

Glaciomarine Sediment Archives – Integrating Traditional
Approaches and Novel Techniques to Constrain Ice-Stream
Collapse in The Minch, NW Scotland

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Abstract

This PhD thesis covers a number of topics relating to glaciomarine sediment archives. It presents a novel method for quantifying ice-rafted debris (IRD) and characterising glaciomarine sediments. It identifies strengths and weaknesses of existing IRD techniques and combines traditional and innovative approaches to constrain Minch Ice Stream behaviour before and after its demise. A new IRD method which automatically characterises glaciomarine sediments, based on X-ray imaging properties, affords significant advantages over existing IRD techniques – reducing analysis times, minimising human bias, and operating at the highest resolution of any technique. A participatory study of different researchers undertaking X-ray gravel counting (> 2 mm) on X-ray images to quantify IRD yielded significant inaccuracies between different users, which indicates that there is a strong need for automation in sediment characterisation. A multiproxy investigation of laminated glaciomarine sediments in the Minch (NW Scotland) indicates that colour-banded glaciomarine sediments formed via alternating sediment-laden meltwater plume locations, rather than simple suspension settling or seasonally deposited terrigenous v biogenic sedimentation. Finally, the timing and behaviour of the Minch Ice Stream is constrained before, during and after collapse, via a multiproxy approach. Two main stable phases are identified while the ice stream was grounded in the central Minch: the first remains poorly constrained, but occurred *before* 17.2 ka cal BP; the second was a ~ 600 -year stable phase from 17.2 to 16.6 ka cal BP with a short 5-10 km ice shelf. At 16.6 ka cal BP, the Minch Ice Stream underwent a step-change in behaviour, entering a “runaway retreat” or “collapse phase”. These results indicate that sea-level-rise projections must consider marine ice sheet dynamics if they are to accurately predict the contributions of marine-terminating glaciers and ice streams such as those in West Antarctica and Greenland.

Table of Contents

Abstract.....	i
Table of Contents.....	ii
List of Figures.....	vii
List of Tables.....	xiv
Acknowledgements.....	xvi
 Chapter 1: Introduction.....	 17
1.1 The impact of marine-based ice sheets on sea level rise	17
1.1. The importance of ice shelves in the stability of ice streams.....	17
1.1.1. The importance of ice shelves in the stability of ice streams...18	
1.2. Glaciomarine sedimentation model.....	22
1.2.1. Ice-rafted debris	22
1.2.2. Palaeo-ice sheets and the 'ice-shelf problem'	23
1.2.3. Palaeo-ice shelf distribution	23
1.2.4. Toolkit for identifying palaeo-ice shelves.....	24
1.2.5. Geomorphology.....	24
1.2.5.1. Grounding-zone wedges.....	24
1.2.5.2. Ice-shelf and iceberg scours.....	25
1.2.5.3. Corrugation ridges.....	26
1.2.6. Sedimentology	28
1.2.6.1. Ice-shelf sediment stratigraphy.....	28
1.2.6.2. Foraminifera in ice-shelf sediments.....	29
1.2.7. Challenges with palaeo-ice shelf identification.....	32
1.3. Study site	33
1.3.1. The British-Irish Ice Sheet.....	33
1.3.2. The Minch Palaeo-ice Stream.....	35
1.4 Aims and Objectives	37
 Chapter 2: Automated Characterisation of Glaciomarine Sediments using X-ray Computed Laminography	 39
2. Introduction	39
2.1. The use of X-ray image analysis in IRD detection	39
2.2. Methods.	41
2.2.1. Image acquisition: X-ray computed laminography	41
2.2.2. Image pre-processing.....	42

2.2.3. Sediment characterisation tool	44
2.2.4. Characterising sediments by X-ray imaging properties	44
2.2.5. Comparison with existing IRD-identification methods.....	45
2.3. Results.....	47
2.3.1. Glaciomarine sediment characterisation	49
2.4. Discussion	50
2.4.1. X-ray computed laminography: comparisons with conventional X-ray imaging techniques	50
2.4.2. The benefits of using sediment heterogeneity to detect and characterise IRD	53
2.4.3. Inaccuracies associated with sediment heterogeneity as an IRD proxy	53
2.4.4. Sediment mean GV (radiodensity) as a proxy for energy of sediment deposition.....	56
2.5. Conclusions	57

Chapter 3: A Methodological Study of Different Ice-Rafted Debris Quantification Techniques 59

3.1. Introduction – ice-rafted debris.....	59
3.1.1. Techniques commonly applied for quantifying Ice-rafted debris (IRD).....	59
3.1.1.1. Destructive IRD detection techniques.....	59
3.1.1.2. Non-destructive techniques.....	60
3.1.1.3. Automated image analysis routines	61
3.1.1.4. Grey value standard deviation (GV SD) using X-ray computed laminography	61
3.1.2. Previous comparisons of ice-rafted debris methodologies	62
3.1.3. Study site and sediment depositional environments.....	65
3.1.4. Aims and objectives	69
3.2. Methods.....	69
3.2.1. Ice-rafted debris quantification techniques	69
3.2.1.1. Destructive methods.....	69
3.2.1.2. Non-destructive methods	69
3.2.2. Inter-facies comparison of different IRD methodologies	69
3.2.3. Statistical analyses.....	70
3.3. Results.....	72
3.3.1. Comparison of different IRD methodologies.....	72
3.3.2. Correlation between different IRD techniques	74
3.4. Discussion	75
3.4.1. Strengths and weaknesses of IRD techniques.....	75
3.4.1.1. Sieving	75
3.4.1.2. Laser particle size analysis (LPSA)	75
3.4.1.3. X-ray clast counting (> 2 mm).....	76
3.4.1.4. Grey value standard deviation (GV SD).....	76
3.4.2. Most appropriate techniques for analysing IRD in palaeo-ice sheet settings.....	77

3.4.3. Wider implications	81
3.5. Conclusions	82

Chapter 4: Quantifying User Variability in the Traditional X-ray Ice-rafted Debris (clast) Counting Technique84

4.1. Introduction.....	84
4.1.2. Why might inaccuracies and inconsistencies occur?	84
4.1.3. Aims and Objectives.....	86
4.2. Methods	87
4.2.1. Clast counting participatory study	87
4.2.2. Participatory analysis.....	88
4.2.3. Statistical analyses.....	89
4.3. Results	90
4.3.1. Accuracy of manual clast counting in glaciomarine sediments.....	90
4.4. Discussion.....	95
4.4.1. Accuracy and reproducibility of clast counting	95
4.4.2. Does expertise increase the accuracy of X-radiographic clast counting?.....	95
4.4.3. Why is the Grobe (1987) technique prone to inconsistencies between users?	98
4.4.4. A protocol to improve consistency between users when undertaking the Grobe (1987) IRD method.....	99
4.4.5. Final considerations	99
5. Conclusions	100

Chapter 5: Constraining the Timing of Marine Ice Sheet Instability in The Minch, NW Scotland.....102

5. Introduction.....	102
5.1. Chapter aims and importance	102
5.2. Methods and materials	102
5.2.1. Sedimentology	102
5.2.1.1. Destructive sedimentological methods	103
5.2.1.1.1. Fine particle-size analysis (< 2 mm)	103
5.2.1.1.2. Sediment shear strength	104
5.2.1.2. Non-destructive sedimentological methods.....	104
5.2.1.2.1. Sediment core image analysis.....	104
5.2.1.2.2. Automated sediment characterisation using greyscale analyses.....	104
5.2.2. Micropalaeontological techniques	105
5.2.2.1. Foraminifera abundance and species identification	105
5.3. Results	106
5.3.1. East Minch sediment core facies descriptions and interpretations (JC123-021PC)	106
5.3.2. West Minch sediment core facies descriptions and interpretations (JC123-033PC)	110

5.4. Discussion	116
5.4.1. Chronology of ice stream retreat.....	116
5.4.2. Sequence of events from ice-stream stability to collapse.....	117
5.4.3. Elucidating the triggers of ice-shelf removal and retreat	120
5.4.3.1. Ice-stream retreat via internal dynamics modulated by topography in the East Minch.....	121
5.4.4. Wider implications.....	122
5.4.4.1. Reconstructing ice shelf or ice tongue extent in the palaeo-record	122
5.4.4.2 Marine ice sheet implications	123
5.6. Conclusions.....	123
 Chapter 6: A Multiproxy Analysis of Laminated Glaciomarine Sediments – Evidence from The Minch, NW Scotland (Last British-Irish Ice Sheet)	125
6.1. Introduction	125
6.2. Methods	128
6.2.1. Methodological approach	128
6.2.1.1. Sediment physical and chemical properties – colour, X-ray grey value (density), X-ray fluorescence analysis	129
6.2.2. Laminae specific investigations: particle-size analysis, colour, X-ray grey value (density) and elemental composition	129
6.2.2.1. Fe mineralogy (Mössbauer spectroscopy)	129
6.3. Results.....	129
6.4. Discussion	133
6.4.1. Laminae colour and density – characteristics influenced by a multitude of factors	133
6.4.2. The depositional mechanism behind laminated glaciomarine sedimentation in The Minch, NW Scotland.....	133
6.4.3. Wider supporting evidence and implications.....	134
6.5. Conclusions.....	136
 Chapter 7 - Synthesis and Future Work.....	138
7.1. Introduction	138
7.2. Is there a need for automated sediment characterisation in glaciomarine sedimentology?.....	138
7.3. How can glaciomarine sediment and ice-rafted debris (IRD) be quantified using automated image analysis?.....	138
7.4. Ice-rafted debris (IRD) – how can our current understanding of the strengths and limitations of different IRD techniques be refined?	139
7.5. Can the marine ice sheet instability be constrained over marine and terrestrial boundaries? Can a trigger for ice stream collapse be elucidated within the timeframe?	140
7.6. Reconstructing ice-shelf extent in the palaeo-record	141

7.7. Marine ice sheet sedimentology – how can laminated sediments advance insights into ice-stream stability?	143
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Chapter 8: Thesis Conclusions	145
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9. Appendices	150
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Appendix A - Supplementary materials for Chapter 2 "Automated Characterisation of Glaciomarine Sediments using X-ray Computed Laminography"	150
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Appendix B - Supplementary materials for Chapter 4 "Quantifying user variability in the traditional X-ray ice-rafted debris (clast) counting technique"	159
---	-----

10: References	165
-----------------------------	------------

List of Figures

Figure 1.1. The impact marine ice sheet dynamics may impart on sea-level-rise under scenario 8.5 if factored in to modelling. Sea levels recorded in m above pre-industrial sea levels (IPCC 2021a).	17
Figure 1.2. Marine ice sheet instability under the Antarctic model with retainment of ice shelf. A retreating grounding line further enhances flux at the grounding line, leading to runaway retreat. Warm water bottom currents enhance melting at the grounding line, which triggers grounding line retreat and / or ice shelf thinning (Siebert et al., 2020).....	18
Figure 1.3. Ice shelf volume change around Antarctic 1994 – 2012 (Paolo et al., 2015). Note: excessive thinning on the West Antarctic Ice Sheet relative to thinning on the East Antarctic Ice Sheet (Page 16).....	19
Figure 1.4. Larsen B ice shelf retreat (pre-1998 – 1999) and collapse (2000-2002) and the subsequent impact on feeding glacier velocities (Scambos et al., 2004).	20
Figure 1.5. Variable effect of ice shelf buttressing on Antarctic Ice Sheet (Fürst et al., 2016).	21
Figure 1.6. Examples of geomorphological ice shelf evidence including: 1 – grounding-zone wedges in Baffin Bay and Canadian Beaufort Sea (Batchelor and Dowdeswell, 2015). 2 – Iceberg ploughmarks (deep U-shaped, single scours and multi-keeled iceberg ploughmarks) North Sea (Kirkham et al., 2025). 3 – Corrugation ridges on the Norwegian shelf Margin (Batchelor et al., 2023).....	27
Figure 1.7. Ice shelf sediment signatures from the Northern Hemisphere. A (top) – ice shelf sedimentation model when present; B (middle) – signature of ice shelf collapse; C (bottom) – sediment signatures (as preserved in X-radiographic images); ice rafted debris abundances; Total organic carbon (TOC %); Foraminifera species, abundances and planktic:benthic ratios. Sources: Facies 1 – Peters et al., 2016; Furze et al., 2018; Reilly et al., 2019; Bradwell et al., 2019; O'Regan et al., 2021. Facies 2 – Bradwell et al., 2019; Reilly et al., 2019; O'Regan et al., 2021. Facies 3 – Furze et al., 2018; Reilly et al., 2019; O'Regan et al., 2021; Smith et al., 2023. Facies 4 – Reilly et al., 2019; Jennings et al., 2023. Foraminifera results acquired from Peters et al., 2015; Jennings et al., 2020, 2023; Syring et al., 2020; Detlef et al., 2021; Lloyd et al., 2023). Facies 5 – Peters et al., 2016; Furze et al., 2018; Reilly et al., 2019; Vermassen et al., 2020; O'Regan et al., 2021; Jennings et al., 2023. Total Organic Carbon results are highly variable with two examples in the literature, one from the NE Laurentide Ice Sheet (Lancaster Sound) (Furze et al., 2018, the other from the Petermann Ice Shelf, N Greenland (Detlef et al., 2021). Foraminifera results sourced from Peters et al., 2016; Furze et al., 2018; Jennings et al., 2020, 2023; Detlef et al., 2022; Lloyd et al., 2023.	30
Figure 1.8. Sedimentary signature of sea-ice sediment packages (Dowdeswell et al., 2000; Ó Cofaigh and Dowdeswell, 2001).	33
Figure 1.9. British-Irish Ice Sheet evolution from Last Glacial Maximum (26 ka) to the collapse of the marine portions (17 – 15 ka). Note the uncertainties between minimum (inner grey boundaries), white boundaries – the authors' preferred limits) and grey, shaded boundaries (maximum model	

error) (Clark et al., 2022). This thesis aims to better constrain the limits of the offshore NW Sector in The Minch, NW Scotland between 17 and 15 ka.34

Figure 1.10. Left: grounding-zone wedges and associated terrestrial cosmogenic nuclide (TCN) dates. White box indicates inset map location for panel A (right). Right: A and B – grounding-zone wedge 15, note heavily scoured surface. C – profile of grounding zone wedge 15. D and E – cross-cutting and highly linear iceberg scours on GZW 15 and 16, D = length (X-axis) and seabed incision (Y-axis); e = profiles of U-shaped and V-shaped iceberg scours from GZW 15. F – orientation of iceberg scours.36

Figure 1.11. Grounding-zone wedges (15e – East, 15w – West, 16 and 17) and core locations around the Central Minch. Core sections labelled in shorthand (e.g. JC123-020PC = 20PC). Associated TCN dates (see Bradwell et al., 2021 and references therein). Note: MTBH = mid-trough bedrock high.37

Figure 2.1. Translational computed laminography method. X-rays are emitted from the source and pass through the sediment core before they are captured by a detector, where an algorithm is used to reconstruct images at ‘thin sections’ at specified depth intervals of the core.42

Figure 2.2. Two-stage sampling window selection method which differs slightly for sediments with inclined laminae (annotated on right). Stage 1 involves beam hardening correction as illustrated from changes between blue to red (boxes and lines). Note: some data naturally cropped on core edges during beam hardening correction. Stage 2 involves cropping images free from blurred or disturbed cores edges (yellow boxes). For inclined laminae, stage 2 also involves rotating images at the inclination of laminae until horizontally parallel. Line plots indicate degree of cupping due to beam hardening. Illustrated by polynomial functions (curvature coefficients underlined) pre-beam hardening correction $a = 795$, post-beam hardening correction $a = -12$ (apparent ‘overcorrection’ due to greyscale variation in sediments). Black/yellow boxes: sampling windows. Note: greater sampling window for images post-beam hardening corrections.....43

Figure 2.3. Sediment classification based on X-ray imaging properties (grey value mean and standard deviations). In these (positive) X-radiographic images, lower density sediment is reflected as higher grey values (= whiter); high density sediment as lower grey values (= darker). Each negative departure from the mean represents a high-density (low grey value) clast or grain; positive departures may represent low-density sediment, voids or edge-effect ‘halos’ associated with clasts. Note: the following are the supplementary data related to this article: Video (11MB)–Download: Download video (11MB); Video 2 – Download: Download video (3MB).44

Figure 2.4. Comparison of different IRD proxy measurement techniques. Blue bars: sediment heterogeneity (grey value standard deviation; summed area under curve per cm); green bars: % area of clasts (>~0.5 mm) per cm; red bars: traditional grain counts (>2 mm) at 1 cm downcore intervals. a) JC123-032PC-section-05; b) JC123-032PC-section-06; c) JC123-033PC-section-05; d) JC123-033PC-section-06. Note summed standard deviation (blue bars) expressed in standard form (1×10^6).46

Figure 2.5. Scatter plots of X-ray grey value, expressed as sum of standard deviation (i.e. sediment heterogeneity), per 1 cm downcore area vs % of clasts per 1 cm area; with associated Pearson’s correlation coefficients shown (r).47

Figure 2.6. Grey value mean and standard deviations at pixel-scale resolution (0.066 mm) downcore. a) Core sections JC123-032PC-section-05 and JC123-032PC-section-06. b) Core sections

JC123-033PC-section-05 and JC123-033PC-section-06. Sub-section lengths approx. 10–20 cm.
 48

Figure 2.7. a) Sediments in cores JC123-032PC-section05 + 06 and JC123-033PC-section-05 + 06 characterised by X-ray greyscale properties (mean grey value and standard deviation at pixel resolution). GV data systematically sampled at 10-pixel downcore intervals; b) Sediment classification by greyscale properties, dissected using modified Folk classification (Long, 2006). Colour of symbol indicates fine-grained sediment density. Shapes denote true % of clasts per Folk class. Each class contains a minimum of 50 data points, optically discriminated into dense ($n = 25$) and less dense sediments ($n = 25$) randomly sampled by mean grey value and associated standard deviation..... 49

Figure 2.8. Grey value deviation (16-bit) vs clast abundance (%) measured at pixel-scale resolution. Clast-free sediments (<1%) highlighted in grey near origin (excluded from correlation). Note: log scale on x-axis to aid data visualisation. 50

Figure 2.9. Comparison of X-radiography (XR) and X-ray computed laminography (CL). a) and b) Surface plots of images for each scan (JC123-032PC-section-06) before (top) and after (bottom) beam hardening corrections (a = XR; b = CL). c) Comparison of curvature coefficients between scanning methods and image treatments (flat = post-beam hardening correction for each image). d) Side by side comparison of XR and CL images with glaciomarine sediments from core JC123-032PC-section-05. The lower detail observed in XR images is the result of excessive X-ray attenuation and lower geometric magnification (Zuber et al., 2017). 52

Figure 2.10. Examples of overestimations in sediment characterisation from: i) laminae boundaries; ii) flocculated silts; iii) wavy laminae; iv) bright clast-edge ‘halo’. b) Other examples of artifacts: ‘ghost clasts’ outwith scanning region of interest in CL (red circles); Bright halos at clast edges (black boxes); surface artifact reduced in CL image (blue arrows). 54

Figure 2.11. Statistical phenomena associated with using GV SD as a proxy for % clast abundance (IRD): a) maximum GV SD of 16-bit GV image; bi) overestimations due to small dense clast in low density (high GV) matrix; bii) underestimations due to clasts of variable radiodensity embedded within dense matrix. 56

Figure 3.1. Distributions of each method’s IRD quantification outputs displayed using violin plots. Thicker regions of the violin indicate more closely-distributed values; thinner regions indicate more sparsely-distributed values. Thick black lines indicate means, grey lines indicate Q1 and Q3. Note: no normal distributions, therefore Spearman’s rank correlation was selected..... 71

Figure 3.2. Strip plots (top) indicate IRD abundances per facies, black dotted lines indicate mean values per facies. Core images for each facies (below). Key: OLs (optical linescan images); XR – X-radiography; CL – X-ray computed laminography; Log – sediment log (interpretive representation, not an accurate sketch). 71

Figure 3.3. Downcore IRD signals from different techniques. Note: methods do not have consistent Y-axis for example sieving at $>63 \mu\text{m}$ and sieving $> 250 \mu\text{m}$. Core images: a) optical linescan images; b) X-ray computed laminography; c) sediment log, a graphical representation of the core, not an accurate sketch. 73

Figure 3.4. Scatterplot matrix indicating relationships between different ice-rafted debris techniques. ‘*’ = $P\text{-value} < 0.05$; ‘**’ = $P\text{-value} < 0.01$; ‘***’ = $P\text{-value} < 0.001$ 74

Figure 4.1. Illustration of how to perform clast counting manually from X-radiographs (Grobe, 1987).....	85
Figure 4.2. Sediment facies and core images provided to participants in this study. Panel a) shows the two images in full with the sedimentary facies. Panel b) scale bar visible on images, the scale bar appeared in 10 cm interval on the right hand side of core images (0.2 cm). Panel c) pre-labelled depth intervals to ensure consistency between different users. Inset images are colour coordinated.	87
Figure 4.3. Participant count distributions illustrated by frequency. Wider violin sections indicate more frequent user counts. For example, a wider violin at 5 (y axis = counts) for Participant 1 than at 10 indicates that Participant 1 counted 5 clasts more frequently than 10 clasts. Mean number of counts per image (or stratigraphic facies) are indicated by dark bars and quartiles 1 and 3 are indicated by light bars. Shapiro-wilk test of normality p-values are indicated by orange and black coloured values above each violin. Orange-coloured values indicate that the data are not normally distributed; black values indicate normally distribution data.....	89
Figure 4.4. Cross comparison (scatterplot matrix) of different users in the diamicton facies (Image 1). Values relate to Spearman's rho correlation coefficient, '' = $P\ value < 0.05$; '' = $P\ value < 0.01$; '' = $P\ value < 0.001$. Participants numbered 1 – 14 based on experience level.	90
Figure 4.5. Cross comparison (scatterplot matrix) of different users in the laminated facies (Image 2). Values relate to Spearman's rho correlation coefficient; '' = $P\ value < 0.05$; '' = $P\ value < 0.01$; '' = $P\ value < 0.001$. Participants numbered 1 – 14 based on experience level.	91
Figure 4.6. Participant counts by core depth. Y-axis is ordered by level of experience. Note consistent Y-axis scale between users for each image.....	92
Figure 4.7. The user variability of clast counting on X-radiographs. Bars indicate the standard deviation of all users' counts for each horizon on Image 1 (top) and Image 2 (bottom). Heatmaps indicating the variability between users with warmer colours indicating greater number of users. Green lines indicate modal counts per cm interval (the most commonly returned clast count for each cm interval between all participants).	93
Figure 4.8. Average clasts counted per cm interval for each user. Numbers refer to the expertise ranking of different users.	94
Figure 4.9. Time taken to perform task on Image 1 and Image 2 respectively. Scatter points represent users.	94
Figure 4.10. Average counts for each user on different images. This figure highlights that most users replicate their counts consistently, but some users are more conservative than others. Error bars indicate the standard error for each participant for each image.....	96
Figure 4.11. Participant 1 and Participant 2 counts in relation to the laminated sedimentary package (Image 2). Note: core depths between 50 and 70 cm highlight that lower radiodensity clasts are not counted by Participant 2 but are counted by Participant 1 leading to significant discrepancies between users. Participant 1 also appears to be more liberal in the 2 mm threshold, whereas Participant 2 may be more conservative and stringent.....	97

Figure 5.1. Minch Palaeo-ice Stream setting and associated grounding zone wedges in the Central Minch (Bradwell et al., 2021). Timing of onshore glacial conditions evidenced by Cl36 radionuclide dates (Small et al., 2016; Bradwell et al., 2019). 100

Figure 5.2. Relationship between gamma density (g/cc) and X-ray mean attenuation. Data extracted from X-radiographs on glaciomarine sediments from cores JC123-031PC and JC123-069VC (see Bradwell et al., 2019, 2021 for core locations and descriptions). This figure was produced by researchers at Geotek Ltd. 105

Figure 5.3. Sediment packages sourced from the eastern Central Minch (Core JC123-021PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies. 107

Figure 5.4. Sediment packages sourced from the eastern Central Minch (Core JC123-021PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies. 108

Figure 5.5. Sediment stratigraphy and associated palaeoenvironmental proxies in core JC123-021PC. Sediment core linescan optical images, X-ray images and sediment logs on left. X-radiographic grey value extractions in black and red downcore area plots – black = mean X-ray grey value from X-radiographic images, a proxy for density; red = grey value standard deviation sampled from X-ray computed laminographs, a measure of sediment heterogeneity and a proxy for iceberg rafting) (McDonald et al., 2022). Clast counts (> 2 mm) in purple bars, a proxy for iceberg rafting, note correlation with grey value standard deviation (Grobe, 1987). Laser particle size analysis (Bettersizer S3) output displayed on heatmap, brighter colours indicate increased percentages of the sediment. Sediment shear strength in grey bullet points. Foraminiferal abundances and assemblages displayed 2nd and 3rd from the right, note assemblages on bars are measured in 50 cm intervals downcore (relative to 5 cc of sediment); assemblages are resampled with higher abundances. Red crosses indicate locations where 20 ml of foraminifera were sampled for analysis but were found to be barren of foraminifera. Radiocarbon dates calibrated using RBAcon (Blaauw & Christen 2011). Note samples correspond to both core stratigraphy (top to bottom) and years BP (ka cal) (left to right). 109

Figure 5.6. Sediment packages sourced from the western Central Minch (Core JC123-033PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies. 111

Figure 5.7. Sediment stratigraphy for West Minch (JC123-033PC). Sediment stratigraphy and associated palaeoenvironmental proxies in core JC123-033PC. Sediment core linescan optical images, X-ray images and sediment logs on left. X-radiographic grey value extractions in black and red downcore area plots – black = mean X-ray grey value from X-radiographic images, a proxy for density; red = grey value standard deviation sampled from X-ray computed laminographs, a measure of sediment heterogeneity and a proxy for iceberg rafting) (McDonald et al., 2022). Clast counts (> 2 mm) in purple bars, a proxy for iceberg rafting, note correlation with grey value standard deviation (Grobe, 1987). Laser particle size analysis (Bettersizer S3) output displayed on heatmap; brighter colours indicate increased percentages of the sediment. Sediment shear strength in grey bullet points. Foraminiferal abundances and assemblages displayed 2nd and 3rd from the right, note assemblages on bars are measured in 50 cm intervals downcore (5 cc of sediment); abundances are resampled with higher abundances. Radiocarbon dates calibrated using RBAcon (Blaauw & Christen, 2011). Note: samples correspond to both core stratigraphy (top to bottom) and years BP (ka cal) (left to right). Air temperature (proxy – $\delta^{18}\text{O}$) as presented in Greenland ice core

(NGRIP). Summer sea-surface temperature (Mg / Ca – <i>G. bulloides</i>) sourced from Porcupine Seabight (MD 01-2461) (Peck et al., 2008).	112
Figure 5.8 Foraminifera assemblages for core JC123-033PC. Samples taken every 50 cm upcore from 800 cm to 150 cm with one further sample recorded at 110 cm.....	113
Figure 5.9. Sediment packages sourced from the western Central Minch (Core JC123-033PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies.....	114
Figure 5.10. Central / Inner Minch retreat chronology constrained via our new suite of AMS ¹⁴ C dates. Dates in grey text are sourced from cosmogenic radionuclide ³⁶ Cl ages from the Isle of Skye and Isle of Raasay (Stone et al., 1998; Small et al., 2012; Ballantyne and Small, 2018; Bradwell et al., 2021).	120
Figure 6.1. Characteristic laminated glaciomarine sediments. Figures adapted from Ó Cofaigh and Dowdeswell, (2001); Mackiewicz et al. (1984); Maddison et al. (2005); and Furze et al. (2018).	126
Figure 6.2. Sediment core images used in this chapter. Two sediment core sections with ITRAX optical images (left) and ITRAX X-radiograph images (right) (histogram window applied to improve visibility, but was not used for data analysis). Cores: JC123-031PC-section-7 (left); JC123-031PC-section-4 (middle); JC123-020PC-section-7 (right). Note: strong red colouration within core JC123-020PC-section-G (East Minch).	128
Figure 6.3. Panel a) colour (R/B) vs mean grey value (16-bit) for each core section. Panel b) elemental composition vs mean grey value (16-bit) for each core section. Panel c) elemental composition vs colour (R/B) for each core section.....	130
Figure 6.4. Particle-size analysis results for core JC123-020PC-section-7; JC123-031PC-section-4 and JC123-031PC-section-7 – labelled 20(7), 31(4) and 31(7) respectively. Panel a) Distributions of particle-size analysis results for core JC123-020PC-section-7; JC123-031PC-section-4 and JC123-031PC-section-7. Statistics refer to p-value results using Shapiro-Wilk test for normality. Panel b) Core images for core JC123-031PC-section-7 (core length = 40 cm), relevant particle-size distributions for representative red, blue-grey and dark laminae are presented. Panel c) Relationship between laminae colour (R/B) and associated particle size for each core section. Panel d) Relationship between laminae median particle size (µm) and associated particle size for each core section.	131
Figure 6.5. Fe mineralogy measured using Mössbauer spectroscopy at room temperature (RT), 77 K and the lower temperature (4.2 K). Right panel = red layer; left panel = blue-grey layer. This figure was produced by Emily Bonsall, University of Stirling.....	132
Figure 7.1. BRITICE-CHRONO British-Irish Ice Sheet limits from 18 – 15 ka (Clark et al., 2022). Minch Ice Stream (NW British-Irish Ice Sheet sector) ~18 – 16.6 / 16.0 ka cal BP (Chapter 5; Stone et al., 1998; Small et al., 2012; Ballantyne and Small, 2018; Bradwell et al., 2021).	140
Figure 7.2. Iceberg scours and associated curvature coefficients ('a' in the polynomial quadratic function) used to emphasise flatness (U- or V-shaped). Minch iceberg scours share a close association with those calved from iceberg scours. Pine Island Bay examples sourced from Wise et al. (2017).	142

Figure 7.3. British-Irish Ice Sheet limits at 29 ka BP as reconstructed by the BRITICE-CHRONO model (Clark et al., 2022). Note: large ice shelves surrounding the North-Western ice sheet sectors.
..... 143

List of Tables

Table 2.1. Pearson's correlation coefficients (r) between the sum of sediment heterogeneity (grey value standard deviation) per cm; number of clasts per cm downcore; and % area of clasts per cm for each core section	47
Table 3.1. Correlations of existing work assessing different ice-rafted debris techniques on two sediment cores (McKay et al., 2022). Note variable correlation coefficients between the same methods on different cores (notable LPSA and X-ray clast counting). Values = Pearson's R correlation coefficients; or R^2 denoted by *	62
Table 3.2. Comparison of IRD techniques: strengths, drawbacks and unknowns (Ruddiman, 1977; Andrews, 2000; Bartels et al., 2017; Reilly et al., 2019; McKay et al., 2022; McDonald et al., 2022)	66
Table 3.3. The mean IRD abundances per stratigraphic unit (facies). Colour denotes facies of higher or lower average IRD abundance.	72
Table 3.4. Checklist for selecting and implementing IRD techniques. Suitability of each technique to quantifying IRD in sediment cores of deglacial marine-terminating glacier / ice streams of palaeo-ice sheets (e.g. British-Irish Ice Sheet).	78
Table 5.1. Atomic Mass Spectrometry (AMS) ^{14}C radiocarbon dates, core depths, description of sample type and integrity. Note: not all radiocarbon dates are reported in this study, as some are rejected based on erroneous dating with regard to the core stratigraphy, while others are recovered from sediment cores which are not investigated in this chapter.	115
Table 6.1. Relationships between laminated sediment properties.	135

Statement of Original Authorship

I certify that the work contained within this thesis, including text, figures and tables, is my own, except where specifically stated. The thesis has been composed by myself and has not previously been accepted for a degree or professional qualification.

Signature: N. McDonald

Date: 27/07/2025

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Chapter 1: Introduction

1. Introduction

1.1. The impact of marine-based ice sheets on sea level rise

The largest sea-level-rise uncertainty stems from the long-term unpredictability of marine-terminating glaciers and ice streams – fast flowing sectors of ice sheets (Weertman, 1974; Bennett, 2003; Durand et al., 2009; Robel et al., 2021; IPCC, 2021a; Montelli et al., 2023; Bett et al., 2024; Figure 1.1). This is due to a range of contributing and poorly understood factors which may promote or suppress ice-sheet instabilities. The major societal concern is the ‘marine ice sheet instability hypothesis’ which suggests that marine-based ice sheets or outlet glaciers flowing over reverse (or retrograde) bed slopes may be prone to irreversible, self-reinforcing, runaway retreat (Schoof, 2007; Favier et al., 2014; Pattyn and Morlighem, 2020; Robel et al., 2021; Figure 1.2).

