exceeding this amount would be unfeasible.

The smaller future ice loss projected by Geyman and colleagues is welcome news for an area experiencing some of the fastest warming rates on the planet. However, the ice lost will still have consequences for coastal environments around the world, and the result does not change projections for other areas that have land ice. Glaciologists must now address the reasons for the shift in study outcomes – a question that Geyman *et al.* leave unaddressed.

For those who might consider using a space-for-time substitution for glaciological projections elsewhere, the 70-year time period in Geyman and colleagues' study might make the method seem impractical. The authors' tests, however, suggest that shorter records might still provide robust results. Researchers will have to assess the confidence with which they can link similar or different climate metrics to glacier mass change over small time periods for other locations. Geyman *et al.* found little evidence in Svalbard for threshold behaviours – tipping points that might make a glacier respond differently to temperature change above or below some value. Whether this holds true for other glaciated regions remains to be determined.

Geyman and colleagues' robust Svalbard-wide results are laudable but have limitations. Individual glaciers and smaller subregions might display different relationships between mean summer temperature (or other metrics) and glacier thinning. Those seeking to understand the local future of Svalbard's ice loss – to project changes in local habitat or plan for regional conservation – might require further detail. But the authors' rich historical data set and observation-based projection framework can provide a foundation for such work. They will also inspire other glaciologists looking to make new use of short-term observations to improve projections for the roughly 200,000 glaciers across the rest of the world.

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Archaeology

A radiocarbon revolution sheds light on the Vikings

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Advances in the precision of radiocarbon dating can offer year-specific data. Analyses of archaeological sites in Denmark and Canada provide insights into the chronology of the global networks of the Viking Age. **See p.388 & p.392**

During the twentieth century, our knowledge of the past was revolutionized by the introduction of radiocarbon dating, by the calibration of radiocarbon data to calendar dates using wood controls of known age and by advances in dating increasingly small samples. Now, another radiocarbon revolution is under way. There is a growing trend in harnessing calibration data that can be pinpointed to an individual year – measured using single rings of individual trees. For the years for which such calibration data exist, the most-recent international radiocarbon calibration curve, called IntCal20, represents a principal advance over the previously used approach (which often combined several tree rings for calibration analysis)[1]. Philippsen *et al.*[2] (page 392) and Kuitems *et al.*[3] (page 388) report how this method was used to clarify the timelines of two key Viking sites.

The potential of this new calibration curve is being tapped by research projects that also harness the opportunities presented by solar particle events (SPEs). SPEs are marked by spikes in atmospheric carbon in the form of carbon-14 that occur during years of extreme solar flares. These spikes are detectable in sequences of radiocarbon dates crossing chronologies that include an SPE. Radiocarbon dating becomes exceptionally precise in these, admittedly rare, circumstances – in the best cases, the exact year of an SPE can be identified in the archaeological record.

Two such SPEs occur near key chronological thresholds of the Viking Age. One is in AD 775, shortly before the conventionally accepted beginning of the Viking Age (approximately AD 793, as defined by the appearance of characteristic artefacts in Scandinavia, and the onset of Scandinavian raiding in Britain and Ireland). Another is in AD 993, near the time of the westernmost Scandinavian expansion of the Viking Age – to Greenland and north-eastern North America. In Newfoundland in Canada, a short-lived settlement existed at L'Anse aux Meadows (Fig. 1), which is the only definite Viking site known in North America.

The opportunity therefore now exists to gain further insights into the chronology and character of the Viking Age. Philippsen and colleagues have established the chronology of the introduction of Middle Eastern glass trade beads (in AD 785–810) to the important medieval trading town of Ribe in Denmark. Crucially, the authors show that this introduction occurred after the emergence of long-range regional trade in Scandinavia (as revealed by imported Norwegian products such as reindeer antlers) and with continental western Europe (based on finds such as pottery from the Rhineland, Germany). Therefore, on the basis of chronological analyses, world-system linkages with the Middle East were probably not the main causal factor in the emergence of expanding networks during the Viking Age, although they were essential to its later development.

This discovery is notable because the arrival in Scandinavia of Middle Eastern silver coins called dirhams, which circulated alongside the beads, has sometimes been viewed as a crucial Viking Age catalyst of Scandinavian trade, urbanism and piracy. Instead, it seems that a more-prolonged and more-local process was responsible. Valued, but not always precious, resources (such as pottery or reindeer antlers) were incrementally obtained from ever-larger surrounding areas, fuelling the growth of urban centres such as Ribe. These items were traded before silver and beads from the Middle East entered the markets. A single explanation of the Viking phenomenon, albeit simplified for brevity, is thus ruled out.

Turning to the culmination of expansion during the Viking Age, Kuitems *et al.* determined the precise date of L'Anse aux Meadows, a medieval Scandinavian outpost. The previously available dating information for this UNESCO World Heritage Site was surprisingly limited. More than 150 dates for L'Anse aux Meadows have previously been obtained using the ^{14}C method, 55 of which relate to the time of the Scandinavian occupation. However, many dates are for materials of varying

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Figure 1 | The Viking site at L'Anse aux Meadows, Canada.

'inbuilt' age (for example, wood that was old at the time it was used to construct items), which does not accurately represent the chronology of occupation. Moreover, these data were gathered several decades ago when the precision of radiocarbon dating was poor. The artefact record from this short-lived site is also too sparse to provide a strong basis for typological dating (estimations based on the physical characteristics of objects). Its Scandinavian occupation could previously be attributed only to the tenth or eleventh centuries, partly on the basis of later medieval Icelandic accounts rooted in oral history.

Kuitems and colleagues date the occupation of L'Anse aux Meadows by identifying the SPE of AD 993 in single tree rings of timber. The authors focused on three pieces of wood (all originally cut using metal tools) that include this year within their growth rings. The metal toolmarks, and the excavation contexts of the finds, indicate that they were from the medieval Scandinavian phase of the site. After identifying which tree ring of each timber represented the year 993, the authors counted forwards in time to the youngest growth ring of the tree (the waney edge), when the wood was cut, to obtain the date of the Scandinavian presence.

Remarkably, the results of this analysis pointed to 1021 for all three timbers. Moreover, in two cases, the pattern of wood cells at the waney edge revealed the season of the tree felling, which was spring in one instance and summer or autumn in the other. Whatever the duration of settlement occupation (a paucity of extensive archaeological deposits suggests it was brief), the inhabitants of L'Anse aux Meadows during the Viking Age seem to have been present there in the spring and summer or autumn of 1021.

This discovery does not change the broad outlines of our knowledge regarding the Scandinavian expansion during the Viking Age. It does, however, anchor a key and previously ambiguous episode of human mobility in absolute time.

"The opportunity therefore now exists to gain further insights into the chronology and character of the Viking Age."

The wider relevance of this chronology rests with the fact that Icelandic sources describe Vinland (a name for the region of North America that the Vikings reached) as the location of cultural contact between Scandinavian mariners and the Indigenous peoples of North America. Kuitems *et al.* describe some possible outcomes of such contact, such as disease transmission, transfers of invasive flora and fauna, or children born of both parentages and thus the exchange of DNA. There is no convincing evidence for such outcomes, and the authors do not imply that there is. Nevertheless, for global history, it remains notable that the Vinland occupation happened early in the eleventh century, and that it was quickly abandoned. On the basis of written Icelandic sources, this abandonment was due to resistance from the Indigenous population. As a result, the large disease outbreaks caused by the colonization of the New World by Europeans, as well as other impacts of the colonization, were avoided until the sixteenth and seventeenth centuries[4].

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