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A 725-year integrated offshore terrestrial varve chronology for southeastern Sweden suggests rapid ice retreat ~15 ka BP

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The Swedish Varve Chronology is an unparalleled tool for linking the deglacial history of Sweden with associated palaeo-environmental change at an annual time scale, and it forms part of Sweden's cultural heritage. A full deglacial chronology connected to the present day does not yet exist; a notable gap is in southeasternmost Sweden, where few varved records are successfully connected to reconstruct ice-margin retreat. Deglaciation in southern Sweden covers both the climate transition to the Bølling warm period (~14.7 ka BP) and the ice-margin transition from a subaqueous to terrestrial terminus. To facilitate investigations into the links between ice-margin dynamics and abrupt climate change, we revisited the varve chronologies of southern Sweden. We digitized unpublished records, reanalysed existing varve thickness records, and obtained and analysed new varve series both on land and offshore. This combined approach has enabled us to refine and extend the existing south coast chronology east and 78 km northwards. Our new Skåne-Småland chronology records 725 years of deglaciation, in addition to a younger floating chronology in parts. This chronology suggests that the glacial-lake terminating Fennoscandian Ice Sheet in southern Sweden initially retreated northwards at ~110–160 m a^{-1} slowing to 60–70 m a^{-1} near the palaeo-shoreline. Between today's mainland and the (now) island of Öland the retreat rates increase three- to fivefold. Ice-margin retreat was initially oriented towards the north (as along the south coast), but later pivoted towards the northwest, signifying a landward retreat of terrestrial 'Swedish' ice that became divorced from the Baltic Sea ice-sheet catchment. Our new 725-year-long varve thickness series reveals repeated multidecadal scale episodes of increased sedimentation. These likely signify phases of enhanced ice-sheet melting that repeat and persist throughout the deglaciation of Skåne-Småland.

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One of the most critical uncertainties in the behaviour of continental ice sheets is the response time in relation to climate forcing and the rates of ice margin or grounding line change. While the observational record of contemporary ice-sheet change is a few decades long at best, the geological record of former ice-sheet demise offers an opportunity to assess rates of ice-margin retreat (i.e. ice-sheet mass loss) over several thousand years of climate change after a glacial maximum. Sediments from within and in front of the ice sheet, transported by glacial meltwater and deposited in proglacial lake basins, can provide such records with annual to seasonal precision in the form of laminated sediments or glaciolacustrine varves. Varved proglacial sediments give an unparalleled means to not only reconstruct the annual pattern of ice-sheet decay (De Geer 1912; Antevs 1922; Wohlfarth *et al.* 1993, 1998; Ridge *et al.* 2012), but also to infer the associated ablation, climate, and meltwater regimes (Ringberg *et al.* 2003; Ridge *et al.* 2012; Bendle *et al.* 2017).

Meltwater from the southern sector of the Fennoscandian Ice Sheet, retreating after the Last Glacial Maximum, delivered glacifluvial sediments to the large, proglacial Baltic Ice Lake (BIL), dammed between the retreating ice margin and higher topography to the south and west that was exposed by low glacial sea levels (Björck 1995). Below the wave base and removed from near-shore sediment reworking, an extensive archive of fine-grained clastic varves formed on the lake-bed (De Geer 1912; Björck & Möller 1987; Wohlfarth *et al.* 1993; Andrén & Sohlenius 1995), parts of which are now exposed above sea level due to post-glaciation isostatic land uplift. Gerard De Geer, inspecting these laminations exposed in industrial claypits, described *hvarfvig lera* (lit. 'cyclical clay'; De Geer 1912), from which the modern term 'varve' is derived; De Geer initially recognized the laminations as annual in 1878, formed due to seasonal contrasts in meltwater sediment influx and settling (De Geer 1940). Interannual variability in sedimentation yields distinct up-record patterns of varve thickness changes. By matching the varve thickness 'barcode' between sites, and taking the 'bottom varve' (the first varve deposited above the glacial substrate) at each site to mark a nominal year of ground exposure from

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ice, De Geer, his students and his family attempted to create an annually resolved chronology of ice retreat along Sweden's coastal areas and abroad (De Geer 1912, 1937; Antevs 1915).

A varve chronology for the Skåne-Blekinge area (Fig. 1) has been under construction since the birth of varve science: De Geer worked in northeastern Skåne between 1884 and 1911 (Antevs 1915), and De Geer's student Ernst Antevs compiled a chronology in 1915 (Antevs 1915). The chronology in its most recent form, using Antevs' (1915) local time scale, was constructed by Ringberg (1979, 1991); 640 varve years (vyr)), using a combination of existing varve thickness series and his own new sites. Wohlfarth *et al.* (1994) added further sites and successfully radiocarbon-dated terrestrial plant remains extracted from varves (Wohlfarth & Possnert 2000) thus tying a now 701-vyr relative chronology to an absolute time scale. The radiocarbon ages range between 12.1–12.7 ka BP with large uncertainties (130–370 years) even before calibration; the sites were therefore estimated to date from the early Bølling or up to a few hundred years earlier (Wohlfarth & Possnert 2000). Several other independent local varve chronologies exist along the Swedish east coast, including the 2310-vyr Småland-Ö stergötland chronology (Kristiansson 1986; Wohlfarth *et al.* 1998; Fig. 1), which crosses the Vimmerby Moraine (independently ^{10}Be-dated to 14.6±1.0–14.5±0.8 cal. ka ago; Anjar *et al.* (2014), Johnsen *et al.* (2009)) and the Middle Swedish end-moraine zone; these sites also come close to lake Vättern and Mt. Billingen, site of the well-dated catastrophic drainage of the BIL at 11 620±100 cal. a BP (Stroeven *et al.* 2015).

A long-standing ambition of Swedish varve science is to establish a single robust varve chronology that tracks the entire time-span of deglaciation, with reliable ties to an absolute time scale via radiometric dating and the present-day varves forming in Ångermanälven, northeast Sweden (Cato 1987; Wohlfarth *et al.* 1997; Sander 2003). This would provide an annually resolved and accurately timed record of ice-sheet decay across several thousand years of post-Last Glacial Maximum climate change: an immensely powerful opportunity to assess rates, styles and mechanisms of ice-sheet response to climate forcing. However, the Skåne-Blekinge and the Småland-Östergötland chronologies, as well as existing records in southeast Sweden, are, at present, 'floating' chronologies and unconnected from each other.

The southeast corner of Sweden marks a transition between predominantly terrestrial-based ice-sheet retreat over southernmost Sweden and predominantly subaqueous retreat through the BIL. The BIL during deglaciation likely hosted reactivated ice streams (Houmark-Nilsen & Kjær 2003; Kjaer *et al.* 2003) that made the offshore catchment dynamically distinct from the terrestrial portion and subject to additional retreat forcing: mass loss from not only surface melt, but also subaqueous melt and iceberg calving (Van Den Broeke *et al.* 2009; Rignot *et al.* 2010; Clason *et al.* 2016). The style, mechanisms and timing of flow and retreat in the offshore catchment, as well as the nature of coupling to the terrestrial catchment are, however, very poorly constrained (Greenwood *et al.* 2017). A connected varve chronology linking the southern and eastern floating chronologies, including the offshore sector, would illuminate both pattern and rates of ice-margin decay across this transition, and provide a fundamental basis for exploring styles and mechanisms of retreat.

The unearthing of unpublished varve diagrams in the Geochronological Museum at Stockholm University along with new possibilities for offshore coring with Stockholm University's RV 'Electra', provided an excellent possibility to revisit this unsolved issue. Here, we reanalyse the existing Skåne-Blekinge chronology (Ringberg 1979, 1991; Wohlfarth *et al.* 1994). We then incorporate newly digitized legacy varve measurements (1906–1985, many unpublished) and newly acquired varve core data from Blekinge, southern Småland, and Kalmarsund to extend the chronology along the east coast of Sweden. We aim to use this extended chronology to explore ice retreat rates and patterns in the Skåne-Småland region as the ice margin transitioned from primarily water-terminating to terrestrial-terminating.

Study area

The geology of much of southern Sweden comprises Precambrian crystalline rocks such as granitic rocks and porphyries of the Transscandinavian igneous belt; Cambrian sandstone underlies the northeasternmost corner of Skåne, the Kalmarsund strait, a narrow strip of the eastern Swedish coast, and the west coast of the island of Öland (Fig. 1). The remainder of Öland is made up of Ordovician limestone and shale (Bergman *et al.* 2012). The topography of the crystalline bedrock along Sweden's southern coast in the Blekinge is rough and fractured, with several deep joint valleys extending inland (Lidmar-Bergström 1995). In contrast, a much more subdued topography is offered by the sandstone along the eastern coast and Öland's limestone. Öland's highest point is only 55 m above sea level (below the highest raised shoreline), such that during initial ice retreat in southern Sweden the island was completely covered by the BIL. The glacial geomorphology of the study area comprises a largely hummocky landscape as also seen in the southern Swedish uplands (Möller 2010; Peterson *et al.* 2017; Peterson & Johnson 2018). Glacial lineations and large-scale eskers in southernmost Sweden are distributed in an approximately radial pattern from the central uplands with smaller-scale directional variations, indicating a broadly concentric ice-sheet retreat with minor lobate margins (Dowling *et al.* 2015; Peterson *et al.* 2017). Southeastern Sweden has very little evidence of ice-margin positions south of the prominent Vimmerby Moraine north of Öland, making the exact