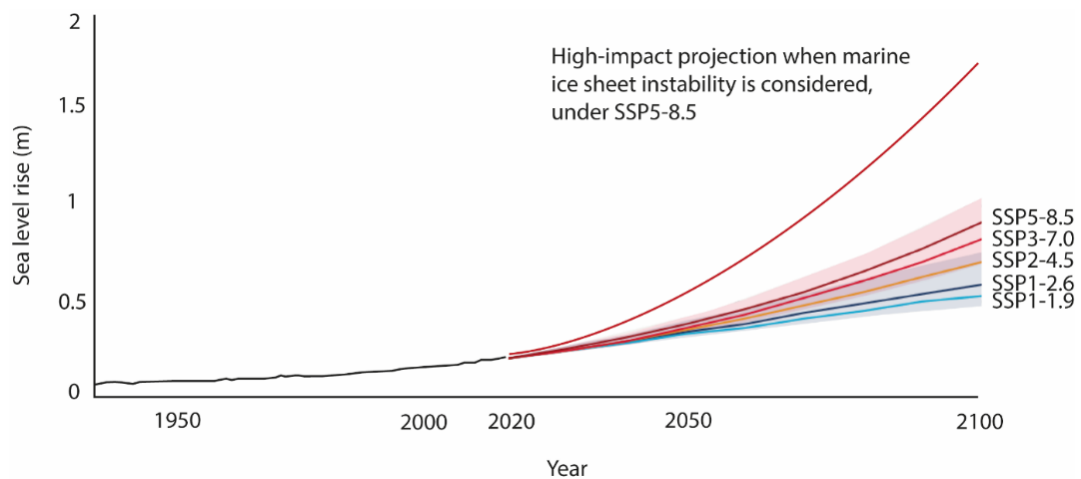


Figure 1.1. The impact marine ice sheet dynamics may impart on sea-level-rise under scenario 8.5 if factored into modelling. Sea levels recorded in m above pre-industrial sea levels (IPCC 2021a)

Marine-terminating glaciers and ice streams such as those in West Antarctica and Northern Greenland are subject to both external forcing factors such as rising air, sea-surface temperatures, precipitation and internal forcings such as topography, bed roughness, trough geometry and ice-shelf thinning / collapse (Rack and Rott, 2004; Rignot et al., 2004; Jamieson et al., 2012; Gudmundsson et al., 2012; Gudmundsson, 2013; Favier et al., 2014; Pegler, 2018; Haseloff and Sergienko, 2018).

Current evidence of Antarctic glaciological configurations suggests that marine ice sheet instability is not yet underway, however, if retreat from the current positions occurs, MISI style retreat *may* be triggered (Hill et al., 2023; Reese et al., 2023). It is critical, therefore, to better understand the marine ice sheet instability, including the nature and timescales on which the phenomenon operates.

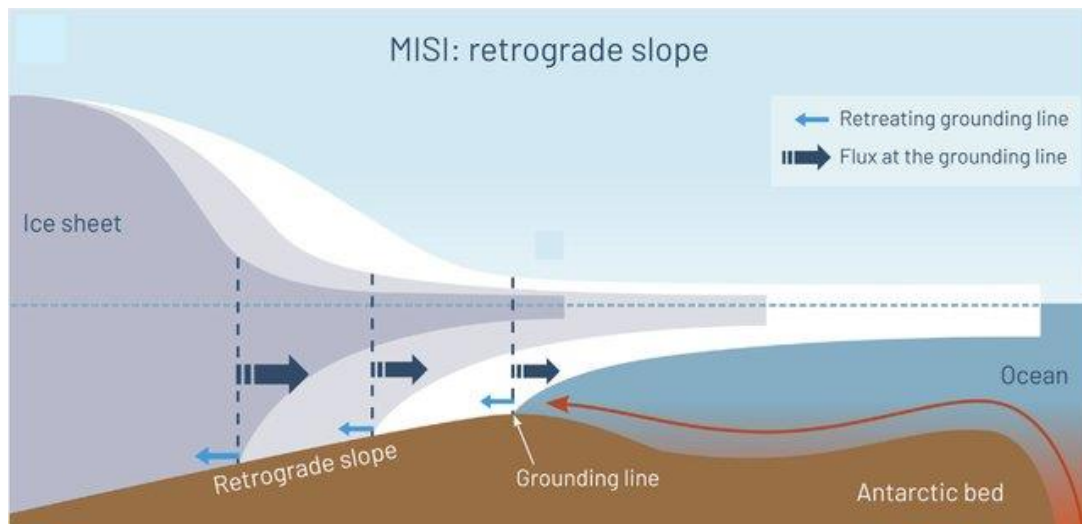


Figure 1.2. Marine ice sheet instability under the Antarctic model with retainment of ice shelf. A retreating grounding line over a retrograde slope, further enhances flux at the grounding line – leading to runaway retreat. Warm water bottom currents enhance melting at the grounding zone, which triggers grounding line retreat and / or ice shelf thinning (Siegert et al., 2020).

1.1.1. The importance of ice shelves in the stability of ice streams

Although ice streams which flow over reverse beds are typically unstable, transient stabilisations can occur in certain situations (Jamieson et al., 2012; Gudmundsson et al., 2012). The many factors determining marine ice sheet (in)stability include: surface mass accumulation; velocity, topography, trough shape, bed roughness, ice-shelf (de)buttressing etc. (Schoof, 2007; Jamieson et al., 2012; Gudmundsson, 2013; Favier et al., 2014; Bradwell et al., 2019). Anthropogenic climate warming may trigger alterations in ice-stream configurations which could impart dynamical glacial retreat and potentially ice-sheet collapse, for example, in the case of the West Antarctic Ice Sheet (Thomas, 1979).

Uncertainties persist regarding whether ice streams and their associated floating components (ice shelves) have been thinning and retreating principally due to atmospheric or oceanic warming (Pritchard et al., 2012; MacDonald et al., 2018; Etourneau et al., 2019). Observations of the Petermann ice shelf (or tongue) show significant increases in summer supraglacial pool development thought to promote large-scale calving events providing a trigger for calving via atmospheric warming (MacDonald et al., 2018).

It is important to understand whether ice streams are equally, more or less sensitive to alterations in sea-surface temperatures than air temperatures, as the advection of warm ocean currents has been suggested to be a vector for ice-shelf calving – weakening the ice shelves buttressing capacity (Schoof, 2007; Gudmundsson, 2013). Evidence of oceanic, bottom-current driven thinning has been observed in the Amundsen Sea, West Antarctica captured in satellite radar altimeter data, however, recently thinning rates have slowed in response to changing ocean conditions since 2008, particularly

on larger ice shelves with deeper draft depths, such as Pine Island and Crosson ice shelves, potentially suggesting that ice shelf size may play an important factor in responding to oceanic modulations (cf. Paolo et al., 2015; Paolo et al., 2023; Figure 1.3).

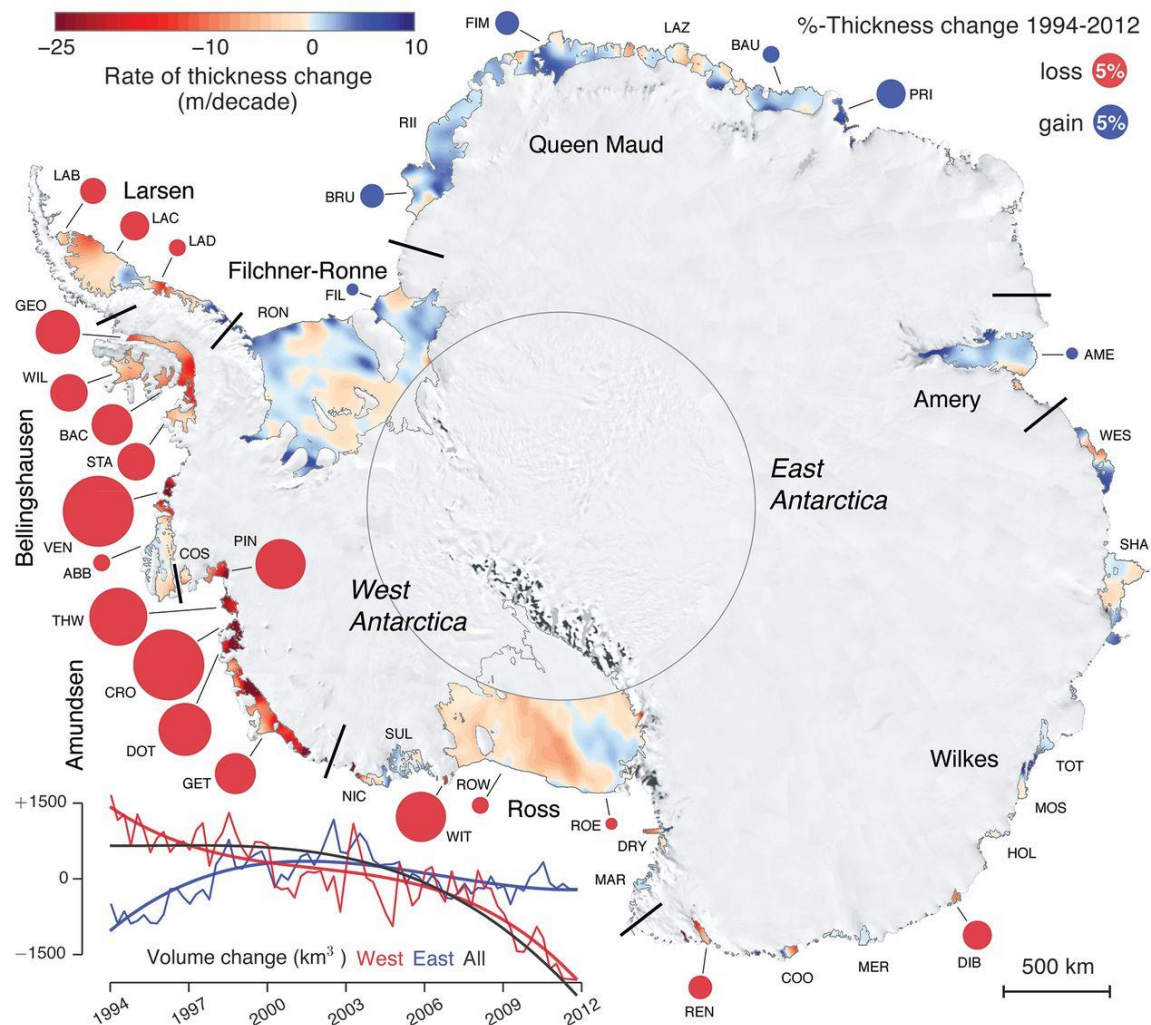


Figure 1.3. Ice shelf volume change around Antarctic 1994 – 2012 (Paolo et al., 2015). Note: excessive thinning on the West Antarctic Ice Sheet relative to thinning on the East Antarctic Ice Sheet.

Therefore, it is important to understand the roles of ocean and atmospheric warming in relation to ice shelf de-buttressing in order to determine thresholds (or tipping points) for ice-stream destabilisation. Understanding the relative inputs of atmosphere / ocean warming on ice shelves is of imminent importance, as the loss of large ice shelves may occur over a single summer – as observed in the Larsen B embayment – where the ice shelf lost $\sim 3200 \text{ km}^2$ of ice, which triggered a 2 - 8 fold increase in feeding glacier velocities (Rignot et al., 2004; Scambos et al., 2004; Figure 1.4).

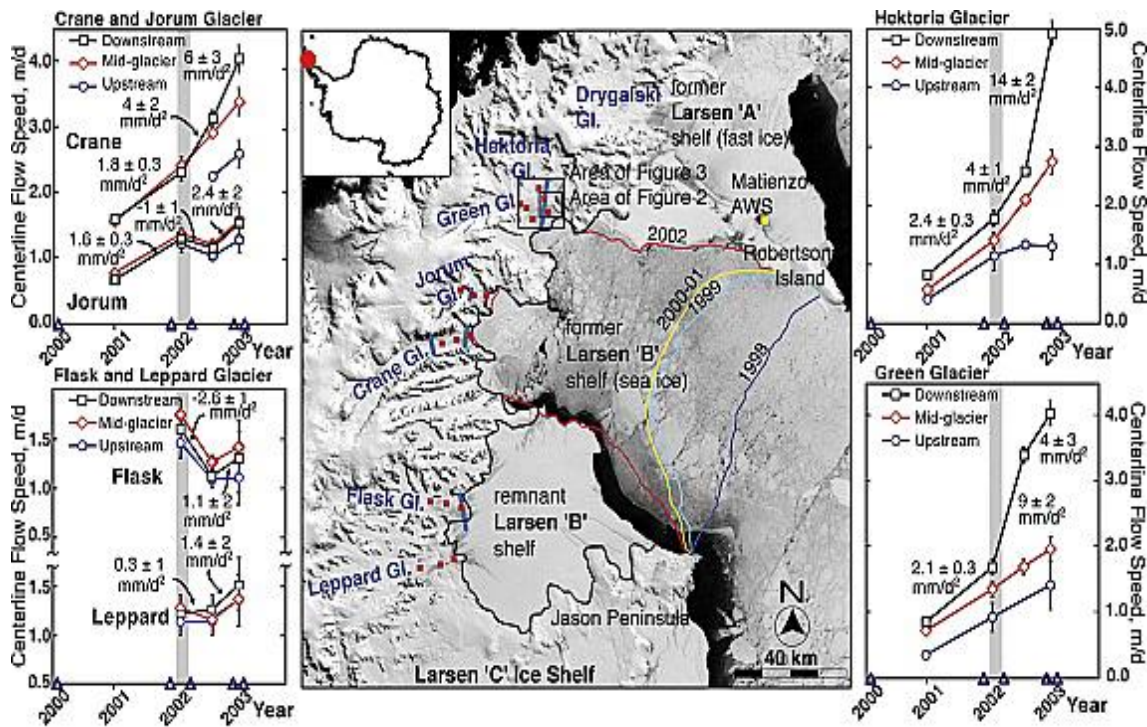


Figure 1.4. Larsen B ice shelf retreat (pre-1998 – 1999) and collapse (2000-2002) and the subsequent impact on feeding glacier velocities (Scambos et al., 2004).

Ice shelves are anticipated to inevitably thin and potentially collapse at an increasing rate in response to climate warming (Naughten et al., 2023). Additionally, recently conflicting evidence shows that ice shelves may not always buttress flow, rather ice shelves buttressing relies on a complex interplay of stress, concerning: thickness, width, ice rises, ice rumpled and trough width (Goldberg, 2017). Thus, across Antarctica variable buttressing impacts of ice shelves is observed (Furst et al., 2016; Figure 1.5).

Despite being critical in the future evolution of ice stream and marine-terminating sectors of ice sheets, whether ice-shelf size has an impact on ice-stream buttressing remains unclear and is still largely unexplored. For example, Petermann Glacier, N Greenland has recently lost a significant portion of its ice shelf and further reductions in the size of its ice shelf are projected in future (Hill et al., 2021; Åkesson et al., 2022). There is limited empirical evidence whether a significant reduction in ice shelf extent necessarily destabilises marine-terminating glaciers and ice streams over long timescales. By studying palaeo-ice streams, ice-ocean interactions and the effect of ice-shelf presence, size, removal and collapse can be explored over long timescales, allowing clearer insights into how contemporary ice sheet sectors (for example Petermann Glacier) will respond to such phenomena.

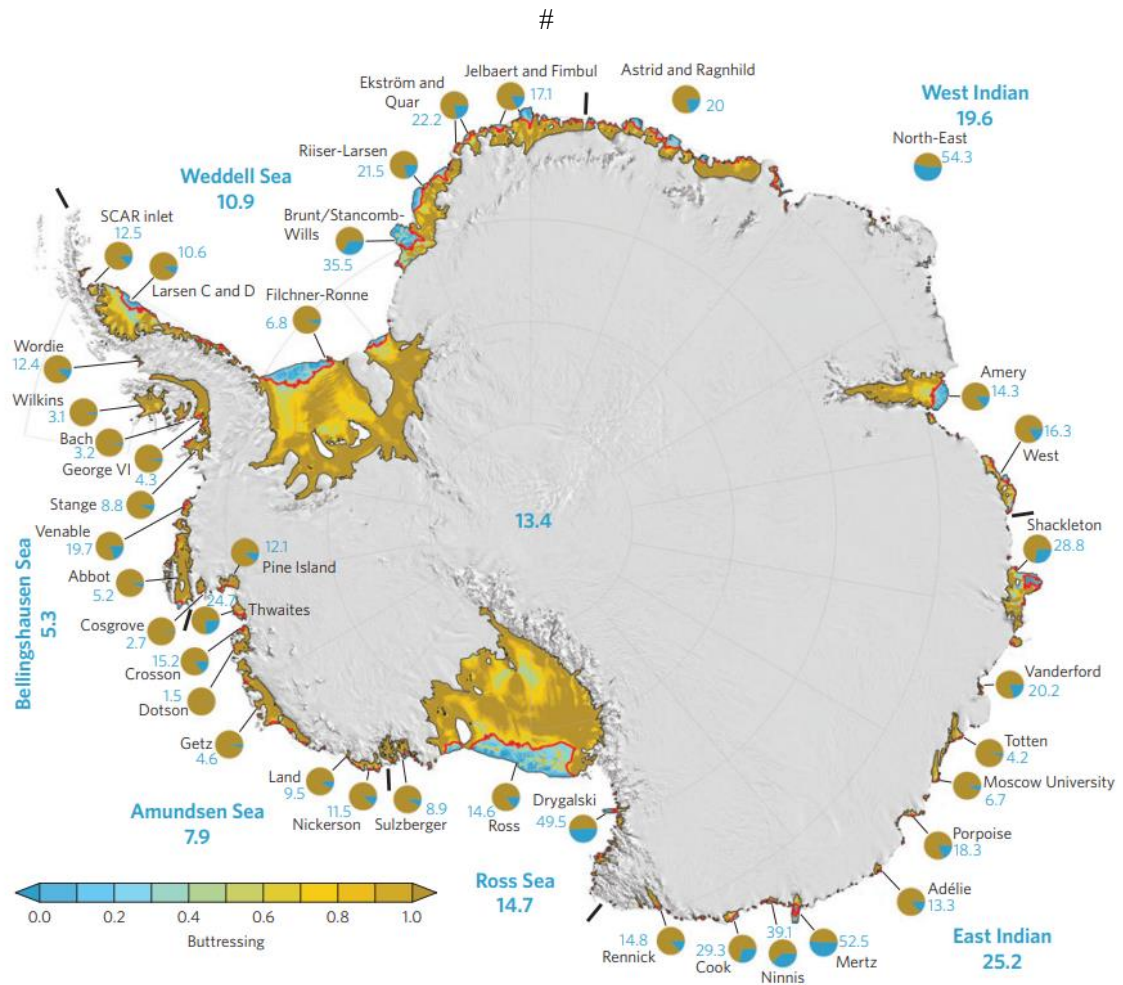


Figure 1.5. Variable effect of ice-shelf buttressing on the Antarctic Ice Sheets. Note the lack of apparent correlation between ice shelf size and buttressing capacity (Fürst et al., 2016).

Observations of ice sheets and marine-terminating glaciers with remote sensing observations only span multiple decades rather than centuries or millennia. An empirically robust mechanism for obtaining prolonged records of marine ice sheets is possible through studying the record of past ice sheets, allowing a complete record of deglaciation (the transition from extant to extinct ice-stream conditions) something which is not afforded by contemporary ice sheets. However, in order to reconstruct centennial to millennial scale ice-stream and ice-shelf legacies, robust sedimentation models must be developed.

This thesis aims to improve understanding of long-term ice-stream behaviour by exploring new techniques for analysing glaciomarine sediments, critique established techniques and undertake a comprehensive multi-proxy investigation of a palaeo-ice stream in the NW sector of the last British-Irish Ice Sheet (BIIS). Specifically, this research seeks to refine how glaciomarine sediments are classified, including the identification and quantification of ice-rafted debris (IRD), and improve understanding over the chronology and nature of ice-stream demise in the Minch NW Scotland,

during the last glacial cycle. This includes establishing the extent of ice shelf(ves), duration of stability, rate of retreat and if possible, a trigger for ice-stream collapse.

1.2. Glaciomarine sedimentation model

Multiproxy investigations of glaciomarine sediments allow insights into long-term ice-sheet / ice-stream dynamics, ice-marginal conditions (ice shelf / sea ice) and ice-ocean interactions (Scourse et al., 2009; Vermassen et al., 2020; Clark et al., 2022; Smith et al., 2023). Many sedimentological proxies can be combined to achieve such goals, including (but not limited to): sediment physical properties (stratigraphy, structure, texture, colour and X-ray imaging properties), ice-rafted debris, foraminifera, atomic mass spectrometry (AMS) ^{14}C dating and inorganic chemistry (e.g., elemental composition) and organic chemistry (e.g., total organic carbon and lipid biomarkers).

1.2.1. Ice-rafted debris (IRD)

Of all of the methods used in glaciomarine sedimentology, perhaps the most commonly and inconsistently applied techniques (with regard to methodological adaptation) is ice-rafted debris (IRD). IRD refers to material which is transported by icebergs and deposited in the seas / oceans and can comprise the entire spectrum of glacial sediment depending on the origin of sediment – e.g. supraglacial or englacial inheritance (see Andrews, 2000). IRD is typically differentiated from other glaciogenic or oceanographic sediment by quantifying the abundance of coarse sediment – typically sand or gravel (Heinrich, 1988; Scourse et al., 2009; Hodell et al., 2017; Callard et al., 2018; McKay et al., 2022).

Increases and decreases in IRD concentrations for any given proxy are *generally* considered to infer increases or decreases in iceberg flux (e.g. Weber et al., 2014; Grobe, 1987; Rack et al., 1996; Grobe and Mackensen, 1992; Weber et al., 2014; Graham et al., 2017). However, several inconsistencies persist in IRD interpretation, these factors may include inclusion of coarse sediments via non-IRD sedimentation due to mass flows or turbidity / bottom currents, variability of debris rainout due to ocean thermal changes, sediment inheritance, background sedimentation rates and alterations in ocean current patterns which may cause iceberg trajectory deviations or variations in melting rates (Mackiewicz et al., 1984; Garcia and Parker, 1993; Cowan et al., 1997; Andrews 2000; Reilly et al., 2019; Vermassen et al., 2020; Starr et al., 2021). These uncertainties may bias interpretations of iceberg flux / delivery in any particular location.

IRD has proven a versatile proxy in (glacio)marine sedimentology and has been utilised to infer climate and oceanic circulation changes, ice-sheet growth and decay, and floating-ice margin (sea ice or ice shelf) presence and removal (e.g. Rack et al., 1996; Dowdeswell et al., 2000; Kneis et al., 2001; Andrews et al., 2014; Weber et al., 2014; Graham et al., 2017; Jennings et al., 2022; López-Quirós et al., 2024). Sufficient investigation of sediment cores with multiple proxies is required to tease out different components, for example, alkenone palaeothermometry to consider ocean

warming or ocean current activity (e.g. Vermassen et al., 2020) and geomorphological and micropalaeontological assessments to infer ice-shelf cover (Smith et al., 2019).

A range of approaches are applied, many of which differentiate IRD from non-IRD sediment in different manners (e.g. different sediment cut-off size thresholds ranging from $> 63 \mu\text{m}$ to $> 2000 \mu\text{m}$, different micromorphology, presenting IRD based on absolute counts or counts per sediment fraction / percentage) (Grobe, 1987; St John et al., 2015; Vermassen et al., 2019).

All of these different approaches may bias IRD records in different ways and there remains significant uncertainties surrounding what palaeoenvironmental information can be inferred from IRD records.

One of the major goals of this thesis is to advance our understanding of how different IRD methodologies may bias IRD reconstructions. And, in turn develop a new IRD quantification technique which is freely available, improves consistency and operates with increased resolution compared to existing techniques.

1.2.2. Palaeo-ice sheets and the ‘ice-shelf problem’

Many palaeo-ice sheets have been reconstructed, including the BIIS, Fennoscandian Ice Sheet, Laurentide Ice Sheet and Barents Sea Ice Sheet, via:

- i) Onshore – Geomorphology, sediment core archiving and logging, micropalaeontological investigations etc. (e.g. Mickelson and Colgan, 2003; Friere et al., 2015; Bickerdike et al., 2018)
- ii) Marine – Offshore sonar bathymetry, sub-bottom acoustic profiling, sediment core recovery and analyses, including palaeontological and geochemical methods (e.g.; Rea et al., 2018; Batchelor et al., 2019; Clark et al., 2022).

This thesis focuses on advancing understanding and best practice surrounding marine-terminating ice sheets, specifically glacial sedimentology. A persistent challenge when understanding the dynamics of past ice sheets is whether or not floating-ice shelves were present.

Until the past decade, palaeo-ice shelf reconstruction has been exceptionally challenging for researchers. The recent calving and / or collapse of ice shelves on the Antarctic Peninsula and northern Greenland, combined with advancements in sediment coring – allowing direct sub-ice-shelf penetration and sediment core recovery – have allowed for the direct extraction of sub-ice-shelf sediments (Smith et al., 2017, 2023; Reilly et al., 2019; O’Regan et al., 2021; Clark et al., 2024). These studies have revealed sedimentological signatures which allow the reconstruction of palaeo-ice shelves in deglaciated settings.

1.2.3. Palaeo-ice shelf distribution

It was highlighted by Hambrey et al. (2015), that outwith a handful of ice-shelf moraines (e.g., England et al., 1978; Evans et al., 2002), no palaeo-ice-shelves have ever been identified. Over the past ten years, however, significant progress has been made in this field. Several disintegrated sectors of present-day ice sheets / shelves have been reconstructed around Antarctica (Mcglannan et al., 2017; Minzoni et al., 2017), Greenland (Jennings et al., 2017; Vermassen et al., 2020; O'Regan et al., 2021) and the Canadian Arctic Archipelago (Antoniades et al., 2011). More recently ice shelves have been suggested based on geomorphological and sedimentological signatures pertaining to the Canadian Arctic (Furze et al., 2018) and the British-Irish ice sheet (Callard et al., 2018; Bradwell et al., 2019, 2021; Kirkham et al., 2025), occasionally supplemented with micropalaeontological (Peters et al., 2020) or modelling evidence (Gandy et al., 2018).

1.2.4. Toolkit for identifying palaeo-ice shelves.

The signature of Northern Hemisphere ice shelves is very similar to those recorded in Antarctica (cf. Smith et al., 2019; Jennings et al., 2022). Ice-shelves can be reconstructed via a multiproxy approach, combining geomorphology, sedimentology and micropalaeontology (Smith et al., 2019; Figure 1.6; Figure 1.7).

1.2.5. Geomorphology

The subaqueous geomorphological signature of ice shelves includes four main landforms: grounding zone wedges (GZW), wide U-shaped iceberg scours, multi-tooth 'toothcomb' scours and corrugation ridges (Jakobsson et al., 2011; Batchelor and Dowdeswell, 2015; Bradwell et al., 2019; Batchelor et al., 2022; Kirkham et al., 2025).

1.2.5.1. Grounding-zone wedges

Grounding zone wedges (GZWs) are asymmetric landforms situated transverse to the ice margin, and are generally accepted as forming exclusively at (or immediately proximal to) the boundary between grounded and floating ice (grounding zone) (Batchelor and Dowdeswell, 2015; Callard et al., 2018). GZWs have been associated with palaeo-ice shelves in regions such as the British Isles (Callard et al., 2018; Bradwell et al., 2019, 2021; Ó Cofaigh et al., 2021), Norwegian shelf (Rebesco et al., 2011; Bjarnadóttir et al., 2013), Greenland (Batchelor and Dowdeswell, 2015; Jennings et al., 2017; Jennings et al., 2018), North America (Lajeunesse et al., 2019) and Baffin Bay (Couette et al., 2022).

Debate is, however, ongoing regarding whether these grounding features are indicative of ice-shelf presence or simply longer-term marine terminating glacier stability / dynamics. Simkins et al. (2018) summarise the literature in this area succinctly, highlighting two competing hypotheses:

1. GZWs are fundamentally a function of ice-shelf presence whereby accommodation space, and the implicit ice-shelf stabilising implications, facilitate large asymmetric, low-amplitude wedge formation (Powell, 1990; Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015).
2. Ice shelves are not essential in the formation of GZW, rather subglacial sediment delivery is the controlling factor (Powell and Alley, 1997).

Simkins et al. (2018) prefer ‘Hypothesis 2’ – in their assessment of 6275 bedforms in the Ross Sea found that GZWs w

ere not more strongly associated with topographic highs:

“Furthermore, we might expect topographic highs to maintain grounded ice whilst ice over deeper troughs would tend towards flotation and preferentially form an ice shelf, as is argued for late-stage deglaciation in the western Ross Sea (Yokoyama et al., 2016). However, there is not a consistent relationship among recessional moraines and grounding zone wedges and their topographic context that would support this association.”

Moreover, their results also suggest that GZW in the Ross Sea have a higher amplitude than recessional moraines and they also observe typical subaqueous moraines and GZWs across the same lateral margin. GZW formation was therefore interpreted to be a combined function of sediment delivery and stability. However, the question of whether an ice shelf is essential in their formation remains unanswered.

The results from Simkins et al. (2018) simply suggest that GZWs are not the only ice-marginal landform which form at grounding lines of marine-terminating glaciers with ice shelves. Evidence of active or recently formed GZW at ice margins with no ice shelves (e.g. the present-day margin of Kangerlussuaq glacier in SE Greenland) may validate the results of Simkins et al. (2018). Secondly, Batchelor and Dowdeswell (2015) argue, convincingly, that unlike other moraine classifications, there are a lack of GZWs onshore, strengthening the case that ice-shelf presence is a prerequisite for GZW formation as echoed in the recent literature review of ice-shelf geological imprints in Antarctica (Smith et al. 2019).

1.2.5.2. Ice-shelf and iceberg scours

Ice shelves and their associated icebergs can scour soft sediment in two ways:

1. Tabular icebergs, which only calve from ice shelves and ice cliffs (Dowdeswell and Bamber, 2007; Wise et al., 2017), may scour the seabed. Ice-shelf derived ploughmarks are U-shaped and, wide and ‘deep’ whereas ice-cliff ploughmarks have shallower seabed incision and are V-shaped in profile (Dowdeswell and Bamber, 2007; Wise et al., 2017).
2. When large ice shelves, or their associated tabular icebergs override sediment, they may simultaneously carve toothcomb ploughmarks via multiple keels. These ploughmarks are characterised by highly linear, multi-keeled and parallel subaqueous ridges (Wise et al., 2017; Smith et al., 2019; Kirkham et al., 2025).

Palaeo-ice shelves have also been identified based on iceberg scouring. Including wide U-shaped scours around the western British Isles and are associated with GZWs and low clast-abundance laminated sediments – all indicators of palaeo-ice shelves (Peters et al., 2015; Bradwell et al., 2019, 2021).

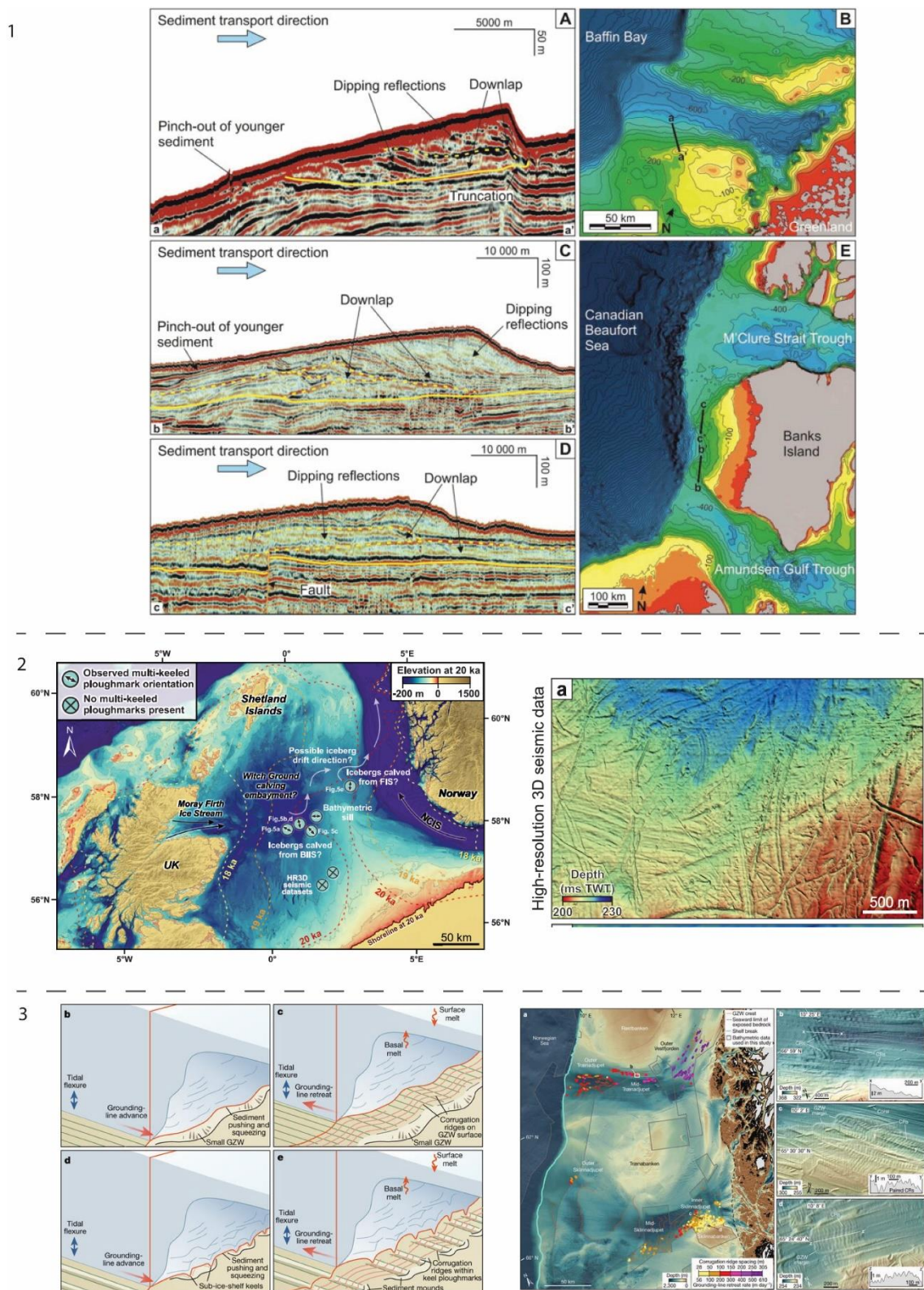
In palaeo-ice shelf settings, multi-keeled toothcomb scours are rare, but have recently been identified around the eastern British Isles, in the North Sea suggesting large ice shelves were present (Kirkham et al., 2025). Other examples of multikeeled iceberg scours have been identified in the western Barents Sea relating to the palaeo-Storfjordrenna ice stream (Shackleton et al., 2020). Despite the association of these scours with low clast abundance, laminated sediments typical of sub-ice-shelf sedimentation (Smith et al., 2019), debate has persisted over the possibility of ice shelves ever having existed in western Barents Sea (cf. Rasmussen et al., 2007; Jessen et al., 2010; Lucchi et al., 2015; Lantzsich et al., 2016). However, the evidence presented by Shackleton et al. (2020) unequivocally shows past ice-shelf presence in the region.

