. 960 Ma (Möller et al., 2015; Tual et al., 2017).

Extension-related magmatism in the eastern part of the Sveconorwegian Province, including the foreland, between 978 and 946 Ma (Blekinge-Dalarne dolerite dike swarm; Söderlund et al., 2005) coincides with extension and exhumation of HT/UHT crust in the western part of the orogen (Slagstad et al., 2022), suggesting that the entire orogen and its foreland was in extension at this time. Extension unrelated to earlier crustal thickening throughout most of the orogen and in its foreland led Slagstad et al. (2020) to suggest an orogen-external driving force. In many ways, the Sveconorwegian Orogeny therefore appears to be part of a several hundred million year-long continuum of alternating compressional and extensional tectonics, rather than the termination of such processes.

2.3. *The Mylonite Zone and Sveconorwegian Front*

The Mylonite Zone is one of the largest shear zones in the Sveconorwegian Province and separates the Idefjorden unit in the hanging wall from the Eastern Segment in the footwall (Andersson et al., 2002) (Fig. 1). The Mylonite Zone contributed to significant E–W shortening and shows an overall ramp-like geometry with dip-slip thrusting in the N–S-trending frontal zone and strike-slip shearing to the north and south where the Mylonite Zone swings around to a more westerly orientation (Viola et al., 2011). The timing of thrusting is poorly constrained, but most authors attribute high-pressure metamorphism in the Eastern Segment footwall at ca. 990 Ma to overthrusting of the Idefjorden unit along the Mylonite Zone. Sveconorwegian eclogite-facies metamorphism (16–19 kbar/850–900 °C) in the Eastern Segment is recorded between 990 and 950 Ma (e.g., Johansson et al., 2001; Piñán Llamas et al., 2015). Importantly, no pre-990 Ma Sveconorwegian metamorphism is recorded in the Eastern Segment and, along with contrasts in age and Hf compositions (Petersson et al., 2015b), there are clear indications of significant crustal shortening on the Mylonite Zone, leading Andersson et al. (2002) to refer to rocks in the hanging wall as allochthonous.

Ar–Ar age data on micas from the Mylonite Zone suggest extension until 920–860 Ma (Viola et al., 2011). Similar data from the Porsgrunn–Kristiansand Shear Zone, separating the Bamble and Telemark units (Fig. 1), show extension until 880 Ma (Mulch et al., 2005), and mafic dikes in Telemark dated at ca. 850 Ma (Walderhaug et al., 1999) are indicative of extension up to 50–100 Myr after the main period of orogeny.

The Sveconorwegian Front delineates the eastern boundary of the Eastern Segment and is defined as the easternmost extent of Sveconorwegian deformation and metamorphism (Wahlgren et al., 1994).

2.4. *Regional magnetic, gravity, and seismic data*

The distribution of Sveconorwegian metamorphic and magmatic activity defines an approximately equidimensional, ca. 500 x 500 km region, which is highly unlike typical curvilinear orogenic belts. It is, however, likely that poor exposure resulting from eastward thrusting of early Paleozoic Caledonian nappes and associated strong deformation and metamorphism, in addition to both pre- and post-Caledonian episodes of rifting, effectively conceals Sveconorwegian effects outside of the Sveconorwegian Province and will require much more targeted approaches to identify.

The regional magnetic and gravity maps (Fig. 2; Olesen et al., 2010) do not clearly record the Mylonite Zone, whereas the Sveconorwegian Front appears to coincide with a westward transition from high to low magnetic values. Tracing this anomaly northwards, the Sveconorwegian Front can be inferred to continue north-northeastward to central Norway, where it swings in a more westerly direction. The gravity map is isostatically corrected, meaning that it largely shows differences in rock density in the uppermost crust, and shows that the Sveconorwegian Front coincides with a low-gravity anomaly that, like in the magnetic data, can be traced north-northeastward to central Norway.

The map of lithospheric thickness compiled from Gradmann (2013), Plomerová and Babuška (2010), and Artemieva et al. (2006) shows that western and central Norway is characterized by relatively thin lithosphere (<130 km) with a sharp eastward increase in thickness to > 160 km in Sweden (Fig. 3A). In central Norway, the step in thickness coincides relatively well with the possible continuation of the Sveconorwegian Front gleaned from the magnetic and gravity data. In the south, however, the transition is located below the Idefjorden unit and does not coincide directly with Sveconorwegian tectonic features.

Seismic tomography data show that the lithospheric mantle under the Sveconorwegian Province is characterized by significantly lower velocities than elsewhere in Fennoscandia (Kolstrup et al., 2015; Mauerberger et al., 2022), corresponding to a temperature anomaly on the order of 300 °C (Fig. 3B; Kolstrup et al., 2015). The anomaly is ca. 200 km wide and underlies most of the Telemark unit, before tapering out rapidly eastwards under the high-pressure domain of the Sveconorwegian Province. The largest anomaly forms a north–south-trending linear belt corresponding geographically to the Sirdal Magmatic Belt, a more than 50 x 200 km, N–S-trending, 1070–1020 Ma granite batholith (Coint et al., 2015). Relatively recent tectonic events, such as Permian rifting in the Oslo and Viking grabens, Eocene opening of the North Atlantic, or possible plume fingers stemming from the Iceland plume, do not appear to be feasible explanations for the low-velocity anomaly and Slagstad et al., (2018a) suggested that it might, at least partly, represent refertilized mantle following oceanic subduction west of the Sveconorwegian Province. However, the numerical modeling by Slagstad et al., (2018a) also showed that the observed anomaly requires radiogenic heat production orders of magnitude higher than that found in even metasomatized mantle, and addition of continental material seems to be required (e.g., Hieronymus and Goes, 2010).

We note that magnetic and gravity anomalies, lithospheric thickness, and thermal structure of the lithosphere in the Sveconorwegian Province are likely to have been altered since the Sveconorwegian Orogeny. However, several lines of argument support that the step in lithospheric thickness, and probably also contrast in lithospheric mantle temperature, was present at least before 300 Ma. Pascal et al. (2002) suggested that the step was integral in focusing stress during Permian extension, thus causing the Oslo Rift to be located along the step. Also, propagation of the Permian Oslo rift came to a halt when it encountered the Mylonite Zone and the thicker lithosphere in its footwall (Fig. 3A), both of which suggest that a step in lithospheric thickness existed already in the Permian. Anomalous radiogenic heat production is the only likely process by which thermal contrasts can be maintained on time scales of several hundred million years. Repeated magmatic events in the