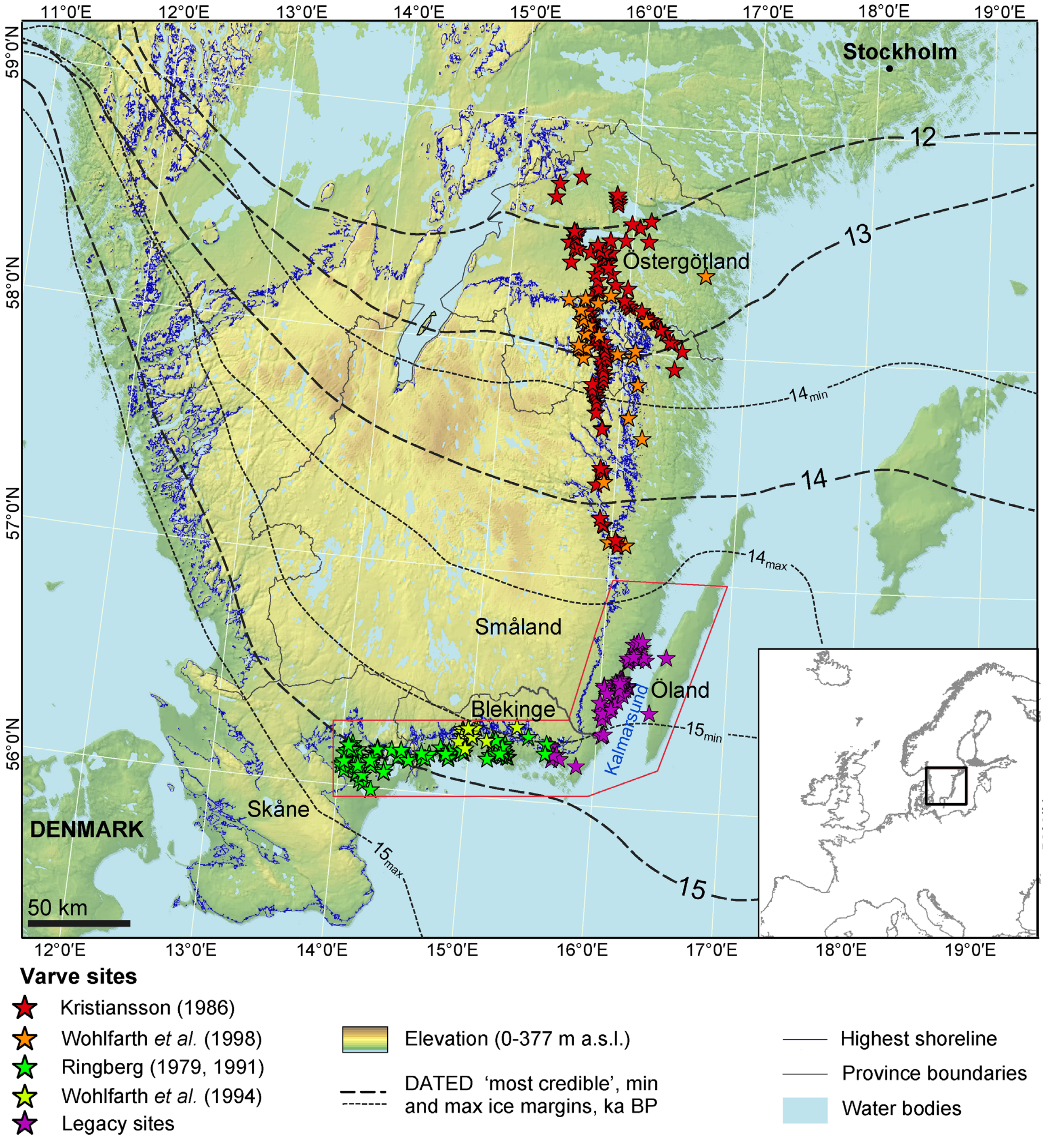

Fig. 1. Map of southern Sweden showing the two existing varve chronologies in the region of interest. The Skåne-Blekinge (southern) chronology is denoted by green stars (representing the locations of individual varve sites); the Småland-Östergötland (eastern) chronology is given by red and orange stars, and legacy sites are shown with purple stars. Ice retreat margins according to DATED (Hughes *et al.* 2016) are shown as dashed black lines. Relevant modern geo-cultural province boundaries are given by solid black lines. The highest shoreline is shown by a dark blue line. The region of interest for this study is enclosed in the red box. 1″ DEM from http://viewfinderpanoramas.org; highest coastline from SGU; modern coastline from Lantmäteriet.

retreat pattern uncertain; in the coastal areas the shape of the retreating margin is especially unclear. Almost nothing is known about the local glacial geomorphology offshore, such that neither margin retreat behaviour nor timing across the subaqueous–terrestrial transition is understood. Ice retreat from the southern part of the study area has been estimated at approximately 15 ka ago (Fig. 1) based on radiocarbon-dated varves, luminescence dating and cosmogenic isotope dating. However, uncertainty of tens of kilometres exists for the 15 ka ago retreat isochron such that the position of the ice margin at the onset of the Bølling warm period (14.7 ka ago) is unknown (Wohlfarth 1996; Hughes *et al.* 2016; Stroeven *et al.* 2016).

All varve sites that form part of the existing local chronologies in southern Sweden are located below the highest raised palaeo-shoreline (between 55–85 m above modern sea level in our study area) of the BIL. We also targeted this zone for our new sites, such that all sites in the region represent sedimentation in the same proglacial water body.

Material and methods

Revisiting published and unpublished data

Statistical cross-correlation analysis (CCA) performed previously (Wohlfarth *et al.* 1994; Holmquist & Wohlfarth 1998) recommended, but never enacted, modifications to Ringberg's part of the Skåne-Blekinge chronology (Ringberg 1979, 1991). Revisiting these chronologies, we first tried following these recommendations (e.g. 'move series X 19 years later') but found little or no improvement. Possible reasons for this lie in the scale of and the approach to CCA. Correlations are evaluated at an individual varve scale, which heightens the effect of local variations in varve thickness (i.e. weakens statistical correlation) whereas varves may show a good match on a cluster scale (~≥3 varves). Additionally, CCA typically does not consider the amplitudes of peaks in time series; information that is contextually important for varve thickness matching. Blanket removal of the bottom 20 varves from each series (Holmquist & Wohlfarth 1998), intending to remove the influence of ice-proximal basal varves, likely removed a number of valid matches in the lower parts of the series and inadvertently reduced the strength of the CCA values, while the thin (<1 to ~3 mm) upper varves that are difficult to measure and often show visual disagreement were preserved in the analysis. Our approach was therefore to reconstruct the Skåne-Blekinge chronology independently, initially visually.

Close inspection of the individual and problematic varve series revealed occasional miscounts. For the few legacy varve series that clearly contained a counting discrepancy, we experimented with manually adding or removing varves to see if this improved the match with neighbouring series. Although we have left the existing series as is, we have noted discrepancies in Supporting Information tables S2 and S4 Sections of series with varve gaps (e.g. due to heavy disturbance) were treated independently when building our chronology, and the size of the varve gaps in some cases changed; these are also noted in Supporting Information tables S2 and S4.

A number of additional varve series, not thus far included in the Skåne-Blekinge chronology (Ringberg 1991), had been measured by a number of researchers between 1906 and 1985. Some of these were published later (Rudmark 1975; Ringberg & Rudmark 1985; Ringberg *et al.* 2002), but many other unpublished series were archived in the Geochronological Museum at Stockholm University. These latter data sets were digitized from the original diagrams where available and used to extend the Skåne-Blekinge varve chronology eastwards and northwards along the Swedish coastline. Almost all varve thickness series that were shorter than 30 vyr were discarded, since series that short usually have too many ambiguities when correlating. For these legacy series, site locations were mostly descriptive (e.g. the parish and estate names). We used site descriptions where available to estimate the co-ordinates of these older series as best we could, and note the original (translated) descriptions and our reasoning in Table S4. However, we urge a degree of caution when interpreting ice recession rates based on bottom varve ages and locations in areas where legacy data are the primary source.

New core acquisition

Terrestrial fieldwork. – We undertook an extensive fieldwork campaign in 2018–2019 in order to acquire new varved sediment cores in southeastern Sweden from below the highest coastline. We aimed to collect cores both from areas where no data currently existed and from areas near the locations of existing unpublished archives to 'ground-truth' them. We used two Russian corers, 0.5 and 1.0 m long with internal diameter 5 cm. Our approach was initially to target wetlands and small lakes, on the assumption that wetlands can form above impermeable clay. As it became clear that impenetrable sand layers often sat below the Holocene peat, we broadened our strategy to include existing ditches, reasoning that sand or soil that would otherwise be impossible to penetrate with a Russian corer had been mechanically removed, providing direct access to older clays. Where detailed surficial geology was available from Swedish Geological Survey mapping, we initially aimed for areas underlain by clay or peat, but varved sediment cores were also found elsewhere.

Offshore fieldwork. – In April 2019, cruise EL19-IGV02 with Stockholm University's RV 'Electra' targeted varved basins in Kalmarsund, the strait between mainland Sweden and Öland (Fig. 1). We used a Kongsberg EM2040 multibeam echo-sounder and TOPAS PS40 chirp sonar to first obtain high-resolution bathymetry and sub-bottom acoustic stratigraphy data, respectively. These data guided us to select promising sites in Kalmarsund that would yield varved sediments, namely depocentres that showed parallel layered reflectors in the sub-bottom echograms and that were of such thickness as to offer both good resolution and the possibility to reach the bottom varve with a 6-m core. Using both piston and gravity coring, we obtained twelve ~10-cm-diameter varved cores from eleven coring sites, which were cut into 1.5-m sections. Cores from all field excursions were processed in the sediment laboratory at Stockholm University and stored in a cold room at 4 °C. Cores are named after the cruise, appended with the site number, core type and core number, and core section numbers where appropriate (e.g. EL19-IGV02-10-GC02-03). We hereafter refer to the cores in this text without cruise code for clarity (10-GC02-03).

Varve measurement and site connection

At the Department of Geological Sciences at Stockholm University, all new cores were imaged at 300 dpi using a Geotek MSCL, then imaged (at lower resolution) and X-radiographed using an ITRAX XRF core scanner from Cox Analytical. The X-radiographs were processed to a useful brightness and contrast using a MATLAB script (Bloemsma *et al.* 2018). A horizontal line at the base of each varve was manually marked on a vertical line using the Adobe Photoshop pen tool with pixel precision, then the paths were exported from the digital images and the thicknesses calculated from the values of the horizontal line co-ordinates using methods similar to Francus *et al.* (2002) and Avery *et al.* (2019). We used the X-radiographs as the primary image in preference to the optical photographs, since density changes are usually more reliable than colour changes for varve identification. In some cases, the original sediment was revisited and the laminations measured manually on paper. Terrestrial cores comprising several sections were measured separately, then the varve thicknesses in overlapping sections, defined by marker varves, were averaged (mean) to create a single series for each site.

All newly measured and newly digitized series were initially arranged following a hypothesis of the general pattern of ice retreat, approximately parallel to eskers and lineations (Stroeven *et al.* 2016; Peterson *et al.* 2017), then the interannual thickness trends were visually correlated between records. The offshore series were first treated internally, matching series using a combination of varve thicknesses and marker varves (varves or varve groups that are very distinctive and are seen in multiple cores), to build the composite series EL19-IGV02. Each individual offshore record was statistically cross-correlated against the others using the ANTEVS software (Rayburn & Vollmer 2013), after removal of any basal ‘drainage’ varves and detrending each series with a 16-term Fourier curve and using a minimum overlap of 50 points; this showed the offshore visual correlation to be statistically robust. We then used the EL19-IGV02 composite as a ‘master curve’ to tie in terrestrial sites from the south and east coasts. Additional CCAs between EL19-IGV02 and key terrestrial sites were performed where data quality allowed. Any varve thickness series that did not visually correlate locally with other sites (likely due to local sedimentation variability or disturbances e.g. slumping, but also perhaps miscounting and misidentification from the measurer) was discarded.

Results

Tables S1–S4 summarize our results; additionally the dataset for this study is available on the Bolin Centre database (Avery et al., 2020)

Varve series from Kalmarsund

Of the 13 sites chosen for coring, we obtained cores from 11 sites (Fig. 2; Table S1). Varves measured from structurally sound sediment saved from the cutter at the base of the corer (08-GC01, 10-GC02, 13-GC02) are also included in the results.

All 12 cores collected with RV ‘Electra’ contain regular couplets of silt fining upwards into a clay cap. Given the nature and regularity of the couplets, we are confident that the laminations are indeed annual clastic varves. The silt of the melt-season layer is typically pale beige, although significant colour variation is present in the silt throughout the cores, from grey through teal and purplish-brown (Fig. 3, Fig. S1). The colour of the clay is almost always some variant of pinkish brown, as described from elsewhere in south-central and western Sweden (Stevens 1985; Johnson *et al.* 2013); a notable exception is the uppermost varves in core 03-GC01, where the sediment transitions to greenish-grey (Fig. S1). X-radiography reveals the internal structure of each varve, showing considerable variation. The melt-season layers of the basal varves are thicker than the winter layers, and in cores 11-GC01, 02-PC01 and 01-PC01, they are very compact and with sub-annual laminations. The nature of the non-basal varves is variable, with both simple and laminated melt-season layers present. Micro-faulting is not uncommon, but the faulting is generally minimal enough so as not to disrupt the primary varve unit. The varves in 01-PC01 contain thick (relative to the winter layer) melt-season layers of fine clayey silt, with the X-radiograph showing relatively little contrast between the two seasonal components (Fig. 3). These varves are similar to the ‘diffuse’ varves described for Blekinge by Ringberg (1971, 1979) and Wohlfarth *et al.* (1994).