1.2.5.3. Corrugation ridges

One recently identified group of features which have been revealed as a likely fingerprint for past ice shelf presence are a set of grounding-line features known as corrugation ridges. These features have been noted off the western Antarctic coast, western Barents Sea, the eastern Norwegian Shelf and the British Isles (North Sea) (Jakobsson et al., 2011; Batchelor et al., 2023; Kirkham et al., 2025). Typically identified in exceptionally deep waters (> 500 m) with a height of ~ 0.1 to 1 m and a spacing of up to 84 m, it is observed that these features are regularly spaced (Batchelor et al., 2023). Research on corrugation ridges has led to several competing hypotheses regarding their formation including mega-icebergs resulting from ice-shelf collapse (Jakobsson et al., 2011), periodic grounding of ice-shelf keels (Graham et al., 2013) or as tidally buoyant features formed at the grounded / floating ice interface during rapid retreat (Batchlor et al., 2023).

Regardless of the precise formation mechanism, all three explanations require ice shelves. However, recent work by Batchelor et al. (2023) suggests via the regular spacing that these features are likely

the result of tidal forcing elevating and lowering ice margins via tidal pressure exerted on the ice shelf. It may be argued that large ice shelves must be required to facilitate this process.



(Kirkham et al., 2025). 3 – Corrugation ridges on the Norwegian shelf Margin (Batchelor et al., 2023).

1.2.6. Sedimentology

1.2.6.1. Ice-shelf sediment stratigraphy

The main characteristics used in ice-shelf reconstruction include the combination of sediment structure (stratified / laminated / massive) which gives an indication of distance from the grounding line, and the presence (or scarcity) of IRD which indicates ice-shelf rafting (Powell, 1984), iceberg rafting or a lack thereof (Smith et al., 2019; Jennings et al., 2022). By combining these two sedimentological proxies with geomorphological and palaeoecological signatures, the configuration and dynamics of ice shelves can be reconstructed, as explained below.

Sediments deposited nearer the grounding line (Unit 1) are dominated by coarse debris input from meltwater plumes, typically in the coarse sand – silt fractions and rich in ice-shelf rafted debris (Powell et al., 1984; Reilly et al., 2019; O’Regan et al., 2021) (Figure 1.7). Typically, unstable mass flow events and turbidite layers are common in this ice-proximal setting (Kuvaas and Kristoffersen, 1996; Vermassen et al., 2020). The transition between proximal and distal sediments (Unit 1 and Unit 2) often contains granulated sedimentary units occasionally with till pellets (Domack et al., 1998; Evans and Pudsey, 2002; Peters et al., 2015).

Unit 2 is usually deposited within the zone where debris filtering – a reduction in coarse debris due to excessive ice-shelf rafting near the grounding zone – is operational, but the ice shelf is not devoid of debris – therefore, IRD is rare in this unit (see Smith et al., 2019 and references therein). In this region a combination of rare IRD (significantly rarer than unit 1) and meltwater plume sedimentation (mud - silt) dominates, resulting in clast-poor laminated sediment packages. At this proximity to the glacier (< 5 km), laminae may exhibit lenticular bedding (O’Regan et al., 2021). Numerous examples of potential sub-ice-shelf clast-poor sediments have been identified indicating moderately distal sedimentation, including the western British Isles (Peters et al., 2015; Callard et al., 2020; Bradwell et al., 2019, 2021).

Unit 3 represents the zone of no IRD, where IRD rainout closer to the glacier is sufficient to no longer have IRD incorporated in the ice shelf via debris filtering (Smith et al., 2019; Jennings et al., 2022). In Lancaster Sound, NE Canadian Arctic, a finely, crudely laminated band devoid of IRD provides strong evidence of a past ice shelf (Furze et al., 2018). These units are actively forming at Greenland ice shelves / tongues such as Petermann, Ryder and 79°N Ice Shelf and have been tracked deeper in sediment cores to identify past oscillations of these contemporary ice shelves (Reilly et al., 2019; O’Regan et al., 2021; Smith et al., 2023).

These exceptionally clast-poor units are unlikely to form beneath smaller ice shelves or tongues due to a lack of debris filtering in laterally less extensive (or shorter) floating margins. The absence of

these clast-free units has been suggested as a potential determiner for smaller ice shelves or ice tongues (Smith et al., 2019). Interestingly, there are very few clast-free laminated units in British Isles Pleistocene sediments (see Clark et al., 2022 and references therein). Beneath large Antarctic ice shelves, Unit 3 may transition into a ‘null zone’ an area almost devoid of sedimentation (Domack and Harris, 1998).

Unit 4 is a complex unit and forms in sub-ice-shelf distal settings (near the ice-shelf margin) or in the pro-ice-shelf setting (Jennings et al., 2022). This unit is commonly associated with smaller, unstable ice tongues (Reilly et al., 2019; Vermassen et al., 2020). Unit 4 is also associated with large ice shelves where there is influence from ocean bottom currents, whereby IRD, aeolian and biogenic material may be advected beneath floating ice (Domack and Harris, 1998; Gilbert and Domack, 2003). Unit 4 may be either laminated or massive in structure and contains occasional IRD (depending on distance from meltwater plume delivery or the nature of ocean current sedimentation). As is the case with Petermann ice tongue sediments deposited when the ice tongue was unstable, bioturbation may be present, indicating a more biologically productive environment through sedimentary signatures (Reilly et al., 2019).

Unit 5 evidences ice-shelf collapse via significant volumes of IRD. Examples of ice-shelf collapse sediments have been identified in northern Greenland, Lancaster Sound and the western British Isles (Furze et al., 2018; Reilly et al., 2019; Bradwell et al., 2021; O’Regan et al., 2021; Jennings et al., 2022). These units can be crudely stratified (Furze et al., 2018), or massive / structureless (Jennings et al., 2022) likely depending on proximity to meltwater plumes. Ice-shelf collapse diamictons have patchy preservation across seafloors and this unit may be missing from ice-shelf stratigraphies depending on the topographic, glaciological and oceanographic configuration (Smith et al., 2019).

1.2.6.2. Foraminifera in ice-shelf sediments

Foraminifera within glaciomarine environments must be tolerant of glaciomarine conditions, low-light penetration and low nutrient abundances. Given the challenging ecological conditions, sub-ice-shelf sediments may be barren of foraminifera (Smith et al., 2023). Additionally, many species typical of glaciomarine conditions, in particular *Elphidium clavatum*, a fairly ubiquitous species across glaciomarine settings in the Northern Hemisphere, cannot tolerate sub-ice-shelf conditions (Jennings et al., 2020). Similarly, *Cassidulina reniforme*, another proximal glaciomarine foraminifera, is more common in non-ice-shelf settings, but not entirely exclusive to environments with no floating ice cover (Korsun and Hald, 1998; Jennings et al., 2020).

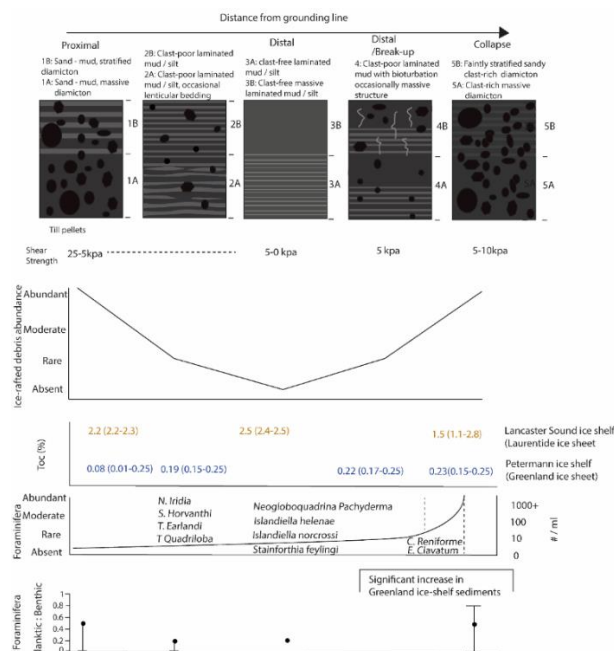
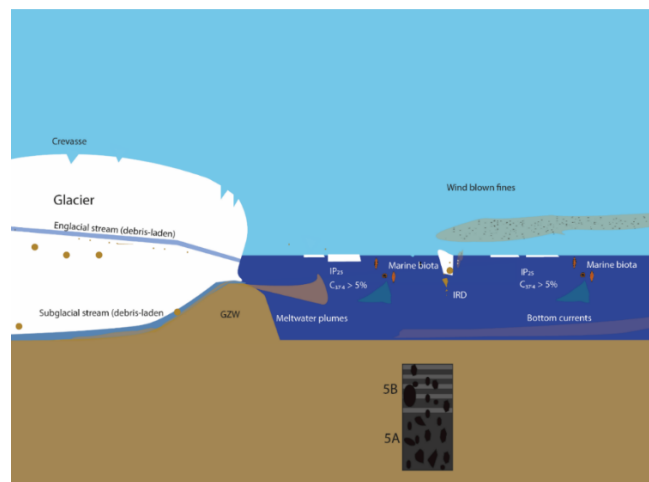
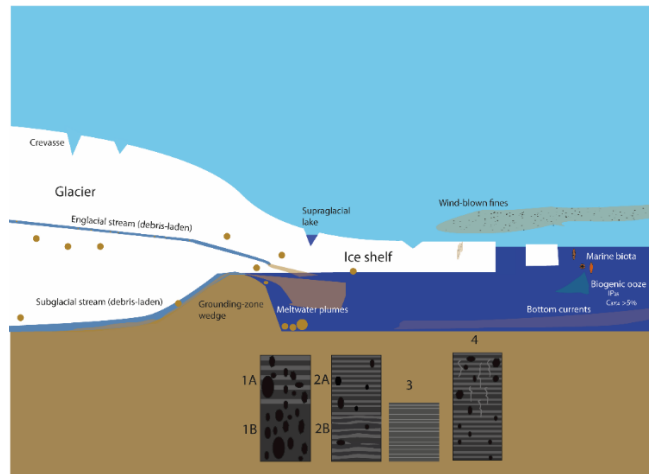


Figure 1.7. Ice shelf sediment signatures from the Northern Hemisphere, drawing on Antarctic examples where appropriate. A (top) – ice shelf sedimentation model when present; B (middle) – signature of ice-shelf collapse; C (bottom) – sediment signatures (as preserved in X-radiographic images); ice-rafted debris abundances; Total organic carbon (TOC %); Foraminifera species,

abundances and planktic:benthic ratios. Sources: Facies 1 – Peters et al., 2016; Furze et al., 2018; Reilly et al., 2019; Bradwell et al., 2019; Smith et al., 2019; O'Regan et al., 2021. Facies 2 – Bradwell et al., 2019; Reilly et al., 2019; O'Regan et al. 2021. Facies 3 – Furze et al., 2018; Reilly et al., 2019; Smith et al., 2019; O'Regan et al., 2021; Smith et al., 2023. Facies 4 – Reilly et al., 2019; Jennings et al., 2022. Foraminifera results acquired from Peters et al., 2015; Jennings et al., 2020. Facies 5 – Peters et al., 2016; Furze et al., 2018; Reilly et al., 2019; Vermassen et al., 2020; O'Regan et al., 2021; Jennings et al., 2022. Total Organic Carbon results are highly variable with two examples in the literature, one from the NE Laurentide Ice Sheet (Lancaster Sound) (Furze et al., 2018, the other from the Petermann Ice Shelf, N Greenland (Detlef et al., 2021). Foraminifera results sourced from Furze et al., 2018; Peters et al., 2020; Jennings et al., 2020, 2022; Detlef et al., 2022; Lloyd et al., 2023).

In northern Greenland, ice shelves such as the Petermann Ice Shelf and 79°N Ice Shelf, several species: *Textularia earlandi*, *Textularia quadriloba*, *Nonion Iridia*, *Stetsonia horvathi*, *Stainforthia concava*, and *Glomulina oculus* are key indicators of ice-shelf presence (Jennings et al., 2020; Smith et al., 2023; Stoltenberg et al., 2025). However, for lower latitude settings, such as the BIIS, *S. horvathi* has never been recorded in sediments, therefore, this species is not a useful indicator south of Iceland.

Sub-ice-shelf sediments can also be elucidated, not only based on foraminifera species, but other foraminifera phenotypic traits. For example, high relative abundances of agglutinated species can be used as an indicator of ice-shelf cover (Majewski et al., 2018; Jennings et al., 2020). Furthermore, higher species evenness has been observed in sub-ice-shelf sediments, given the low species richness (total number of species) in these settings (Jennings et al., 2020).

Additionally, a low planktic:benthic ratio is typically indicative of sub-ice-shelf conditions, with a significant increase in this ratio, when ice shelves are removed (Detlef et al., 2021). However, planktic foraminifera such as *Neogloboquadrina pachyderma* or *Globigerina bulloides*, prefer deeper open water (Pados and Spielhagen, 2023) and thus – regions such as The Minch and many other sectors of the BIIS, therefore, may not be well suited to using proxies such as planktic:benthic ratios.

Therefore, in BIIS settings, particularly in relatively shallow water and straits such as the Inner Minch, an absence of foraminiferal evidence may be the best indicator of ice-shelf cover. For example, if species intolerant of ice-shelf conditions such as *E. clavatum* are present, in relatively high abundances, ice-shelf cover can be excluded. However, the caveat here, is that foraminifera may be advected beneath ice shelves (Pudsey et al., 2006; Stoltenberg et al., 2025). One potential indicator of advected foraminifera fossils is observing a high number of tests at juvenile stage of development, due to high mortality rates beneath ice shelves (Hillenbrand et al., 2017). Therefore, a multi-proxy approach combining foraminifera abundances, species assemblages, sedimentology and

geomorphology must be carefully applied to fully understand whether ice shelves were i) present and ii) covering the core site during deposition.

1.2.7. Challenges with palaeo-ice shelf identification

A major challenge with the identification of palaeo-ice shelves is the similarity of sediments deposited beneath ice shelves and landfast sea ice (Dowdeswell et al., 2000, Ó Cofaigh and Dowdeswell, 2001; Figure 1.8). Multi-year landfast sea ice may, however, be differentiated from ice shelves based on the characteristic ice-shelf geomorphological imprint, if preserved (e.g. grounding zone wedges, ice shelf / melange scours) (Normandeau et al., 2017). Additionally, seasonal-sea-ice signals are distinct from sub-ice-shelf sediments as they produce rhythmic IRD sediments with winter sea-ice cover blocking IRD delivery, and spring melting allowing sea ice to traverse fjords through spring and summer (Dowdeswell et al., 2000).

Lipid biomarkers which are indicative of sea-ice cover (e.g. IP₂₅, HBI II (diene) and the tetra-unsaturated C_{37:4} alkenone fraction) can help to differentiate ice shelves and sea-ice margins (Syring et al., 2020a; Wang et al., 2021). However, IP₂₅ and HBI II have never been observed in the seas surrounding the British Isles (Syring, 2020). C_{37:4} has been observed in sediment cores recovered from isolation basins in northern Scotland, in elevated abundances (> 5 %), which would suggest sea-ice cover (Bendle et al., 2009; Wang et al., 2021). Therefore, C_{37:4} potentially presents a powerful and underutilised sea-ice biomarker around the British Isles, although alkenones are prone to advection by ocean currents limiting their power as a sea-ice biomarker (Vermassen et al., 2020). Additionally, lipid biomarkers cannot differentiate between ice shelves and landfast sea ice as both settings offer limited sunlight and nutrients, leaving no distinct biomarker record due to the uninhabitable environment for key diatom species.

Another significant challenge is reconstructing the former length of ice shelves, which has only ever successfully been achieved when using ice-shelf moraines (or ridges) (Peters et al., 2016; England et al., 2022), and sometimes by the presence of IRD and associated non-ice-shelf biota (e.g. *E. clavatum*) within sediment cores (Jennings et al., 2022). One aim of this thesis is to test whether a multi-proxy approach – combining geomorphology, sedimentology and micropalaeontology (foraminifera abundance and identification) – can determine ice-shelf extent around the former Minch Ice Stream, NW Scotland.

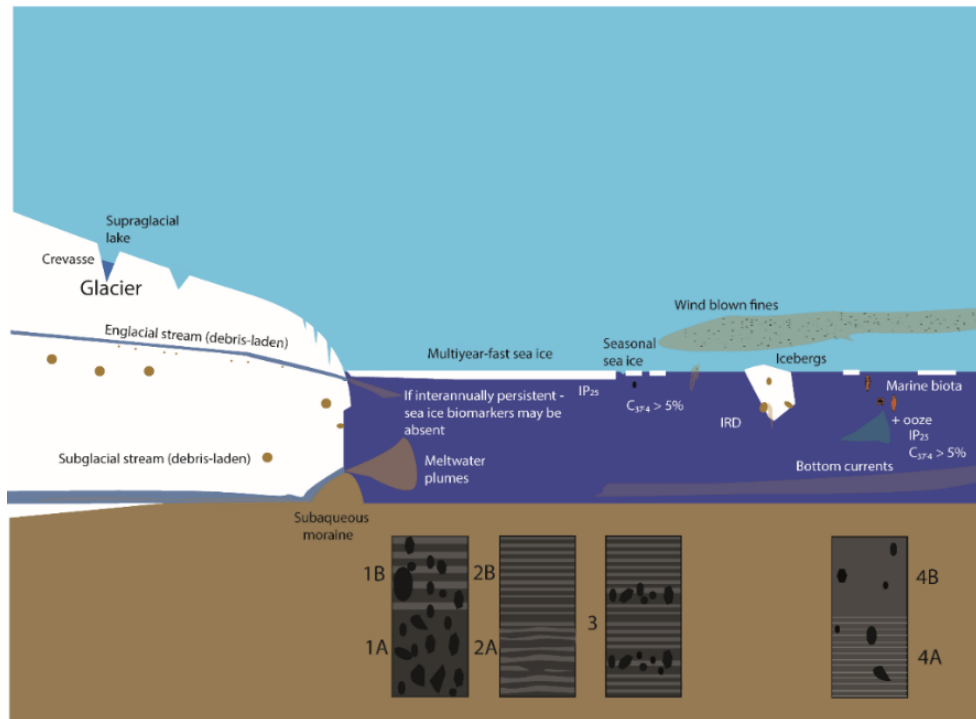


Figure 1.8. Sedimentary signature of sea-ice sediment packages (Dowdeswell et al., 2000; Ó Cofaigh and Dowdeswell, 2001).

1.3. Study Site

1.3.1. The British-Irish Ice Sheet

The British-Irish Ice Sheet (BIIS) is a palaeo-ice sheet which has existed several times throughout the Quaternary (Zaragosi et al., 2001; Scourse et al., 2009; Scourse et al., 2024). During the last glacial cycle (Marine Isotope Stage 2 or MIS 2), the ice sheet history has been comprehensively reconstructed by the BRITICE-CHRONO model, a 3-dimensional numerical model constrained by empirical data (see Clark et al., 2022 and references therein; Figure 1.9). This model spans 31,000 – 15,000 ka cal BP, from initial growth to the final demise of marine-based sectors.

The BIIS hosted many marine-terminating sectors, making it a useful (albeit not direct) analogue for the West Antarctic Ice Sheet (Hubbard et al., 2009; Clark et al., 2012; Clark et al., 2022) and marine-terminating sectors of the Greenland Ice Sheet. Marine sectors include palaeo-ice streams such as the Irish Sea Ice Stream, Hebrides Ice Stream, Moray Firth Ice Stream and The Minch Ice Stream (Eyles and McCabe, 1989; Merrit et al., 1995; Finlayson and Bradwell, 2008; Howe et al., 2012; Chiverrell et al., 2013; Callard et al., 2018; Bradwell et al., 2019).

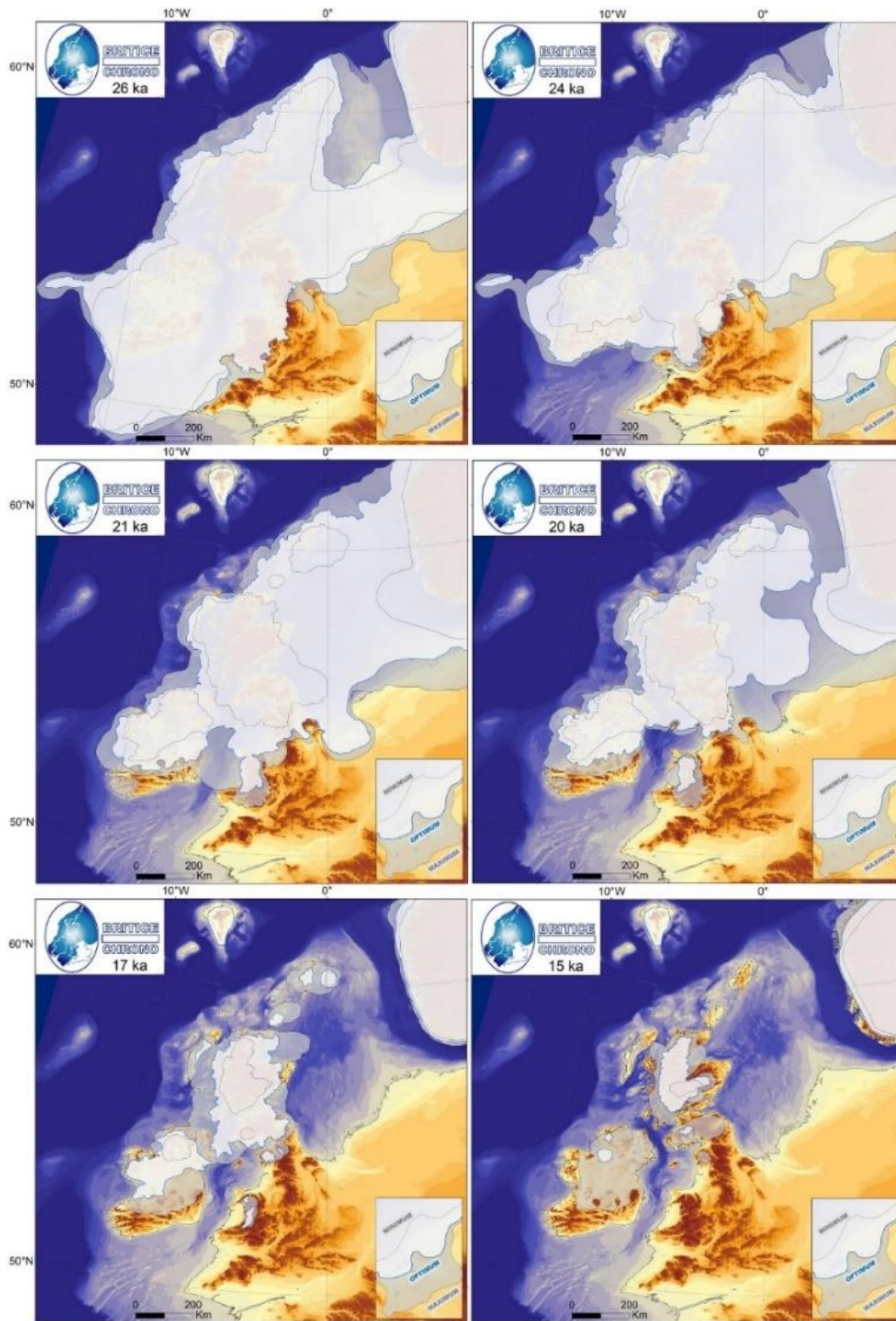


Figure 1.9. British-Irish Ice Sheet evolution from Last Glacial Maximum (26 ka) to the collapse of the marine portions (17 – 15 ka). Note the uncertainties between minimum (inner grey boundaries), white boundaries – the authors’ preferred limits) and grey, shaded boundaries (maximum model error) (Clark et al., 2022). This thesis aims to better constrain the limits of the offshore NW Sector in The Minch, NW Scotland between ~ 17 and 15 ka.

1.3.2. The Minch Palaeo-ice Stream

The Minch palaeo-Ice Stream (MnIS), NW Scotland, represents a uniquely well-placed sector of the former BIIS for understanding long-term marine ice sheet dynamics. It is very likely that the MnIS underwent marine ice-sheet instability during MIS 2, in part facilitated by the loss of its floating ice shelf (or ice tongue) and the conducive reverse-sloping bed topography (Gandy et al., 2018; Bradwell et al., 2019; Clark et al., 2022).

The Minch palaeo-ice stream (MnIS) was a fast flowing, highly dynamic ice stream which operated in The Minch, NW Scotland and drained much of the NW sector of the BIIS during the last glacial cycle (~30 – ~17 ka cal BP) (Bradwell et al., 2007; Bradwell and Stoker, 2015; Clark et al., 2022). The MnIS displays the hallmarks of ice streaming with a high velocity regime and dynamic retreat, which makes this ice stream a suitable (albeit not necessarily direct) analogue for many marine-terminating sectors of the West Antarctic and Greenlandic ice sheets (Stoker and Bradwell, 2005; Bradwell et al., 2007, 2008; Clark et al., 2022).

The MnIS was the first operational ice stream of the last BIIS (Clark et al., 2022). The maximum extent of the MnIS during MIS 2 has been contested with some authors suggesting the MnIS reached the continental shelf-break only during previous glacial cycles (Stoker et al., 1993; Stoker and Bradwell, 2005; Bradwell and Stoker, 2015), meanwhile others suggest that during the Last Glacial Maximum (MIS 2) shelf edge glaciation occurred (Bradwell et al., 2008; Chiverrell and Thomas, 2010; Clark et al., 2012). Recent work has found that the MnIS terminated near, and occasionally at, the shelf-edge during the last glacial cycle (Bradwell et al., 2019, 2021).

Evidence of episodic ice-stream retreat in the Minch is preserved by 17 large, asymmetric wedges which are orientated transverse to the ice-flow direction. Their size and shape characteristics are comparable to grounding-zone wedges (GZW) found at the grounded / floating ice-stream boundary in contemporary settings (Figure 1.10) (Bradwell et al., 2019). During the final stages, before ice stream withdrawal from the Minch strait, a submarine topographic high – the mid trough bedrock high (MTBH) acted to stabilise the ice stream; resulting in GZWs 15 - 17 and a thick drape of glaciomarine sediments (Gandy et al., 2018; Bradwell et al., 2019; Figure 1.10).

The timing of this stabilisation event remains loosely constrained by tied terrestrial cosmogenic nuclide (TCN) dates and sedimentology to sometime between ~18.5 - 17 ka BP (Bradwell et al., 2019, 2021). Furthermore, the GZW and finely laminated sediments with very low gravel content in this vicinity provide primary evidence that this stability was probably facilitated by a floating-ice shelf. Evidence of ice-shelf removal is recorded by large, wide U-shaped iceberg ploughmarks, thought to derive from an ice-shelf collapse event (Bradwell et al., 2019; Bradwell et al., 2021; Figure 1.10).

However, the timing, extent and precise nature of this floating margin remains uncertain. This remains a critical question in order to understand whether the MnIS is an appropriate analogue for sectors of the Greenland ice sheet where ice shelves are small, undergoing removal or even absent (Enderlin and Howat, 2013; Reeh, 2017; Hill et al., 2017; Vermassen et al., 2020). Alternatively, the MnIS (and northern BIIS) may have been more comparable to West Antarctica with large and extensive ice shelves ($= / > 50$ km).

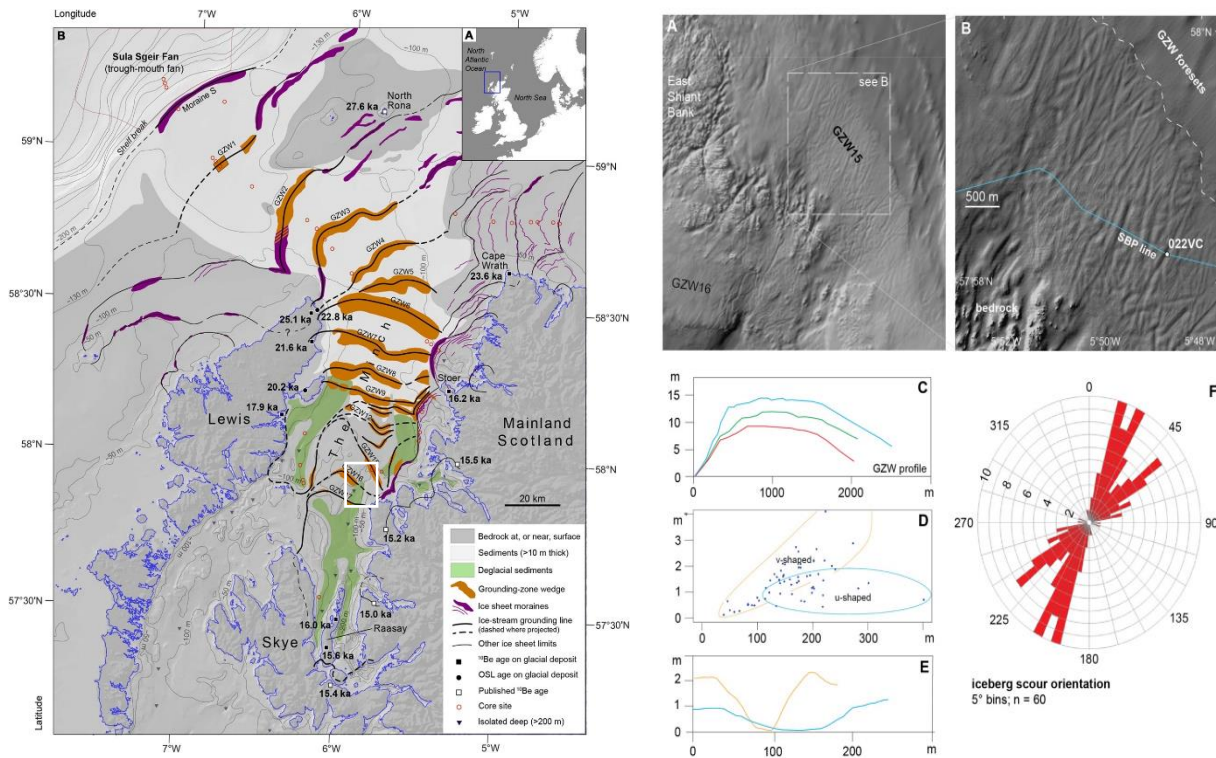


Figure 1.10. Left: grounding-zone wedges and associated terrestrial cosmogenic nuclide (TCN) dates. White box indicates inset map location for panel A (right). Right: A and B – grounding-zone wedge 15, note heavily scoured surface. C – profile of grounding zone wedge 15. D and E – cross-cutting and highly linear iceberg scours on GZW 15 and 16, D = width (X-axis) and seabed incision (Y-axis); e = profiles of U-shaped and V-shaped icebergs from GZW 15. F – orientation of iceberg scours, note: cross-cutting and regular nature of iceberg scours (Bradwell et al., 2019, 2021).

This thesis principally investigates sediment cores recovered from around the MTBH in The Minch, analysing two cores, one from the East (JC123-021PC) and one from the West (JC123-033PC) of the MTBH, will allow important insights into ice-stream behaviour on different sides of a major bathymetric/topographic high (Figure 1.11). Other stratigraphically tied sediment cores are also used in this research where appropriate (e.g. JC123-031PC; JC123-032PC and JC123-020PC) (Figure 1.11).