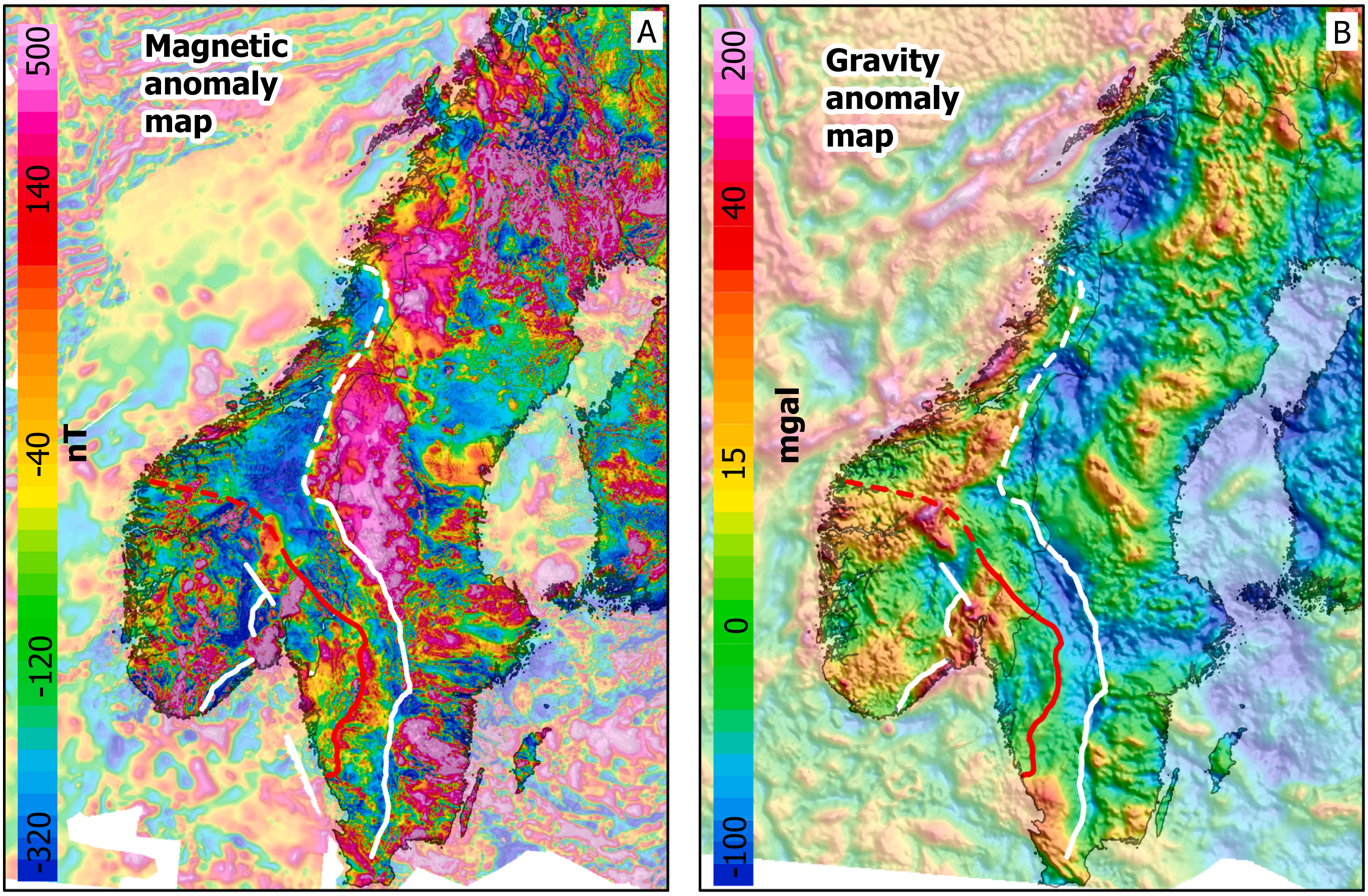

Fig. 2. (A) Magnetic and (B) gravity anomaly maps from Olesen et al. (2010). The red line is the Mylonite Zone with the dashed line indicating its continuation inferred here. The white lines are major shear zones except the easternmost line which is the Sveconorwegian Front; the dashed white line indicates its continuation inferred here.

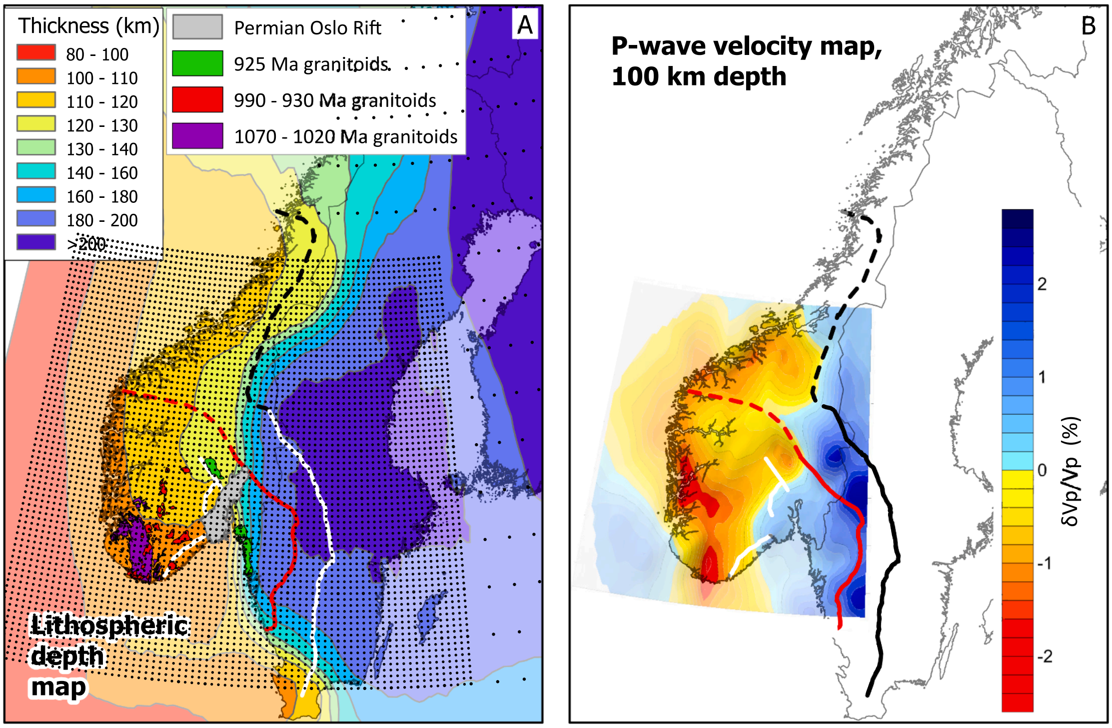

Fig. 3. (A) Lithospheric depth map based on data compiled from Gradmann (2013), Plomerová and Babuška (2010), and Artemieva et al. (2006). The black and gray spots show data points used in the depth estimate; note the significantly lower data density in northeastern Fennoscandia. The location of Sveconorwegian magmatic rocks is also indicated. In purple is the 1070–1020 Ma Sirdal Magmatic Belt, in red are granitoids dated at 900–930 Ma displaying distinctly more evolved isotopic compositions, and in green are the peraluminous Flå–Iddefjord–Bohus leucogranites with evolved isotopic compositions indicative of derivation from subducted continental crust (Granseth et al., 2020). (B) P-wave velocity map at 100 km depth from Kolstrup et al. (2015). The low seismic velocities under much of the Sveconorwegian Province are typically interpreted to reflect anomalously hot lithosphere that appears to require contamination with continental material (Slagstad et al., 2018a).

Sveconorwegian Province through the Neoproterozoic that are not observed elsewhere in Fennoscandia, further suggest an anomalously hot and weak lithosphere following the Sveconorwegian Orogeny (Slagstad et al., 2023). As for the regional gravity and magnetic data, they are closely aligned with Precambrian geologic features (Olesen et al., 2010) and, apart from areas with thick Caledonian nappe cover, most likely represent Precambrian geology.

3. Results

Ninety-one samples were analyzed for whole-rock major and trace element geochemistry and zircon U–Pb and Lu–Hf by laser ablation induced coupled plasma mass spectrometry at the Geological Survey of Norway (NGU) and Curtin University, Australia. A summary of the results is presented in data repository (DR) 1, analytical methods are presented in DR2, and data in DR3 (U–Pb) and DR4 (Hf). The study also includes comprehensive compilations of U–Pb zircon data from the Geological Surveys of Norway and Sweden, and a new compilation of Lu–Hf zircon data from Fennoscandia (DR5). Whole-rock chemical data is presented in DR6.

3.1. *Whole-rock geochemistry of igneous rocks*

The studied granitoids have been subdivided into age groups to identify temporal changes in composition. Chemically, the granitoid rocks along the 1200 km-long transect studied here are calc-alkaline, range between 55 and 75 wt% SiO_2, and yield linear trends in Harker diagrams (Fig. 4). There are few differences between the different age groups, although the two youngest groups (1650–1550 and 1550–1450 Ma) are skewed towards intermediate and felsic compositions. Trace element compositions are typical of magmatic arcs, with mildly fractionated Chondrite-normalized rare earth element patterns and negative Nb–Ta, P, and Ti anomalies in Primitive Mantle-normalized plots (Fig. 5).