Each core contains between 58 and 178 varves. Core 04-PC01 reached till, and cores 01-PC01 and 02-PC01 reached couplets with thick summer layers that are interpreted as being ice proximal and therefore close to or actually being the basal varve. A 60-cm sediment gap in 04-PC01 exists between the bottom section (containing two thick, basal varves overlying till) and the second section (containing typical cm-scale varves). This gap is most likely due to shearing during the coring process (R. Gyllencreutz, pers. comm. 2019) and the gap was artificially closed when counting varves.

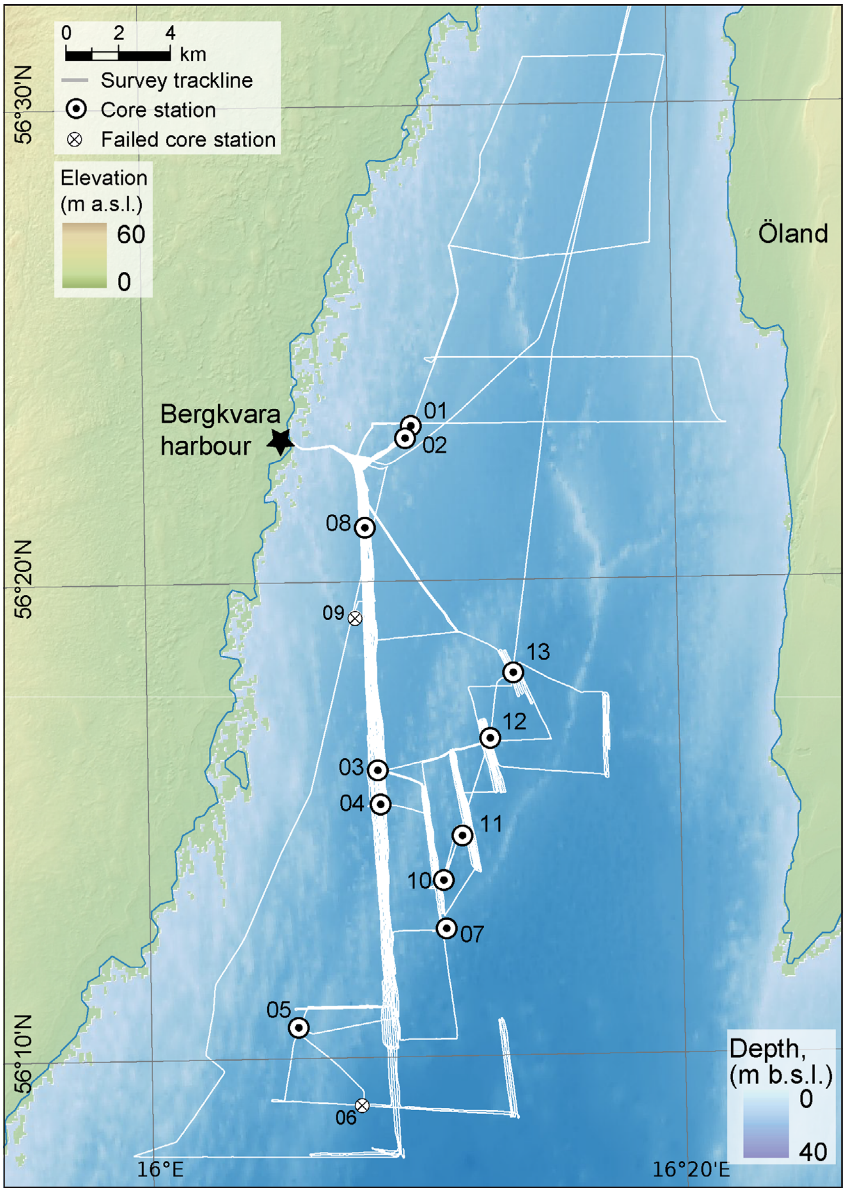

Fig. 2. Map of the study area showing all acquisitions made by RV 'Electra'. Core stations are black dotted circles and failed core stations (e.g. where the corer bounced repeatedly) are crossed circles. Acoustic data tracklines are shown in white. Bathymetry from EMODnet Bathymetry Consortium (2018).

The varve thickness series, stacked from south to north (Fig. 4), show that there are remarkable similarities in the interannual pattern of varve thickness variability, even from cores taken 27 km apart (e.g. the varves encapsulated by the grey bar in Fig. 4). These similarities, and additional evidence from e.g. marker varve groups (Fig. S1), give us high confidence in the varve thickness measurements of each core and the correlations presented in Fig. 5 and Fig. S2. The excellent visual connections between each series yield CCA maximum r-values of 0.59–0.92 at a zero lag (mean 0.77, median 0.77), and *z*-scores (the strength of the peak at the maximum *r* value) of 3.74–7.59 (mean 5.83, median 6.05; Fig. S2). Rayburn & Vollmer (2013) suggest that *r* values (primary correlation indicator) of ≥0.6 at a lag of 0 indicate an acceptable correlation, and of our 36 cross-correlations, 35 were above this value (Fig. S2). Every one of our CCA results had its primary peak at a lag of zero. An auxiliary measure to evaluate the correlation is the z-score, where a score of ≥6 (low variability in *r*) is desirable. Nineteen of our CCA results had *z*-scores above 6, with ten between 5 and 6, and seven below 5. Given the excellent visual correlation and high *r* values, in combination with e.g. marker varves and the spatial origin of the cores, we believe our offshore varve correlations to be robust.

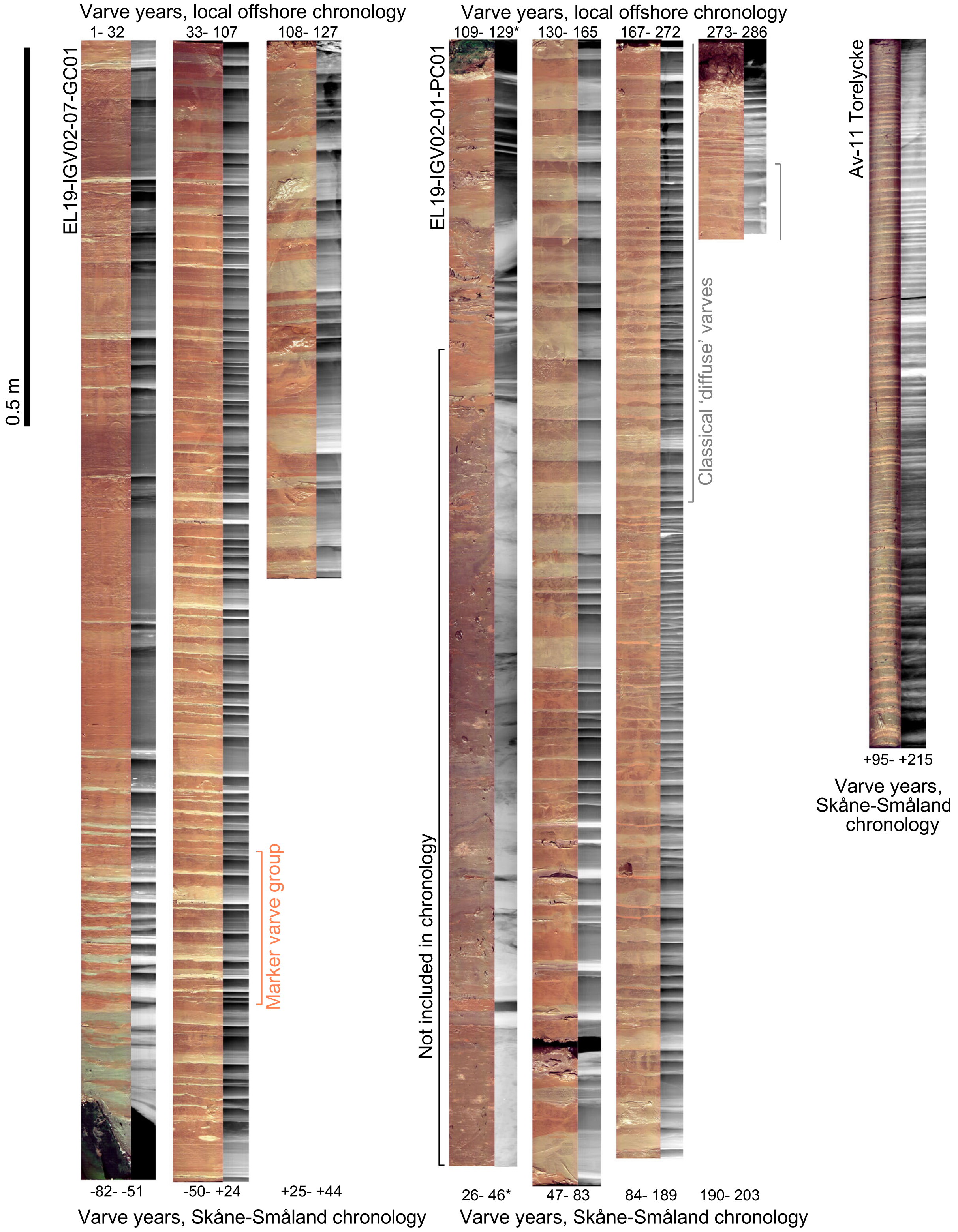

Fig. 3. Examples of newly acquired offshore and terrestrial varve series. Each core is displayed as an optical image (left) and an X-radiograph (right). Two cores are shown from the EL19-IGV02 series: 07-GC01 and 01-PC01. With these two cores, all 286 varves from the EL19-IGV02 chronology are displayed. Local (EL19-IGV02) varve numbers are written above the images, and the corresponding varve years in the new Skåne-Småland chronology are shown below. A terrestrial core, Av-11 (Torelycke) is also shown for comparison. The thick basal 'drainage' varves in 01-PC01-04 denoted with an asterisk were not included in the composite curve as they represent only local sedimentation. Varve numbers of those varves from 01-PC01-04 that were included are 115–129 (local) or 32–46 (Skåne-Småland).

This long offshore 286-vyr varve record with compelling, robust internal correlations is a powerful new tool for building regional site connections, as well as capturing aspects of ice retreat within Kalmarsund. To produce a single, composite thickness curve from the EL19-IGV02 cores that could be used for comparison with terrestrial series, thick bottom varve measurements were removed from each series in which they occur (six from 01-PC01, eight from 02-PC01 and one from 04-PC01). These bottom varves, formed very soon after site exposure from retreating ice, generally represent local sedimentation and rarely correlate with other sites (Holmquist & Wohlfarth 1998). Each thickness series was then normalized to its thickest varve, such that each series was now scaled between 0 and 1 and, for each varve year in the composite, a mean normalized varve thickness was calculated. When compared with a curve calculated by using the mean of the un-normalized measurements, the variations in thickness are preserved in both cases (Fig. 5), showing that the normalization procedure captured all of the thickness variations needed for it to be used as a comparison curve. It should be noted that that the youngest 85 varves of the succession are present only in one core (01-PC01) and that this part of the composite succession, though well defined, is therefore less reliable. We use our new EL19-IGV02 record from Kalmarsund as a regional framework curve to guide, check and correct the correlations between individual terrestrial series on the south coast and extend the chronology to the east coast.