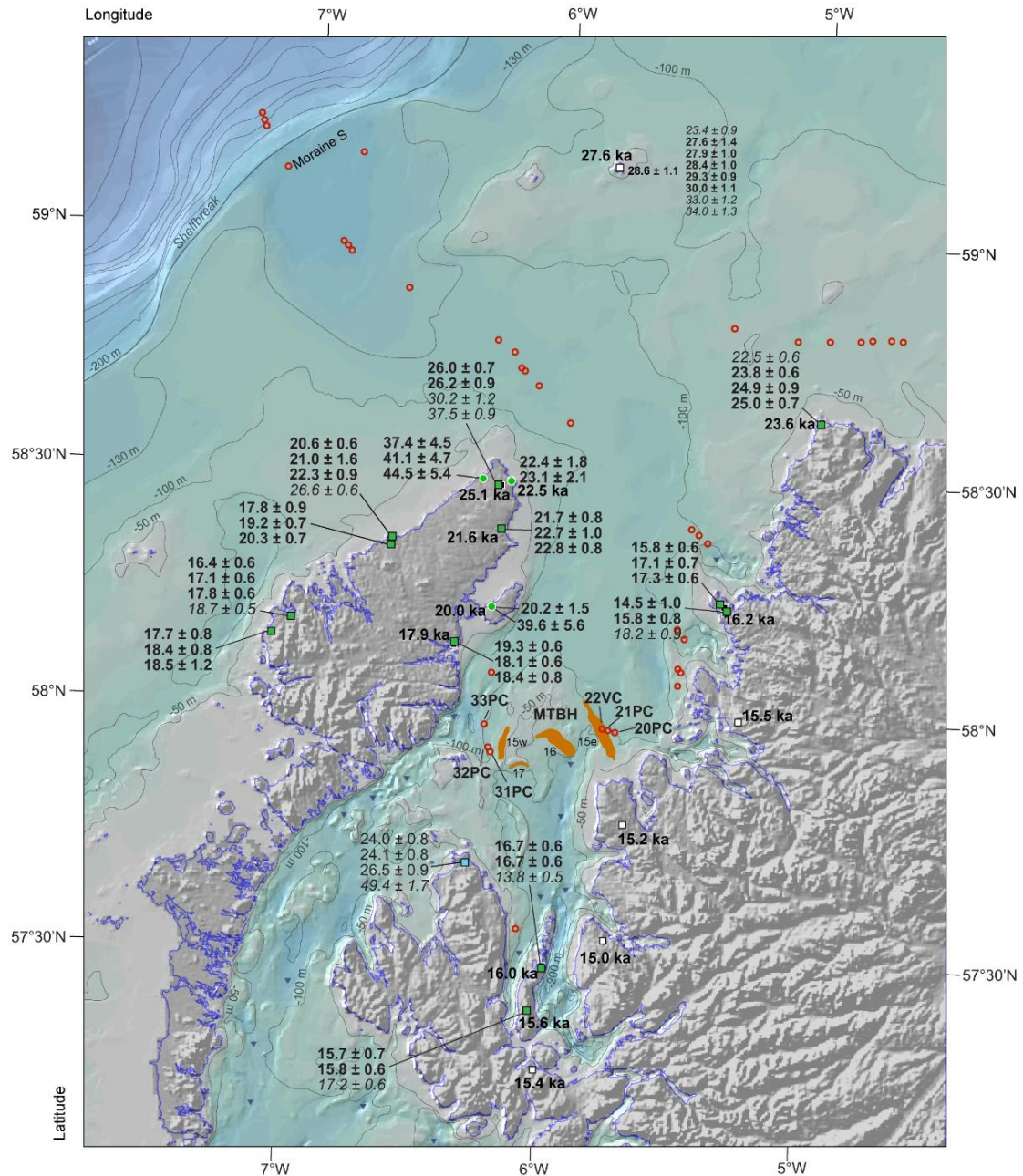


Figure 1.11. Grounding-zone wedges (15e – East, 15w – West, 16 and 17) and core locations around the Central Minch. Core sections labelled in shorthand (e.g. JC123-020PC = 20PC). Associated TCN dates labelled (see Bradwell et al., 2021 and references therein). Note: MTBH = mid-trough bedrock high.

1.4. Aims and objectives

This thesis aims to refine understanding and improve methodological best practice when analysing glaciomarine sediments. This research aims to identify palaeoglaciological and palaeoenvironmental changes accompanying iceberg rafting; ice-shelf presence / absence; ice-shelf extent; ice-shelf removal (collapse); ice-stream stability and rates of ice-stream retreat. This research includes a strong

methodological component, with a focus on developing new sediment core analyses, techniques, quantitative tests, and new frameworks for existing methods aiming to quantify IRD. This research also includes a multi-proxy investigation to refine the timing and behaviour of a past ice stream sector (The MnIS, NW Scotland). These investigations are all undertaken with the overarching aim of understanding of how ice streams respond to internal and external forcing factors and ultimately contribute to sea-level-rise.

The specific aims of this thesis are:

- i) To develop a new, ultra-high-resolution technique for quantifying ice-rafted debris. The method should remove or significantly minimise user bias from the process. [Chapter 2]
- ii) To investigate and quantify the strengths and weaknesses of different IRD techniques (e.g., sieving, laser particle size analysis, clast counting on X-ray images, and a new ultra-high resolution automated method). [Chapter 3]
- iii) To quantify the user variability in the technique most commonly used to determine the presence of past icebergs from sediment core archives – i.e. manual clast counting on X-radiographs (Grobe, 1987). [Chapter 4]
- iv) To devise a refined and fully transparent protocol for better implementing clast counting for the quantification of IRD. [Chapter 4]
- v) To refine the timing and behaviour of the MnIS (NW Scotland) from the final stable ice-stream phase to tidewater glaciers phase. [Chapter 5]
- vi) To elucidate the nature and extent of the Minch ice shelf(ves) during the final stable phase before collapse. [Chapter 5]
- vii) To identify, if possible, the trigger for ice shelf / ice-stream removal (collapse) in the Central Minch. [Chapter 5]
- viii) To identify the main physical and geochemical characteristics of laminated sediments in glaciomarine settings. This should help to elucidate the depositional mechanism of laminated glaciomarine sediments in The Minch, NW Scotland and elsewhere. [Chapter 6]
- ix) To synthesise the findings of this research, placing the methodological advances and geographical-specific results into a wider scientific context. [Chapter 7]

Chapter 2: Automated Characterisation of Glaciomarine Sediments using X-ray Computed Laminography

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2. Introduction

2.1. The use of X-ray image analysis in IRD detection

The reconstruction of glaciers and ice sheets is vitally important for understanding past and projecting future environmental change (e.g. Clark et al., 2012; Gowan et al., 2021). In order to better constrain models of ice-sheet response to climate change, robust reconstructions of past ice sheets are essential. In marine settings, this is of particular importance due to instabilities inherent to marine ice sheets and tidewater glaciers (Scambos et al., 2004; Rignot et al., 2004; Schoof, 2007; Favier et al., 2014).

One way to track ice sheet and tidewater glacier instability is through terrigenous sediments that are transported to the ocean predominantly via iceberg rafting or meltwater pulses and leave distinct sedimentary signatures on the seafloor (Syvitski et al., 1996). Ice-rafted debris (IRD) forms a key component of glaciomarine reconstructions and represents a powerful proxy for past iceberg presence. IRD is chiefly used to infer past iceberg flux, however, concentrations of IRD may be biased by contrasting sediment inheritance due to the presence/removal of ice shelves (Reilly et al., 2019; O'Regan et al., 2021), ocean temperature changes or iceberg melt rates (Andrews, 2000), and changes in ocean currents (Starr et al., 2021). The identification and quantification of IRD allows reconstructions of global climatic events (Heinrich, 1988; Bond and Lotti, 1995; Obrochta et al., 2014; Margari et al., 2020); the growth, demise and deglaciation of ice sheets (Scourse et al., 2009; Hibbert et al., 2010; Pierce et al., 2017); as well as high resolution ice stream and ice shelf processes – including calving intensities (Andresen et al., 2011) and collapse events (Kilfeather et al., 2011; Vermassen et al., 2020). Despite ice-rafted sediments providing a valuable record of past environmental change, the best way to characterise IRD in sediments remains contentious and non-standardised.

Particle-size discrimination is generally used to distinguish IRD, with icebergs transporting larger-grade sediments – usually in the sand ($>63\ \mu\text{m}$) or gravel ($>2\ \text{mm}$) fractions (cf. Andrews, 2000; Grobe, 1987; Scourse et al., 2009) – over greater distances than suspended sediments – usually silt or clay ($<63\ \mu\text{m}$). IRD layers may also be characterised by greater heterogeneity (i.e. be more poorly sorted) than sediments formed through ‘normal’ glaciomarine sedimentation from settling via meltwater discharge from marine-terminating glaciers (Dowdeswell et al., 2000, 2001).

Currently, there are two main approaches for characterising IRD, these use: (1) grain abundances or (2) sediment fractions by volume or weight. These different approaches can use destructive methods, typically for fine-grained material (*sensu* Scourse et al., 2009; Vermassen et al., 2019) or non-destructive X-ray-imaging methods on coarser clastic material ($>\sim 1$ mm or >2 mm) (*sensu* Grobe, 1987; Bartels et al., 2017). The most commonly employed technique remains a grain-counting method introduced by Grobe (1987), which employs manual counts of the number of clasts >2 mm for every 1 cm slice of sediment in traditional 2-dimensional X-radiographs (XR) to represent the ice-rafted fraction of sediments. Owing to its relative ease, familiarity, and non-destructive nature, this method remains popular today, more than 30 years after its introduction (e.g. Graham et al., 2017; Jennings et al., 2018; Joe et al., 2020).

The application of X-ray computed tomography (CT) in Quaternary Science has advanced significantly in recent years. X-ray attenuation coefficients (grey values, CT numbers or Hounsfield units), a proxy for density (Reilly et al., 2017; Tonai et al., 2019), have been used to identify sedimentary structures in different depositional settings, including glacial and postglacial environments (St-Onge and Long, 2009; Jennings et al., 2018); as well as bottom-current velocity variations (Vandorpe et al., 2019); and precise varve counting (Damci and Çağatay, 2015). Additionally, X-ray attenuation coefficients have been used to effectively discriminate sediment facies based on differences in radiodensities (in Hounsfield units) between sedimentary structures (Mena et al., 2015), suggesting that the radiodensity of sediments can provide diagnostic criteria on the nature of sedimentation, facies depositional setting and genesis. Innovations in quantitative analyses using CT scans of sediment cores have introduced a new framework for the analysis of glaciomarine sediments typically through the MATLAB™ interface SedCT (Reilly et al., 2017). Radiodensity thresholding allows a quantification of the percentage coverage or number of all clasts (>1 mm) per unit area (Bartels et al., 2017; Reilly et al., 2019). Additionally, the standard deviation (SD) of the remaining fine grained (<1 mm) fraction may be assessed using the horizontal SD of radiodensities (in Hounsfield units) across the width of the image (Bartels et al., 2017). This type of analysis is not yet widely reported, however, it suggests that radiodensity SD can be used to assess fine:coarse-grained compositional ratios and infer former depositional styles in certain settings.

Two X-ray imaging approaches currently dominate the analysis of cored sediments: 2-dimensional XR and 3-dimensional CT. XR is by far the most common method for cost and practicality reasons, and is routinely applied in glaciomarine sediment analyses (e.g., Graham et al., 2017; Joe et al., 2020; Bradwell et al., 2021). XR produces an averaged 2D projection of the whole or split sediment core, whereby the X-ray beam passes through the core and an image montage is produced as the core moves past the X-ray source and detector. CT is a higher cost, data intensive, longer exposure-time technique, which has gained popularity in the geosciences over the last two decades. The CT method

involves acquiring X-ray projections from 360° around the core (or less for limited angle CT); these data ‘slices’ are then processed to create axial views or true 3D data representations (e.g., Bartels et al., 2017; Hodell et al., 2017). Whole core CT scans are performed on large medical-grade scanners, however availability is growing outside of hospitals. A third type of X-ray scanning technique, computed laminography (CL), produces thin 2D scans of an object at specified depth intervals. Through computed reconstruction of these 2D scans, the interior of the object can be imaged in sharp focus without the depth-averaging of traditional projection XR scans. As a valuable non-destructive technique, CL is increasing in prominence in the geosciences (e.g. Zuber et al., 2017) but has not yet been used to investigate glaciomarine sediments.

This article proposes a new non-destructive, automated, high-resolution method for discriminating IRD in cored glaciomarine sediments based on a combination of practical application and theory. The study tests whether automated sediment classifications can be effectively derived from X-ray CL properties of cored sediments using freely available image processing and statistical software (FIJI/ImageJ) (Schindelin et al., 2012). Wider applications, strengths and methodological uncertainties are also discussed.

2.2. Methods

Glaciomarine sediments were recovered by piston core from the present-day seafloor off NW Scotland (See Bradwell et al., 2021 for details of core recovery, locations, descriptions, etc.). Four split half-round sediment cores are presented, which were scanned using a Geotek XCT X-ray core scanner. All four split cores were scanned once using traditional projection XR, and scanned a second time using the CL technique. Digital images are presented in radiodensity positive form of separate scans using XR and CL [0.066 mm x-y plane resolution]. Of the core sections, three predominantly comprise mud-silt laminae of varying clastic content ranging from gravel-rich to gravel-free (JC123-032PC-section-05, JC123-032PC-section-06, JC123-033PC-section-06); the fourth core section contains a matrix-supported, generally structureless, glaciomarine diamicton (JC123-033PC-section-05). A comprehensive list of operations and scripts implemented within this study are provided (see Appendix A).

2.2.1. Image acquisition: X-ray computed laminography

This study utilises the popular XR scanning technique by way of comparison with the new CL scanning method for sediment core analysis. CL produces ‘thin slice’ cross-sectional internal images of samples, typically through an angular intrusion of the X-ray beam (see Gondrom et al., 1999; Xu et al., 2012). In this study CL is implemented using an adaptation of XR by translational laminography, whereby the need to rotate samples is negated, hence this method is well suited to sediment core scanning (Figure 2.1). CL exhibits less excessive X-ray attenuation than traditional XR scanning methods, reducing cupping artifacts and producing higher image quality (in the plane

parallel to the object face) with higher contrast of ‘flat’ samples. This results in increased fine-detail resolution compared to CT approaches (Xu et al., 2012; Zuber et al., 2017; Fisher et al., 2019). However, to our knowledge, it has not yet been documented whether CL images are of improved contrast and clarity with reduced artifacts when scanning glaciomarine sediments. This is also investigated in our study.

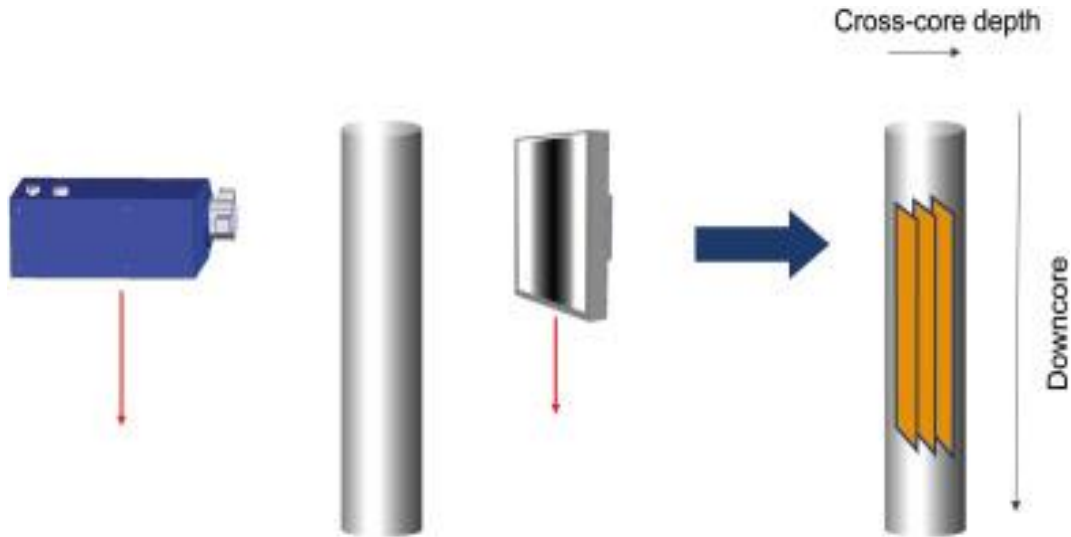


Figure 2.1. Translational computed laminography method. X-rays are emitted from the source and pass through the sediment core before they are captured by a detector, where an algorithm is used to reconstruct images at ‘thin sections’ at specified depth intervals of the core.

2.2.2. Image pre-processing

Initially, a beam-hardening correction algorithm was applied to reduce cupping due to greater X-ray attenuation within the thicker region at the centre of cores. This correction was manually applied using the Geotek Gquickview software. Images were then imported to FIJI/ImageJ to evaluate the degree of cupping due to beam hardening using a quadratic curvature coefficient (Figure 2.2). The rectangular selection tool was used to select the grey values over the whole core width (horizontally). These data were then exported to Microsoft Excel (which was selected for this specific analysis due to flexibility with data manipulation) where the degree of cupping was investigated and detrended using a quadratic polynomial function ($y = ax^2 + bx + c$). This was repeated for XR and CL scans pre- and post-beam hardening and the curvature coefficient (‘a’ within the polynomial function) was used to highlight the degree of cupping. The greater the ‘a’ value, the greater the degree of cupping; slight overcorrections, are represented by negative values.

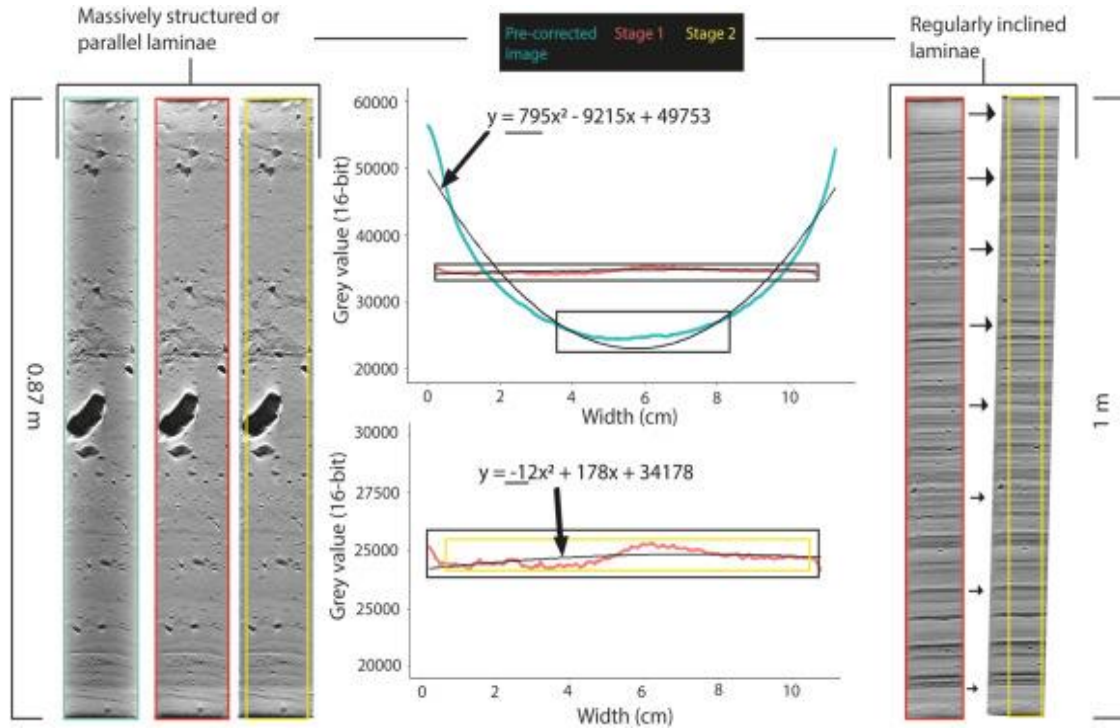


Figure 2.2. Two-stage sampling window selection method which differs slightly for sediments with inclined laminae (annotated on right). Stage 1 involves beam hardening correction as illustrated from changes between blue to red (boxes and lines). Note: some data naturally cropped on core edges during beam hardening correction. Stage 2 involves cropping images free from blurred or disturbed core edges (yellow boxes). For inclined laminae, stage 2 also involves rotating images at the inclination of laminae until horizontally parallel. Line plots indicate degree of cupping due to beam hardening. Illustrated by polynomial functions (curvature coefficients underlined) pre-beam hardening correction $a = 795$, post-beam hardening correction $a = -12$ (apparent ‘overcorrection’ due to greyscale variation in sediments). Black/yellow boxes: sampling windows. Note: greater sampling window for images post-beam hardening corrections.

These data were then used to determine the optimal sampling window, as displayed in Figure 2.1. The optimal sampling window is one where the curvature coefficient (a) of grey values across the width of the image is as close to 0 as possible. A manual, iterative approach is used where the beam hardening algorithm is altered and tested several times until the lowest possible degree of cupping, without overcorrection, is attained. Edge effects, including any laminae bending during piston core recovery (Skinner and McCave, 2003), may be avoided by selecting a further reduced-width window free from distorted or blurred edges at the image margins (Figure 2.2, yellow boxes). An additional step was required if laminae exhibit a significant slope or inclination. This involved measuring the inclination in FIJI using the straight-line tool across laminae. The image was then rotated by the laminae inclination angle. Finally, images were then cropped to the sampling window size allowing analysis of the sampling window only.

2.2.3. Sediment characterisation tool

The Sediment Characteristics (SC) plugin utilises the straight line-profile tool in FIJI/ImageJ to produce a horizontal line across the sampling window width (code provided in Appendix A). The mean grey value (GV) and grey value SD across this horizontal line are measured at pixel intervals downcore i.e., if an image is x pixels in length, the SC plugin will sample x measurements. The mean or median GVs provide a very high-resolution proxy for sediment density and the associated SD a proxy for sediment heterogeneity (or degree of sorting) (Figure 2.3). Two videos illustrating the process are presented (see Figure 2.3 caption for video link via *Quaternary Sciences Advances*).

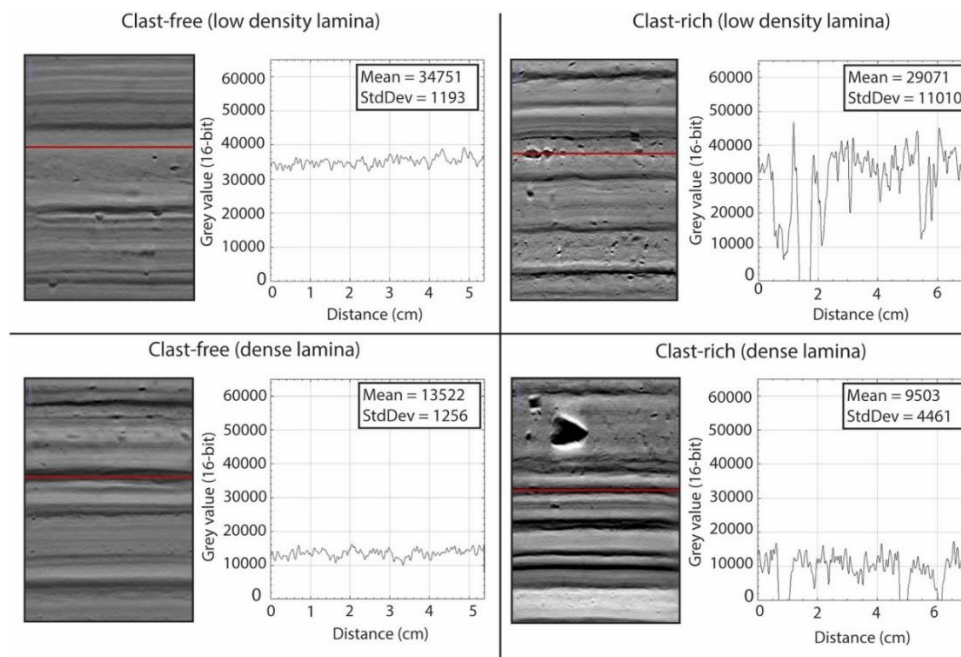


Figure 2.3. Sediment classification based on X-ray imaging properties (grey value mean and standard deviations). In these (positive) X-radiographic images, lower density sediment is reflected as higher grey values (= whiter); high density sediment as lower grey values (= darker). Each negative departure from the mean represents a high-density (low grey value) clast or grain; positive departures may represent low-density sediment, voids or edge-effect ‘halos’ associated with clasts. Note: the following are the supplementary data related to this chapter: Video (11MB)– [Download: Download video \(11MB\)](#); Video 2 – [Download: Download video \(3MB\)](#).

2.2.4. Characterising sediments by X-ray imaging properties

Initially, the SC tool was used on all four split-cores to highlight the applicability of the method for conveniently and non-destructively identifying the type and nature of sediments at very high-resolution (<0.1 mm). When comparing the pixel-interval sampled GV SD result to existing IRD methods, the sum of standard deviation per cm was totalled to allow a like-for-like direct statistical comparison to other more common practices (see below). Secondly, images were sampled incrementally at 10-pixel intervals and plotted on a scatter plot (mean GV vs SD) to identify

any trends in imaging properties. Measurements from the first and last ~700 pixels on each image (~5 cm on 1-m-long cores) were removed as outliers, due to overestimations from a scanning artifact which occurs as a result of X-ray scatter around the ends of the core samples. Finally, three facies were then discriminated quantitatively based on clast abundances using the Folk sediment classification scheme whereby glaciomarine sediments are grouped based on gravel content (>2 mm) (adapted from Long, 2006). These facies classes were *clast-free* (<1% gravel), *clast-poor* (1–5% gravel) and *clast-rich* (5–30+% gravel). 50 random samples of each facies were interrogated via their X-ray CL imaging properties (mean GV and SD). These 50 measurements included both dense laminae and less dense laminae. Clasts (>2 mm) diameter were selected from existing clast maps (see below) (clasts >0.5 mm diameter) using the ‘Analyze Particles...’ function, by selecting particles with an area >3.14 mm² – the minimum area for clasts >2 mm in diameter (modified from Reilly et al., 2019). The clast abundance (%) from clast maps extracted using the ‘Area Fraction’ function (at pixel resolution across core for each measurement) was directly compared to the corresponding greyscale image properties (mean GV and GV SD). Scatter plots were used to visually discriminate the characteristics and tendencies of these statistically classified sediments.

2.2.5. Comparison with existing IRD-identification methods

Alternative IRD detection methods use medical-grade CT scanning (Bartels et al., 2017; Reilly et al., 2019). To test one of these detection methods we isolated clasts (>~0.5 mm) on CL images and derived the % of clasts per unit area of sediment. After trialling an automated segmentation method (adapted from Principato, 2005) using the FIJI/imageJ threshold function, manual segmentation was preferred. This was due to flocculated silt or fine sand layers falling within the radiodensity threshold, as originally outlined by Reilly et al. (2019). Three of the cores in this study have dense laminae which resulted in overestimations in volume fraction methods, contrary to the results of the massive (non-laminated) core section (JC123-033PC-section-05) which showed a degree of correlation with manual segmentation methods (Figure A1). Segmentation was applied for each core by isolating clasts manually by outlining; images were subsequently converted into binary (8-bit) images using density thresholding. The % volumes of identifiable clasts were then calculated for the width of the sampling area, in 1 cm intervals downcore (Appendix A).

On-screen grain counting (sensu Grobe, 1987) at 1 cm depth intervals, was also undertaken on all four cores. Gravel clasts (>2 mm), considered to be ice-rafted debris, were summed over 1 cm downcore increments. Both these methods (i) volume % of clasts using binary image ‘thresholding’ (sensu Bartels et al., 2017) and (ii) grain counting (sensu Grobe, 1987) are compared statistically with the sediment heterogeneity output (GV SD) from the Sediment Characteristics (SC) tool using Pearson’s correlation coefficient.

2.3. Results

When comparing sediment heterogeneity (GV SD) data with other IRD measurement techniques or proxies in the same cores, generally good agreement is observed. Each of the methods (sediment heterogeneity, grain counting and volume fractions) are broadly synchronous in their peak distributions of IRD characterisation. However, the magnitude of peaks differs between methods (Figure 2.4).

There are strong, statistically significant, correlations when comparing automatically generated sediment heterogeneity (using GV SD) with the observed proportion of clastic grains (% volume $> \sim 0.5$ mm) in each core section ($r = 0.72\text{--}0.87$; $p < 0.001$) (Figure 2.5). The highest correlation was seen in massive matrix-supported diamicton (JC123-033PC-05; $r = 0.87$); and the lowest on clast-poor strongly laminated mud (JC123-033PC-06; $r = 0.72$). The statistical correlations when comparing GV SD to clast counts are less strong ($r = 0.32\text{--}0.69$). Although all four core sections show statistically significant relationships ($p < 0.001$), the correlation coefficients (r) from the clast count data are lower than the area % clast data (Table 2.1).

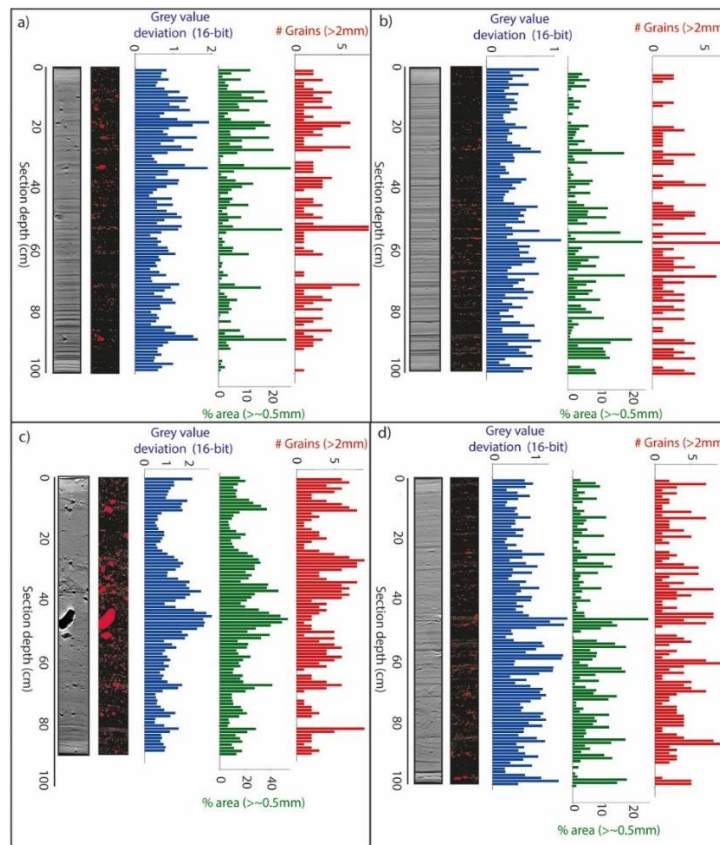


Figure 2.4. Comparison of different IRD proxy measurement techniques. Blue bars: sediment heterogeneity (grey value standard deviation; summed area under curve per cm); green bars: % area of clasts ($> \sim 0.5$ mm) per cm; red bars: traditional grain counts (> 2 mm) at 1 cm downcore intervals. a) JC123-032PC-section-05; b) JC123-032PC-section-06; c) JC123-033PC-section-05; d) JC123-033PC-section-06. Note summed standard deviation (blue bars) expressed in standard form (1×10^6).

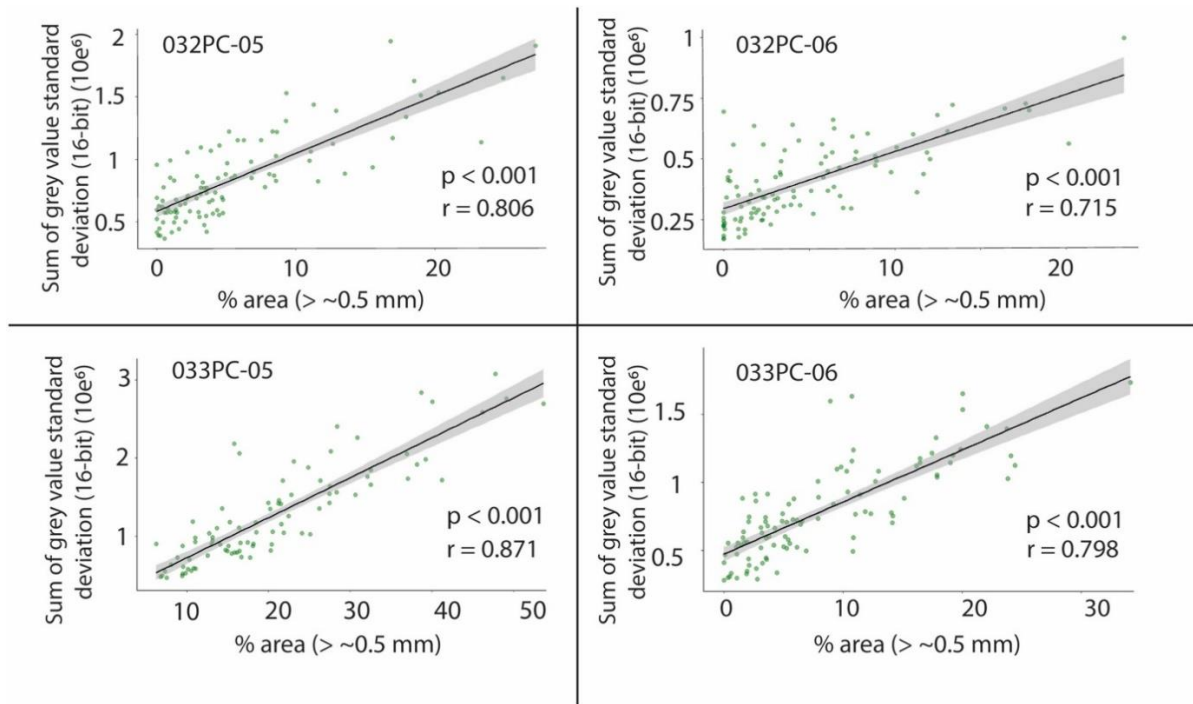


Figure 2.5. Scatter plots of X-ray grey value, expressed as sum of standard deviation (i.e. sediment heterogeneity), per 1 cm downcore area vs % of clasts per 1 cm area; with associated Pearson's correlation coefficients shown (r).

Table 2.1. Pearson's correlation coefficients (r) between the sum of sediment heterogeneity (grey value standard deviation) per cm; number of clasts per cm downcore; and % area of clasts per cm for each core section.

Core section	# of clasts > 2 mm (r)	% area of clasts (r)
JC123-032PC-section-5	0.540	0.806
JC123-032PC-section-6	0.692	0.715
JC123-033PC-section-5	0.440	0.871
JC123-033PC-section-6	0.322	0.798

Distinct sedimentary structures are observed in the very high-resolution (<0.1 mm) CL images. Most apparent is the evidence of prolonged relatively high GV SD, indicative of clast-rich layers. Conversely, structureless and clast-free muds are characterised by a low GV SD signal (Figure 2.6). The radiodensity (=GV) of sediments, a function of density and/or atomic number, can be affected by either sediment matrix (Figure 2.6a) or clast proportion and clast density (Figure 2.6b). However, it appears that the largest control on sediment density in these cores is from fine-sediment variations (most evident in Figure 2.6a). The effect of fine sediment (matrix densities) as the largest control on

sediment radiodensity, however, breaks down when gravel percentages are very high ($>\sim 30\%$), where large abundances of dense clasts raise the average density of sediment, despite low radiodensity matrices (Figure 2.6b).