Our preferred interpretation for the geochemical data involves continuous, juvenile, calc-alkaline magmatism between 1900 and 1450 Ma in a long-lived magmatic arc most likely located at the western margin of Fennoscandia, as is commonly inferred (Åhäll and Connelly, 2008; Högdahl et al., 2004; Roberts and Slagstad, 2015).

3.2. *U–Pb and Hf zircon data from Archean to Mesoproterozoic igneous rocks*

The new and compiled U–Pb and Hf zircon data are presented as maps (Fig. 6) and an age vs. ε_{Hf} plot (Fig. 7). There are no apparent differences between the new and compiled datasets, and for the sake of clarity we present and discuss the data together. To facilitate the discussion, we focus on three profiles (Fig. 6): A–A' is an ENE-to-WSW transect from central Sweden through the northern Western Gneiss Region (WGR); B–B' is a N-to-S transect through the WGR; C–C' is a W-to-E transect from the Sveconorwegian Front across the Mylonite Zone.

Magmatism between 1900 and 1750 Ma forms a distinct N–S trend from northern Norway to southcentral Sweden. This dominantly granitoid magmatism is typically considered to belong to the TIB, and most likely represents arc magmatism along the western margin of Fennoscandia (Högdahl et al., 2004). A gradual westward younging is apparent for 1750–1450 Ma magmatism in the northern WGR (profile A–A'), consistent with continued westward growth (Røhr et al., 2013; Tucker et al., 1990). Moving south from profile A–A', there is a sharp drop (profile B–B') in crystallization age, with pre-1650 Ma rocks all but absent farther south in the WGR and in the Sveconorwegian Province.

In the eastern Sveconorwegian Province, the range of ages is similar

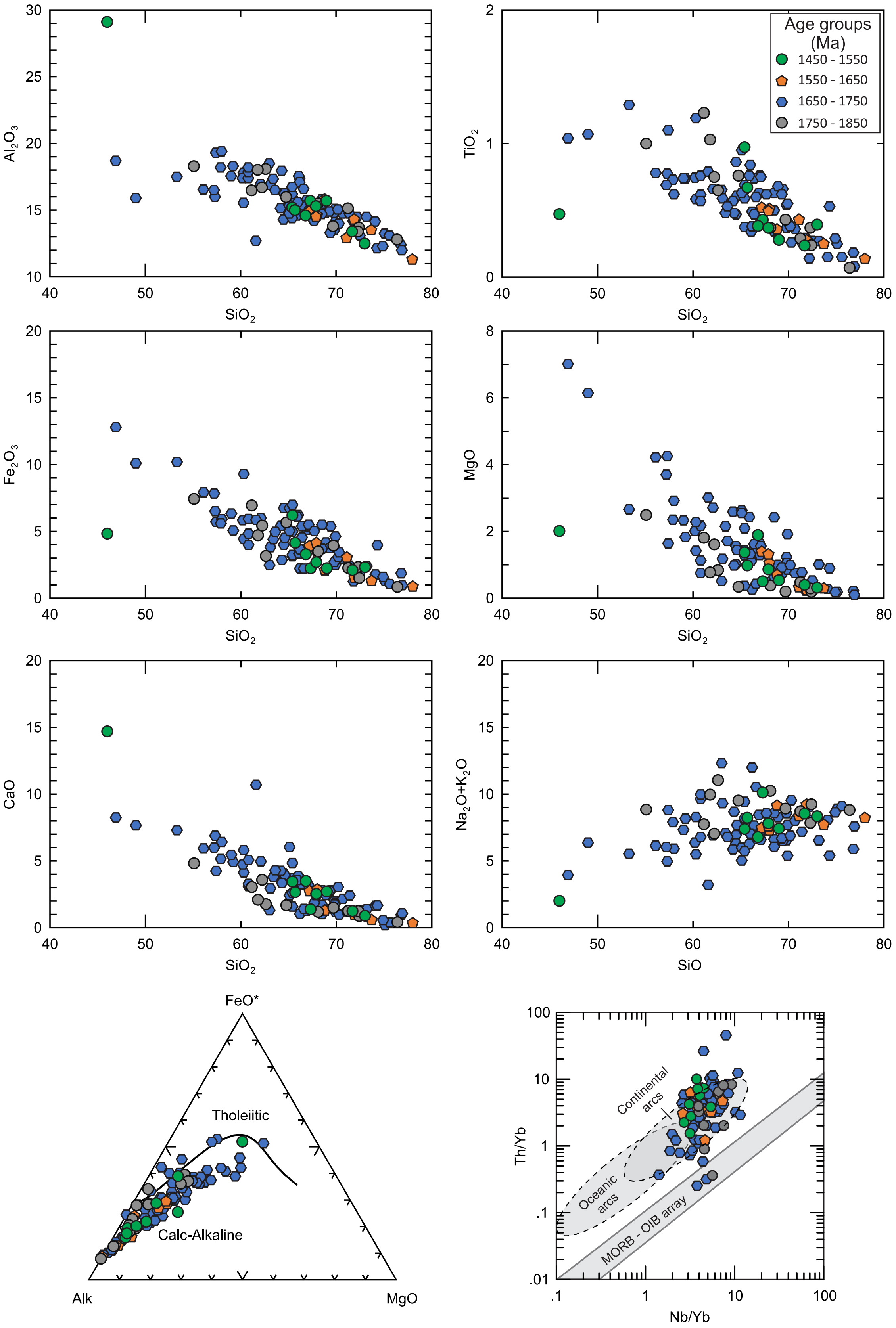

Fig. 4. Harker diagrams presenting major element chemistry of samples analyzed in this study, grouped by age.