Revisiting the existing Skåne-Blekinge chronology

Table S2 summarizes the existing Skåne-Blekinge chronology, amended in this study from earlier efforts (Ringberg 1971, 1979, 1991; Ringberg & Rudmark 1985; Wohlfarth *et al.* 1994) following careful reassessment of the chronology using individual series; the sites are ordered approximately from southwest to northeast. The changes to the Skåne-Blekinge chronology (Table S2) are based on distinctive thickness patterns in neighbouring series and, in particular, draw strongly on such patterns seen throughout the EL19-IGV02 composite record reflecting regional variability in sedimentation rates. The new, integrated chronology retains the Skåne-Blekinge local year −100, defined by a very thick varve in almost every south coast site of sufficient age (Antevs 1915). Alignment of the Skåne-Blekinge series with the EL19-IGV02 composite curve places the offshore chronology start at −82 vyr on this chronology (Table S1).

Of the 117 individual varve series in the chronology, four were removed as there was no clear correlation with neighbouring series, and one was removed as counting discrepancies were too severe. A further 17 were removed as they were too short to provide a reliable correlation. Of the remaining 95 series, 75 remained unchanged from their original placements in the chronology, and 20 were shifted to be older or younger than their original placements. Two sites were noted to have minor counting discrepancies.

Changes to the placement of those varve series first presented together in Wohlfarth *et al.* (1994; W-1 to W-13a in Table S2) appear more substantial. The original correlation of these series had been made in part by aligning those core sections that contained the so-called ‘diffuse’ varves of Blekinge (Ringberg 1971, 1979; Wohlfarth *et al.* 1994 and references therein: sites Sandsjön, Hemsjön, Trehörnan, Skälgylet, Kroksjön and Bokesjön). In our revisions, these, and almost all of the other sites, remain at the same chronological position relative to one another (Kroksjön was moved by 1 vyr) but are shifted 8 vyr younger after comparison with our offshore chronology (including ‘diffuse’ varves identified in the youngest part of the composite curve; Fig. 4) and two of Ringberg’s sites, R-128 and R-127. The upper part of the site Trehörnan remains in place, but the disturbance gap between the lower and upper parts is additionally decreased by 9 vyr. Farslycke and Korsliden, not noted to have ‘diffuse’ varves, are the only series in the area moved significantly (4 vyr older and 36 vyr younger, respectively) based on the correlation with the EL19-IGV02 composite. It should be noted that the Skåne-Blekinge chronology entirely overlaps the EL19-IGV02 curve, due to the significant lengths of some south coast varve series.

Extension of the Skåne-Blekinge chronology to the east coast

During an extensive terrestrial fieldwork campaign, we visited at least 290 sites and successfully obtained varved cores from 24 sites (Table S3, Fig. 6). In most cores the clay is pinkish brown (oxidizing to dark brown), but greenish-brown and greenish-grey clay is not unusual. There is no clear geographical consistency to variations in sediment colour, and indeed in Av-16a (Smedby Kanal (Water)) the clay transitions from pinkish brown to greenish-grey. Similarly the silt colour ranges between pale beige, darker yellowish brown, and reddish brown. Basal varves, recovered in some cores (noted in Table S3), yield much coarser silt and even fine sand in the melt-season layers. The primary sedimentation in some cores is interrupted by mass transport deposits or sand layers leading to gaps in the series, some exceeding 100 vyr (see cores with only lower part used, Table S3). A large number of targeted sites did not yield viable cores, which sheds some light on the historical difficulties in connecting varve chronologies in this area. Figure S3 visualizes the major obstacles to site core recovery.

The new composite marine EL19-IGV02 record not only enables improvement and extension of the Skåne-Blekinge chronology eastwards along the south coast, but also establishes a high-confidence connection between the south and east coasts (Fig. 7). The crucial connection is to the oldest and southernmost

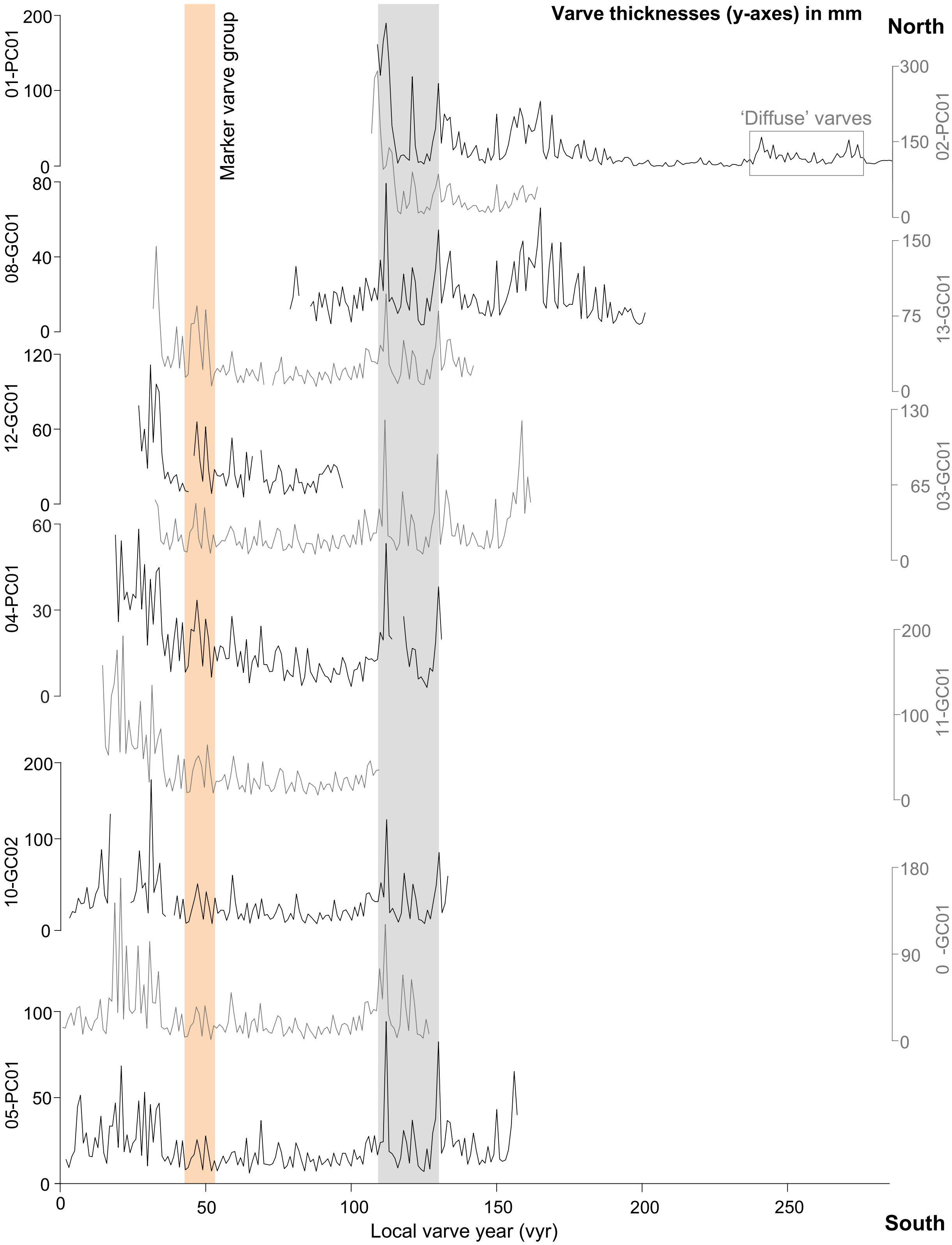

Fig. 4. Stacked varve thickness plots from the offshore 'EL19-IGV02' cores. Plots are stacked from south (bottom) to north (top), and all varve thicknesses are in millimetres. The grey vertical bar demonstrates a series of varves whose thicknesses correlate along the entire 27-km long coring area. The grey box on 01-PC01 indicates the varves that correspond to the 'diffuse' type seen previously in Blekinge (cf. Ringberg 1971, 1991; Wohlfarth *et al.* 1994).

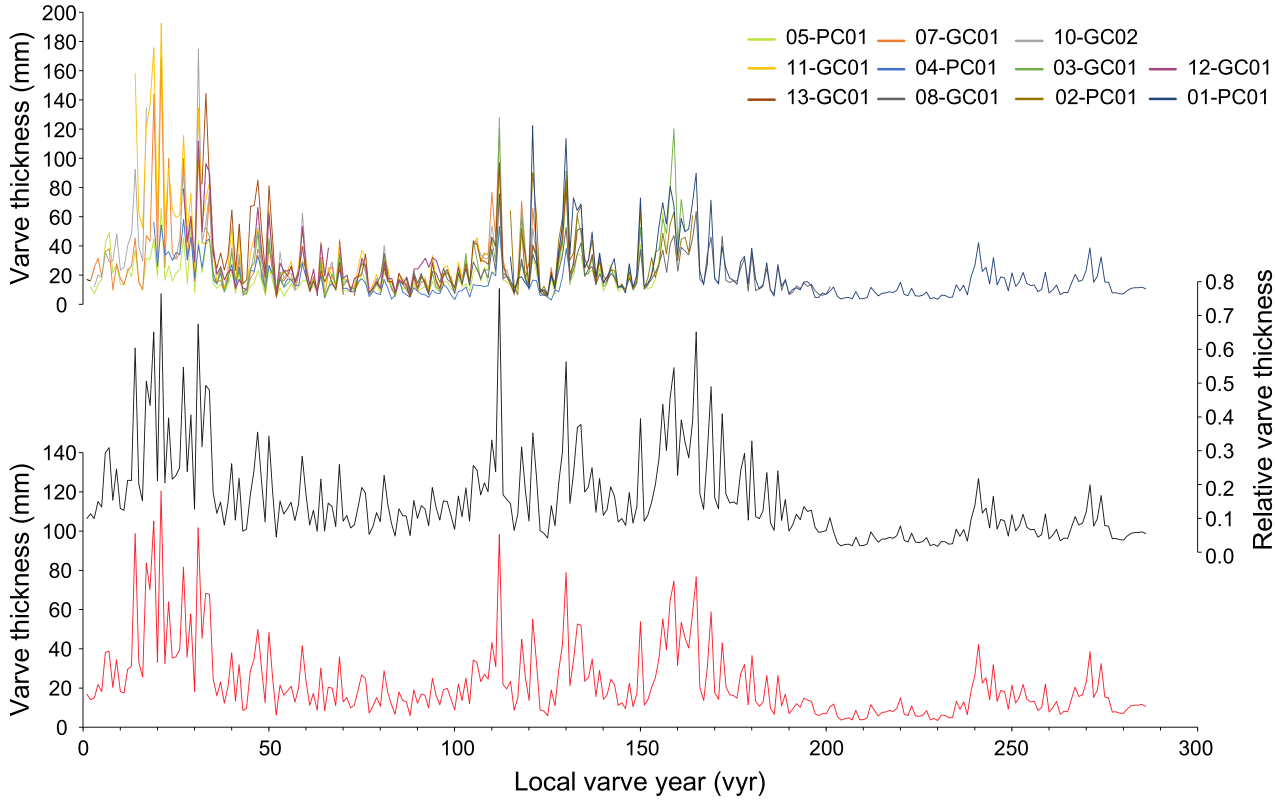

Fig. 5. Creating a single thickness curve from the EL19-IGV02 series. Top: all varve thicknesses from the RV 'Electra' cores on the same axes. Middle: a single 'relative' curve, where each series was normalized to its thickest varve before a mean of the relative series was taken. Bottom: a single 'absolute' curve, where a mean of the series was taken using direct measurements.

varve site cluster on the east coast (R-181 Högaryd, R-180 Björkelycke, R-306 Bröms and Av-04 Bredavik; Fig. 6, Table S4). Of these, R-306 and Av-04 are the higher-quality series with no suspected discrepancies. Correlation of Av-04 to the EL19-IGV02 series establishes the tie point to the east coast at –23 local vyr, with the oldest east coast bottom varve age being −20 vyr for R-180 and R-181.