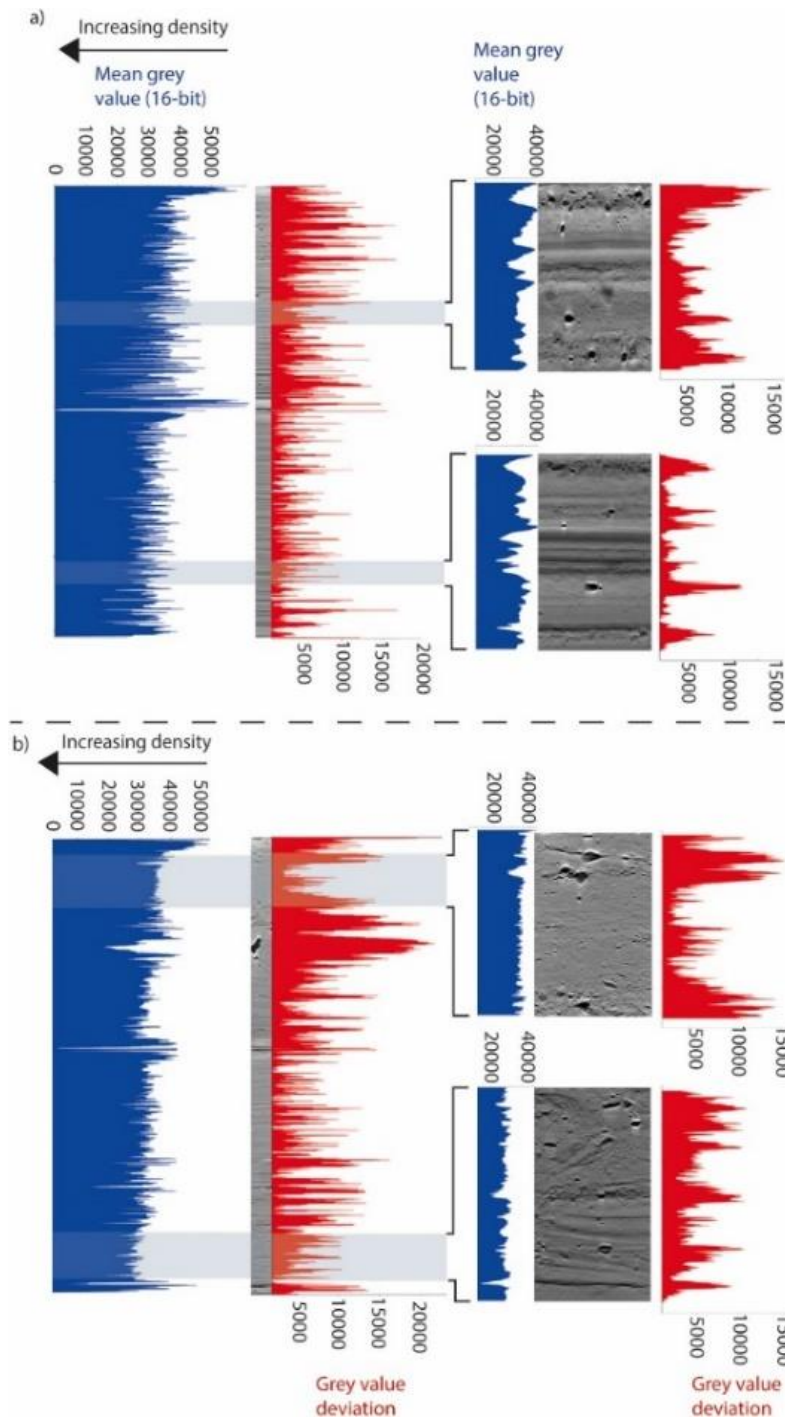


Figure 2.6. Grey value mean and standard deviations at pixel-scale resolution (0.066 mm) downcore. a) Core sections JC123-032PC-section-05 and JC123-032PC-section-06. b) Core sections JC123-033PC-section-05 and JC123-033PC-section-06. Sub-section lengths approx. 10–20 cm.

2.3.1. Glaciomarine sediment characterisation

Extracting sediment mean GV and sediment heterogeneity values (GV SD) at regular 10-pixel intervals generates a data-point cloud between ~23000 and 38000 (mean GV) and ~1000–5000 (SD). There is no discrete clustering of different sediment facies by X-ray characteristics, with sediment characterisation appearing gradational across different classes (Figure 2.7a). However, when attributing sediment heterogeneity (GV SD) to the corresponding Folk classification by gravel abundance (% clasts >2 mm), clear classification groups appear (Figure 2.7b). This confirms that cored sediments can be effectively classified by their greyscale image properties (mean GV and GV SD) into well-established Folk sediment classification categories. The statistically significant relationship between % clast abundance (>~0.5 mm) per cm and the sum of GV SD (per cm) is validated by a similarly strong relationship between % clast abundance of gravels (>2 mm diameter) and GV SD both sampled at pixel-scale resolution ($p < 0.001$, $r = 0.808$) (Figure 2.8).

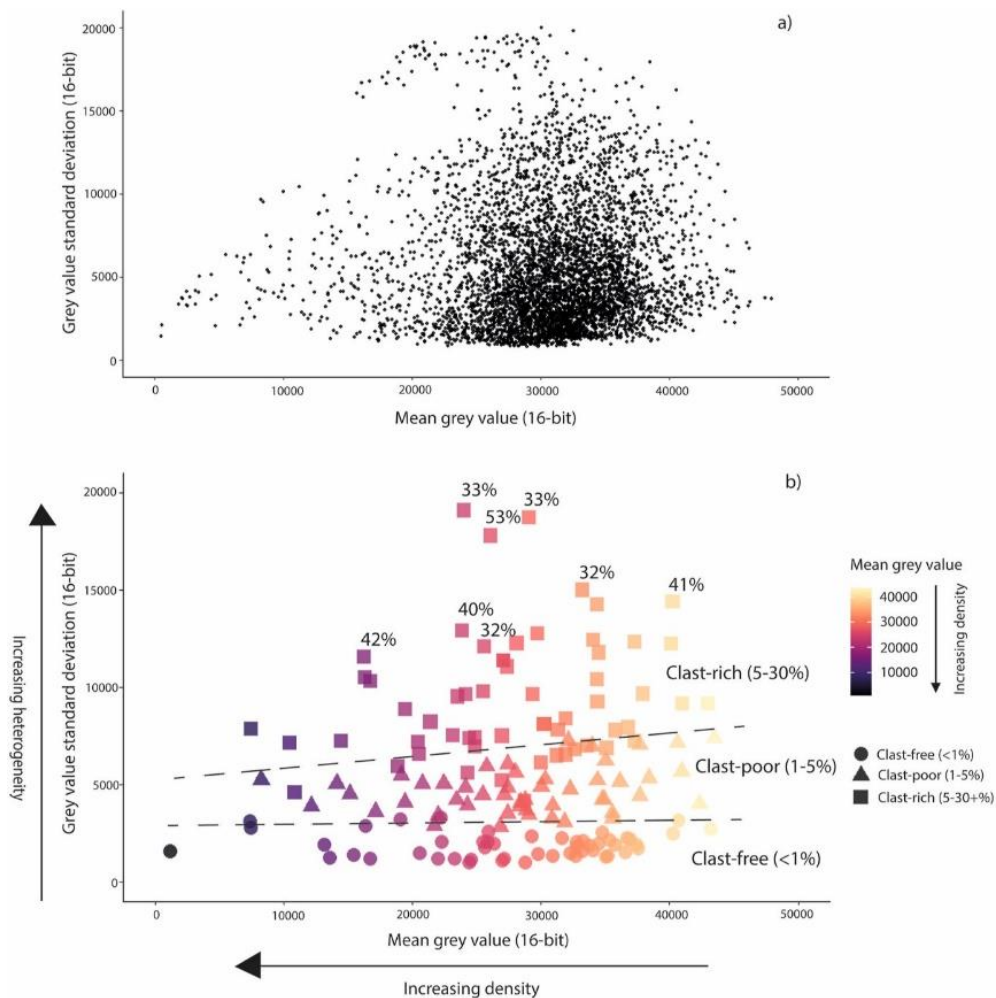


Figure 2.7. a) Sediments in cores JC123-032PC-section05 + 06 and JC123-033PC-section-05 + 06 characterised by X-ray greyscale properties (mean grey value and standard deviation at pixel resolution). GV data systematically sampled at 10-pixel downcore intervals; b) Sediment

classification by greyscale properties, dissected using modified Folk classification (Long, 2006). Colour of symbol indicates fine-grained sediment density. Shapes denote true % of clasts per Folk class. Each class contains a minimum of 50 data points, optically discriminated into dense ($n = 25$) and less dense sediments ($n = 25$) randomly sampled by mean grey value and associated standard deviation.

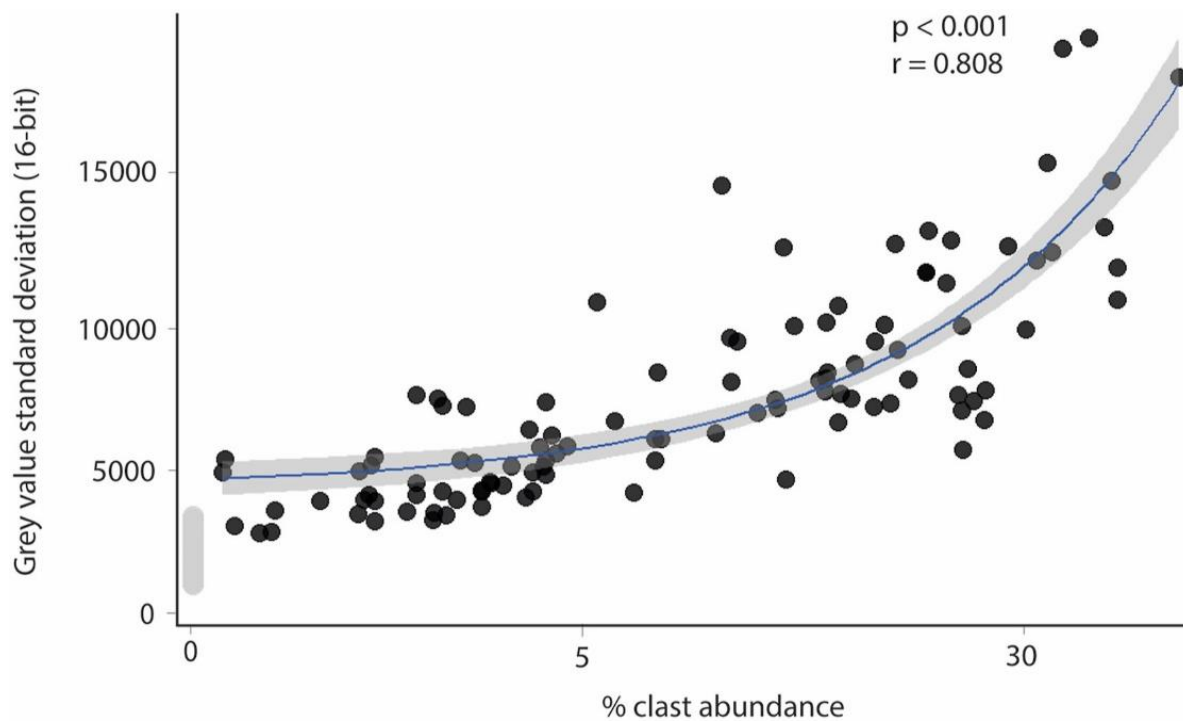


Figure 2.8. Grey value deviation (16-bit) vs clast abundance (> 2 mm) (%) measured at pixel-scale resolution. Clast-free sediments ($<1\%$) highlighted in grey near origin (excluded from correlation). Note: log scale on x-axis to aid data visualisation.

2.4. Discussion

2.4.1. X-ray computed laminography: comparisons with conventional X-ray imaging techniques

CL represents a currently under-utilised approach in Quaternary science highly tailored towards extracting X-ray attenuation coefficients and deriving valuable non-destructive information on sediment properties. The resolution of CL images is significantly greater (ca. 5–7 times) than existing methods using medical-grade CT and allows analysis of mm-sized clasts and finer details (0.066 mm in this study vs 0.35–0.5 mm; cf Bartels et al., 2017; Reilly et al., 2019). Due to the ‘thin slice’ approach, CL images can be less data intensive than CT scanning approaches, this can reduce scanning times and data processing.

It should be noted, however, that CT has significant merits. Researchers are currently offered a trade-off between the different cost vs analytical capabilities of CT, CL or XR. Bespoke 3D CT scanners now exist which have been designed to generate higher-resolution images for geological applications (e.g. Condrón and Hill, 2021). The 3D nature of CT allows for analysis of sedimentary structures in full 3D space, including 3D clast maps (see Bartels et al., 2018) which may allow analysis of clast properties (e.g., size and angularity) more robustly than 2.5D CL and 2D XR images. Using CT image processing software such as SedCT or Amira (Reilly et al., 2017; Bartels et al., 2017), grey values can be analysed from CT images without any bias from voids, cracks or scanning artifacts (Reilly et al., 2017) and in some cases without the bias of larger clasts (Bartels et al., 2017) by removing them after segmentation. In this area, CT images could prove more powerful than our CL sediment characterisation method. To account for this, we also include use of the median GV in the script, as in some cases this may prevent sediment density overestimation from anomalous dense clasts. CT scans also use CT numbers, which translate easily to absolute density (in Hounsfield units) (Reilly et al., 2017). By comparison, XR and CL images measure X-ray attenuation on a relative GV scale – although methods for calibration do exist for XR scanners (Francus et al., 2015). Calibration will always be preferable for studies comparing imagery between a large number of different cores.

Although XR may produce images at the same resolution, CL produces higher quality, sharper, more detailed images in the x-y plane (Figure 2.9d). CL is stated to be more suited than XR and CT to laterally extended samples due to reduced variations in beam transmission during scanning (Helfen et al., 2007). This effect is also observed in this study when sampling split glaciomarine sediment cores. With 2D XR excessive X-ray attenuation towards the centre of circular cores where sediment is thicker results in a high degree of cupping (Figure 2.9 panels a–c) and striping artifacts (Figure 2.9d). The lower degree of beam hardening in CL images allows quantitative GV extraction at depth-specific intervals, while maintaining large sampling windows. In XR images, with a higher degree of beam hardening, the sampling window is significantly reduced (Figure 2.9).

Our findings show that CL is better suited to quantitatively analysing X-ray attenuation coefficients (or sediment radiodensities) on split cores, not only due to improved image quality, but also artifact reduction, with images exhibiting a consistent generally ‘flatter’ appearance (Figure 2.9). Thus, although the SC analysis could be performed on XR images, the reduced image quality and artifacts with XR (e.g. striping, cupping and surface effects) renders these images significantly less well suited to this style of quantitative image analysis. The relative benefits and disadvantages of X-ray CL are examined further (below) in relation to IRD analyses.

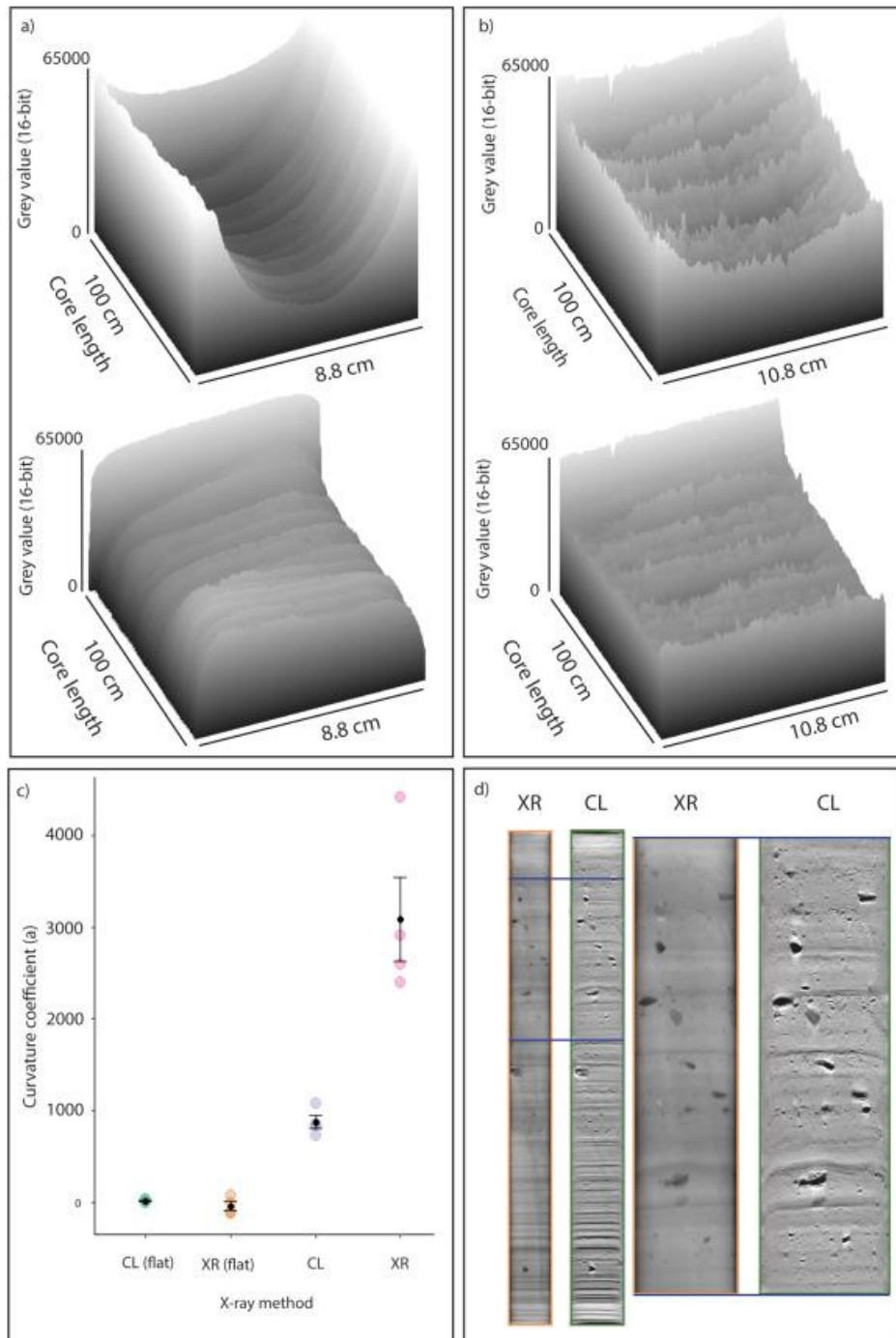


Figure 2.9. Comparison of X-radiography (XR) and X-ray computed laminography (CL). a) and b) Surface plots of images for each scan (JC123-032PC-section-06) before (top) and after (bottom) beam hardening corrections (a = XR; b = CL). c) Comparison of curvature coefficients between scanning methods and image treatments (flat = post-beam hardening correction for each image). d) Side by side comparison of XR and CL images with glaciomarine sediments from core JC123-032PC-section-05. The lower detail observed in XR images is the result of excessive X-ray attenuation and lower geometric magnification (Zuber et al., 2017).

2.4.2. The benefits of using sediment heterogeneity to detect and characterise IRD

Sediment heterogeneity (GV SD) provides a highly reliable IRD proxy merited by its efficiency and lack of observer bias. Using the ‘Sediment Characteristics’ FIJI/ImageJ plugin presented here can reduce IRD estimation times significantly when compared to on-screen manual grain counting. Moreover, by employing X-ray CL, clast abundance can be quantified at significantly higher resolution. The greatest difference between GV SD and existing IRD methods is observed when compared to manual grain counting (Figure A2). This is likely because the three IRD measurements quantify IRD in very different ways: (1) sediment heterogeneity (GV SD) is a function of the spread of relative sediment density values; (2) on-screen grain counts are a function of the absolute (or total) number of grains (>2 mm); and (3) volume fractions are a function of the size of grains (>~0.5 mm) per sampling region. Sediment radiodensity variations (GV SD) are observed to be more closely associated with the percentage area coverage of clasts on images, rather than clast abundance (grain counts). This is most evident in core section JC123-033PC-section-05 (Figure 2.4c) where at ca. 42–55 cm large and very dense clasts covering most of the image are significantly underestimated by the grain counting method (and see Figure A2). However, towards the base of the core (~79 cm) where there are a number of small, relatively low-density clasts, % area of clast and GV SD methods both underestimate the proportion of these smaller clasts. Therefore, we propose that combining sediment heterogeneity (GV SD) and grain counting may allow for a more comprehensive multiproxy approach, capable of better quantifying the contribution of iceberg-rafted debris to glaciomarine sediments.

The strong statistically significant relationship between gravel abundance (%) and GV SD allows classification of sediments using the modified Folk classification scheme (Long, 2006) and also provides appropriate calibration (Figure 2.7b). This result is consistent with our findings that a strong positive correlation exists between % area of clasts (>~0.5 mm) and the sum of GV SD per cm (Figure 2.5). Although a degree of overlap was noted within facies (between % clast abundance and GV SD), our results suggest that the statistical difference between classes is sufficient to automatically quantify gravel abundance and therefore classify sediments based on the clastic component. Notably, outliers increase in abundance with increasing gravel (IRD) content (Figure 2.8).

2.4.3. Inaccuracies associated with sediment heterogeneity as an IRD proxy

A few factors may account for the inaccuracies and outliers when predicting gravel abundance using sediment heterogeneity. Firstly, a lack of synchronicity in the magnitude is observed between all three IRD methods, this is probably due to the three distinctly different measurement techniques mentioned previously. The relationship between heterogeneity (GV SD) in glaciomarine sediments and clast abundance (%) (or IRD) is further complicated by several phenomena. Clasts may differ in composition giving unequal GV results between different rock types of identical size (or mass). Some

clasts may also appear faint (unrepresentatively high GV, suggesting lower than true density) if they lie outside or are only partially within the CL region of interest (Figure 2.10b) – similar partial volume effects have been noted by others to complicate the segmentation process (e.g. Withers et al., 2021). Such clasts were treated in the same way as all other clasts when creating ‘clast maps’ to maintain consistency but this may lead to underestimations in GV SD IRD measurements when compared to other IRD detection methods. An artifact which is more common in the CL images than XR and CT are bright ‘halos’; these are associated with clasts with a high contrast between the clast-matrix media (Figure 2.10a iv). These artifacts can lead to overestimations of matrix densities and clast abundance. However, as this effect is highly associated with clasts, correction is considered beyond the scope of this study. Additionally, the disadvantages of this scanning artifact in CL images are offset significantly when compared with XR, with a trade-off for increased image detail and a reduction in other artifacts e.g. beam hardening, cupping and striping. Investigations into reducing certain CL artifacts are currently ongoing (Bradley and Shreeve, 2020).

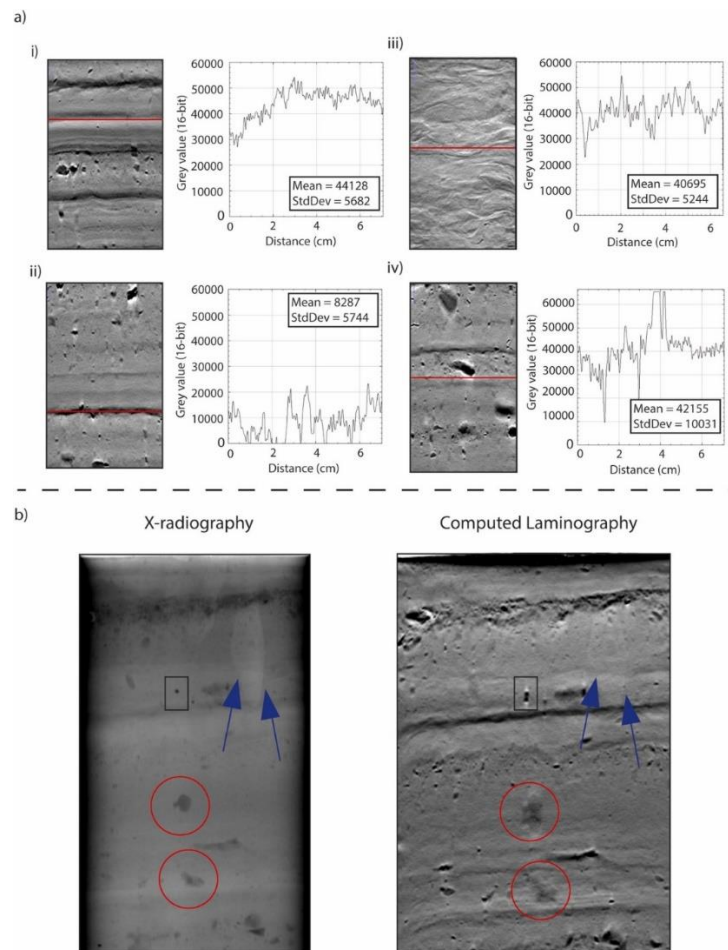


Figure 2.10. a) Examples of overestimations in sediment characterisation from: i) laminae boundaries; ii) flocculated silts; iii) wavy laminae; iv) bright clast-edge ‘halo’. b) Other examples of artifacts: ‘ghost clasts’ outwith scanning region of interest in CL (red circles); Bright halos at clast edges (black boxes); surface artifact reduced in CL image (blue arrows).

Non-clastic heterogeneous structures are found to be a common factor leading to overestimations in IRD. Occasionally, high GV SD occur due to measurements across laminae boundaries (Figure 2.10a i). Such overestimations are characterised by GV SD pulses which are high in magnitude but short in distance (downcore); these can be picked out by sudden erratic peaks in area charts (Figure 2.6). Matrix density variations are interpreted to result in the lower correlation coefficient in JC123-032PC-section-06 ($r = 0.72$) in comparison to other cores (e.g. the structureless matrix-supported diamicton JC123-033PC-section-05).

Similar GV SD overestimations are observed relating to other non-clastic heterogeneities. Examples include sediment with abundant flocculated laminae (Figure 2.10a ii), wavy laminae or deformation structures (Figure 2.10a iii), biogenics, bioturbation and mud pellets. These non-clastic heterogeneities may lead to overestimations in apparent IRD content (GV SD) and, if not recognised, could have implications when attempting to automatically quantify IRD content in different sediments. We therefore stress that this automated tool should be viewed and implemented as a measure of sediment heterogeneity, but that it can also be used as a proxy to infer IRD in sediment with a horizontally homogeneous sediment matrix. Combining sediment heterogeneity (GV SD) with on-screen grain counting may allow for a more accurate and comprehensive understanding of sediment structures and IRD, as different IRD measurement techniques can produce varying results (cf Andrews, 2000; Bartels et al., 2018).

There are a number of effects from piston core sampling which may potentially lead to inaccuracies in greyscale imaging properties. These sampling artifacts may include flow-in (Jutzeler et al., 2014) which can lead to data loss, or to the inclusion of poorly consolidated or highly fluidized sediment. Ultimately, any compression of sediment during sampling can lead to overestimations in sediment radiodensity (lower mean GV), with extensions of sedimentary structures resulting in underestimations (Skinner and McCave, 2003).

The maximum theoretical SD of a 16-bit greyscale image with a greyscale value range of 0–65535 $\approx$ 32767. The maximum SD would require 50% clast abundance to allow for sufficient deviation within the dataset (Figure 2.11a). Thus, the relationship between GV SD and clast abundance (%) likely breaks down at clast abundances >50%, with increasing uncertainty of GV SD at clast abundances >30% (Figure 2.7b). Matrix sediment with higher GV can also lead to overestimations of clast abundance and vice versa (Figure 2.11b). We deem this statistical phenomenon unavoidable, as the coefficient of variation was found to be a significantly weaker IRD proxy, with significant overestimations observed in dense matrix sediments. Despite these phenomena, a statistically significant relationship is observed between clast abundance (%) and GV SD ($p < 0.001$).

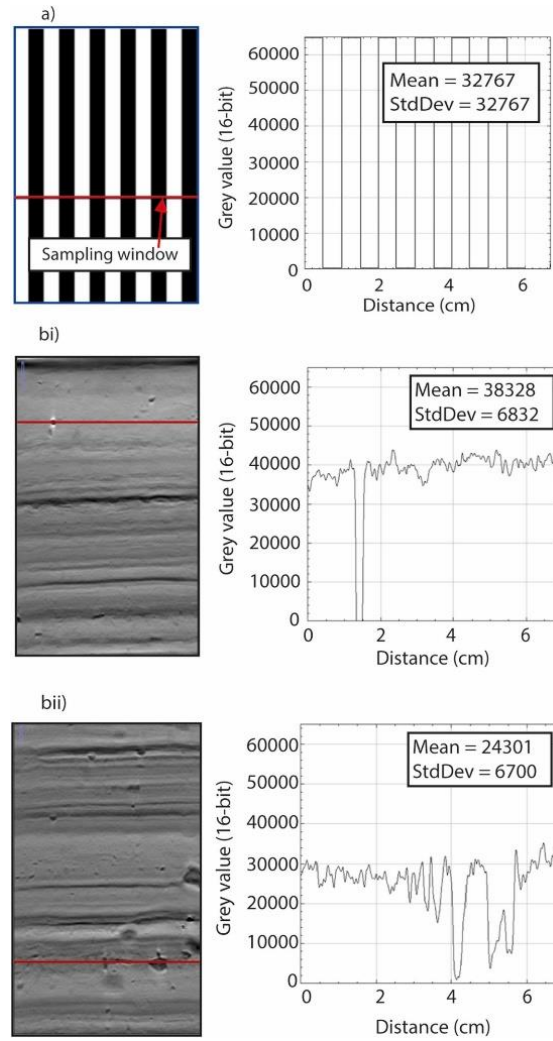


Figure 2.11. Statistical phenomena associated with using GV SD as a proxy for % clast abundance (IRD): a) maximum GV SD of 16-bit GV image; bi) overestimations due to small dense clast in low density (high GV) matrix; bii) underestimations due to clasts of variable radiodensity embedded within dense matrix.

2.4.4. Sediment mean GV (radiodensity) as a proxy for energy of sediment deposition

Homogenous clast-free laminae can be indicative of a range of different glaciomarine environments (Ó Cofaigh and Dowdeswell, 2001; Maddison et al., 2005; Normandeau et al., 2017; Jennings et al., 2018; Smith et al., 2019), where the delivery of sediment-laden meltwater controls the character of glaciomarine sediment (Dowdeswell et al., 2000) with laminae density largely dependent on the energy of water flow at the time of deposition. The radiodensity of sediments could therefore be a powerful under-used proxy in deciphering the nature of deposition. As previously stated, for the cores in this study the fine sediment matrix appears to be the largest control on mean sediment radiodensity and the difference in laminae density is concurrent with changes in the mean grain size and composition of mud-silt couplets – with the finest-grained mud representing very low-energy settling and coarser silt indicating more energetic subaqueous deposition (Bradwell et al., 2021). This

suggests that sediment radiodensity in fine-grained material could be indicative of the energy of deposition, in line with Vandorpe et al. (2019) who highlight a causal relationship between high X-ray attenuation coefficients (in Hounsfield units) and increased marine bottom-current activity. However, differing sediment provenance (e.g. alternating carbonate vs mafic mineral assemblages) resulting in differing radiodensities could also explain the variations in matrix GV between laminae. We suggest that higher radiodensity (lower mean GV) silt/mud glaciomarine sediments in this study are probably typical of minerogenic laminae of higher energy, probably terrigenous, origin (mean GV < 28000); conversely, lower radiodensity sediments (higher mean GV) are more typical of lower energy laminae of predominantly marine/biogenic origin (mean GV > 28000). Alternatively, in laminated sediments suspension settling could also be a factor, with coarse material settling first followed by finer material, giving rise to the cyclic variations in radiodensity. As the abundance (%) of clasts increases, the relative effect of matrix density on mean GV decreases. Therefore, to maintain the highest degree of predictive power, we suggest that the clast-free and clast-poor Folk classes provide the best proxy for sediment pathway and energy of deposition.

Despite the theoretically sound and robust relationships identified in this study, there are limitations with this approach. The density of glaciomarine sediments can be a function of phenomena other than transport energy or transport distance, as the relationship between bulk density and particle size/particle density is not a 1:1 relationship (McCave and Hall, 2006). Other factors affecting fine-sediment fraction density in glaciomarine settings include fine-sediment flocculation, sediment compaction (Crémer et al., 2002), and (partial) cementation (Hodell et al., 2017). The incorporation of rock flour or any other fine (silt-sized IRD) from icebergs and/or ice shelves/ice tongues to form dense silty fines may also be a factor in density overestimations (Hesse and Khodabakhsh, 2006). This problem has been observed in reconstructions of deep-sea bottom current velocities when using high-resolution particle-size analysis to discriminate sorted silts (bottom current material) from heterogeneous fines (IRD) (Jonkers et al., 2015). The increased resolution and detail of CL over CT helps to mitigate this effect.

2.5. Conclusions

The findings of this study show encouraging results for a new non-destructive, automated image-analysis technique of glaciomarine sediments. A number of significant findings are summarised:

- 1) Computed laminography (CL) images are better suited to quantitative analyses of cored glaciomarine sediments than traditional 2D X-radiography for two main reasons: (i) image quality is greatly increased, evidenced by an enhanced clarity of features (particularly clasts), higher contrast and sharper detail within the ‘thin slice’ plane of view; (ii) artifacts are found to be significantly reduced (beam hardening, striping and surface effects), although there is an increase in clast-edge ‘halos’.