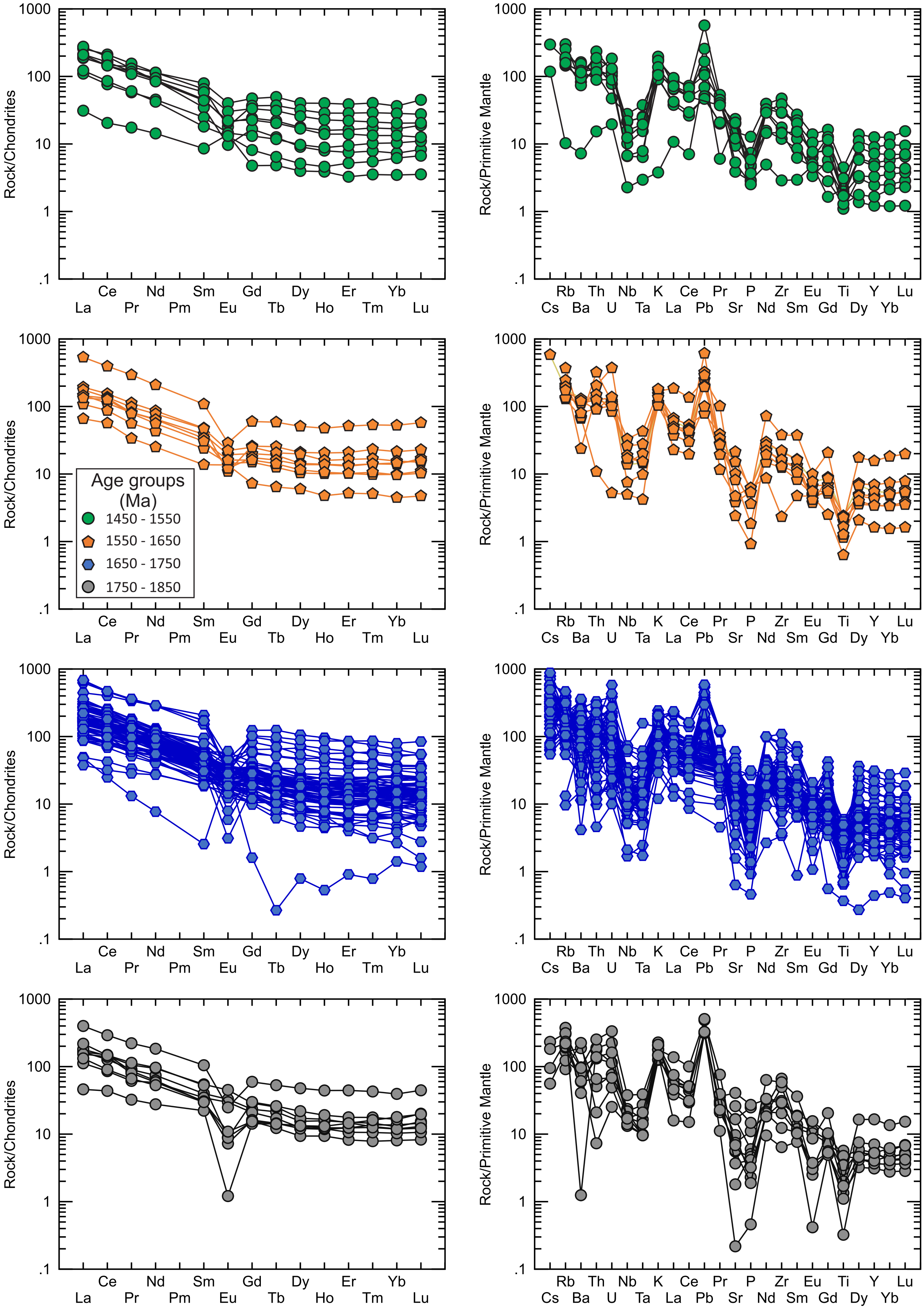

Fig. 5. Chondrite- and Primitive mantle-normalized multi-element diagrams for the samples analyzed in this study, grouped by age. Normalizing values from Sun and McDonough (1989).

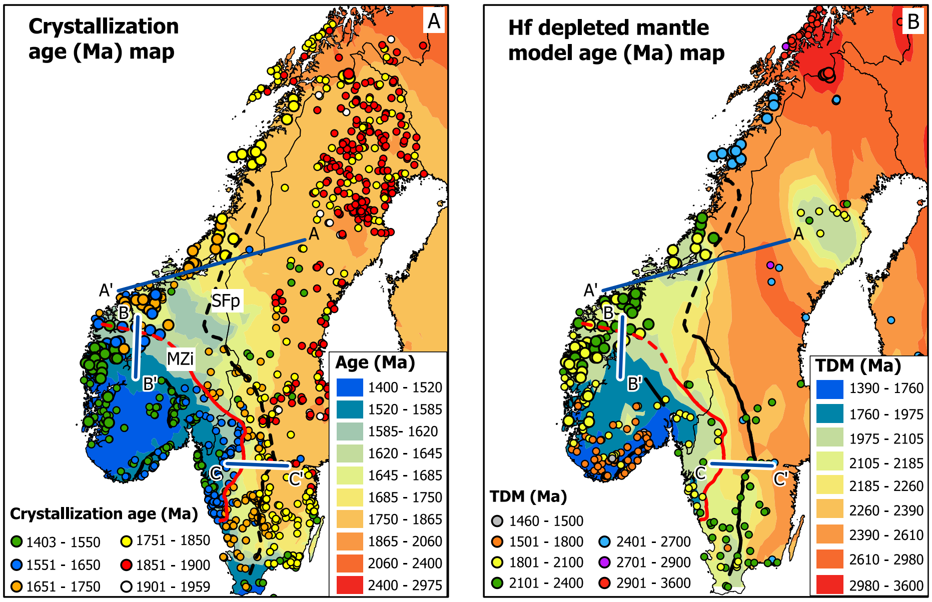

Fig. 6. (A) New (large symbols) and published U–Pb crystallization ages plotted on a crystallization-age map based on interpolation between all data points. (B) Median T_{DM}s from new and published Lu–Hf data plotted on an interpolated grid of T_{DM}s. Profiles A–A', B–B', and C–C' highlight trends and steps in ages and Hf isotopic compositions, discussed in the text.

to that observed in the WGR, but their distribution is different. Unlike in the WGR where there is a wide swath of 1750–1550 Ma ages, these ages are largely confined to the Eastern Segment, with a sharp break between rocks > 1650 Ma in the Eastern Segment and < 1650 Ma in the Idefjorden unit (profile C–C'). This abrupt change in age and structural style observed across the Mylonite Zone has previously been used to argue that it represents a major structural contact (Andersson et al., 2002; Petersson et al., 2015b).

The new and compiled zircon Lu–Hf data from Fennoscandia show that Svecofennian (1950–1800 Ma) magmatism is characterized by mixed Archean and juvenile sources, followed by largely superchondritic ε_{Hf} values until ca. 1200 Ma (Fig. 7), suggesting significant crustal addition during this period and consistent with earlier studies (Andersen et al., 2004; Petersson et al., 2017; Petersson et al., 2015a; Petersson et al., 2015b). A trend toward more negative values after ca. 1200 Ma reflects a larger degree of crustal reworking and coincides with the Sveconorwegian Orogeny (Andersen et al., 2007; Granseth et al., 2021; Wang et al., 2021). The map of two-stage depleted mantle model ages (T_{DM}, Fig. 6B) shows (south)westward younging, from over 2400 Ma in central Sweden to around 1800 Ma in the northern WGR (profile A–A'). Profile B–B' in the WGR shows a trend toward more juvenile compositions and, similar to crystallization ages, the youngest T_{DM}s are almost exclusively recorded in the Telemark unit, ranging from 1800–1500 Ma, with some samples yielding older ages. As noted by Petersson et al., (2015b) and shown in Fig. 6B (profile C–C'), there is a jump from $T_{DM} > 2100$ Ma in the Eastern Segment to dominantly < 2100 Ma in the Idefjorden unit.

During the Sveconorwegian Orogeny, zircon Lu–Hf compositions largely follow a trend consistent with crustal reworking, with or without juvenile additions (Granseth et al., 2021; Wang et al., 2021). An exception is the period 980–940 Ma where ε_{Hf} values dropped from chondritic to subchondritic (−5), requiring addition of a less radiogenic source. The shift to more evolved isotopic compositions appears to have followed shortly after a magmatic lull around 1000 Ma in Telemark and high-pressure metamorphism in the Eastern Segment related to thrusting along the Mylonite Zone. The possible link between these events is discussed further below.

Importantly, both the U–Pb and Lu–Hf data show that within a framework of (south)westward growth, the Sveconorwegian units located structurally above the Mylonite Zone stand out as younger and more juvenile than rocks outside of the Province.

3.3. *U–Pb zircon ages of Sveconorwegian metamorphism*

The map of metamorphic ages (Fig. 8C) shows that the Eastern Segment only records the youngest (<990 Ma) period of Sveconorwegian metamorphism, as discussed above. Importantly, the new data presented here along with existing data appear to pick up the same contrast in the WGR, coinciding geographically with the break between rocks older and younger (and more juvenile) than ca. 1650 Ma (Fig. 6A, profile A–A') and a major E–W lineament in the form of Nordfjord. The range of Sveconorwegian metamorphic ages in the WGR north of Sognefjorden is 980–943 Ma, similar to that observed in the Eastern Segment.

The character of Sveconorwegian metamorphism in the WGR is obscured by strong Caledonian overprinting but in one outcrop studied by us, foliation-parallel leucosomes in granitic gneiss are cut by leucosomes in an *en échelon* pattern indicative of top-to-east thrusting corresponding to the main Caledonian transport direction (Fig. 9). A foliation-parallel leucosome yields a zircon U–Pb age of 962 ± 11 Ma whereas the cross-cutting leucosome is 406 ± 26 Ma, consistent with high-grade Sveconorwegian metamorphism overprinted during the Caledonian Orogeny (see DR7 for U–Pb data). While pressure–temperature conditions cannot be determined for this leucosome, it clearly attests to (upper) amphibolite-facies metamorphic conditions comparable to those observed in the Eastern Segment following initial high-pressure metamorphism (Möller et al., 2015).