We have extended the Skåne-Blekinge chronology northwards along the east coast, integrating EL19-IGV02, our new terrestrial sites, and older sites that were previously difficult to link (Table S4, Fig. 6). Towards the north of our data set (i.e. younger in age), varve series younger than the EL19-IGV02 record (sites 143–174 from north of 56°35′N and from further inland around 56°33–34′N) display distinctive regional thickness patterns and therefore extend our new chronology further north to 56°49′N.

Our integrated marine, terrestrial and legacy varve series yield a new chronology totalling 725 vyr, successfully linking the long-standing Skåne-Blekinge chronology with annually resolved records of deglaciation from southeastern Sweden. We now refer to this entire combined chronology as the Skåne-Småland chronology, extending and replacing the Skåne-Blekinge chronology, and we use the unit vyr_{ss}. The local zero year is retained from previous iterations of the Skåne-Blekinge chronology (Antevs 1915; Ringberg 1971).

An additional floating chronology

The lower units in three of our cores Av-13 (Binga), Av-16 & 16a (Smedby Kanal) and Av-19 (Kulteback-etorpet; Fig. 6) contain varves that are assigned to our new Skåne-Småland chronology. However these cores also display younger varves in their upper parts, which are separated from the lower unit by erosive sandy layers. These upper varve units above erosive layers do not form part of the Skåne-Småland chronology, but represent floating sections younger than the Skåne-Småland chronology, with varved intervals separated by thin erosive layers representing unknown time periods.

Discussion

Extent and limitations of the new Skåne-Småland chronology

Potential, preservation and recovery of varved archives. – Offshore coring proved highly successful in locating and

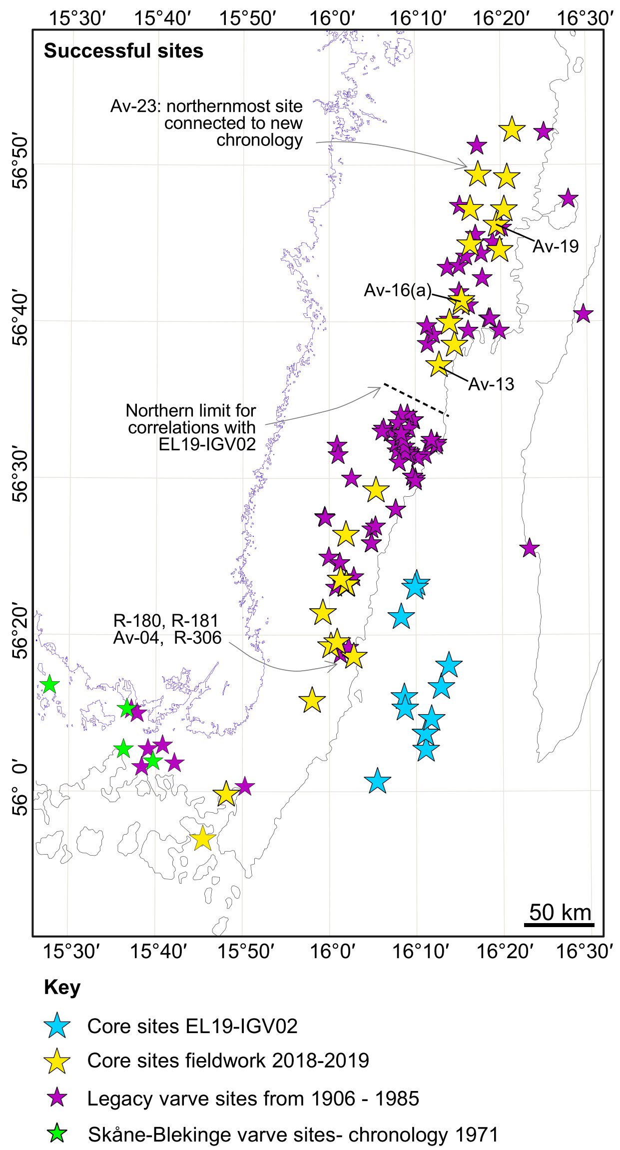

Fig. 6. Successful sampling locations overlain on Sweden's modern (black) and palaeo-highest (dark blue) coastlines. Varve sites are colour-coded by origin; sites are included regardless of correlation to our Skåne-Småland chronology. The oldest sites on the terrestrial east coast (R-180, R-181, Av-04, R-306) are marked, enabling extension of the old Skåne-Blekinge chronology into Småland. Varves from sites north of the dotted line are too young to correlate with our EL19-IGV02 offshore chronology. Av-23 is the youngest and northernmost site in our Skåne-Småland chronology; note that the more northerly sites could not be connected. Av-13, Av-16/16a and Av-19 all contain floating varves younger than the Skåne-Småland chronology.

recovering varved sediment units, in the quality of recovered core material, and in producing a robust composite record of such length that it has enabled uncertainties in the terrestrial record to be confidently corrected or confirmed. The new composite varve series has enabled integration of widespread local varve records into a single deglaciation chronology for south-eastern Sweden. Offshore depocentres were straightforward to find using sub-bottom acoustic imaging, in contrast to the scattergun approach necessary on land, and cores often contained over 100 undisturbed and well-defined varves (Table S1). The varved clay units from this setting record sedimentation variations from a larger catchment and filter out local variability. They therefore represent a reliable regional pattern that can be used to link clay varve series from tens of kilometres away.

Offshore coring has extended the Skåne-Blekinge chronology ~80 km further eastwards and northwards. The oldest varve in the new Skåne-Småland chronology dates to −325 vyr$_{ss}$, and the youngest 'bottom varve' dates to +230 vyr$_{ss}$, such that 556 vyr of ice-margin positions are recorded. An age of +399 vyr$_{ss}$ for the youngest varve means that our chronology encompasses 725 vyr of ice retreat. The integration of offshore coring along the Baltic Sea coast with terrestrial records has proven to be a powerful tool to correlate and connect local varve chronologies with each other; such an approach will be necessary to achieve a full and valid deglacial varve chronology for Fennoscandia that is robustly tied to the present day.

Varves from Skåne-Blekinge have a distinctive and regionally consistent thickness pattern, and the newly digitized varve series from the south coast (purple stars south of R-180, Fig. 6) are reasonably straightforward to correlate with the Skåne-Blekinge varve series. The greater length of the terrestrial varve series found on the southern Blekinge coast (green stars, Figs. 1, 6) and also from the Småland-Östergötland chronology (red and orange stars, Fig. 1) may be due to meltwater funnelling through prominent bedrock valleys in both regions. Such valleys are not prevalent on the mainland southeast coast of our study area where most of the varve series are of lower quality (shorter series with less distinctive thickness patterns), suggesting less focussed meltwater delivery. Further north of ~56°30′N, it was again more straightforward to connect local varve series due to a resumption of regional distinctiveness in the thickness patterns, although the series were still shorter and less distinctive than those of the south coast.

The paucity of successful sample sites and the lower quality of successfully acquired varve series found in the southeasternmost area likely contributed to the earlier difficulties of connecting local varve chronologies with each other in this part of Sweden. Using these lower-quality and short terrestrial varve archives without the addition of the offshore EL19-IGV02 series, it would not have been possible to confidently extend the Skåne-Blekinge varve chronology into Småland.

Difficulties of working with old data. – Our new terrestrial sediment cores were successful in replicating the varve thickness patterns of local legacy varve diagrams (1906–1985) measured in the study area, increasing our confidence in the reliability of old varve thickness measurements where the original material is no longer

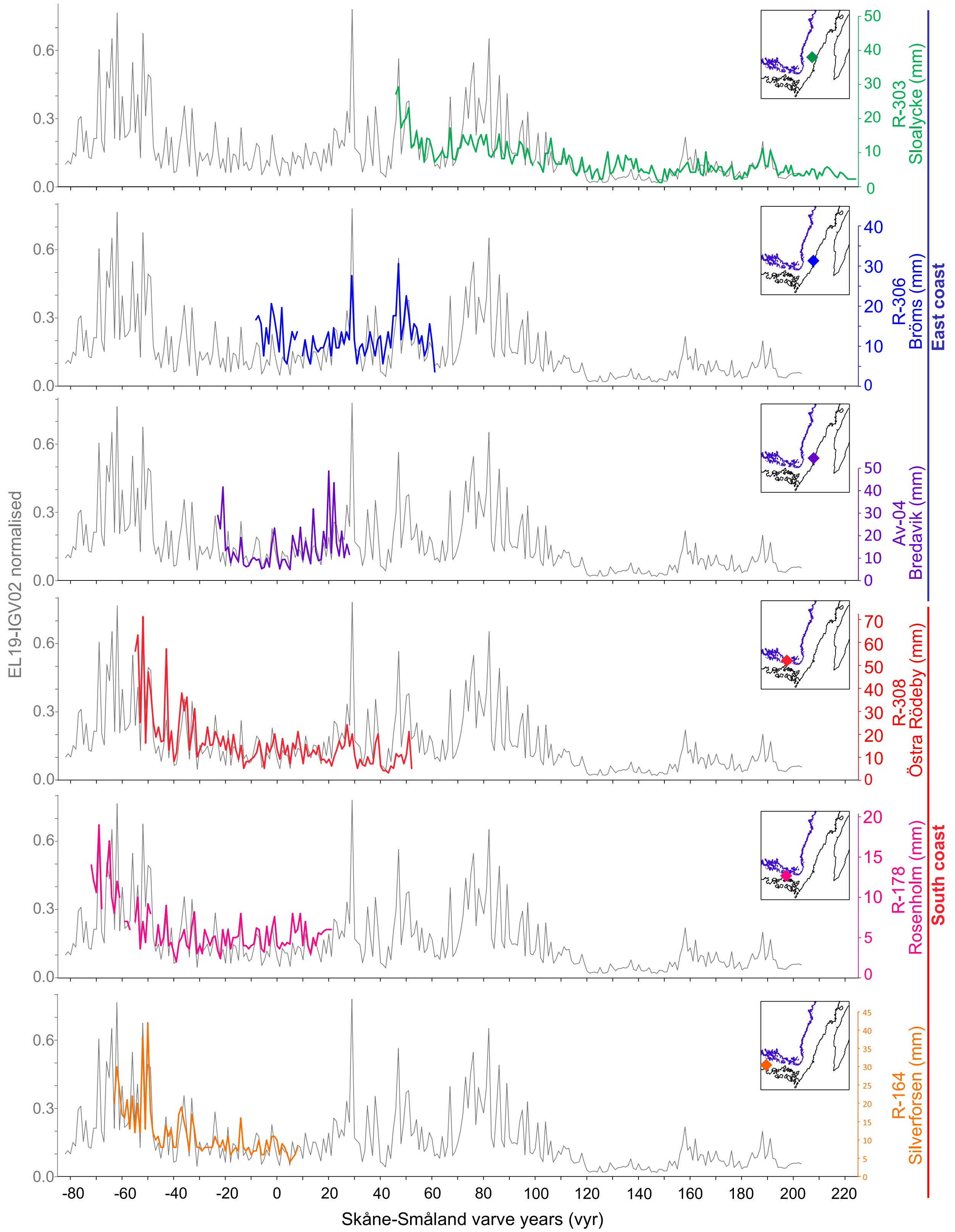

Fig. 7. Examples of terrestrial varve thickness series overlain on the offshore relative thickness composite curve (grey). The curves in warm colours (pink, orange and red) are from varve series from the south coast of Blekinge, and the cool colours (blue, green and indigo) represent varve series from the east coast. The location of each varve site is shown on the colour-coded inset maps, top right. Cross-correlation analysis results for these series can be found in Table 1.