- 2) CL acquisition and processing produces smaller datasets compared to full 3D computed tomography (CT) but at significantly higher resolution than medical-grade CT imaging – resolving sedimentary structures and gravels which presently can only be identified using higher-resolution CT scanners made specifically for geological applications. As CL is cheaper, more efficient and less data intensive than CT, it offers multiple benefits, especially if absolute radiodensities (in Hounsfield Units) are not required.
- 3) Sediment heterogeneity measured by grey value standard deviation (GV SD) of CL imagery provides a very good approximation of clast abundance (%) in cored sediments with a strong statistically significant linear correlation ($r = 0.72\text{--}0.87$) ($p < 0.001$). GV SD can therefore be used as a proxy for IRD in glaciomarine sediments. Using our Sediment Characterisation tool (in the form of a FIJI/ImageJ plugin), IRD can be derived automatically at pixel-scale resolution. We hope this technique will improve efficiency but also improve resolution over existing IRD-identification methods.
- 4) Combining CL sediment heterogeneity (GV SD) with mean GV – a measure of sediment radiodensity – allows for automated classifications of marine and glaciomarine sediments into Folk sediment classes. This classification system could also be used to define the nature of sediment deposition in a range of marine settings.

In addition to the numerous benefits of this new technique, there are however certain drawbacks. Firstly, X-ray CL despite being better suited to GV quantification, suffers from certain artifacts which XR and CT are less affected by. These include: bright clast-edge ‘halos’ and out-of-plane features outwith the scanning region of interest. Sediment heterogeneity (GV SD) may also be better suited to quantifying clast abundances in certain sediments than others. A horizontally homogenous matrix (over the width of the core) is desirable, otherwise non-elastic variations in GV SD are also measured. These overestimations can be largely corrected for in regularly inclined laminated sediments by rotating images accordingly prior to analysis.

Finally, this study was borne out of the recent trend toward standardised practices using automated open-access tools for analysing glaciomarine sediment. We hope that the application of CL in Quaternary science will enable new tools and new practices to be implemented to rapidly and non-destructively characterise high-value glaciomarine sediments. Additionally, we propose that the tools presented in this study should have broader applications in the geosciences beyond glaciomarine sediment classification and IRD quantification including: precise varve counting; the identification of bioturbation structures; void space quantification (porosity); and sediment deformation analyses.

Chapter 3: A Methodological Study of Different Ice-Rafted Debris Quantification Techniques

3.1. Introduction – ice-rafted debris

Ice-rafted debris (IRD) is terrigenous material transported by icebergs to oceans or lakes. The detection of IRD forms a key component of studies aiming to track changes in global climate, ocean circulation, ice sheets, and ice shelf / ice tongues (Heinrich, 1988; Watkins et al., 2007; Scourse et al., 2009; Reilly et al., 2019; Vermassen et al., 2020). IRD may be derived from any glacial sediment which reaches the terminus and is incorporated in calving icebergs. As such, IRD can encompass the entire spectrum of grain sizes (Andrews, 2000). However, it is generally characterised by either sand or gravel-sized detritus or the heterogeneity of sediment (Lawson et al., 1998; Andrews, 2000; Dowdeswell et al., 2000; Scourse et al., 2009; Bartels et al., 2017; McDonald et al., 2022).

Debate continues surrounding whether icebergs (and associated debris) are more common during advancing or deglaciating glacial stages – but there is consensus that IRD deposition occurs during both rapid advance and retreat phases (Wilton et al., 2021). In general, increases and decreases in the presence of IRD are used to infer increased and decreased past iceberg flux, respectively (Heinrich, 1988; Auffret et al., 2002; Hodell et al., 2017). However, there are some caveats which detach IRD abundances from iceberg flux, including ocean thermal changes, variable sediment inheritance, background sedimentation rates, non-IRD related coarse-grain input due to mass flows or turbidity / bottom currents, and ocean current patterns (Mackiewicz et al., 1984; Garcia and Parker, 1993; Cowan et al., 1997; Andrews, 2000; Reilly et al., 2019; Vermassen et al., 2020; Starr et al., 2021).

Before considering the above complexities, significant methodological uncertainties remain regarding how different IRD-quantification techniques may bias interpretations of the palaeo-record. The methodological inconsistencies and biases of each technique are very rarely considered and only rarely explored (e.g. Andrews, 2000; McKay et al., 2022). This study, therefore, aims to investigate the relationship between four IRD quantification methodologies: (i) sieving; (ii) laser particle-size analysis (LPSA); (iii) clast counting on X-radiographs (XR); and (iv) automated analysis of X-ray grey-values using X-ray imagery, for example, X-ray computed laminography (CL). More information on the application of these 4 techniques can be found in the following works: Grobe (1987); Andrews, (2000); Hansen et al. (2015); McDonald et al. (2022).

3.1.1. Techniques commonly applied for quantifying Ice-rafted debris (IRD)

3.1.1.1. Destructive IRD detection techniques

Sieving is one of the oldest and most commonly used IRD quantification techniques. Workers have used various sand fractions to quantify IRD (63 μm – 2000 μm +) (Connolly and Ewing, 1965; Ruddiman, 1977; Heinrich, 1988; Andrews, 2000; Hass, 2002; Scourse et al., 2009; Weber et al.,

2021; McKay et al., 2022; Dong et al., 2024). Sieving is an accessible, low-cost and respected technique, and has often been used to validate other established IRD detection techniques (Grobe, 1987; McKay et al., 2022). Sieving remains popular in studies to this day, however, there is no consensus on the most effective approach regarding the cut-off size fraction to determine IRD (cf. Vermassen et al., 2019; Horowitz, 2021; Dong et al., 2024).

Researchers are faced with a trade-off between preserving sediment core material, gaining a representative sample and selecting a threshold grain-size which robustly represents IRD, as finer grain sizes are readily transported through other mechanisms (Ó Cofaigh and Dowdeswell, 2001; Hass, 2002; McKay et al., 2022). It is important, therefore, to provide more clarity over how different cut-off sediment grain sizes ($> 63 \mu\text{m}$, $> 250 \mu\text{m}$ and $> 2 \text{ mm}$) relate to each other in deglacial sediments. If these size fractions are correlated in particular settings, e.g. deglacial sediments of the British-Irish Ice Sheet, researchers may select a fine grain size for determining IRD and preserve valuable sediment core material.

Fractions of various fine sediments can be quantified more efficiently by laser particle size analysis (LPSA) (e.g. Passchier, 2011; Hansen et al., 2015). However, LPSA systems specifically require significantly smaller sample sizes, depending on the turbidity of the sample. In particularly muddy sediments this is likely to be $\sim < 0.1 \text{ mg}$. McKay et al. (2022) argue that 10 – 20 g of sediment is required to attain a representative sample from the sand fraction, while others suggest $\sim 5 \text{ g}$ is appropriate (Ruddiman, 1977). Therefore, small sample volumes can limit the potential to detect IRD, particularly in IRD sparse sediments, for example in glaciomarine settings where meltwater flux is high and in sub-sea-ice or sub-ice-shelf settings (e.g. Mackiewicz et al., 1984; Dowdeswell et al., 2000; Smith et al., 2019). A cross-comparison between sieving at different grain sizes and LPSA with small volumes of sediment is necessary to confirm whether this is the case with deglacial glaciomarine sediments from different settings. Another drawback of LPSA is that it cannot (typically) measure sediment greater than 2-3 mm in diameter, however, it does benefit from being fast and doesn't require a high degree of expertise to operate.

3.1.1.2. Non-destructive techniques

A revolutionary IRD quantification proxy was developed by Grobe (1987) in a brief 2-page paper. This is a non-destructive, rapid and less labour-intensive method which involves manually counting clasts ($> 2 \text{ mm}$), in cm slices of sediment core X-radiographs. This technique is considered a straightforward, fast, robust, and cost-effective method for identifying IRD, and is still used in high impact Quaternary Science to this day (Graham et al., 2017; Bollen et al., 2022; Jennings et al., 2022; Andrews et al., 2023; López-Quirós et al., 2024). Despite its common application there are still significant uncertainties regarding the robustness and user variability of this method (McKay et al., 2022; McDonald et al., 2022; Jasper et al., 2024) – See Chapter 4 for a full description and quantification of these uncertainties. Also, with the introduction of new, automated or supervised

routines which allow for automated grain counting (using Computed Tomography – CT) (Bartels et al., 2017; Reilly et al., 2019; Cederstrøm et al., 2021) or automated sediment characterisation of X-ray imagery (McDonald et al., 2022), it may be much more user intensive than alternative methods.

3.1.1.3. Automated image analysis routines

Several newer, automated routines have been implemented recently, pioneered by Bartels et al. (2017), where authors use CT scans to automatically count clasts on images (e.g. Reilly et al., 2019). To achieve automated clast segmentation, CT scans are necessary to obtain density calibrated 3-dimensional sediment core montages. User defined thresholds allow the removal of the core liner, void space, biogenic material and other non-sedimentary fractions of the image. Clasts can then be segmented, counted and the remaining fine fraction analysed for its horizontal CT values (density) and associated standard deviation (small fraction sediment heterogeneity) using MATLAB or AMIRA (Bartels et al., 2017, 2018; Reilly et al., 2019; O’Riley et al., 2022). Cederstrøm et al. (2021) also explored a supervised routine using phantom cores to segment and count sand grains.

The main drawbacks of these methods lies in the cost and time-consuming nature of CT scanning and licensing Amira or MATLAB software. The cost of MATLAB and AMIRA is currently ~ \$1,076.50 and \$4000 - \$9000 per year, respectively. The resolution of CT imaging is typically lower than XR or CL imagery, however, ultra-high resolution micro-CT does exist, but it comes with the burden of significantly longer scanning times (~ 10 hours for a m-long sediment core) (see Cederstrøm et al., 2021 for details on the method).

Segmentation of clasts can be performed on XR images (Principato, 2005), however, as these images are two-dimensional and not density calibrated, manual segmentation is generally required as implemented by McDonald et al. (2022), but this approach is very time consuming. Therefore, the horizontal sediment heterogeneity using CL images provides a more useful proxy for IRD.

3.1.1.1.4. Grey value standard deviation (GV SD) using X-ray computed laminography

The previous chapter highlighted how GV SD can be used to measure sediment heterogeneity which, in turn, can be used as a proxy for IRD abundance. This method is the highest resolution IRD methodology to date (0.066 mm downcore resolution) and is exceptionally rapid to implement (near instantaneous). However, like Bartels et al., (2017), who use a clast % area coverage technique (which correlates strongly with this method), GV SD is prone to overestimating the flux of IRD when large, dense clasts are present and GV SD also can mis-identify non-IRD related sedimentary features as ‘IRD’ (e.g. bioturbation, deformation) (McDonald et al., 2022).

3.1.2. Previous comparisons of ice-rafted debris methodologies

A small number of previous studies have specifically investigated the relationship between different IRD quantification techniques. The two most comprehensive studies compared a combination of sieving, LPSA and X-ray clast counting from cores recovered near the contemporary ice sheets. The first analysed a relatively proximal sediment core, in Nansen Fjord, E Greenland (JM96-1210) and a distal core on the Labrador-Newfoundland margin (HU75-054) and the other study investigated a transect of distal sediment cores recovered from E Ross Sea, Antarctica (Andrews, 2000; McKay et al., 2022).

In the only study to compare the 3 traditional techniques (sieving, LPSA and X-ray clast counting), McKay et al. (2022) found high agreement between all methods, with the exception of LPSA and clast counting (> 2 mm) in one of the two comparisons, whereby, LPSA underestimated IRD due to low sampling volumes (Table 3.1). The strength of relationships between IRD techniques varied depending on which sediment core was analysed, suggesting that different environmental settings could affect the signals of IRD proxies (Table 3.1).

Table 3.1. Correlations of existing work assessing different ice-rafted debris techniques on two sediment cores (McKay et al., 2022). Note: variable correlation coefficients between the same methods on different cores (notable LPSA and X-ray clast counting). Values = Pearson's r correlation coefficients; or R^2 denoted by *.

Sediment core and study (top cell) Location of core (cell beneath core label)	Sieve 63–125 µm	Sieve (88 – 210 µm)	Sieve (> 88 µm)	Sieve (210 – 500 µm)	Sieve (> 210 µm)	Sieve % (250 – 2000 µm)	210 µm against > 88 µm	LPSA % (125 - 2000 µm)	125–4000 µm	Clast counting # (> 2 mm)	Method
LC 42 (McKay et al., 2022)								0.758		0.677	Sieve % (250 – 2000 µm)
E Ross Sea, Antarctica						0.758				0.527	LPSA % (125 - 2000 µm)

						0.677		0.527			Clast counting # (> 2 mm)
LC 48 (McKay et al., 2022)								0.417		0.608	Sieve % (250 - 2000 µm)
E Ross Sea, Antarctica						0.417				0.175	LPSA % (125 - 2000 µm)
						0.608		0.175			Clast counting # (> 2 mm)
POR-13-05 (Vermassen et al., 2019)									0.79		Sieve 63–125 µm
Kangerlussuaq fjord, E Greenland	0.79										Sieve 125– 4000 µm
POR13-03 (Vermassen et al., 2019)									0.57		Sieve 63–125 µm
Kangerlussuaq fjord, E Greenland	0.57										Sieve 125– 4000 µm
POR13-16 (core is incorrectly labelled in Vermassen et									0.51		Sieve 63–125 µm

al. (2019) text).											
Kangerlussuaq fjord, E Greenland	0.51										Sieve 125– 4000 µm
POR13-16 (Vermassen et al., 2019)								0.30			Sieve 63–125 µm
Kangerlussuaq fjord, E Greenland	0.30										Sieve 125– 4000 µm
JM96-1210 (Andrews, 2000)				0.42*							Sieve (88 – 210 µm)
Nansen Fjord, E Greenland		0.42*									Sieve (210 – 500 µm)
JM96-1210 (Andrews, 2000)					0.82*						Sieve (> 88 µm)
Nansen Fjord, E Greenland			0.82*								Sieve (> 210 µm)

These results support earlier studies, where very strong agreement was noted between X-ray clast counting and traditional sieving (> 2 mm threshold) in a single sediment core (Grobe, 1987). Later, Andrews (2000) found that the sieving method underestimates clast abundances when the sampling volume is lower than that of the XR sampling window (28 cm³ X-ray clast counting window volume v 10.4 cm³ sieving volume). Andrew's (2000) study emphasises that sampling volume can play a significant role in attaining a representative estimation of IRD.

Several studies have investigated the effect that different cut-off size thresholds (for example, fine, medium or coarse sand or gravel) can have on IRD outputs (Table 3.2). Molnia et al. (1972) reportedly found strong correlation between the > 62 µm and > 500 µm sieved sand fractions (as cited in Ruddiman, 1977). Vermassen et al., 2019 explored the effect that sieving at various size

fractions can have on ‘apparent’ IRD outputs (see Table 3.1). Strong trends are seen, but coarser size fractions are responsive to larger peaks in IRD (and potentially iceberg-rafting). Meanwhile, Andrews (2000) investigated different sieving thresholds (500-210 μm against 210-88 μm and > 210 μm against > 88 μm). They found strong agreement with discrepancies, particularly with the latter comparison ($R^2 = 0.42$ and 0.82) and with these methods versus counts of particles (> 2 mm) but still with a reasonable degree of variability (> 50%).

GV SD remains unexplored compared to destructive techniques. As outlined in Chapter 2, when comparing GV SD and clast counting (> 2 mm) strong statistically significant, but variable agreement was observed, but the relationship depended on the sediment structure and clast abundances. Sediments with low and variable gravel abundances throughout the unit returned the strongest correlations, while highly clast-rich or deformed sediment core regions returned weaker correlations (Pearson’s $r = 0.692, 0.540, 0.440, 0.322$). This is largely because GV SD was discovered to be more representative of the percentage area coverage of clasts on CL images than the raw clast abundance. Therefore, it was found that GV SD would overestimate the input of large, high radiodensity clasts, and clast counting would overestimate the contribution of small pebbles (Bartels et al., 2017, 2018; McKay et al., 2022; McDonald et al., 2022).

It is clear that different IRD signals may be returned depending on the chosen methodology or in different glaciological and / or oceanographic settings (Table 3.2). Here, we explore the pros and cons of various IRD approaches including sieving (> 63 μm , > 250 μm , > 2 mm); LPSA (> 63 μm , > 250 μm); manual clast counting using XR; and GV SD on CL images on a sediment core which records an ice-stream deglacial signal from the last British-Irish Ice Sheet in NW Scotland – The Minch palaeo-ice stream (MnIS).

3.1.3. Study site and sediment depositional environments

The sediment core examined in this study was collected by the BRITICE-CHRONO consortium, in July 2015, recovered from the seabed in The Minch, NW Scotland (JC123-021PC). Sedimentary facies broadly relate to glaciomarine / ice-shelf deglacial stratigraphy (Bradwell et al., 2021), however, a postglacial unit is also interrogated which covers the upper section of this core. To date, no studies providing a methodological critique of traditional and innovative IRD techniques have been undertaken on British-Irish Ice Sheet (BIIS) sediments, therefore, it is important to compare how different IRD methods relate to each other in this setting. Additionally, ice-shelf related deglacial stratigraphy shows significant variations in IRD, with sparse and clast-rich units alike (Smith et al., 2019), making them ideal facies for comparing different techniques. This study also provides unique insight into how different methods perform in this sedimentary environment.

1 Table 3.2. Comparison of IRD techniques: strengths, drawbacks and unknowns (Ruddiman, 1977; Andrews et al., 1997; Andrews, 2000; Bartels et al.,
2 2017; Reilly et al., 2019; Vermassen et al., 2019, 2020; McKay et al., 2022; McDonald et al., 2022)

	Sieving (e.g. Andrews, 2000; Cowan et al., 2008; Scourse et al., 2009; Vermassen et al., 2019, 2020; Ahn et al., 2024)	Laser particle size analysis	Clast counting (Grobe, 1987)	Sediment Heterogeneity (Grey value standard deviation) (McDonald et al., 2022)	Automated CT counting (Bartels et al., 2017; Reilly et al., 2019)
Strengths	• Well established and trusted. • Low skill level required. • Shells / non-clastic material can be removed from the sample.	• Well established and trusted. • Fast sampling time with modern equipment. • Low skill level required.	• Traditionally fast to apply. • Inexpensive. • Can decipher non-IRD from IRD (although this can be challenging). • Fast. • Non-destructive.	• Fast application (~ 2 seconds per 15000-pixel tiff). • Inexpensive compared to CT scans. • Non-destructive. • Consistent results for each measurement. • Ultra-high resolution (0.066 mm). • Non-destructive.	• Analyses 3D information. • Fast to implement once CT scans are attained. • Non-destructive.

Weaknesses	• Destructive. • Can be costly if samples are in limited supply (e.g. extensively sampled cores).	• Destructive. • Can be costly if samples are in limited supply (e.g. extensively sampled cores) • A relatively small number of studies opt to use this method to directly constrain IRD abundances.	• Potentially time consuming compared to newer methods. • Clasts can overlap introducing complexity of the technique.	• Incorporates non-IRD in results. • Method cannot distinguish between dense or less dense non-homogeneous sediment (horizontally) or shells. • Imaging artifacts will result in overestimations of IRD. • Overestimates the input of small pebble-sized IRD, underestimates large cobble-sized IRD. • New and only trialled in one study.	• Typically limited to DICOM files (limits resolution) unless ultra-high-resolution CT is acquired but this significantly increases scanning times over X-radiographs and X-ray computed laminography. • Can incorporate non-IRD if particularly dense. • Expensive software e.g. Amira or MATLAB. • Understanding of CT software operations necessary (expertise).
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Unknown	• How results from different size cut-off thresholds compare to other IRD method in deglacial sediment cores from the British-Irish Ice Sheet. • Are smaller size fraction (e.g. 63 μm) representative of IRD? Do they strongly correlate with coarser fraction ($> 250 \mu\text{m}$ or 2 mm)?	• How results from different size cut-off thresholds compare to other IRD method in deglacial sediment cores of the British-Irish Ice Sheets • Can this technique produce a representative measure of IRD in deglacial British-Irish Ice Sheet sediments?	• Whether the method is consistent between users • Whether experience can affect results. • Time taken to perform task.	• How the statistical output compares to sieving, LPSA and other automated techniques.	• Is there potential for user variability based on thresholding / segmentation-based decisions?
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3.1.4. Aims and objectives

This study aims to:

1. Explore the strengths and weaknesses of various IRD techniques (sieving, LPSA, XR clast counting, and semi-automated sediment heterogeneity (GV SD)).
2. Refine our understanding of how different IRD techniques may bias interpretations of the Quaternary record.
3. Guide users on best practice when it comes to investigating IRD in palaeo-ice sheet settings such as the British-Irish Ice Sheet.

3.2. Methods

Four IRD quantification techniques were undertaken to identify similarities and differences between the methods. The four methods compared in this study are:

1. Sieving (at $> 63 \mu\text{m}$, $> 250 \mu\text{m}$ and $> 2 \text{ mm}$) (as per Ruddiman, 1977).
2. Laser particle size analysis (at $63 \mu\text{m}$ and $250 \mu\text{m}$) (as per Hansen et al., 2015).
3. XR Clast counting (as per Grobe, 1987).
4. Grey value standard deviation (GV SD) using X-ray Computed laminography (as per McDonald et al., 2022).

3.2.1. Ice-rafted debris quantification techniques

3.2.1.1. Destructive methods

A small volume of sediment ($\sim 0.5 \text{ g}$) was extracted from core JC123-021PC at 37 different horizons for sieving and LPSA analysis. Sieving was applied using a 63, 150, 250, and 2000 μm sieves with $\sim 0.3 \text{ g}$ of sediment, and LPSA was undertaken with the remaining sample ($\sim 0.2 \text{ g}$) at the same cut-off size thresholds (except 2000 μm). Dissolution of biogenic opal / carbonate material was not undertaken as:

- i) previous investigations into these sediments revealed that like many other glaciomarine sediments they are inherently poor in marine carbonate material (Bradwell et al., 2021; Chapter 5).
- ii) The bed of the Inner Minch bed has large areas comprising Jurassic calcareous mudstone, which incorporates fossilised organisms (Fyfe et al., 1993). This potentially makes up a significant percentage of sediments contained within these glaciomarine facies. Any extraction or dissolution of these fossilised organisms would potentially bias estimations of IRD.

A sample was extracted from the sediment cores at each horizon and was left to air dry for 48 hours, before being weighed. The sample was then wet sieved using the four mesh sizes, again left undisturbed for another 48 hours to dry before being weighed. The difference between the dry bulk sample weight and dry sieved weight represents the % IRD output. All weights are inclusive – presented as including sediment of any given grain size and larger. For example, for sediment captured $> 63\ \mu\text{m}$ all sediment $> 250\ \mu\text{m}$ is also present within the result as this material can all be considered to be iceberg-rafted.

For LPSA sampling, the small sediment sample ($\sim 0.2\ \text{g}$) was added to a solution containing water and the dispersing solution Sodium Hexametaphosphate (Calgon), before being left on a shaker table overnight. Samples were then analysed on the University of Stirling's Bettersizer S3 Plus system where they were further dispersed by sonification and mechanically by turbulence before the particle size distribution was measured.

3.2.1.2. Non-destructive methods

X-ray clast counting was undertaken according to Grobe (1987) by counting gravel clasts ($> 2\ \text{mm}$) per cm interval on X-radiographs. However, the analysis was undertaken on-screen rather than using cm-thick X-ray slabs as was traditionally the case. The GV SD of CL images was then extracted, at pixel-interval following the steps in McDonald et al. (2022). To compare the GV SD to other techniques, the sum of the standard deviation per-centimetre was used to produce the output for an entire centimetre (151 pixels), rather than a single pixel width.

3.2.2. Inter-facies comparison of different IRD methodologies

To assess whether different methods were broadly synchronous at discriminating different facies based on the IRD abundance, strip plots are presented with the mean values plotted on each chart. This allows an investigation into the spread, detection rate, overestimations / underestimations and consistency of each technique.

3.2.3. Statistical analyses

To assess whether the numerical output for each technique followed a univariate normal distribution, the Shapiro-Wilk test for normality was implemented. As the outputs of all techniques followed a non-normal distribution (Figure 3.1), the strength of correlations between different methods was assessed using Spearman's rank correlation (ρ). As the non-parametric equivalent of Pearson's correlation coefficient, Spearman's ρ assesses the strength and direction of relationships by ranking data for each set, comparing the ranks and calculating how closely they match each other (monotonic increases and decreases).

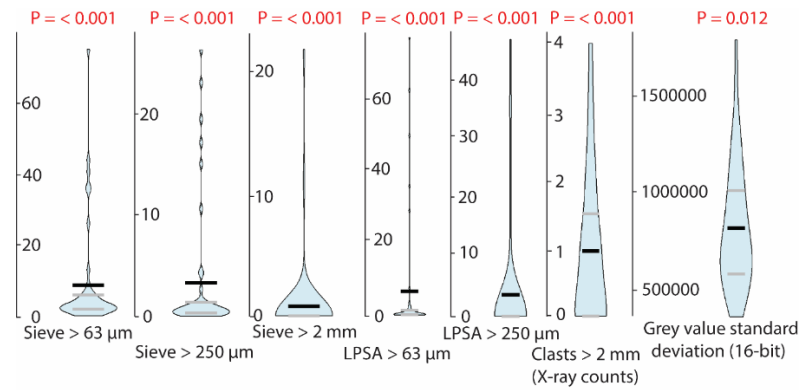


Figure 3.1. Distributions of each methods' IRD quantification output displayed using violin plots. Thicker regions of the violin indicate more closely-distributed values; thinner regions indicate more sparsely-distributed values. Thick black lines indicate means, grey lines indicate Q1 and Q3. Note: no normal distributions, therefore Spearman's rank correlation was selected.

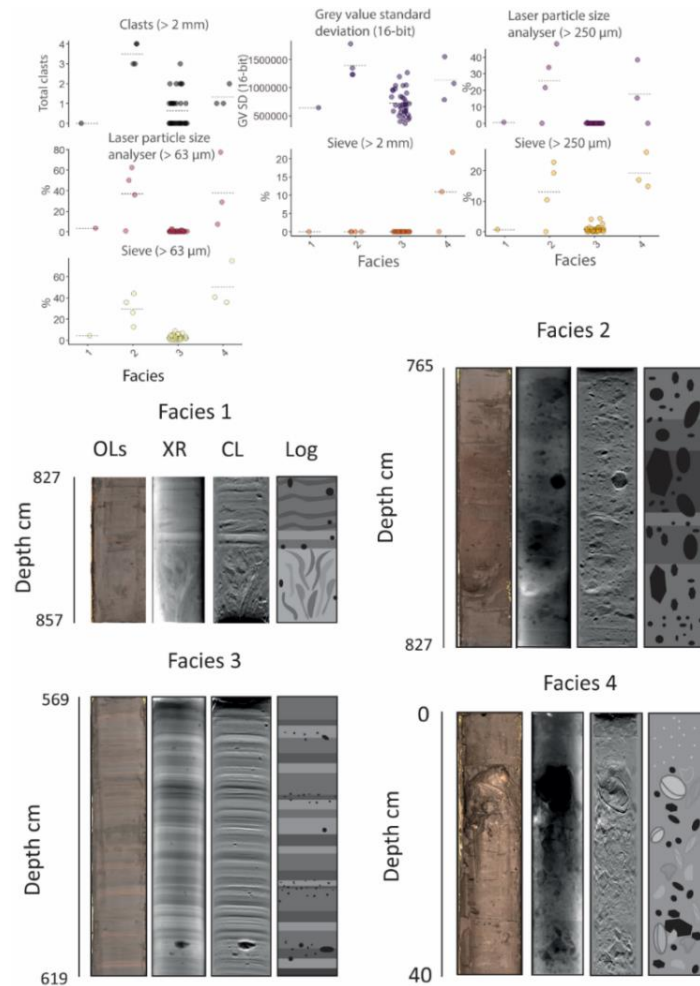


Figure 3.2. Strip plots (top) indicate IRD abundances per facies, black dotted lines indicate mean values per facies. Core images for each facies (bottom). Key: OLs (optical linescan images); XR – X-radiography; CL – X-ray computed laminography; Log – sediment log (interpretive representation, not an accurate sketch).

3.3. Results

3.3.1. Comparison of different IRD methodologies

The inter-facies analysis of IRD reveals that Facies 1 and Facies 3 have the lowest abundances of IRD, meanwhile, Facies 2 and 4 returned the highest values of IRD for all techniques (Figure 3.2). This indicates that all methods reliably discriminate the IRD of these different stratigraphic facies. A visual analysis of the cores corroborates that Facies 1 and 3 are muddier with a smoother texture on optical linescan images and Facies 2 is sandier with a rougher texture, while Facies 4 is a mixed unit, with both rough and smooth sections. Facies 2 and 4 have more coarse-grained material (such as clasts) visible on X-radiographic images (Figure 3.2; Table 3.3). However, some discrepancies are apparent with LPSA and sieving at 63 μm suggesting that IRD is less abundant in Facies 1 than Facies 3, whereas other methods show the opposite (Figure 3.2). Some techniques also returned elevated IRD abundances in Facies 2 over their respective abundances for Facies 4. The exception here is sieving using a gravel-sized cut-off ($> 2\text{ mm}$), which returned exceptionally low values and only detected gravel in Facies 2 and thus is excluded from correlation analyses (Figure 3.2; Figure 3.3).

Table 3.3. The mean IRD abundances per stratigraphic unit (facies). Colour denotes facies of higher or lower average IRD abundance.

Sieve ($> 63\mu\text{m}$)	Sieve ($> 250\text{ }\mu\text{m}$)	Sieve ($> 2\text{ mm}$)	Clast counts ($> 2\text{ mm}$)	LPSA ($> 63\text{ }\mu\text{m}$)	LPSA ($> 250\text{ }\mu\text{m}$)	GVSD	Facies
4.298904	0.750144	0	0	3.497389	0.62	641928.8	1
29.64401	13.17111	0	3.5	37.31956	25.87254	1399888	2
2.712093	0.820548	0	0.657143	0.472497	0.026084	725713.1	3
50.49766	19.34185	10.91972	1.333333	37.96523	17.87944	1136329	4

Differences are observed when comparing the detection rate of the IRD signals between the techniques. Some techniques have high detection rates, with IRD reported in all (or nearly all) samples (Sieving at 63 μm and 250 μm , LPSA at 63 μm , GV SD and clast counting) (Figure 3.3). However, some of these methods returned exceptionally low abundances, despite detection, such as LPSA ($> 63\text{ }\mu\text{m}$ and sieving at $> 250\text{ }\mu\text{m}$) (Figure 3.2; Figure 3.3). Therefore, with sieving and LPSA, in keeping with studies elsewhere, the detection of IRD is dependent on the size threshold selected, with smaller size thresholds ($> 63\text{ }\mu\text{m}$) having the highest detection and larger size thresholds ($> 250\text{ }\mu\text{m}$ or $> 2\text{ mm}$) often having very low or no detection (Figure 3.2; Figure 3.3; Table 3.4; Andrews, 2000). The exception here is sieving $> 250\text{ }\mu\text{m}$ which maintains relatively high detection rates, but very low abundances (Figure 3.3).

This is best highlighted in Facies 3, a clast-poor laminated unit, interpreted to have possibly formed in a sub-ice-shelf setting (Bradwell et al., 2021). This unit returned variable abundances of IRD when comparing the results of different techniques. This highlights the strengths and weaknesses of each method in IRD-sparse sediment. LPSA and sieving returned exceptionally low mean percentages (0.47 % and 2.71 % in the 63 μm fraction and 0.03 % and 0.82 % in the 250 μm fraction, respectively). Conversely, when comparing the results of clast counting and GV SD on Facies 3, the mean result was relatively high (compared to other facies) and a greater spread of data points was observed, indicating a higher detection rate in this unit with these methods (Figure 3.2).

XR clast counting registered an average of 0.66 clasts per cm in Facies 3, however, the spread of values is much greater with many samples registering three or four clasts, which is a much higher spread compared to sieving and LPSA in this facies (Figure 3.2). GV SD has the highest detection limit in this facies with an average sum of standard deviation per cm = 725713 which is a GV SD of ~ 4806 for each 0.066 mm horizon (151 pixels at 0.066 mm per cm of sediment core X-ray image), which is in keeping with clast-poor abundances in these CL images (see Chapter 2). Additionally, the spread of GV SD results are comparable to XR clast counts, results range into the ‘clast-free’ to ‘clast-rich’ Folk class (values between 2402 – 8398 per pixel width) (see McDonald et al., 2022; Chapter 2).

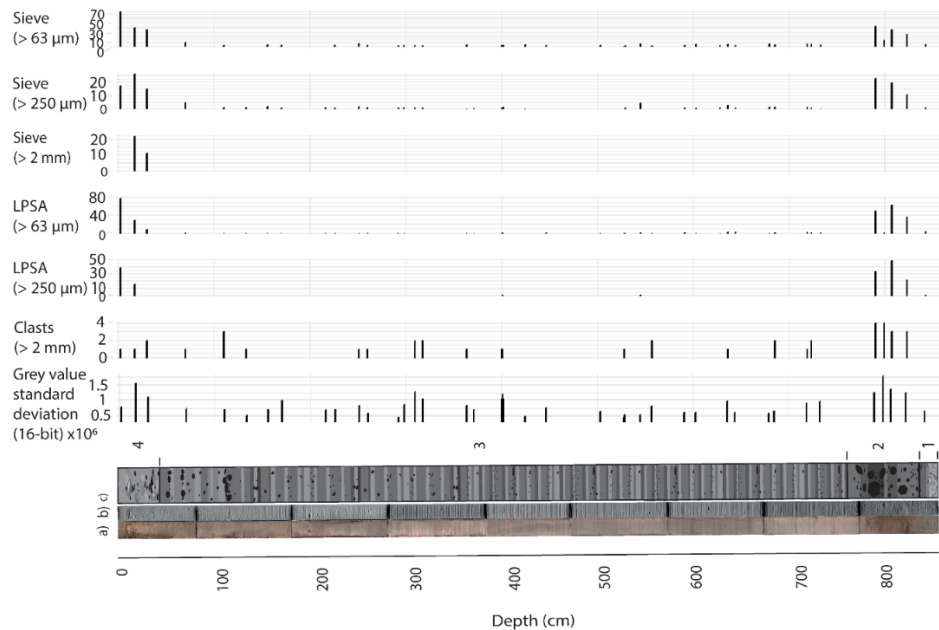


Figure 3.3. Downcore IRD signals from different techniques. Note: methods do not have consistent Y-axis for example sieving at $> 63 \mu\text{m}$ and sieving $> 250 \mu\text{m}$. Core images: a) optical linescan images; b) X-ray computed laminography; c) sediment log, a graphical representation of the core, not an accurate sketch.