The distinct distribution of metamorphic ages in the WGR suggests that the Mylonite Zone can be traced westward for about 300 km from where it becomes concealed by Caledonian nappes (Fig. 1). Its orientation in the WGR is, however, unclear, and a more northerly trend resulting in a component of thrusting is probably needed to account for the observed metamorphism there.

4. Discussion

The significance of the following features is discussed below:

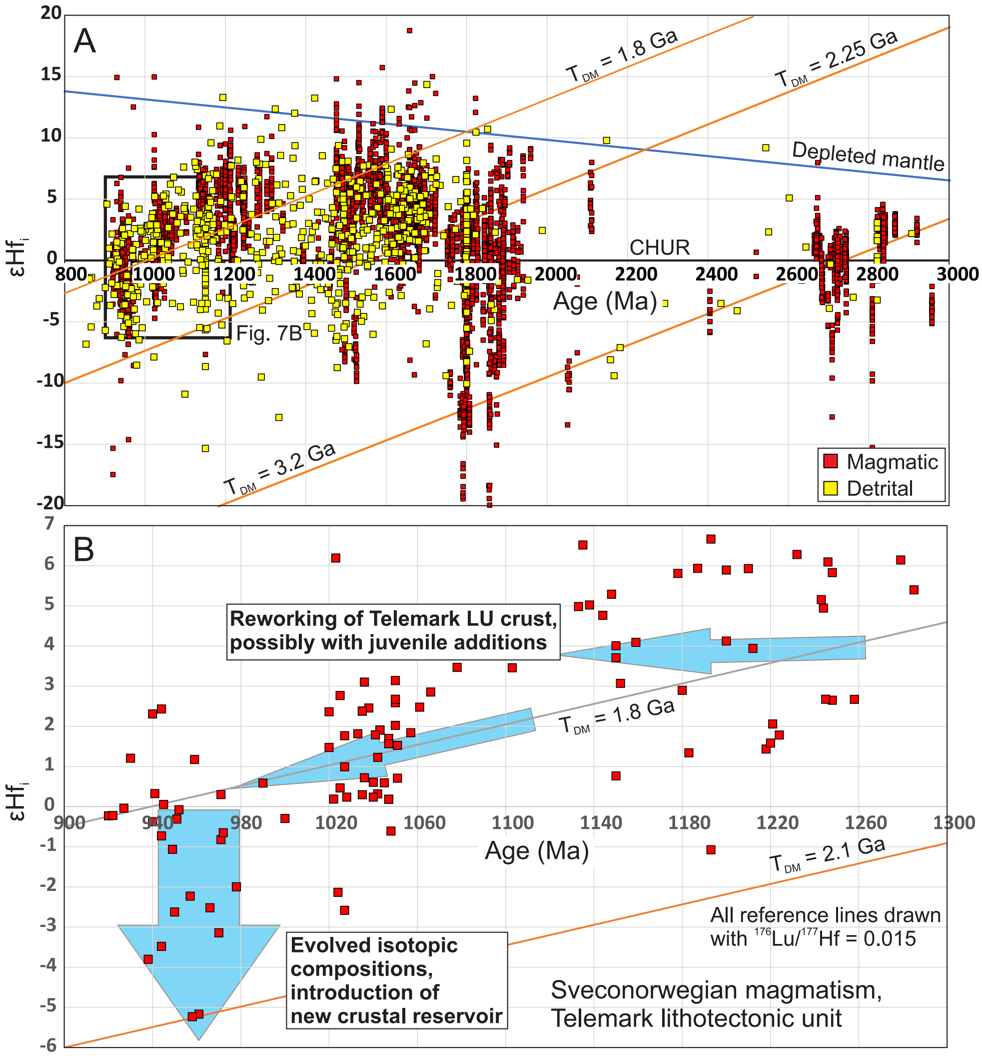

Fig. 7. (A) Age vs. initial ε_{Hf} for all new and compiled data from Fennoscandia. (B) Similar data from the Sveconorwegian Orogen, covering the period 1300–900 Ma. The data points represent individual zircon analyses. All reference lines (in orange) show Lu–Hf depleted mantle model ages calculated assuming a $^{176}Lu/^{177}Hf = 0.015$. Initial εHf (εHf$_i$) was calculated from $^{176}Hf/^{177}Hf_i$ relative to CHUR (at the age of the zircon domain) with present-day $^{176}Hf/^{177}Hf = 0.282785$ and $^{176}Lu/^{177}Hf = 0.0336$ (Bouvier et al., 2008). Two-stage depleted-mantle model ages (T_{DM}) were calculated relative to a depleted mantle model reservoir with present-day $^{176}Hf/^{177}Hf = 0.28325$ (Griffin et al., 2000; Griffin et al., 2002; Nowell et al., 1998) and $^{176}Lu/^{177}Hf = 0.0384$ (Griffin et al., 2002), and the crustal average $^{176}Lu/^{177}Hf = 0.015$ (Griffin et al., 2002) for the Hf isotopic evolution of crustal magma sources after separation from the depleted mantle.

1. U–Pb and Lu–Hf age data suggest continuous (south)westward growth of the Fennoscandian margin between ca. 1900 and 1450 Ma. The Sveconorwegian Province, however, preserves abrupt changes in age and isotopic composition with adjacent crust that require tectonic juxtaposition.
2. The Sveconorwegian Province preserves a ca. 1180 to 990 Ma metamorphic and magmatic record that is not observed to the north or east in Fennoscandia and requires that units located structurally above the Mylonite Zone are allochthonous, although not necessarily exotic, to Fennoscandia.
3. A lull in magmatism around 1000 Ma in the Telemark unit is coeval with thrusting of the Idefjorden unit onto the Eastern Segment along the Mylonite Zone. Following this event, magmatism in Telemark records more evolved isotopic compositions with metamorphic and extension-related magmatic activity recorded both within and outside the Sveconorwegian Province until ca. 930 Ma.
4. The overall Precambrian crustal architecture of the western Fennoscandian margin is obscured by Caledonian nappes and repeated rifting; however, magnetic, gravity, and lithospheric thickness data appear consistent with an overall north–south tectonic grain that coincides with the Sveconorwegian Front.
5. The lithospheric mantle under the Sveconorwegian Province has anomalously low seismic velocities, suggestive of temperature anomalies on the order of 300 °C. These temperatures cannot be accounted for by any known, recent tectonic processes and require a radiogenic heat production that is orders of magnitude higher than normal lithospheric mantle.