available for inspection. Despite this, there were still several series that could not be correlated with the main chronology and we suggest that these mostly represent either local sedimentation patterns, miscounted varves (including graded beds identified as varves), or both. We do not consider that CCA is a useful tool in these or other terrestrial cases, either for assessment of reliability or for highlighting potential improvements. An issue with the approach is that once a correlation is statistically acceptable (generally $r \geq 0.6$, $z \geq 6$ for large basins, although the decision lies with the researcher (Rayburn & Vollmer 2013)), it is usually also obvious visually: our offshore series have a very strong visual match and represent a relatively integrated sedimentary basin, yet have only moderate (though acceptable) scores. Conversely for correlations that have any caveats visually (e.g. the match is on the varve cluster scale, or spatial variations exist in the thickness pattern), a statistical check is unlikely to clarify the matter – r values of 0.4 are common – and is not constructive for our terrestrial series that are often short and with a high degree of local site-to-site variation. We have chosen therefore to perform CCA only on certain longer, higher-quality terrestrial records (that already have a strong visual match) from near the south coast–east coast gap against the robust, statistically verified, EL19-IGV02 master curve. The lower terrestrial data quality leads to reduced r values (0.4–0.6; Table 1) in comparison to the better r-values between the high-quality offshore sites (0.6–0.9; Fig. S2), but we can see that the results are at least not insignificant at lag 0, broadly supporting our south coast–east coast link (Fig. 7).

Interpretations of ice recession rates using a varve chronology rely on accurately located bottom varve ages. Since our own fieldwork was based on coring and not on measuring varves in open sections, we were not able to recover definitive bottom varves and we need to rely on those noted in the old measurement series.

Table 1. Cross-correlation analysis scores for key selected south coast and east coast varve thickness records against our EL19-IGV02 master curve.

Site number and name	Coast	Statistical cross-correlation against EL19-IGV02 master curve		
		r-value	z-value	Lag
R-162 Ronneby Silverforsen	South	0.61	4.8	0
R-308 Östra Rödeby	South	0.5	4.59	0
Sofielund 1562	South	0.49	4.37	0
R-178 Rosenholm	South	0.49	4.53	0
Av-04 Bredavik	East	0.48	3.71	0
Ri-306 Bröms	East	0.58	5.09	0
Av-11 Torelycke	East	0.44	4.33	0
R-303 Sloalycke	East	0.45	4.50	0
Av-06 Fritzborg	East	0.48	4.67	0

Comparison with previous chronologies

This study is not the first to try and build a varve chronology in southeastern Sweden, nor the first to try and bridge the south coast–east coast gap. Rudmark (1975) published a chronology along the southeast coast, using almost exclusively terrestrial series that had been investigated previously by G. De Geer, and only series that had a bottom varve overlying till or sand. Of the 25 sites he presented, 23 individual records were long enough to be included in our new chronology based on the EL19-IGV02 composite series. Ringberg & Rudmark (1985) connected Rudmark's chronology to the south coast chronology in Blekinge with tie points at R-180 (Björkelycke) and R-181 (Högaryd; Fig. 6) of −91 vyr_{ss}, and this connection was also used in Ringberg *et al.* (2002). However, based on our new observations, we disagree with the connection they made, and place this connection 71 vyr younger than they did, at −20 vyr_{ss}. Our oldest terrestrial east coast varve age is from one of our new sites (Av-04) at −23 vyr_{ss}, although without a distinct bottom varve. The differences between the chronologies constructed for the east coast by Rudmark (1975), Ringberg *et al.* (2002) and this study are shown in Fig. 8.

Ringberg *et al.* (2002) extended their chronology over larger distances (see e.g. Fig. 8, green circles) and as far north as the southern sites of the Småland-Östergötland chronology (57°24′N; Fig. 1), despite the lower quality of varve series along this part of the east coast. Here we adopted a more cautious approach since variations in varve thickness in sites further to the north did not show enough consistency to provide a compelling connection, even with the addition of our newly acquired cores. Therefore, we only extend our new chronology as far north as Av-23 (Bomossen, 56°46′N; Fig. 6), which is the location furthest north to which we could confidently connect new and existing series.

The floating sections from the upper parts of Av-13, Av-16(a) and Av-19 (Fig. 6) are younger than, and separate from, the Skåne-Småland chronology. We tentatively visually matched these floating sections with the oldest series of the Småland-Östergötland chronology (K1 Högsby-Berga; Kristiansson 1986; Fig. 9). The matches are not robust enough to be evaluated with CCA, but we feel that the visual match is strong enough to suggest that there is a correlation between the three sections (Fig. 9). This match would mean our floating chronology represents 252 vyr including gaps, although we do not consider the matches convincing enough to connect the Skåne-Småland and Småland-Östergötland chronologies yet.

Early Fennoscandian Ice Sheet melt behaviour in southern Sweden

Estimating ice retreat rate and pattern. – Our new Skåne-Småland varve chronology allows estimation of ice

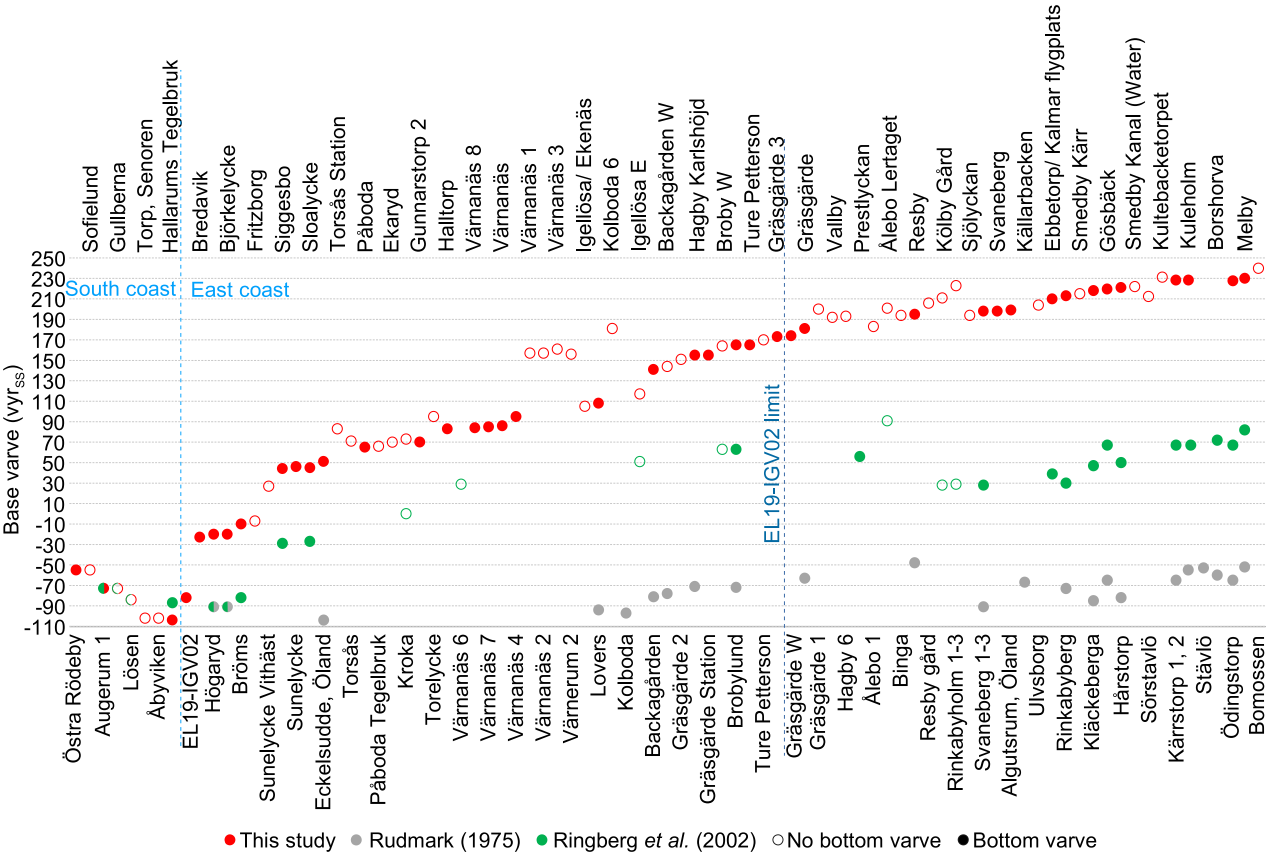

Fig. 8. Comparison of chronologies from this study (red), with those published by Ringberg *et al.* (2002; green) and Rudmark (1975; grey). Open circles refer to series ages where a bottom varve was not reached, and filled circles refer to series where a bottom varve was reached. The bright blue vertical line separates varve series from the south coast (left) and east coast (right), and the dark blue vertical line denotes the limit of the EL19-IGV02 composite curve.

retreat rates in southeastern Sweden. We use sites with bottom varves as a proxy for former ice-margin position, and use sites without bottom varves in an auxiliary capacity. Figure 10 shows our estimation of ice recession rates in southern Sweden to the nearest 10 m a^{-1}. Although we advise caution in deriving detailed ice recession rates due to uncertainties in site locations and local topographically determined retreat directions, it is possible to identify variation in retreat behaviour at a wider scale.

Subaqueous retreat rates from the south (~100–160 m a^{-1}) and east (190 to >300 m a^{-1}) coasts are approximately three- to fivefold faster than when the ice margin is situated close to or above the (palaeo-) shoreline (~60–70 m a^{-1}; Fig. 10B). At the northern extent of our chronology, the youngest retreat isochrons – though less well constrained than the others – point to a possible further acceleration of retreat in the offshore sector to ~490 m a^{-1}, with the margin pivoting near the Kalmar headland (56°39′N). In eastern Blekinge the retreat rate clearly decreases as the grounding line retreats through shallowing water towards the palaeo-shoreline (Fig. 10B). Indeed, across our study area a slowing of retreat rate as the ice margin approaches the palaeo-shoreline appears to occur independently of the shape of the ice margin, i.e. whether it lies parallel or oblique to the coast. For comparison, retreat rates in our study area calculated by Ringberg *et al.* (2002) based on their chronology are 75–125 m a^{-1}.