3.3.2. Correlation between different IRD techniques

The five different approaches were compared to explore their correlations. 13 out of 15 pairwise comparisons returned statistically significant relationships using Spearman's rho ($p < 0.05$) (Figure 3.4). The strongest relationships were generally found when comparing methods which sample similar size cut-offs and a similar volume of sediment. For example, the strongest relationships were found when comparing sieving and LPSA methods, with Spearman's rho values ranging from 0.493 – 0.693, and R^2 values ranging from 0.663 – 0.840 indicating strong statistically significant relationships with a close association between residuals. Similarly, the two methods which utilise X-radiographic imagery, and thus, analyse the entire sediment core volume on a 2-dimensional plane – XR clast counting (> 2 mm) and GV SD – shared the strongest correlations with each other (Spearman's rho = 0.503; $R^2 = 0.366$; Figure 3.4).

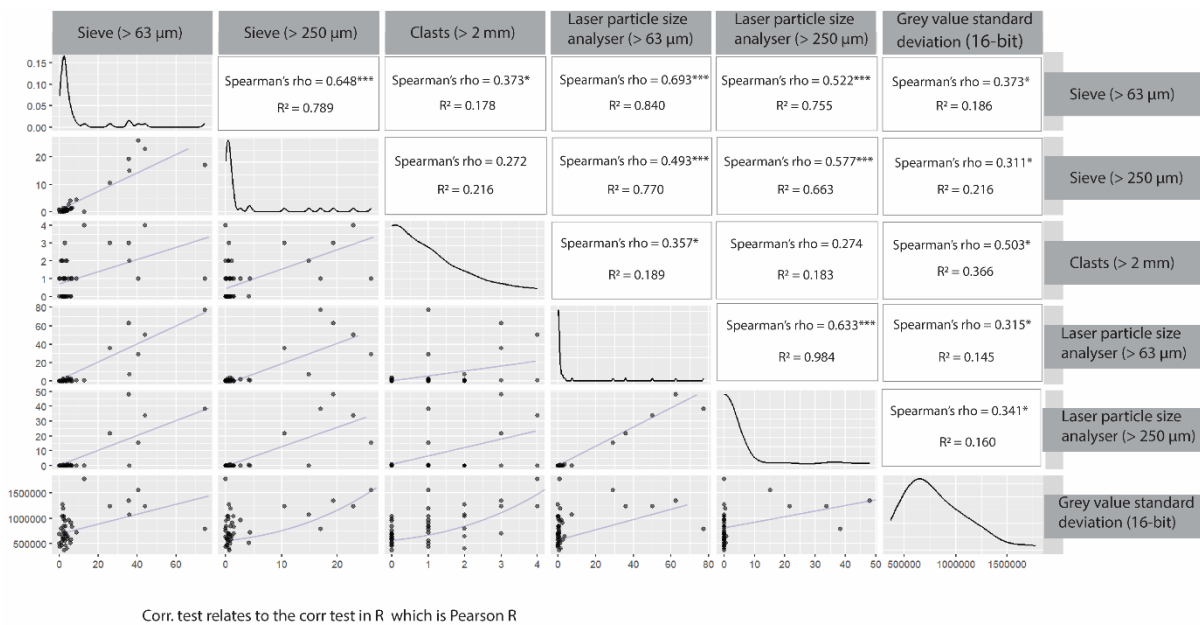


Figure 3.4. Scatterplot matrix indicating relationships between different ice-rafted debris techniques. '*' = P value < 0.05; '**' = P value < 0.01; '***' = P value < 0.001.

Moderate agreement was found when comparing techniques which exploit a large sampling region (GV SD and clast counting) with methods which utilise a combined small sample size and small threshold grain size (sieving > 63 µm and LPSA > 63 µm). These correlations were statistically significant ($p < 0.05$), however, the spread of values was wide with relatively low Spearman's rho and R^2 values. The lowest agreement occurred when comparing sampling techniques with a large sampling area with other techniques which use a small sample size and large grain size cut-off threshold (Figure 3.4). Therefore, the weakest and statistically non-significant relationships related to gravel clast counting on X-radiographs when compared to both LPSA (> 250 µm) and sieving (> 250 µm) (Figure 3.4).

3.4. Discussion

3.4.1. Strengths and weaknesses of IRD techniques

3.4.1.1. Sieving

Sieving is a technique which can be implemented by researchers with only introductory training, this is not necessarily the case for other methods such as XR clast counting or new X-ray CT routines such as those implemented by Bartels et al. (2017, 2018). The low methodological complexity means that it is likely to be consistently implemented between studies, albeit with different cut-off size thresholds and sample sizes (volumes). It is generally assumed that a large sample of material (e.g. 10 – 20 g) is required to return a representative output of IRD (McKay et al., 2022), however, the strong relationships between sieving with a low grain size cut-off (63 μm) and all other methods indicate that sieving can provide reliable detection of IRD, even when sampling small volumes of sediment (~ 0.3 g).

To attain a representative output of IRD, there is a trade-off between sampling size, cut-off grain size threshold and sediment core preservation. Our results indicate that in a deglacial sediment core from the British-Irish Ice Sheet, there is a strong, statistically significant relationship between the fine sand cut-off and a coarser threshold (63 μm and 250 μm), which is reinforced in other studies (cf. Molnia et al., 1972 as cited in Ruddiman, 1977; Vermassen et al., 2019). The > 63 μm fraction also shares a statistically significant relationship with all other methods in this study, unlike the > 250 μm fraction (4 / 5 statistically significant relationships) due to the lower likelihood of detection when compared to XR clast counting. Other studies focusing on sediments like the one in this chapter (deglacial glaciomarine / ice-stream facies), may minimise core destruction by selecting a smaller cut-off grain size threshold.

A major benefit of sieving is that any visible shells or biogenic fragments can be removed manually if pre-treatment is deemed unnecessary or has been insufficient in the removal of all biogenics (McKay et al., 2022). This is not afforded by LPSA and overestimations are possible with X-radiographic images. For example, in clast counting it is possible to misidentify shells as clasts and with GV SD any biogenic material is automatically incorporated in the sediment heterogeneity output (McDonald et al., 2022). In addition, the sieving of grains potentially allows for micromorphological investigation via optical microscopy or scanning electron microscopy allowing the discrimination of sea-ice and iceberg-rafted debris, however, this is generally outwith the remit of most IRD studies (see St John et al., 2015).

3.4.1.2. Laser particle size analysis (LPSA)

LPSA has the benefit of being a fast technique, the samples in this study were run in 3-minutes using the Bettersizer S3 Plus system. Although the technique is destructive, only a small sample (~ 0.1 g) is necessary in order to produce a result. However, the likelihood of encountering coarse material

lowers as the sample size is reduced. This has significant implications for the appropriateness of this technique as an IRD proxy.

As LPSA requires such a small sample size to be analysed, Kowalenko and Babuin (2013) concluded that this is not a well-suited technique to analyse sediments where clay to sand fractions need to be precisely measured. We expand on their finding, adding that in clay-silt rich sediments the sparse nature of sand renders this technique an unrepresentative measure of IRD, as the small sample size results in exceptionally low IRD detection. For example, compared to sieving there was a 2633% and 371% underestimation of IRD between the 63 μm and 250 μm fractions when comparing these techniques. This shows that the necessary small sample size can significantly impact results.

3.4.1.3. X-ray clast counting (> 2 mm)

X-ray clast counting is fast to undertake compared to sieving and LPSA and does not require any specialist laboratory equipment. Clast counting relies on the presence of coarse, visible IRD on X-radiographs. This has pros and cons, for example, more poorly-sorted sediment and larger clasts are more likely to be evidence of ice-rafting compared to sorted sands and gravels (Jonkers et al., 2015; Bartels et al., 2017), however, the likelihood of detecting IRD is reduced as the clast size increases and the sample size decreases (Figure 3.3). Therefore, cores with a lower sediment volume (decreased sample size) have a higher probability of missing iceberg-rafting events. However, despite non-detection in some horizons (Figure 3.3), XR clast counting is found to be well-suited to cores in studies which analyse glaciomarine sediments. Generally, there is a higher likelihood of returning positive values of IRD than LPSA or sieving (at higher cut-off size thresholds), as the entire core diameter (whole or split core) is assessed for IRD (Andrews, 2000; McKay et al., 2022). Studies may wish to decrease the grain size cut-off threshold to > 1 mm to increase the detection rate (e.g. Grobe et al., 1990; Yamamoto et al., 2008; Hillenbrand et al., 2021)

A common criticism of XR clast counting is that it overestimates the input of fine gravel clasts in a manner which is unrepresentative of the percentage volume of IRD in sediment cores (Bartels et al., 2017). However, whether a clast is large or small, it represents a possible indication that ice-rafting occurred. Clark and Pisias (2000) argue that in relation to the Antarctic Ice Sheet, only large pulses of IRD over expansive areas of the seafloor can infer increased iceberg rafting. We argue, that in deglacial palaeo ice-stream settings, only when a sudden significant increase of IRD over an extensive stratigraphic horizon occurs can high flux be inferred and even then, there are certain caveats (see section 3.4.3).

3.4.1.4. Grey value standard deviation (GV SD)

GV SD is a non-destructive technique that investigates sediment heterogeneity across the full sediment core X-ray image, measuring sediment heterogeneity as a proxy for IRD. In JC123-021PC it is a robust IRD proxy returning statistically significant relationships with all other techniques used

in this study (Figure 3.4). This method is also the fastest technique to apply in this study, alongside other (on-screen) automated approaches (Bartels et al., 2017; Bartels et al., 2018; Reilly et al., 2019; Jasper et al., 2024), this rapid approach allows a seemingly instantaneous quantification of IRD for cores at 0.066 mm resolution.

Sediment heterogeneity (GV SD) incorporates any grain-size fraction larger than the scanning resolution (0.066 mm) within the sampling region. Therefore, silt, sand and gravel-sized IRD may be detected, likely playing a role in its statistically significant relationship with all methods in this study (Figure 3.4). However, it is most strongly associated with XR clast counts (> 2 mm). The reason for this is two-fold: i) gravel-sized sediment typically has a higher radiodensity and covers a greater region of the core image than sands, resulting in higher GV SD; ii) Both methods involve sampling the entire core region, and therefore sample a similar sediment volume. As sieving and LPSA were analysed using a small volume of sediment, they cannot be as representative of the entire sediment core.

The methodological limitations of GV SD are covered earlier (in Chapter 2), however, a few considerations are reiterated here to supplement those outlined previously. GV SD on X-ray CL images appears to have the highest detection of IRD. However, a drawback with this method is that it is difficult to determine the boundary between IRD presence and absence as the grey value variation of images comes with natural variation (non-IRD related sediment heterogeneity, noise and imaging artifacts) so calibration on any set of images is required (McDonald et al., 2022). This may have implications for the determination of sub-ice-shelf environments as the absence of IRD is often used to identify them. However, a simple supplementary description as part of a multi-proxy investigation of the sedimentary facies may suffice in support of determining these units in other studies.

3.4.2. Most appropriate techniques for analysing IRD in palaeo-ice sheet settings

The suitability of each technique in quantifying IRD in sediments of marine-terminating palaeo-ice sheets, such as the last British-Irish Ice Sheet, is outlined in Table 3.4. The most suitable techniques are the non-destructive approaches which analyse the entire sediment core volume ensuring maximum core preservation, higher resolution and high detection rates – namely XR clast counting and GV SD. The least suitable technique is LPSA which does not allow for the analysis of large enough sediment volumes to provide a reliable output of IRD, and should typically be avoided as a proxy for IRD based on sand percentages, especially with higher cut-off threshold grain sizes (e.g. > 250 μm).

- 1 Table 3.4. Checklist for selecting and implementing IRD techniques. Suitability of each technique to quantifying IRD in sediment cores of deglacial
- 2 marine-terminating glacier / ice streams of palaeo-ice sheets (e.g. British-Irish Ice Sheet).

	<i>Sieving > 63 µm</i>	<i>Sieving > 250 µm</i>	<i>Sieving > 2 mm</i>	<i>LPSA > 63 µm</i>	<i>LPSA > 250 µm</i>	<i>Clast counting > 2 mm</i>	<i>GV SD</i>
<i>Budget</i>	Research on small budgets	Research on small budgets	Research on small budgets	Research on small budgets	Research on small budgets	Research with moderate to high budgets which can afford X-ray images	Research with moderate to high budgets which can afford X-ray images
<i>Value of sediment core</i>	Cores with higher or moderate value	Cores with lower financial value	Cores that can be destroyed	Any value	Any value	Any value	Any value
<i>coarse sediment abundance</i>	Any (depending on sample size)	Any (depending on sample size)	Any (depending on sample size) more abundant gravels = smaller sample size; sparser gravels = higher sample size	High	Avoid use on mud / silt rich sediments	Sediments with sparse IRD Any	Any
	Low size threshold	Sample size must be					

	affords smaller sample sizes (< 1 g)	sufficient to ensure detection (over 1 g)					
<i>Sediment heterogeneity</i>	No concerns	No concerns	No concerns	No concerns	No concerns	Non-IRD features may lead to misidentification and inclusion in IRD clast counts Overlapping clasts can complicate counting process.	Avoid use on heavily altered sediments e.g., deformation, extreme bioturbation or shell-rich sediments
<i>User variability</i>	No concerns	No concerns	No concerns	No concerns	No concerns	Potential for user variability?	No concerns
<i>Expertise required</i>	Very low	Very low	Very low	Low	Low	Moderate (image preparation)	Moderate (image preparation)
						Does expertise affect results?	
<i>Use in glaciomarine cores</i>	Can be used on glaciomarine cores.	Can be used on glaciomarine cores which but sampling requires large	Can be used on glaciomarine cores which can be sampled with high sample sizes	Avoid use on glaciomarine sediments. Should only be used on	Avoid use on proximal glaciomarine cores	Very well suited to glaciomarine sediments especially with sparse IRD	Well suited to glaciomarine sediments, however, should be avoided in cores with high non-IRD heterogeneity.

		sample sizes (~ 10 – 20 g)		glaciomarine cores if sediment core X-rays are unattainable and high core preservation is imperative			
<i>Conclusion Suitability to cores which are similar to those used in this study</i>	moderate – high	Suitable if sufficient sampling volumes can be recovered (10 – 20 g of sediment).	Moderate	Not suitable	Not suitable	Very high	Very high

Sieving can be appropriate in palaeo-ice sheet settings, our results indicate that smaller cut-off size thresholds can provide high detection of IRD, albeit in percentages which may not be representative of the entire core volume, however this opens up questions relating to best practice regarding how IRD magnitude should be interpreted (relative or absolute) (see section 3.4.1.3.). To analyse at continuous downcore resolutions as the non-destructive techniques allow (XR clast counting and GV SD), would require very considerable amounts of time. Therefore, we strongly recommend XR clast counting and GV SD as the best-suited techniques to build an accurate high-resolution IRD record for sediments of marine-terminating palaeo-ice sheets (Table 3.4).

3.4.3. Wider implications

The results of this study have significant implications for interpreting IRD signals of Quaternary sediments for various reasons. Firstly, between methods which analyse different grain sizes and different sample volumes there are variations in the measured magnitudes of IRD, leading to potential over- or underestimations of IRD in sediment facies depending on which method is chosen. For example, in some glaciomarine settings (such as ice shelf settings), IRD may be present but not detected, especially if a small sample size is selected for sieving or LPSA (Figure 3.2) (McKay et al., 2022).

There are palaeo-environmental implications of this finding, for example the presence of ice shelves where distal sub-ice-shelf sediments are typically devoid of IRD at distances > 5 km from the grounding line (Alley et al., 1998, Domack et al., 1998). Therefore, the presence of IRD-free finely laminated glaciomarine sediment is often used as an indicator of ice-shelf cover (Smith et al., 2019; Reilly et al., 2019; O'Regan et al., 2021). In the analysed core JC123-021PC, XR grain counting (> 2 mm) and GV SD would not suggest distal sub-ice-shelf deposition in Facies 3 (after Smith et al., 2019 and references therein); whereas sieving and LPSA using > 250 μm or > 2 mm thresholds, would potentially suggest ice-shelf cover in this facies (Figure 3.3).

We suggest therefore, that combining IRD proxies in studies which attempt to quantify IRD in different ways (e.g. sieving and XR clast counting, or XR clast counting and GV SD) may provide a better, more comprehensive, understanding of IRD. It is also difficult to interpret the intensity of iceberg rafting from a sediment core record as some icebergs have higher sediment loads than others (Hasholt et al., 2022) which may produce artificially high IRD within cores, in a manner which is detached from typical iceberg flux. Coastal iceberg entrapment (MacAyeal et al., 2008) may result in input from a single berg which overloads sediment cores. Additionally, in sediments with multiple inputs such as bottom-current reworking, background sedimentation rate (bottom-current or meltwater plume regularity / intensity), sea-ice or ice-shelf dynamics, mass flows etc., the IRD record may be biased (Mackiewicz et al., 1984; Ó Cofaigh and Dowdeswell, 2001; Dowdeswell et al., 2000; Reilly et al., 2019; Vermassen et al., 2020).

Moreover, the presence of IRD can only determine that icebergs were present in the past, and determining the flux of icebergs can be complicated by several factors mentioned above. The implication here is that IRD is potentially a better indicator of palaeoenvironmental conditions when combined with a multiproxy analysis (e.g. ice-stream advance / retreat, floating-ice cover or calving bay settings – McGlannan et al., 2017; Jennings et al., 2018; Smith et al., 2019; See Chapter 5), rather than increases and decreases in iceberg flux. Therefore, there has been a focus on reconstructing marine-terminating glaciers and their associated palaeoenvironmental conditions (e.g. ice-shelf dynamics) in recent years, rather than simply using IRD as a proxy for iceberg flux (Reilly et al., 2019; Vermassen et al., 2020; Smith et al., 2021; Smith et al., 2023; Chapter 5). In order to maximise the strength of such studies, we suggest utilising a combination of IRD techniques which measure the entire sediment core width to retain high resolution and ensure comprehensive analysis of glaciomarine sediment archives.

3.5. Conclusions

This chapter explored the strengths and weaknesses of different IRD methodologies in a deglacial ice-stream setting of the former British-Irish Ice Sheet. Using cores from The Minch, NW Scotland, sieving ($> 63 \mu\text{m}$), XR clast counting and GV SD were found to be the most reliable for identifying IRD in this setting. Meanwhile, sieving at $> 63 \mu\text{m}$, LPSA ($> 63 \mu\text{m}$) and GV SD had statistically significant relationships with all other methods in this study. Four main takeaways are presented in this chapter:

1. 13 / 15 pairwise comparisons returned statistically significant relationships ($p < 0.05$). These methods include sieving ($> 63 \mu\text{m}$, $> 250 \mu\text{m}$), LPSA ($> 63 \mu\text{m}$), XR clast counting and GV SD. Sieving and LPSA ($> 250 \mu\text{m}$) do not have statistically significant relationships with XR clast counting ($> 2 \text{ mm}$) due to the low detection rate of LPSA and sieving using higher cut-off size thresholds.
2. Despite the statistically significant relationships with other methods, LPSA is not a suitable measure of IRD as the small sampling volumes result in very low IRD detection in some facies (even in the $> 63 \mu\text{m}$ fraction). Although apparently useful in this study, this cannot be guaranteed in studies of other glaciomarine sediments due to the exceptionally low percentages compared to sieving ($> 63 \mu\text{m}$).
3. Sieving can be undertaken at a smaller size threshold in glaciomarine sediments ($> 63 \mu\text{m}$) to increase IRD detection rate, even in small samples. This will also preserve higher volumes of sediment core material, than if a larger cut-off grain size is selected.
4. Sieving ($> 63 \mu\text{m}$), XR clast counting and GV SD are found to be the most appropriate methods for IRD detection and quantification in glaciomarine sediments. XR clast counting and GV SD are found to be particularly useful as they allow for a higher

resolution and wider sampling window. These non-destructive methods could be combined to allow more comprehensive insights into ice-rafted debris.

Chapter 4: Quantifying User Variability in the Traditional X-ray Ice-rafted Debris (Clast) Counting Technique

4.1. Introduction

As explored in the previous chapter, different sampling strategies can bias ice-rafted debris (IRD) outputs in different ways, with some methods overestimating and others underestimating IRD in certain circumstances. This chapter investigates the accuracy and reproducibility of the most common IRD quantification technique – clast counting on X-radiographic (XR) images (Grobe, 1987). As outlined in the previous chapter, this method involves counting clasts (typically 2 mm or larger) on XR images in defined spatial intervals downcore e.g. in cm slices (Grobe, 1987).

Variations of the original method are occasionally implemented, for example, the grain-size threshold can be reduced to 1 mm for determining IRD, allowing increased detection (Grobe et al., 1990; Yamamoto et al., 2008; Hillenbrand et al., 2021), the sampling interval can also be increased to 2 cm potentially decreasing sampling times (Stein et al., 1996; Callard et al., 2018). While others go further, distinguishing gravel-size classifications such as Smith et al. (2021) who quantify gravels in bins of 2 – 8 mm and 8 mm or greater. However, the typical approach involves counting clasts > 2 mm in 1 cm intervals (Hillenbrand et al., 2008; Graham et al., 2017; Jennings et al., 2022; Ahn et al., 2024).

Supervised and automated clast counting routines using X-ray Computer Tomography (CT) are becoming increasingly popular (e.g. Bartels et al., 2018; Reilly et al., 2019; Cederström et al., 2022; Jasper et al., 2024). It is assumed that these techniques will reduce user bias in clast counting. However, these routines require human training and / or validation, which is subject to error and bias, potentially affecting the accuracy of clast counts. Additionally, manual clast counting (Grobe, 1987) is still commonly implemented in several studies (Jennings et al., 2022; Andrews et al., 2023; Ahn et al., 2024; Gizard et al., 2024). Therefore, it is important to understand the factors which may result in variations in clast counts between users and determine the accuracy and robustness of manual clast counting. In this study we investigate the variability or uncertainty in the traditional approach and in doing so quantify the observer bias of the manual X-ray IRD counting (Grobe) method.

4.1.2. Why might inaccuracies and inconsistencies occur?

The clast counting (> 2 mm) method using XR has been consistently implemented for over 30 years for the identification of IRD as part of studies reconstructing global oceanic circulation, ice-sheet growth and decay, and floating-ice margin (sea ice or ice shelf) presence and removal (Grobe and Mackensen, 1992; Kneis et al., 2001; Graham et al., 2017; Jennings et al., 2022; Gizard et al., 2024). However, when a user implements grain counting, they are faced with many decisions which might influence the results, for example:

1. Is this object a clast? Could it be a shell fragment, an imaging artifact or an amalgamation of finer grains?
2. Should clasts be counted in all intervals or only once if they overlap the sampling grid and appear in more than a single interval?
3. Is this object a single clast or two (or more) overlapping clasts? (Hogan et al., 2016)
4. Is it most appropriate to measure the longest or shortest axis of each grain?
5. Is it essential to measure every clast? Or is size estimation from a scale bar appropriate?
6. Should clasts be counted from the bottom of the image to the top (following the law of superposition); or the top of the image to the bottom?

It is conceivable that these decisions might affect the accuracy and consistency of the technique and experience level alone may not be enough to overcome them. None of these factors are specifically addressed in the literature and the original paper is only 2 pages long. The only questions which can perhaps be answered from Grobe (1987) is that it appears that clasts were counted from the bottom of the sediment core X-ray slab to the top, and gravels were only counted in the first centimetre slice in which they appear. This is deduced directly from a figure in the article (Figure 4.1), but is not stated in the text. Without strictly addressing this and other concerns outlined above, it is reasonable to assume that there is potentially a lack of consistency among researchers who employ this technique.

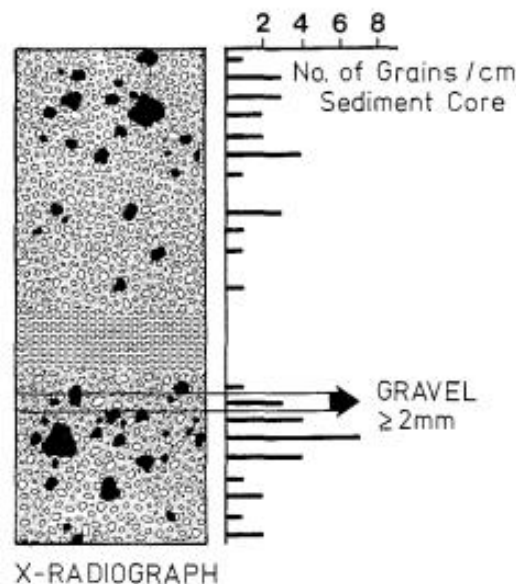


Figure 4.1. Illustration of how to perform clast counting manually from X-radiographs (Grobe, 1987).

The possibility of user bias in IRD clast-counting studies has only recently attracted attention (McKay et al., 2022; Jasper et al., 2024). McKay et al. (2022) found strong agreement between two users of undefined experience with Pearson's correlation coefficients of 0.961 and 0.927. They

suggest some factors for discrepancies between users such as overlapping grains (e.g. Hogan et al., 2016), low radiodensity clasts overlying a matrix comprising intense burrowing or lithological complexity. They also call for greater standardisation of criteria between working groups for determining IRD.

Jasper et al. (2024) used two different teams of researchers to produce two individual datasets on the same images (grain size > 1 mm). These outputs were generally well-matched with some exceptions, with a Pearson's correlation coefficient of 0.555. This does indicate strong agreement, but some variation between users. We aim to provide greater standardisation by investigating whether a larger participatory study could give insight into why these variations occur, for example, whether user experience affects outputs.

In addition, the original method was exceptionally quick when first introduced in the 1980's, being substantially faster and less labour intensive than sieving (Grobe, 1987). However, with the introduction of new, automated or supervised routines which allow for clast counting from X-ray images using CT (Bartels et al., 2017; Reilly et al., 2019; Cederström et al., 2022) or grey value standard deviation (GV SD) (McDonald et al., 2022), this may no longer be the case. Automated routines are, in some cases, near instantaneous or in other cases significantly faster than traditional on-screen clast counting. Therefore, we also aim to quantify the time required to complete manual clast counting on sediment core X-ray images in this chapter.

4.1.3. Aims and Objectives

The results of this chapter aim to improve our understanding of how user variation (including experience level) can impact the reliability of the technique. This will also allow clearer insight in to how best to interpret and implement XR clast counting to most reliably quantify IRD (Grobe, 1987). This is also important given that accurate and precise manual clast counting is imperative for calibration of automated routines. Specifically, this work has the following aims:

1. Robustly quantify, for the first time, the degree of user variability in clast counting, as an IRD proxy, in a participatory study of 14 individuals.
2. Examine whether user experience levels affect the consistency of clast counting on X-radiographs using 3 different groups (experienced, moderate experience and no experience).
3. Determine the time taken to carry out clast counting on two sediment core images from different glaciomarine facies.
4. Provide a more robust, definitive protocol to improve the robustness of clast counting as an IRD proxy.

4.2. Methods

4.2.1. Clast counting participatory study

A comparative study of multiple different researchers undertaking clast counting on two different XR images (Figure 4.2) 93 cm and 100 cm in length, was undertaken. The cores selected in the comparative study are from glaciomarine sediments deposited in the Central Minch, NW Scotland, during the last glacial cycle (Figure 4.2). Both sediment facies are very poor in marine carbonate (and/or organic material), this was key for this study as the inclusion of shells can make the clast counting process significantly more challenging. The two cores differ considerably in clast abundance – one is a clast-rich but matrix-supported subaqueous diamicton (JC123-032PC-section-8); the other is a clast-poor to clast-moderate strongly laminated ‘ice-proximal’ glaciomarine facies (JC123-031PC-section-7), both facies were originally described by Bradwell et al. (2021).

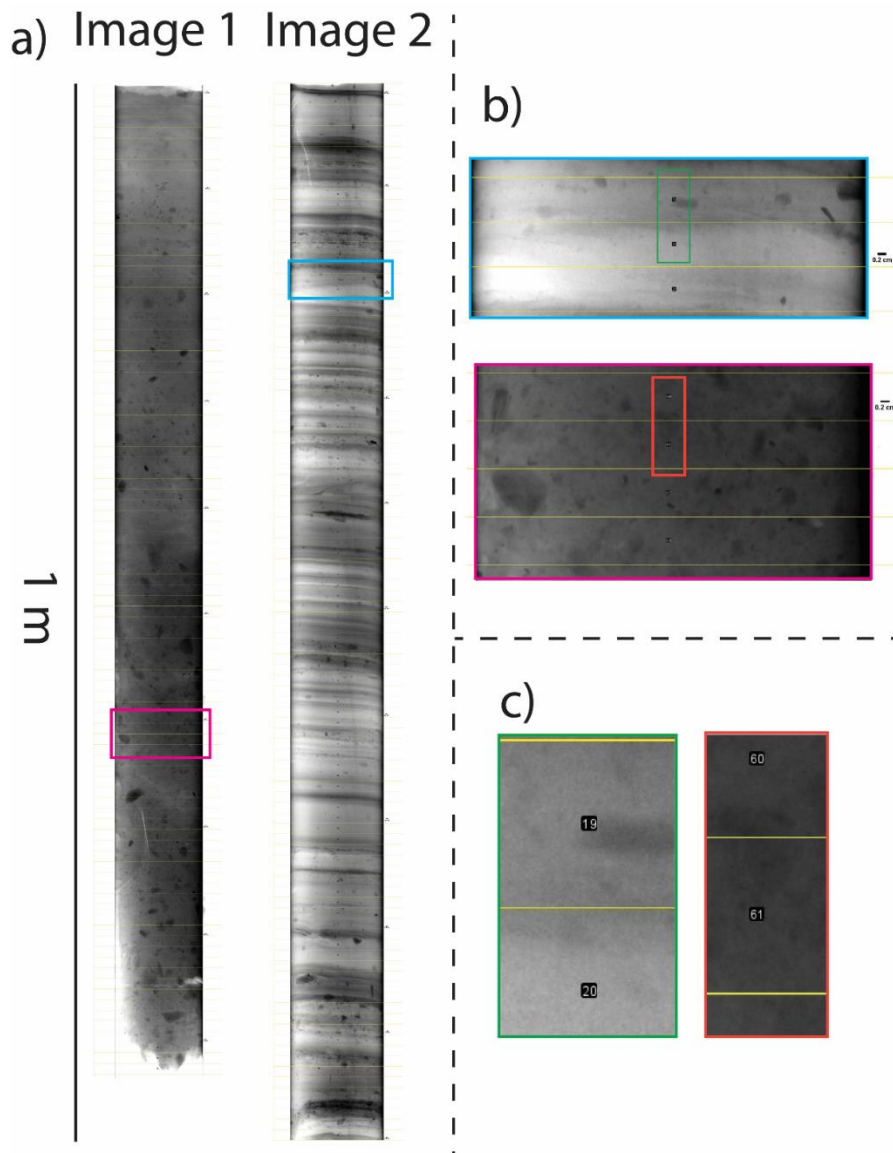


Figure 4.2. Sediment facies and core images provided to participants in this study. Panel a) shows the two images in full with the sedimentary facies. Panel b) scale bar visible on images, the scale bar

appeared in 10 cm interval on the right hand side of core images (0.2 cm). Panel c) pre-labelled depth intervals to ensure consistency between different users. Inset images are colour coordinated.

Selecting these two different sediment types will help to understand the effect of different sediment facies on clast counting (i.e. laminated v massive sediment structure, with different clast abundances). X-radiographic positive images were used for the clast counting analysis and prepared following the methodology outlined in McDonald et al. (2022) (Chapter 2) to enhance image clarity and contrast. Each count was conducted independently and there was no communication between users during the study.

4.2.2. Participatory analysis

For the participatory study a horizontal 1 cm grid was added to the images to divide the core into slices, allowing a like-for-like comparison between all participants (Figure 4.2). Individuals were asked to complete a small questionnaire to understand their educational background and previous experience level (Appendix B). 15 participants were approached with varying degrees of expertise and experience levels. All 15 were at a minimum enrolled on a PhD programme. Unfortunately, one person's data could not be used as they misread the instructions. The remaining 14 participants had the following expertise and experience-levels.

1. X-ray sedimentology expert (>10 yr experience)
2. X-ray sedimentology expert (>10 yr experience)
3. PhD student in Glaciomarine sedimentology
4. Professor in Earth Sciences, experienced in marine geology
5. Expert in sedimentology (>10 yr experience)
6. Postdoctoral researcher in palaeoglaciology
7. PhD student in palaeoglaciology (senior)
8. PhD student in palaeoglaciology (senior)
9. Expert in glaciomarine science (remote sensing)
10. PhD student in palaeoglaciology (junior)
11. PhD student in palaeoecology
12. PhD student in glaciomarine science (remote sensing)
13. PhD student in sedimentary geology / planetary geology, no experience in glaciology
14. PhD student in remote sensing, no experience in glaciology

For analysis purposes, these participants are grouped into categories based on expertise / previous experience. These groups are labelled 'experienced' (participants 1-5), 'moderate experience' (participants 6-10) and 'no experience' (participants 11-14). Participants were provided with a short

background to the study, with training on how to perform the task and a link to the Grobe (1987) paper (Appendix B).