4.1. *Evidence of Sveconorwegian allochthoneity*

Following the Svecofennian Orogeny at ca. 1890–1860 Ma, the westward-facing active Fennoscandian margin was first established on an Archean basement but by ca. 1750 Ma largely record juvenile compositions (Fig. 10A), also reflected in the Hf T_{DM} map (Fig. 6B). A nearly 500 km-wide swath of ca. 1750–1500 Ma crust in central Scandinavia (Fig. 6A, profile A–A') indicates relatively rapid westward growth during this period. Retreat of the margin, at least periodically, during this period is also supported by extension-related rapakivi and I- to A-type

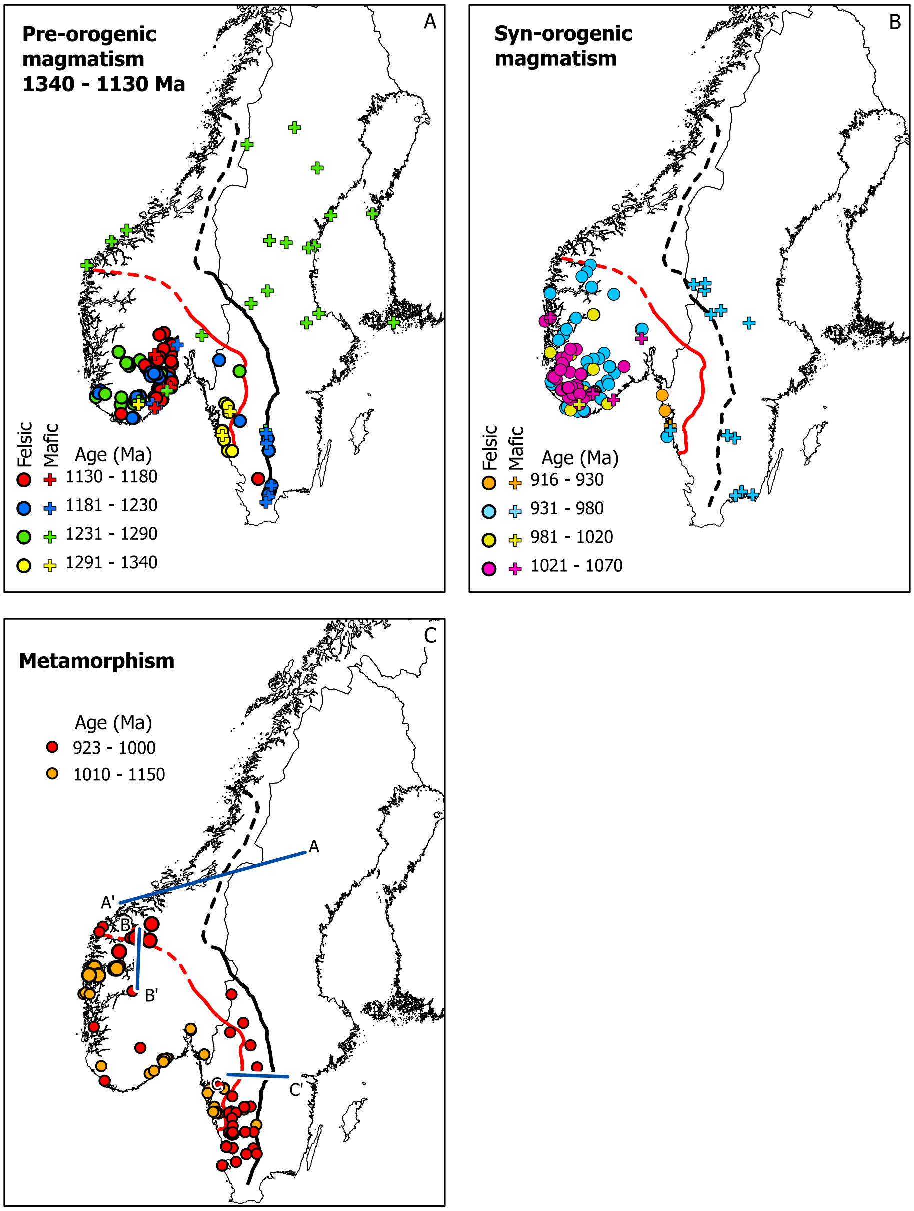

Fig. 8. (A) Age and distribution of pre-Sveconorwegian (>1130 Ma) magmatism, subdivided into felsic and mafic compositions. Intermediate compositions are subordinate. (B) Age and distribution of *syn*-Sveconorwegian (1070–915 Ma) magmatism, subdivided into felsic and mafic compositions. (C) Map showing the distribution of Sveconorwegian metamorphic ages, divided into pre- and post-1000 Ma.

granitic magmatism in inboard Svecofennian and Telemarkian crust (Åhäll et al., 2000; Menuge and Brewer, 1996). Following a period of little magmatic and metamorphic activity apart from the poorly understood Hallandian Orogeny in southern Sweden (Brander, 2011), magmatism in SW Fennoscandia resumed around 1280 Ma and was particularly voluminous in the Telemark unit until ca. 1140 Ma (Fig. 8A). Most workers ascribe this younger period of magmatism to back-arc extension (Brewer et al., 2004; Spencer et al., 2014), and although evidence of the actual arc is largely missing, the proposed setting is consistent with Hf isotopes suggesting reworking of local Telemark crust along with juvenile crustal additions (Fig. 7; Granseth et al., 2021).

In contrast to the width of 1750–1500 Ma crust in central Norway, similar-age crust in the Sveconorwegian Province is limited to the < 100 km-wide Eastern Segment. In addition, the Mylonite Zone represents a sharp contact between pre- and post-1650 Ma rocks (Fig. 6A, profile C–C'), whereas such rocks display intrusive relationships along profile A–A'. Within the framework of a (south)westward-growing margin, a likely scenario is that the intervening "mixed" crust has been tectonically excised or subducted; i.e., the Mylonite Zone represents strong telescoping of the margin. The Hf isotopic data reflect the age data, showing a wide stretch of "intermediate" T_{DM} (ca. 2200–2000 Ma) along profile A–A' (Fig. 6A), whereas there is a sharp transition in T_{DM} across the Mylonite Zone (profile C–C').

The distribution of U–Pb and Hf isotopic data is difficult to explain without invoking significant eastward, horizontal movement along the Mylonite Zone, consistent with structural data (Viola et al., 2011). If we consider profile A–A' in Fig. 6 to represent parautochthonous crust, an origin of the allochthonous Sveconorwegian units somewhere to the west of the present-day Norwegian margin appears likely, which equates to transport distances on the order of at least 500 km (Fig. 10A). We note, however, that this is a minimum transport distance, particularly keeping in mind the long deformational history prior to eastward translation (Slagstad et al., 2020).

An origin west of the present-day Norwegian margin can also explain the disparate pre- and early orogenic histories between units located

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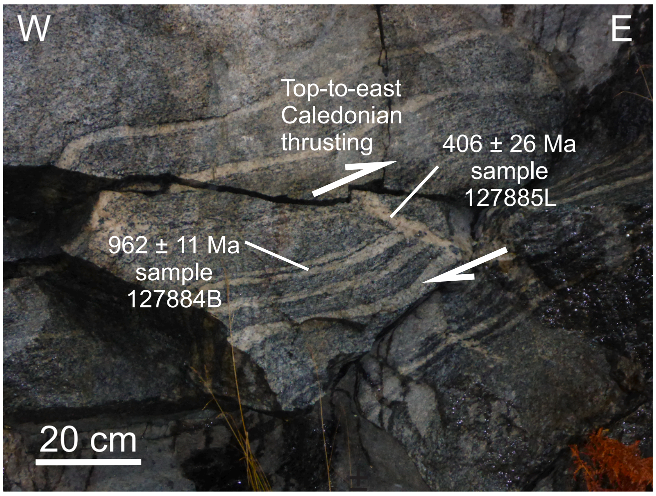

Fig. 9. Field photo showing foliation-parallel leucosome, dated at 962 ± 11 Ma, cut by leucosome occupying a top-to-east en echelon structure and dated at 406 ± 26 Ma.

structurally above the Mylonite Zone, constituting the majority of the Sveconorwegian Province, and that of the Eastern Segment and elsewhere in SW Fennoscandia (Fig. 10B, C). In particular, the contrast in 1180–990 Ma metamorphic and magmatic evolution suggests that units above the Mylonite Zone were located outboard of the present-day coastline until ca. 1000 Ma, followed by eastward translation to their current position resulting in high-grade metamorphism in previously unmetamorphosed (during the Sveconorwegian) rocks of the Eastern Segment and WGR. An apparently shared period of high-grade metamorphism and extension-related deformation after ca. 990 Ma suggests that the entire orogen had been assembled by this time (Slagstad et al., 2020) (Fig. 10D).