The pattern of grounding line retreat is largely coast-parallel (~W–E) along the south coast of Blekinge, consistent with previous authors' findings (De Geer 1888; Ringberg 1971, 1991; Wohlfarth *et al.* 1994; Ringberg *et al.* 2002). Here we also show that this orientation extends eastwards into Kalmarsund and possibly even across Öland. Given that the retreat was preceded by the east-to-west flow of the Young Baltic Advance(s) (Kjaer *et al.* 2003) through the southern Baltic Sea, this coast-parallel ice-margin shape and position (i.e. extending as far east as Öland) suggests that (i) there must have been a rapid retreat of Baltic Sea ice prior to our southernmost (earliest) ice-margin position, and (ii) the boundary between offshore (streaming, Baltic Sea) and terrestrial (non-streaming, Swedish) ice likely lies both south and east of our study area. Subsequent retreat into southern Kalmarsund initially

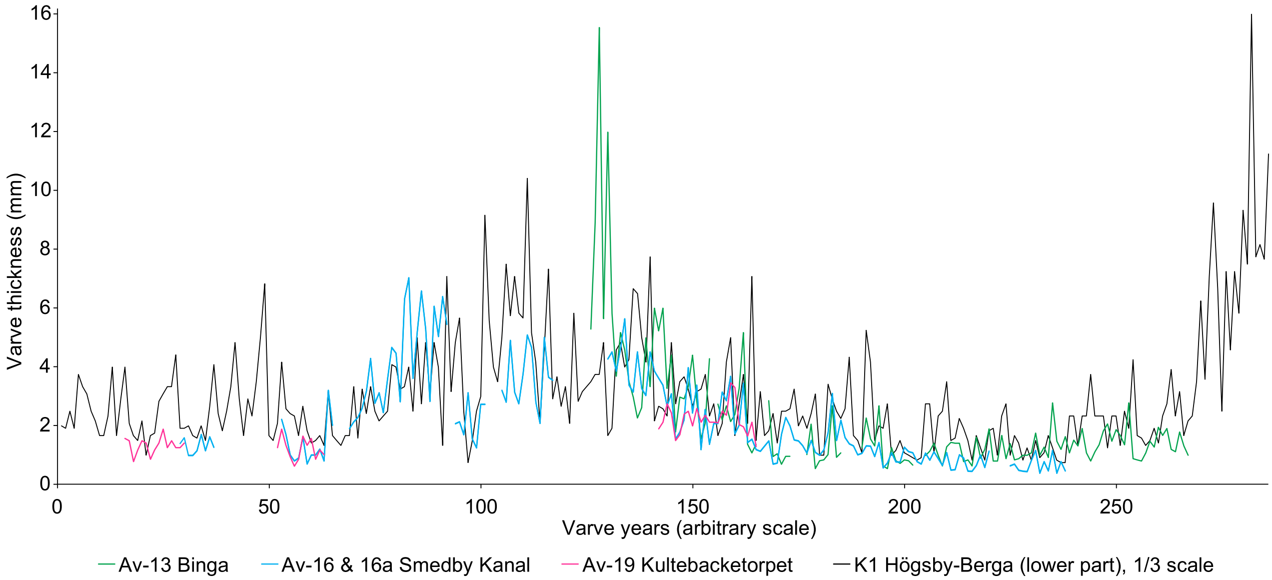

Fig. 9. Additional varves from three new terrestrial sites (Av-13, Binga; Av-16/16a, Smedby Kanal; Av-19, Kultebacketorpet) in six floating parts separated by erosive layers. This fragmented floating chronology is overlain on the lower part of the thickness curve for one of the southernmost sites in the Småland-Östergötland chronology, Högsby-Berga (Kristiansson 1986).

holds towards the north, up-strait (Fig. 10B), contrasting with previously published suggestions of landward (NW) retreat from Kalmarsund (Rudmark 1975; Ringberg & Rudmark 1985; Ringberg *et al.* 2002). This is due to both the south-to-east coast varve connection now being 71 vyr younger than previously published, and to new connections with our offshore cores and a legacy site on southern Öland. Only after ~+60 vyr_{ss} does the retreat direction begin to pivot towards the NW, hinged in the SW of Kalmarsund where the ice margin crosses the palaeo-shoreline.

A 'hinged' ice margin at the palaeo-shoreline is a consequence of enhanced mass loss along its subaqueous parts: a subaqueous grounding line loses mass from not only surface melting, but also from subaqueous melting and calving, both of which generally increase with deeper water. As the grounding line approaches the coast and the water shallows, subaqueous losses will therefore diminish and ice retreat slows; we can interpret from the contrasting on- and offshore retreat rates that losses from subaqueous melting and calving may have accounted for up to 80% of the total ice loss during this period of deglaciation. Subaqueous grounding line retreat proceeds faster along the east coast than the south coast (Fig. 10B), and we may speculate about potential further controls on these dynamics. Since water depth controls both calving and the potential for subaqueous melting, the slope of the bed may be expected to affect the rate of grounding line change. Along the east coast, the slope of the topography towards the palaeo-shoreline is gentle (~15–40 m of elevation change per 10 km), facilitating a faster, unhindered retreat, whereas the rise in Skåne and Blekinge is comparatively steeper (35–55 m of elevation change per 10 km), stabilizing the grounding line. Some of the more widely spaced isochrons (i.e. faster retreat) in easternmost Blekinge do however cross the currently terrestrial domain (Fig. 10B), implying retreat rate controls additional to water depth on the east coast. The greater topographic roughness of the crystalline bedrock on the south coast offers more localized topographic highs that would take up basal stresses (locally slow flow) and reduce local water depth, anchoring the grounding line. Alternatively, or additionally, high-resolution Last Glacial Maximum (Ludwig *et al.* 2016; Schaffernicht *et al.* 2020) and Lateglacial (Schenk *et al.* 2018; Schenk & Vinuesa 2019) climate simulations indicate persistent easterly summer winds advecting warm, dry continental air towards the SE of the ice sheet. Floral evidence shows heightened regional summer temperatures prevailed directly south of the retreating ice sheet with ≥15 to 16 °C prior to the Bølling (Schenk *et al.* 2020); we suggest that these factors could have promoted enhanced ice loss on the east coast through surface melt and evaporation, and wave activity.

The role of low-lying Öland (then a submerged topographic high) in pinning grounding line retreat is an interesting question that has a bearing on where the limits of streaming (fast) flow in the Baltic Sea lie and to what extent ice stream retreat behaviour is transmitted towards mainland Sweden. Öland remains ~50 m below the highest shoreline throughout its deglaciation, and its amplitude relative to strait depth is fairly constant along its length. The W–E ice-margin orientation with a weak grounding line embayment in southernmost Kalmarsund (Fig. 10B) suggests that initially, both the mainland and Öland pinned the

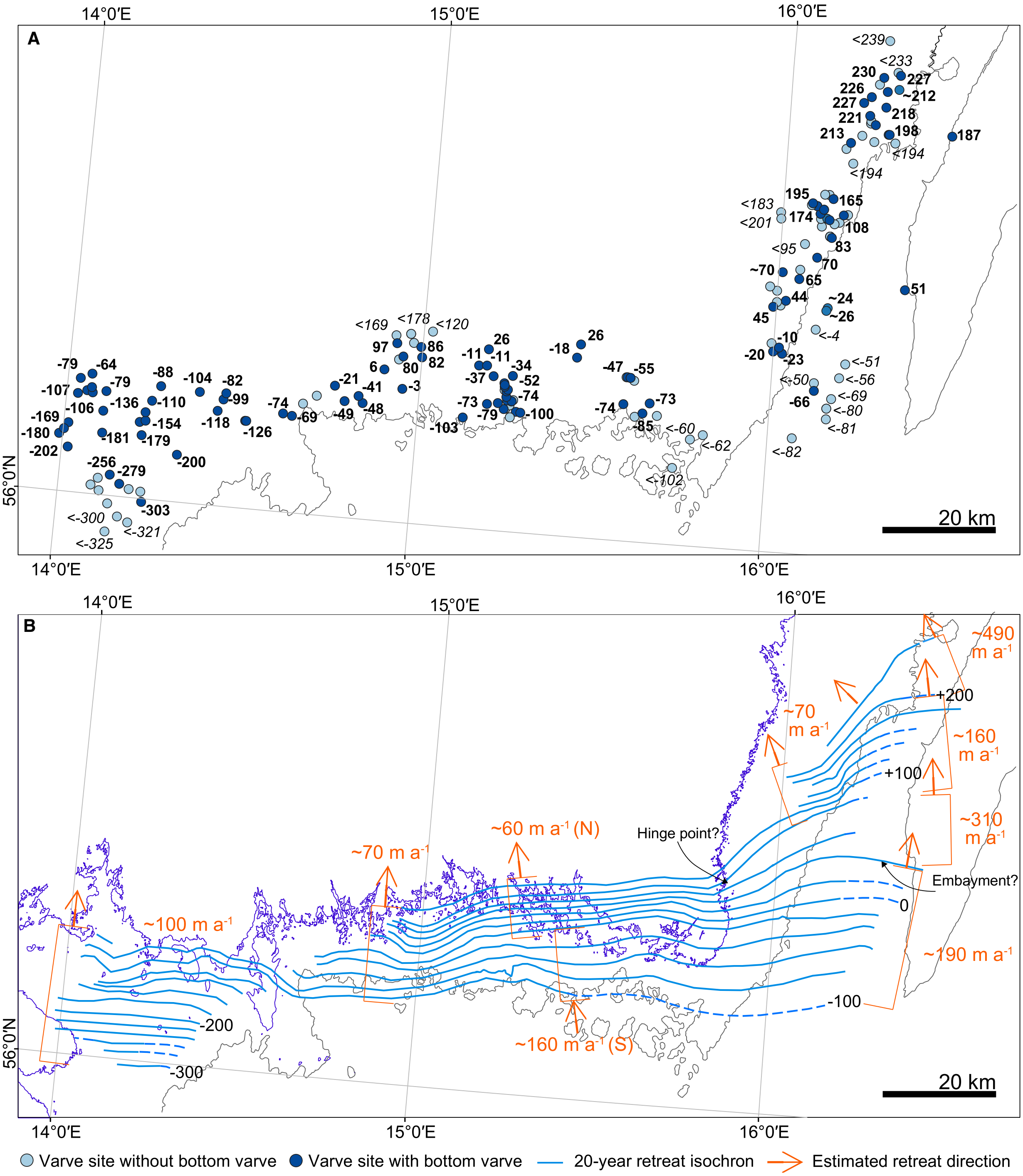

Fig. 10. A. Varve sites in southern Sweden; selected sites are labelled with the basal varve age in each series. Dark blue, bold text: sites with a 'bottom varve'; pale blue, italic text: sites without a 'bottom varve'. B. Estimate of ice recession with 20-year retreat isochrons in blue based on the ages of the bottom varve. Dark blue: highest coastline. Retreat rate estimates and approximate directions are shown for various regions in orange, and retreat isochron ages on the Skåne-Småland time scale are shown for every 100 vyr in black.

grounding line. If fast flow in the Baltic proper was characterized by different retreat dynamics from land-based ice, then any such effects are confined to the east of Öland. As the retreating grounding line begins to pivot beyond +60 vyr_{ss}, however, bottom varve ages from either side of Kalmarsund indicate that retreat proceeds rapidly with no equivalent pinning effect from Öland. The pinning effect from the mainland comes to dominate the transition to a terrestrial-based ice margin towards the west, and/or the effects of accelerated retreat in the Baltic proper are effectively transmitted across Öland. We speculate that the further hinging and retreat rate increase in the northernmost part of our chronology may represent the beginnings of rapid retreat or even collapse of the ice in the offshore sector; further offshore coring would clarify this.