Our proposed westward continuation of the Mylonite Zone coincides with the east–west-trending Lom and Nordfjord shear zones, where preliminary mapping is consistent with our predicted sinistral sense of shear (Wiest et al., 2021). We note that this proposed structure is not the same as the "Approximate Sveconorwegian boundary", proposed by Tucker et al. (1990), which was defined as the northwestern limit of known Sveconorwegian influence.The nature and fate of lost crust.

The nature and fate of the crust originally located between the Eastern Segment and allochthonous Sveconorwegian units can only be inferred from indirect evidence. Three lines of evidence appear to be important in this regard. (i) Granitic magmatism in the Telemark unit was largely driven by underplating of mafic magma (Granseth et al., 2020; Slagstad et al., 2018b) and a lull in magmatic activity around 1000 Ma suggests decreased levels of underplating, as would be expected during a compressional period. (ii) This decreased magmatic activity coincided with high-pressure metamorphism in the Eastern Segment, indicative of westward-dipping continental subduction at this time (Möller, 1998). (iii) When granitic magmatism picked up again in the Telemark unit from ca. 980 Ma, it was characterized by a significant to more evolved isotopic compositions, requiring the introduction of a new isotopic reservoir in the source region (Fig. 10C, D). Westward subduction of continental crust around 1000 Ma, under the allochthonous Sveconorwegian units, appears capable of resolving all three observations and has similarities to the subduction model proposed by Brueckner (2009).

Unlike other regional geophysical datasets that appear to broadly conform to observed or inferred Sveconorwegian structures, lithospheric thickness deviates significantly in the eastern part of the Province (Fig. 3A). Here, the thick, cold Fennoscandian lithosphere extends about 150 km west of the Mylonite Zone. We know from Sm–Nd data that the ca. 930 Ma Flå–Iddefjord–Bohus granite in the Idefjorden unit, immediately above the thick lithosphere (Fig. 3A), formed from partial melting of an isotopically more evolved (less radiogenic) source than other granites in the Sveconorwegian Province and requires a TIB-like source, similar to the Eastern Segment (Granseth et al., 2020). We therefore suggest that the observed westward extent of thick lithosphere reflects stalled subduction of this unsubductable lithosphere (Fig. 10D).

The duration and rate of continental subduction is difficult to estimate. The volume of granitic magmatism (judged by the frequency of ages) in Telemark dropped significantly at ca. 1020 Ma, with onset of high-pressure metamorphism in the Eastern Segment at ca. 990 Ma, and renewed magmatism in Telemark at 990–980 Ma. Thus, the compressional event that caused the lull in magmatism could have lasted up to 30 Myr, although sparse magmatism after 1020 and before 990 Ma (Slagstad et al., 2018b) suggests this is a maximum estimate. The distance from the Mylonite Zone to the present-day coastline is ca. 500 km, which constitutes a minimum estimate for transport distance, corresponding to a minimum plate velocity of 1.5 cm/year. Although uncertain, this is a reasonable tectonic speed and corresponds to plate velocities inferred for Ampferer-type subduction, where negatively buoyant, hyperextended continental crust subducts spontaneously (McCarthy et al., 2020). The presence of subducted continental material also explains anomalously low seismic velocities in the Sveconorwegian lithospheric mantle (Kolstrup et al., 2015) that are difficult to account for by other mechanisms (Hieronymus and Goes, 2010; Slagstad et al., 2018a). The past existence of the prerequisite hyperextended crust needed to drive Ampferer-type subduction is difficult to prove but is compatible with a long period of extension (starting around ca. 1340) prior to onset of orogeny.

While we can only speculate on the exact process by which continental crust was subducted and lost during the Sveconorwegian Orogeny, the amount of crustal loss, associated convergence rate, and the observed geologic history provide some indications. The pre-orogenic, hot, thinned back-arc crust would have been conducive to decoupling and subduction, as observed in a variety of tectonic settings (e.g., McCarthy et al., 2018; Sun et al., 2019), and the estimated convergence rates of 1.5 cm/yr and times scales of several 10 s of Myr are comparable to model estimates for subduction of continental crust (Capitanio et al., 2010). The Telemark unit remained hot and thin during orogeny and could not easily have transmitted stresses from a western plate margin to the eastern orogenic foreland causing thickening and high-pressure metamorphism there. Ampferer-type subduction of thinned continental crust, as described by McCarthy et al., (2018, seems to be a more plausible scenario for generating high-pressure metamorphism in the Eastern Segment. Whether a similar mechanism can explain the disparate tectonic histories of the Bamble and Telemark units between 1140 and 1100 Ma is unclear, but the lack of arc-like magmatism supports this view.

4.2. *Implications on tectonic style*

An increasing amount of geologic and paleomagnetic data acquired over the last decade has shown that the view of the Sveconorwegian Orogeny as being similar in style to the Himalayan–Tibetan Orogeny in a Rodinia-interior position is likely to be wrong. In particular, the persistent lack of crustal thickening in the orogenic hinterland (Telemark) with heat largely delivered by mafic underplating, apparently on time scales of several hundred million years (Slagstad et al., 2020; Slagstad et al., 2018b), and paleomagnetic evidence showing significant separation of Baltica (Fennoscandia) and Laurentia during much of the Sveconorwegian and Grenvillian orogenies (Kulakov et al., 2022) are more compatible with an active-margin setting. However, the exact nature of this orogenic system and whether modern-style plate tectonic scenarios are applicable is unknown (e.g., Roberts et al., 2023).

The Mesoproterozoic most likely witnessed a range of plate tectonic settings and processes including accretionary (Rivers and Corrigan, 2000; Roberts et al., 2013; Santos et al., 2022; Slagstad et al., 2004) and

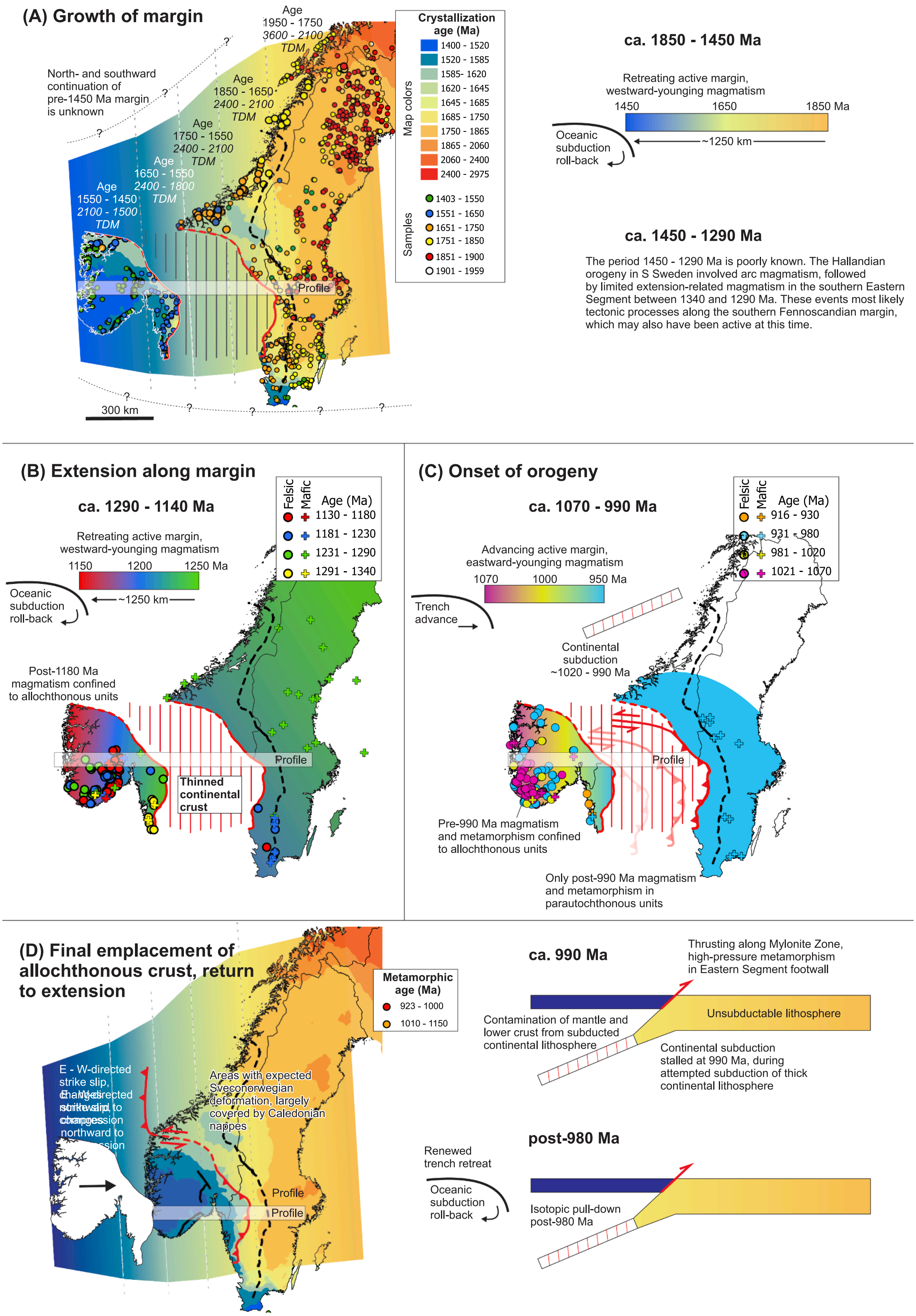

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Fig. 10. Schematic tectonic model. The age ranges stipulated in the headings of all subfigures relate to the main tectonic process being illustrated, whereas the data plotted on the figures shows the geographical distribution of magmatic and metamorphic age data. (A) Westward growth of the margin between 1900 and 1450 Ma, most likely in a retreating arc setting. Assuming dominantly westward growth of the margin, as indicated by crust outside the Sveconorwegian Province, the ages and isotopic compositions of rocks constituting the Province appear to have formed at least 500 km west of their current position. Few rocks exist between 1450 and 1290 Ma, and this part of the history remains obscure. (B) Extension-related magmatism between 1290 and 1130 Ma was largely confined to future Sveconorwegian units. Most authors favor a continental back-arc setting at this time, suggesting that the Sveconorwegian units were located closer to the active margin. (C) Early Sveconorwegian magmatism, deformation, and metamorphism only affected rocks currently located in the hanging wall to the Mylonite Zone and is absent from rocks in the footwall and in areas north of its inferred westward continuation. We take this to suggest that this part of the history took place while the units were located west of the present-day coastline of Norway. (D) From ca. 990 Ma onwards, units located in both hanging and footwall to the Mylonite Zone experienced strong deformation and high-grade metamorphism, suggesting that they were juxtaposed around this time. No arc magmatism is recorded during this period, suggesting that the intervening, subducted crust was continental rather than oceanic. Subduction of this continental crust caused a shift to more evolved isotopic compositions in the upper plate after ca. 980 Ma, shortly after high-pressure metamorphism in the footwall (Eastern Segment). Periods of trench advance and retreat follow Slagstad et al. (2020).

collisional settings (Jamieson et al., 2010; Scibiorski et al., 2015) that resemble modern orogenic systems. In addition to these more or less recognizable orogenic settings, higher temperatures of metamorphism and distinct suites of magmatic rocks, including A-type granites and massif-type anorthosite, led Roberts et al. (2023) to suggest that hot, wide continental back-arc settings may have been much more prevalent during the Proterozoic than at later times. A number of Mesoproterozoic orogens have been ascribed to such a setting, including the Namaqua orogenic belt (Macey et al., 2022), the Musgrave Province (Kirkland et al., 2013), and the Sveconorwegian Orogeny (Slagstad et al., 2020). However, this study shows that in addition to involving processes that may have been much more prevalent in the Mesoproterozoic than later, the Sveconorwegian Orogeny also involved processes that resemble those interpreted from the modern Alpine and Himalaya orogens (Capitanio et al., 2010; McCarthy et al., 2018; McCarthy et al., 2020).

It can therefore be argued that disagreements about the orogenic style of the Sveconorwegian Orogen stems from emphasizing different aspects of the orogeny, i.e., high-pressure, eclogite-facies metamorphism in the Eastern Segment as indicative of continent–continent collision vs. extended magmatic activity in the Telemark unit suggesting active-margin processes. It is, however, clear that the 500 x 500 km piece of crust that is the Sveconorwegian is likely to be part of a much larger orogenic system, of which we have little knowledge.

Here, we attempt to bridge the gap between some of the different camps by highlighting that the processes observed along the Mylonite Zone and in the Eastern Segment footwall do indeed bear some similarities to tectonic processes in collisional settings, such as the Alps, can also be understood within the framework of other settings. It is likely that significant new knowledge will come out of the Sveconorwegian Province, perhaps particularly with respect to the kinematics and timing of major shear-zone systems to resolve the assembly of allochthonous units. However, increased knowledge about the overarching tectonic system is probably going to necessitate eking out information from areas outside of the Province, particularly to the north, that have been strongly overprinted by younger tectonic processes. An interesting aspect in this regard is the previously proposed segmentation of the pre-Caledonian Iapetus margin (e.g., Jakob et al., 2019), which according to our model could be related to inherited Sveconorwegian structures. If so, some of the missing evidence may reside in various Caledonian nappes.

5. Conclusions

1. Sveconorwegian units located structurally above the Mylonite Zone have U–Pb ages and Hf isotopic compositions that indicate derivation from areas west of the present-day coastline of Norway, a distance of at least 500 km. This allochthoneity is supported by disparate 1180–990 Ma magmatic and metamorphic histories between Sveconorwegian units structurally above the Mylonite Zone and the orogenic foreland. However, a shared, pre-1180 Ma history of allochthonous Sveconorwegian units and the parautochthonous orogenic foreland suggest that the former are indigenous to Fennoscandia.
2. The contrast in pre-990 Ma metamorphism in the foot- and hanging wall to the Mylonite Zone allows it to be traced through the WGR, coinciding with a relatively sharp north-to-south contrast in pre- and post-1650 Ma rocks. These features suggest that the Mylonite Zone acted as a major, sinistral strike-slip zone, consistent with structural observations, but must have attained a more northerly direction off the present-day coastline to account for compression and high-grade metamorphism in the WGR.
3. The lack of arc magmatism related to eastward transport of the allochthonous units indicates that the intervening crust was continental. Westward subduction of this crust under the allochthonous units is suggested by a shift to more evolved isotopic compositions after 980 Ma and low seismic velocities indicative of high radiogenic heat production in the Sveconorwegian mantle lithosphere. Subduction stalled when the thicker, more buoyant lithosphere entered the subduction zone.
4. The ca. 500 x 500 Sveconorwegian Province is almost certainly part of a much larger orogenic system, and it is unclear to what extent the former is representative of the latter. The western Fennoscandian margin appears to have an overall N–S-oriented geologic and geophysical grain, and answers to this problem must likely come from areas north of the Province.

CRediT authorship contribution statement

Trond Slagstad: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Øyvind Skår:** Writing – original draft, Formal analysis, Data curation. **Gina Bjerkan:** Writing – original draft, Formal analysis, Data curation. **Nolwenn Coint:** Writing – original draft, Formal analysis. **Anette Granseth:** Writing – original draft, Data curation. **Christopher L. Kirkland:** Writing – original draft, Formal analysis. **Evgeniy Kulakov:** Writing – original draft, Formal analysis. **Eduardo Mansur:** Writing – original draft, Formal analysis. **Alf André Orvik:** Writing – original draft, Formal analysis, Data curation. **Andreas Petersson:** Writing – original draft, Formal analysis. **Nick M.W. Roberts:** Writing – original draft, Formal analysis.

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.

Data availability

All data included as attachments

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.precamres.2024.107454.

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