Enhanced melt phases. – A mean relative thickness curve (each series normalized against its maximum thickness) for our Skåne-Småland chronology displays four intervals of increased varve thickness, each lasting approximately 80–100 vyr and separated by 120–150 vyr (peaks 1–4, Fig. 11). It is tempting to interpret these intervals as repeated, multidecadal episodes of enhanced surface melting with corresponding increases in sediment delivery to the ice margin. Alternatively, they may indicate repeated reorganizations of the en/subglacial hydrological system, or periods of enhanced sediment availability or mobility. A longer varve time series, connection to an absolute time scale, and a more wide-ranging examination of varve physical and/or geochemical properties could, in the future, help to constrain these features better.

The fourth of these intervals with increased varve thickness (peak 4, Fig. 11) corresponds to both the 'diffuse' varves of Blekinge (Ringberg 1979; Wohlfarth *et al.* 1994) and the 'diffuse' varves found in EL19-IGV02 (Figs 3, 4), which are typically thick, with a thicker summer melt-season layer and a thinner winter layer; the melt-season layers moreover contain multiple sub-laminations separated by fine clayey silt. The fine-grained melt-season layers indicate low-energy meltwater or a distal source. The multiple laminations within the melt-season layers indicate multiple seasonal melt or sediment transportation events (Blass *et al.* 2003), while increased thickness indicates high meltwater volumes over each melt season (Ridge *et al.* 2012). East coast terrestrial varve series correlating in time with the diffuse varves (e.g. Av-11, Torelycke) show an increase in varve thickness, but do not exhibit the other classical 'diffuse' characteristics. This may be due to their location closer to the ice margin (near the Kalmar headland, 56°39′N) and coarser grain sizes in the melt-season layer. Nonetheless, it is clear from our offshore cores that the increased sedimentation rate previously interpreted from the so-called 'diffuse' unit in Blekinge (Wohlfarth *et al.* 1994) was not restricted to the Blekinge area (i.e. southward-draining), but represents a wider regional signal and, potentially, was just one of a number of repeated enhanced melt/sedimentation phases over several hundred years of regional deglaciation. Indeed, the additional floating varve chronology present above the erosive sand layers in three of our terrestrial cores also suggests a period of increased melt, occurring after the youngest limit of the Skåne-Småland chronology. We have tentatively correlated this melt phase with one of a similar duration (110 vyr) from the southernmost site in the Småland-Östergötland chronology (Kristiansson 1986; Fig. 9).

Similar periods of enhanced sediment delivery have been noted from a previous iteration of a southeastern Sweden varve chronology (Ringberg *et al.* 2002, 2003). Their chronology differs from ours; their mean curve

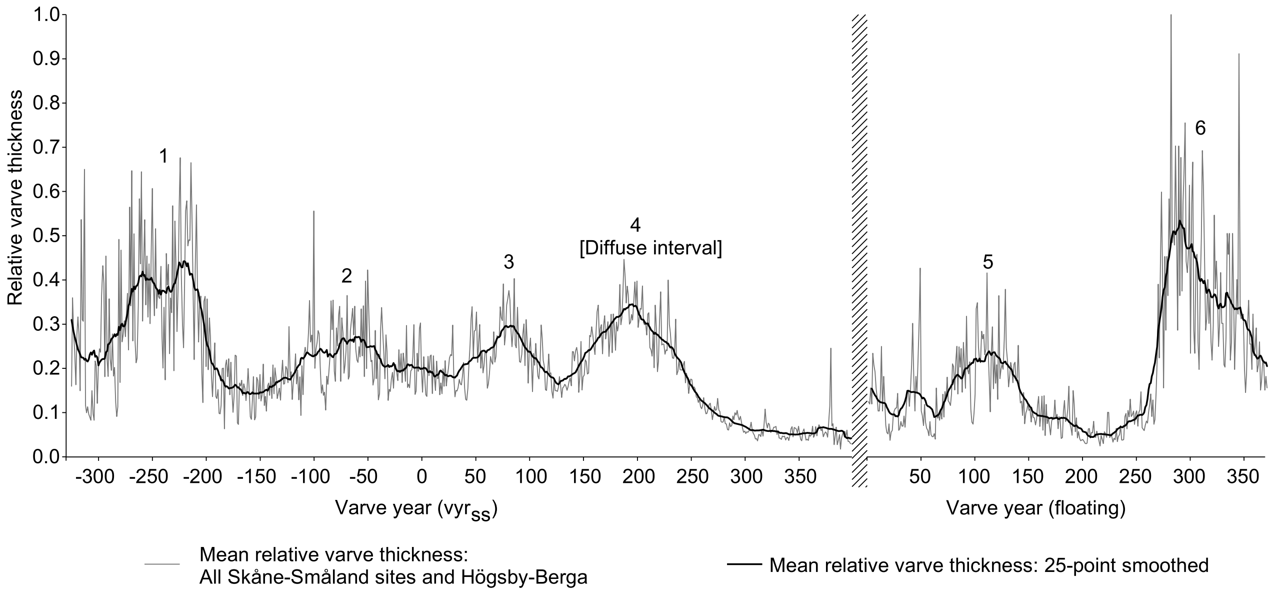

Fig. 11. Mean curve of all varve series in the Skåne-Småland chronology normalized against their maximum thicknesses (thin grey lines), overlain with a 25-point smoothed curve (thicker black line). The Högsby-Berga series integrated with our younger floating chronology is also shown on a separate *x*-axis to the right of the hatched bar. Significant periods of increased sedimentation are labelled 1–6 above the curves.

uses absolute rather than normalized varve thickness series (we account for sedimentation differences between sites); and their curve only includes 18 sites as opposed to our 188. The trends and their timings seen in the two mean curves therefore do not match perfectly and could be considered not directly comparable. However, the presence of similar enhanced sedimentation phases in their curve provides corroborating evidence for Sweden having experienced these enhanced melt periods. Although the younger part of our chronology remains floating, it is evident that multidecadal episodes of increased melt characterize the Skåne-Småland record and continue into the earliest part of the Småland-Ö stergötland chronology (peaks 5 and 6, Fig. 11) and were therefore a persistent trait of pre-Bølling and Bølling deglaciation.

Conclusions

Southeastern Sweden has been a particularly troublesome area for varve recovery and correlation of varve thickness diagrams, precluding a unified southern Swedish varve chronology. In this study we have revisited legacy varve records (1909–1985) and analysed newly acquired onshore and offshore glaciolacustrine varve series in order to evaluate the pattern and rate of ice-sheet retreat in southern Sweden. We particularly highlight the value and potential of near-shore marine sediment cores in achieving this aim. The offshore cores have provided long, continuous archives that were straightforward to analyse/measure and correlate with a high level of visual and statistical confidence, enabling the construction of a master curve that captures a regional sedimentation signal. Using this offshore curve together with legacy varve data (collected by workers including Gerard De Geer since the early 1900s) and new terrestrial cores, we have successfully and confidently extended the existing south coast chronology to the troublesome east coast, providing an answer to a 100-year-old problem. Where our master curve ends we have extended the chronology along southern Sweden's east coast to 56°51′N (Av-23, Bomossen; 18 km N of Kalmar) according to our interpretation of further legacy and newly acquired terrestrial clay varve records. The new Skåne-Småland chronology covers the subaqueous–terrestrial transition of the retreating ice sheet around the Bølling warm period onset (the chronology is floating), and spans 725 vyr of deglaciation. We also present an additional fragmented floating chronology that is younger than the Skåne-Småland chronology and that may tie in with the more northerly Småland-Ö stergötland varve chronology.

Our new Skåne-Småland varve chronology reveals that retreat rates in the (palaeo-)offshore sector were three- to fivefold faster than where the margin was close to or above the palaeo-shoreline. Retreat rates slowed considerably as the bed rose towards the shore. Offshore retreat along the east coast was faster than along the south coast, and in addition to increased water depth we speculate upon additional controls e.g. a smooth bed facilitating unhindered grounding line retreat and/or easterly summer winds driving greater surface melt. Towards the highest coastline and further north along the east coast the retreat isochrons pivot towards NW, suggesting a shift towards landward retreat of terrestrial 'Swedish' ice, increasingly divorced from the Baltic Sea ice catchment. Superimposed on this general pattern and on the relative rates of ice-margin retreat, we find repeated multidecadal scale episodes of enhanced ice-sheet melting that extend throughout the deglaciation of Skåne-Småland and into Östergötland to the north.

Kalmarsund is an excellent trove of plentiful and regionally significant varve deposits that have been critical to our success in building the new 725-year-long Skåne-Småland varve chronology, and we anticipate further offshore research in this vein.

Acknowledgements. – We would like to dedicate this paper to the memory of Lars Brunnberg, who was instrumental in digitizing legacy varve records in this study, and who contributed significantly to varve science over the many decades of his research. We would like to thank those who assisted in the field during acquisition of new terrestrial cores: Svante Björck, Julia Muchowski, Petter Hällberg and Mikis Van Boeckel. We also thank the crew of RV 'Electra' Thomas Strömsnäs, Mattias Murphy and Carl-Magnus Wiltén for their expertise. We are grateful to M. D. Johnson and J. C. Ridge for their helpful comments on an earlier version of this manuscript. This work is funded by a Wallenberg Academy fellowship to SLG (grant number 2016.0144) and Stockholm University funding to BW. Terrestrial fieldwork was funded by Bolin Centre for Climate Research grants to RSA. FS was funded by the Swedish Research Council (VR 2015-04418).

Author contributions. – LB and BW digitized legacy varve measurements made by previous researchers, while RSA performed the laboratory and analysis work. All authors (except LB) contributed to the acquisition of new sediment cores and to the construction of the manuscript.

Data availability statement. – The data we have generated are available in the Bolin Centre Database (https://doi.org/10.17043/avery-2020).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

Fig. S1. All cores from the EL19-IGV02 research cruise in Kalmarsund, from south (left) to north (right).

Fig. S2. Matrix of cross-correlation for the new offshore cores from Kalmarsund, where each varve series has been cross-correlated against the other.

Fig. S3. Unsuccessful field sites for varved core recovery overlain on the modern (black) and palaeo-highest (dark blue) coastlines.

Table S1. Cores collected from Kalmarsund on the RV 'Electra' in April 2019. Listed are site number, location, water depth, core code and type (PC = piston core; GC = gravity core), core length and number of sections, and any comments about the coring process.

Table S2. Summary of the south coast Skåne-Blekinge chronology (Ringberg 1971, 1991; Ringberg & Rudmark 1985; Wohlfarth *et al.* 1994), including original base varve years, changes made in this study and new base varve years, and any series that were removed from the chronology. R91 = Ringberg (1991), R71 = Ringberg (1971), R-R85 = Ringberg & Rudmark (1985), W94 = Wohlfarth *et al.* (1994).

Table S3. Coring details of terrestrial cores acquired with Russian corers between November 2018 and November 2019.

Table S4. Summary of the extension of the Skåne-Blekinge chronology (Ringberg 1971, 1991; Ringberg & Rudmark 1985; Wohlfarth *et al.* 1994) into south-eastern Småland using both newly digitized old varve thickness measurements, and measurements from newly acquired terrestrial cores. R-R85 = Ringberg & Rudmark (1985); R75 = Rudmark (1975); R02 = Ringberg *et al.* (2002), only in cases where Ringberg *et al.* (2002) had connected the site to their chronology.