4.2.3. Statistical analyses

Each user's counts on the two images were initially explored using the Shapiro-Wilk test for normality to assess whether the count data were normally distributed or not. This method compares the observed data for each participant compared to a univariate normal distribution. As count data were almost unanimously found to not be normally distributed (only 2 / 28 tests returned acceptable normal distributions at $p < 0.05$ – Figure 4.3), the results of each participant were compared using a scatter matrix and statistically analysed using Spearman's rank correlation (ρ) to investigate:

1. Whether the clast counting method is consistently replicated (i.e. highly correlated) by different users, when counting clasts on the same images.
2. Whether the clast counting method is consistently replicated (i.e. highly correlated) by the same user on different images. That is to say, whether individual users produce consistent counts when quantifying abundances of gravels on two different images.

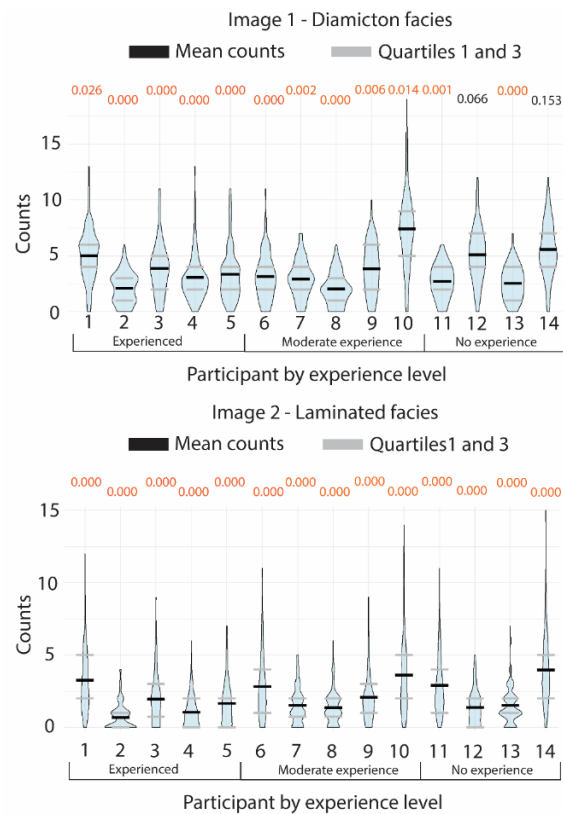


Figure 4.3. Participant count distributions illustrated by frequency. Wider violin sections indicate more frequent user counts. For example, a wider violin at 5 (y axis = counts) for Participant 1 than at 10 indicates that Participant 1 counted 5 clasts more frequently than 10 clasts. Mean number of counts per image (or stratigraphic facies) are indicated by dark bars and quartiles 1 and 3 are indicated by light bars. Shapiro-wilk test of normality p-values are indicated by orange and black coloured

values above each violin. Orange-coloured values indicate that the data are not normally distributed; black values indicate normally distribution data.

Scatter matrices were produced to compare all counts on each image between different users (91 individual comparisons for each image) using GGally in R to provide a visualisation of the strength of relationships and a statistical test of any relationship using Spearman's rank correlation. The standard deviation was selected to assess the variability of all 14 users counts over every cm interval on both images. This serves to determine the spread of users results around the mean – allowing insight into the robustness or reproducibility of the technique.

4.3. Results

4.3.1. Accuracy of manual clast counting in glaciomarine sediments

When analysing the results of 14 participants undertaking XR clast counting on two different glaciomarine facies (after Grobe, 1987), strong statistically significant correlations are identified between all users almost unanimously (Figure 4.4; Figure 4.5). When comparing the counts of all 14 users with each other, making a total of 91 pairwise comparisons, Image 1 (the diamicton facies) returned Spearman's rho values from 0.190 – 0.725 and only one comparison (participants returning a p-value which was not statistically significant, $\alpha = 0.05$) indicated that one user's counts were not in keeping statistically with one other respondent's counts for this image.

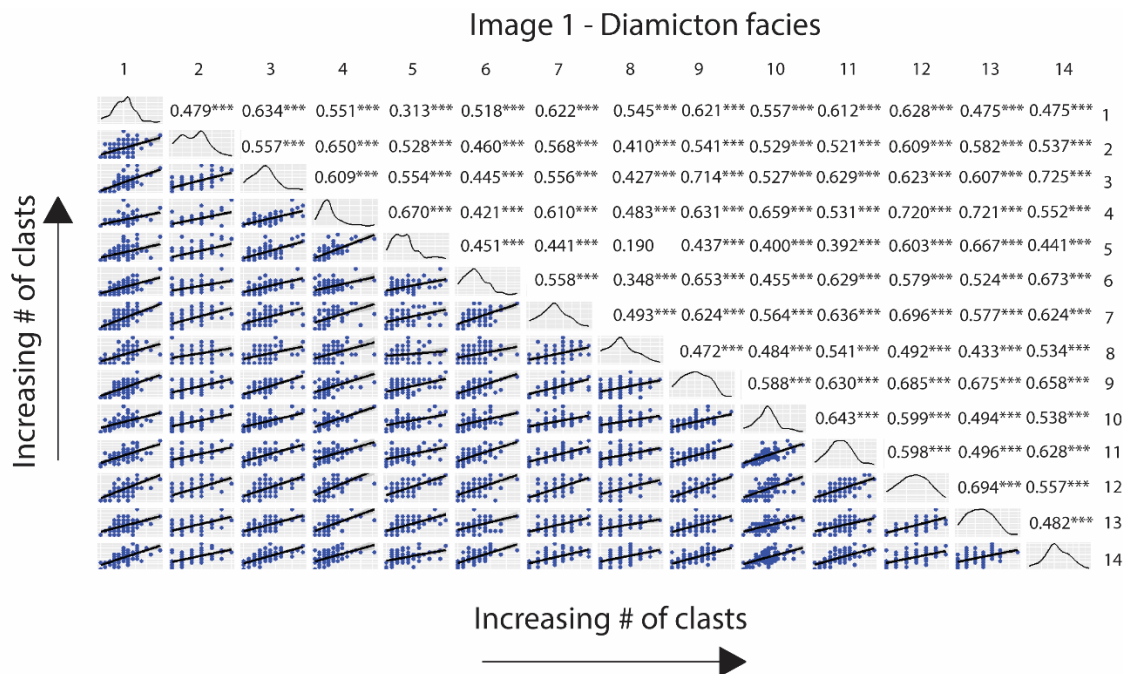


Figure 4.4. Cross comparison (scatterplot matrix) of different users in the diamicton facies (Image 1). Values relate to Spearman's rho correlation coefficient, '*' = P value < 0.05; '**' = P value < 0.01; '***' = P value < 0.001. Participants numbered 1 – 14 based on experience level.

A similar trend was observed for Image 2 (the laminated facies), where all 91 comparisons returned statistically significant P-values ($\alpha < 0.05$), with Spearman's rho values ranging from 0.253 to 0.791, indicating relatively strong phasing relationships between different users (Figure 4.5). Interestingly, the weakest correlation, with a Spearman's rho of 0.253, comes from the two most experienced users (participants 1 and 2), while the users with the lowest-level expertise maintain strong correlations with all participants in this study.

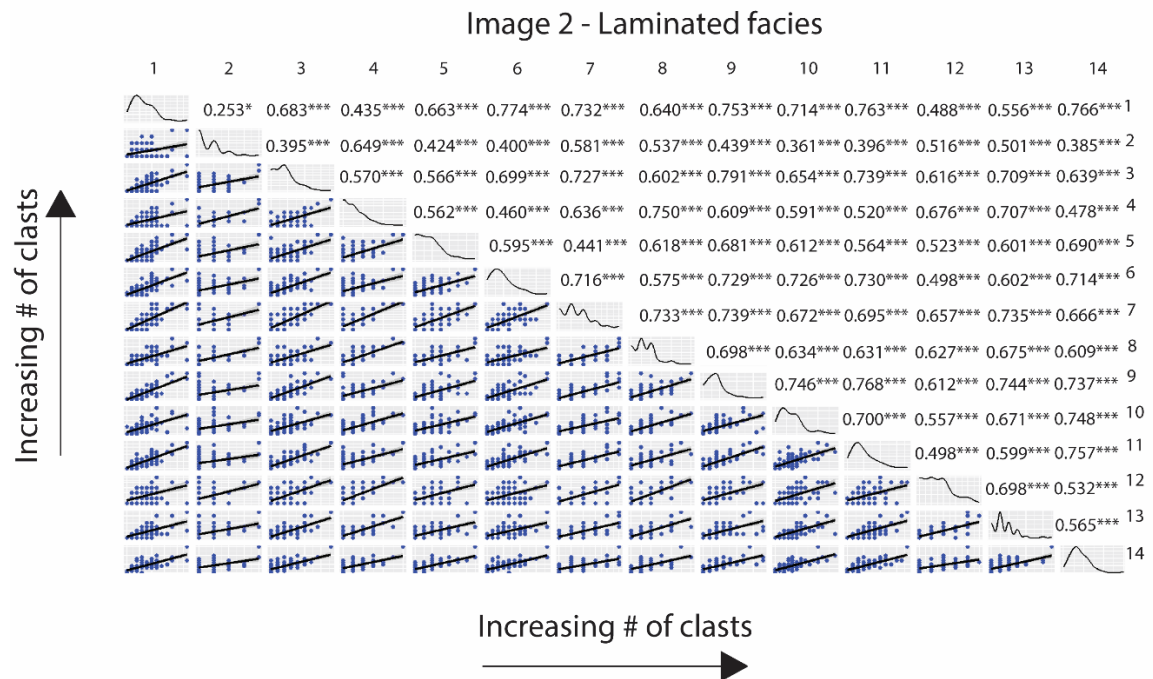


Figure 4.5. Cross comparison (scatterplot matrix) of different users in the laminated facies (Image 2). Values relate to Spearman's rho correlation coefficient; '*' = P value < 0.05; '**' = P value < 0.01; '***' = P value < 0.001. Participants numbered 1 – 14 based on experience level.

When analysing the statistical variability between counts, the results of different users is stark (Figure 4.6; Figure 4.7). Greater count data variability is observed in the diamicton facies (Image 1) with an average (mean) standard deviation of 1.91 (standard deviation range = 0-4.3) (Figure 4.7). On the other hand, the laminated facies (Image 2) returned a standard deviation of 1.29 (standard deviation range = 0-3.68) (Figure 4.7). In general, the greater the clast abundance; the greater the spread around the mean. Due to the strong correlations, but high variability in clast counting between different users, it can be determined that all participants' clast counts were consistent with regard to phasing (broadly increasing and decreasing simultaneously) but not necessarily consistent in terms of absolute counts (magnitude).

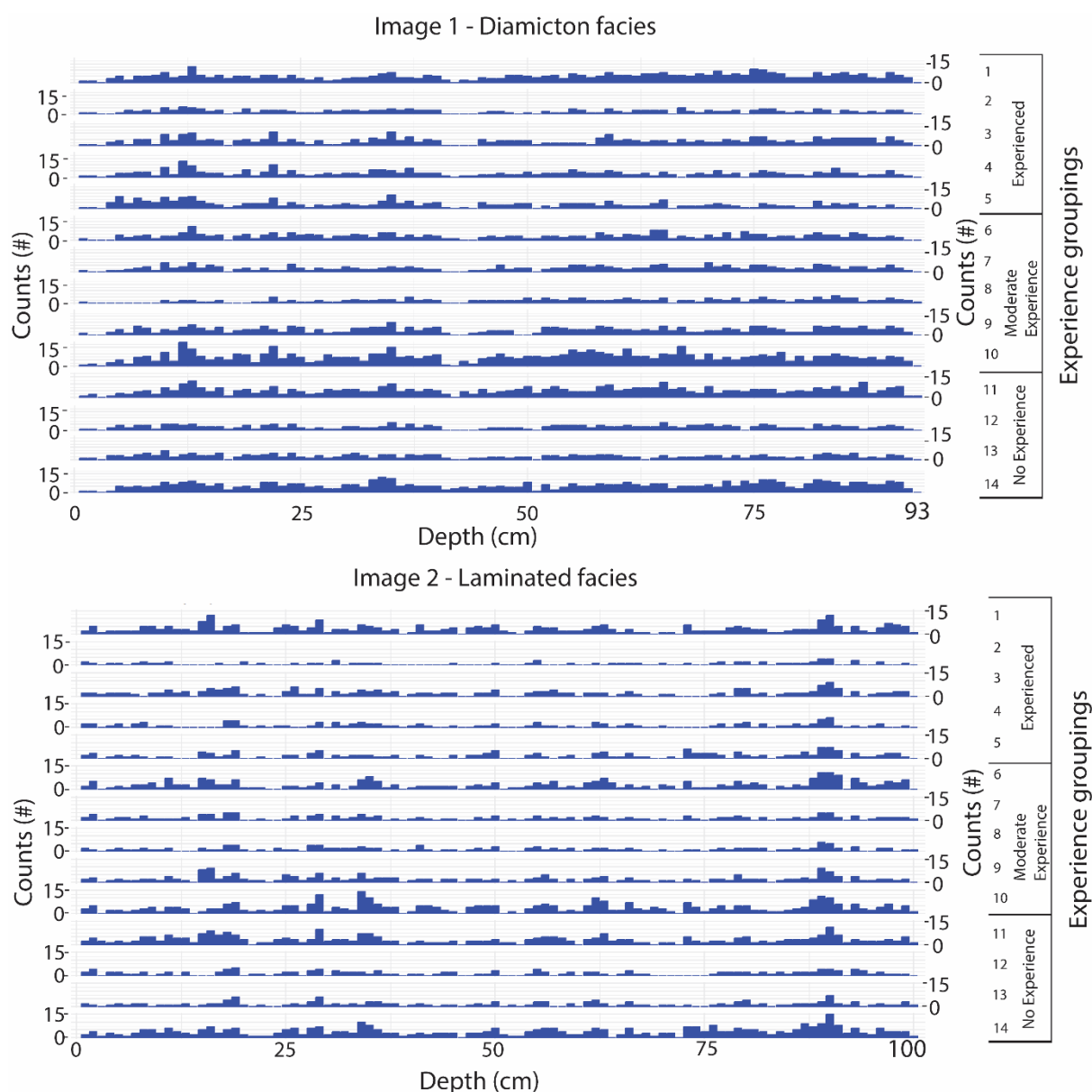


Figure 4.6. Participant counts by core depth. Y-axis is ordered by level of experience. Note consistent Y-axis scale between users for each image.

The major discrepancy between user results is that some individuals are more conservative counters than others (Figure 4.3; Figure 4.6; Figure 4.8). Thus, when comparing results from two different facies, the average number of counts from different users can vary significantly. The mean clast counts per cm slice equalled 3.77 in the diamicton (Image 1) and 2.14 in the laminated facies (Image 2). However, there is significant overlap when comparing the counts of different users, with some users counting fewer clasts in the diamicton facies and more clasts in the laminated facies than others (Figure 4.6; Figure 4.7). For example, participants 1, 10, 11 and 14 counted more clasts per cm slice in the laminated facies than participants 2, 8, 12 and 13 counted in the diamicton facies per cm slice (Figure 4.8).

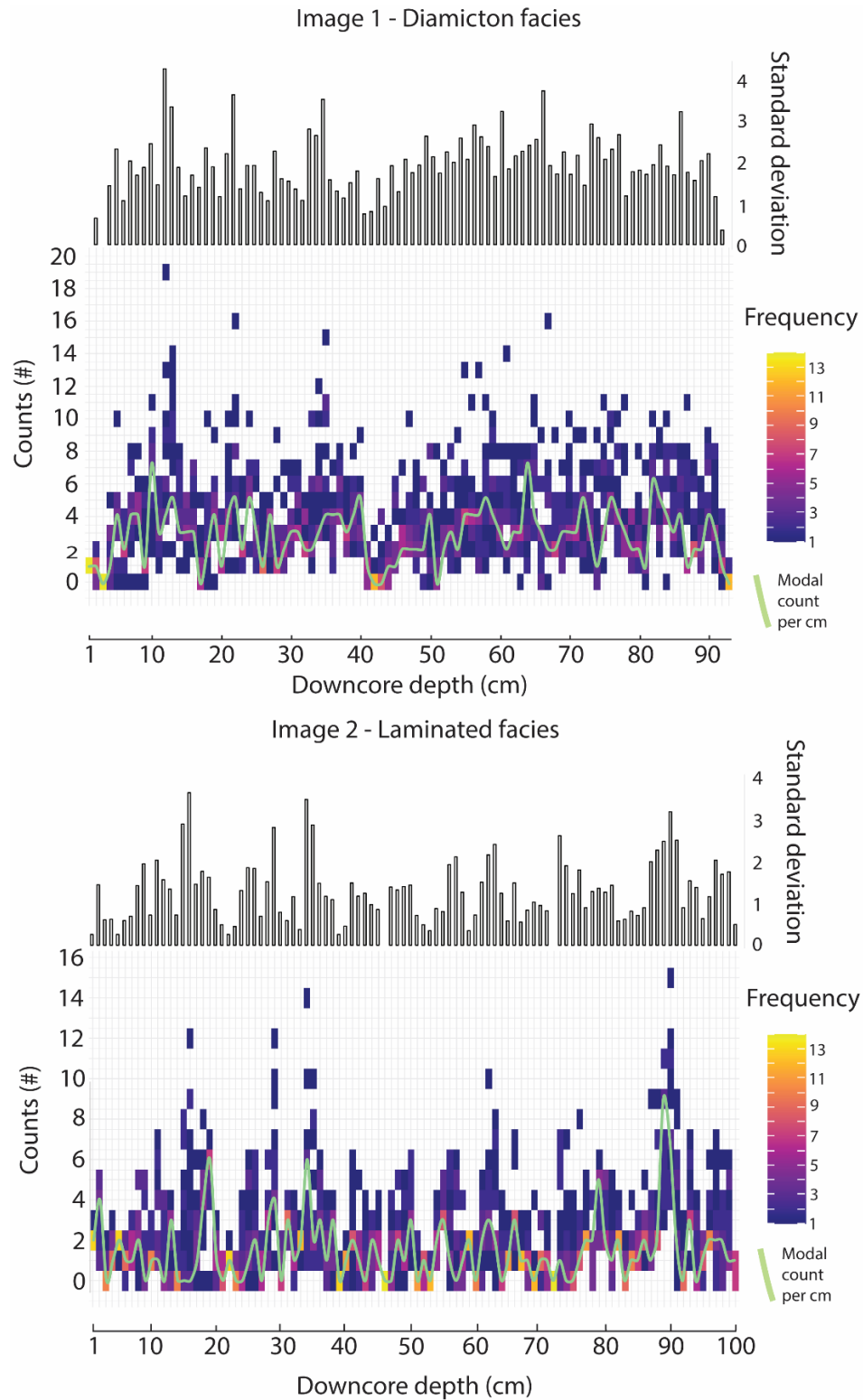


Figure 4.7. The user variability of clast counting on X-radiographs. Bars indicate the standard deviation of all users' counts for each horizon on Image 1 (top) and Image 2 (bottom). Heatmaps indicating the variability between users with warmer colours indicating greater number of users. Green lines indicate modal counts per cm interval (the most commonly returned clast count for each cm interval between all participants).

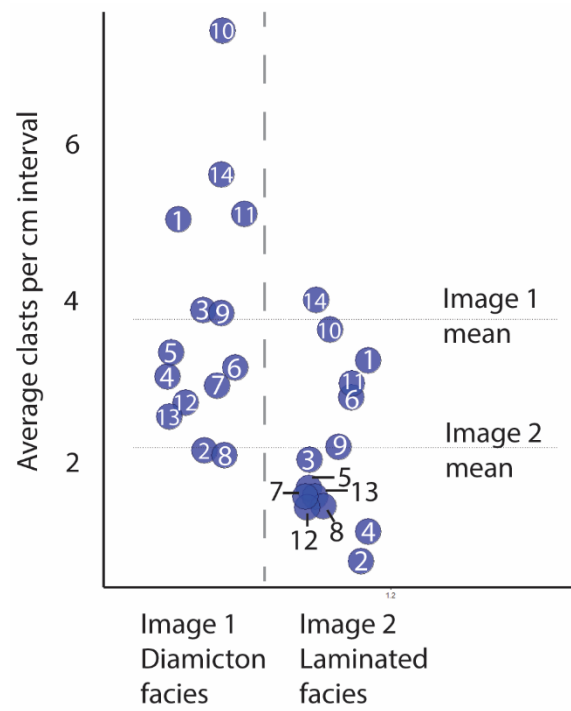


Figure 4.8. Average clasts counted per cm interval for each user. Numbers refer to the expertise ranking of different users.

A reasonable degree of variability was observed with the time taken to complete the task (Figure 4.9). For Image 1 (diamicton facies) the mean time to undertake the entire image was 22 minutes and 8 seconds over 92 cm intervals. Image 2 (laminated facies) had a lower mean completion time of 16 minutes and 31 seconds over a longer core section (100 cm). This gives the first recorded insight into the time taken to perform on-screen manual clast counting (Grobe, 1987) (Figure 4.9).

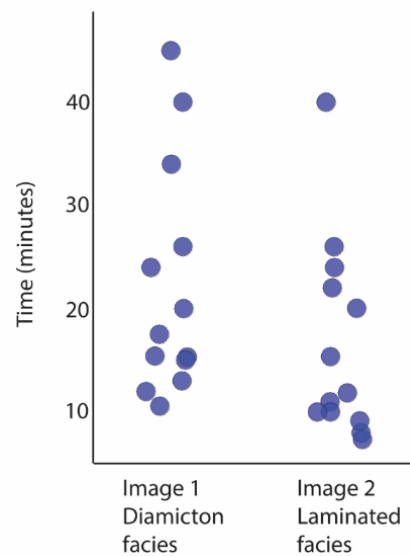


Figure 4.9. Time taken to perform task on Image 1 and Image 2 respectively. Scatter points represent users.

4.4. Discussion

4.4.1. Accuracy and reproducibility of clast counting

Overall, despite the significant variation between respondents, clast counting is an inaccurate, discriminator of IRD using XR images with high variability. This is also validated by the other multiproxy studies which have found strong associations between clast counting and other quantitative ice-rafted debris techniques such as sieving, LPSA and GV SD (Grobe, 1987; Andrews, 2000; McKay et al., 2022; McDonald et al., 2022).

In studies with very small sample sizes ($n = 2$) McKay et al. (2022) and Jasper et al. (2024) found differing agreeability between users, with the former finding agreement at the higher end of correlations in this study. The stronger correlations of McKay et al. (2022) may result from increased cooperation between users, similar training histories, similar levels of experience, or the fact that in some marine sediment cores (e.g. more distal glaciomarine facies), gravel counting is not as challenging as other sediment types.

The sedimentary facies of McKay et al. (2022) were also more variable in IRD abundance, than the cores selected in this study, with some horizons devoid of gravel clasts and others clast-rich. In the images used in this study, IRD is fairly constantly present throughout the sedimentary facies. It is clear from this study that user counts are more consistent in zones with less IRD, and less consistent in units with more IRD (Figure 4.7). Jasper et al. (2024) found similar levels of agreement to this study albeit using a clast size threshold of > 1 mm to determine clasts, and two teams working in parallel to produce the datasets. Their cores appear to have had a consistent spread of IRD and non-IRD features such as pyrite-infilled burrows which *may* have led to lower correlation coefficients, more similar to the typical correlation coefficients in this study than McKay et al. (2022).

4.4.2. Does expertise increase the accuracy of X-radiographic clast counting?

It appears that expertise bears little impact on the accuracy and precision of clast counting. This is evident in both the distributions, correlations, and also in the variability between average counts per image between users of varying experience (Figures 4.3, 4.4, 4.5, 4.6 and 4.7). This is an important finding of this research. However, if the variability of clast counting is not a function of expertise, it must be related to other factors. Figure 4.10 gives an indication of accuracy between different users, specifically, the plot shows the consistency between different participants (Spearman's $\rho = 0.887$; $p < 0.001$). We find that users closest to the trendline (3, 7, 9, 8, 10, 11, 12 and 13) are more consistent in their method and therefore probably more accurate in their counts. However, this also highlights that expertise does not have a significant impact on the consistency or accuracy of the clast-counting method using two sedimentologically different glaciomarine cores.

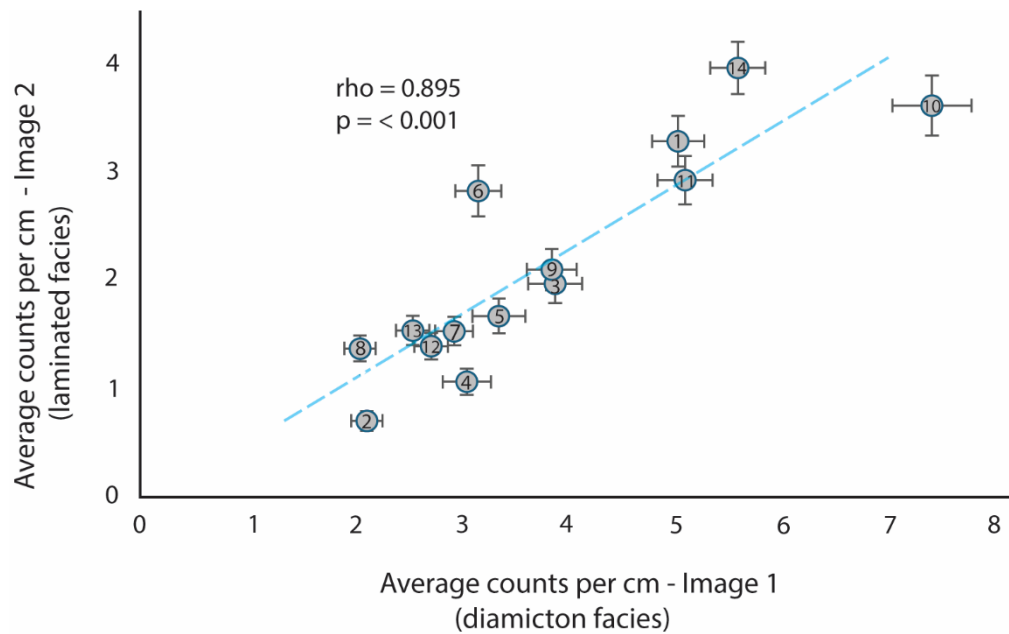


Figure 4.10. Average counts for each user on different images. This figure highlights that most users replicate their counts consistently, but some users are more conservative than others. Error bars indicate the standard error for each participant for each image.

Given this between-user consistency, it is clear that, participants can be generally classed as ‘high’ or ‘low’ counters in this study. For example, participant 1, 11, 10 and 14 can be classed as ‘high counters’ and participants 2, 4, 5, 7, 8, 12 and 13 can be classed as ‘low counters’ (Figure 4.10). There is consistency between both images in this regard, with a strong, statistically significant correlation. This again shows the relatively low accuracy and high variability of the XR clast-counting method.

This also confirms that user experience does not impact the applicability of the method. When reporting clast counts on the laminated facies, the two most experienced users had the lowest correlation with each other (Spearman’s $\rho = 0.253$). This was an unexpected result but probably stems from each user’s differing interpretations of what they consider as clasts on X-radiographic images. Participant 2 appears to have almost exclusively registered clasts which appear very dark, and therefore have a higher radiodensity, relative to the matrix sediment on the X-ray image (Figure 4.11). This may be because their expertise in other settings led them to interpret low radiodensity (less dark on X-ray image) clasts as non-IRD. Alternatively, other factors such as operating with lower screen brightness and differences in eyesight between the two users may play a part in this discrepancy. Participant 1 also appears to have been more generous with the 2 mm threshold, counting clasts which are near to (and possibly below) the 2 mm threshold. Participant 2 appears to have been more conservative by only counting clasts clearly > 2 mm. On the other hand, the least-experienced user had a high degree of correlation with all participants in the laminated facies, including both of the most-experienced users (Figure 4.5). This suggests that regardless of expertise,

with light / introductory training, any early-career scientist can undertake XR clast counting and generate accurate results.

This study was undertaken on two images which had low biogenic marine carbonate material content (proximal glaciomarine sediment with significant fine muddy silts due to meltwater delivery; Bradwell et al., 2019). In more shell-rich sediments (for example Facies 4 in the previous chapter), it is possible that user expertise may affect the accuracy of results. However, given the discrepancies between experienced users, this remains uncertain.

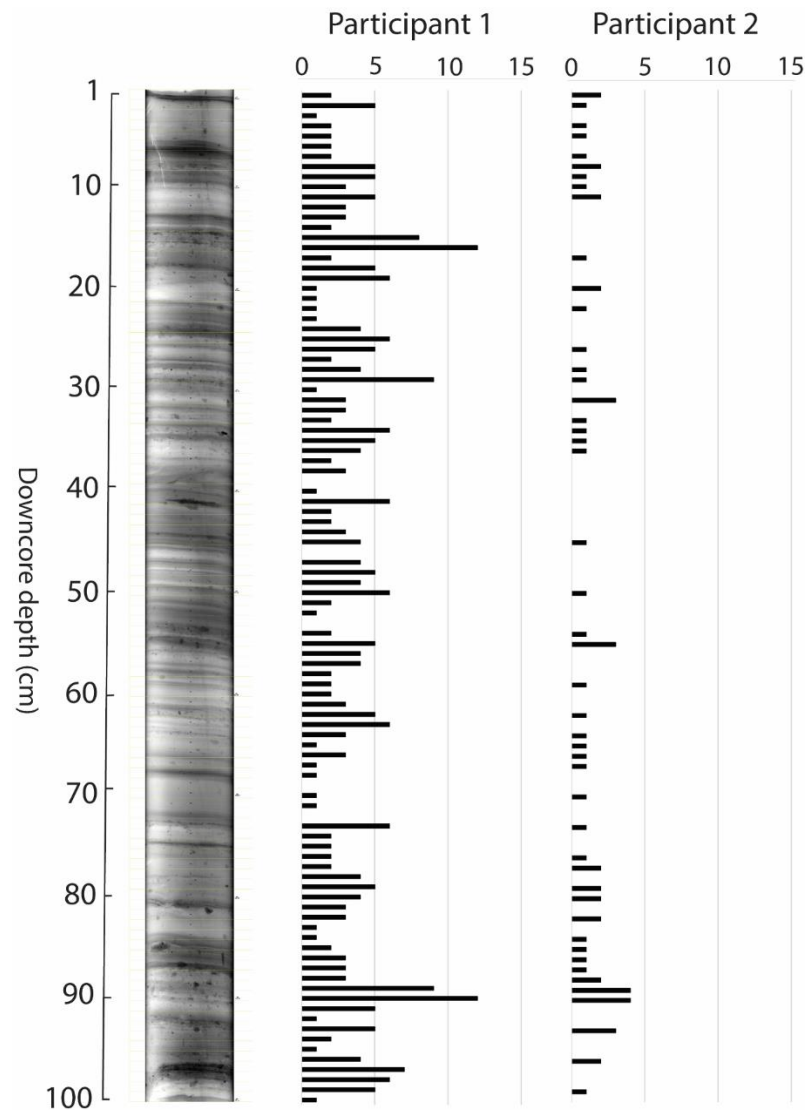


Figure 4.11. Participant 1 and Participant 2 counts in relation to the laminated sedimentary package (Image 2). Note: core depths between 50 and 70 cm highlight that lower radiodensity clasts are not counted by Participant 2 but are counted by Participant 1 leading to significant discrepancies between users. Participant 1 also appears to be more liberal in the 2 mm threshold, whereas Participant 2 may be more conservative and stringent.

4.4.3. Why is the Grobe (1987) technique prone to inconsistencies between users?

Numerous respondents reported differing methods for gravel classification and regarding which slice (or cm-interval) clasts were counted. For example, some users indicated that for clasts which overlap different grid sections (or slices) they:

- i) counted all clasts in each sample slice (whole or partial).
- ii) counted every clast in the interval in which it mostly appeared (also implemented by participant groups in Jasper et al. (2024).
- iii) Counted clasts within the first slice in which it appeared (in a downcore or upcore direction, depending on the participant).

This highlights the need for a more systematic approach when implementing clast counting.

Most respondents considered the axis of interest for clasts to be the a-axis (longest visible axis). Although, to be considered a gravel clast (> 2 mm) the b-axis should technically be considered (the shortest visible axis), as the b-axis would be the critical dimension for a gravel to be classified via sieving. However, X-radiographs are only 2-dimensional not allowing investigation of the entire clast and glacially derived clasts can often be bullet shaped and elongate (or below 2 mm – e.g. Connolly and Ewing, 1965; Ruddiman, 1977; St John et al., 2015; Bartels et al., 2018). It seems reasonable, therefore, to consider the longest axis as the critical dimension. Most respondents also reported estimating clast size with the naked eye, while others reported measuring the clasts using a reference filter or measuring with a ruler. These factors are considered as the main reasons for the high variability (standard deviation) between clast counts.

There are also fundamentally challenging factors such as the fact that clasts may become ‘hidden’ behind others on X-radiographs (Hogan et al., 2016), this is also more likely when sediment becomes rich in IRD. This may have played a factor in the higher standard deviation in the diamicton facies where there are more clasts and subsequently more chance of clasts ‘overlapping’ (Figure 4.2; Figure 4.7). However, the standard deviation becomes inherently greater when more clasts are present as user biases due to different operating decisions become amplified. That is to say, even when clasts are sparsely distributed but in high abundances (e.g. some horizons of the laminated facies) there is a greater spread around the mean as any factors which result in underestimations / overestimations of clast abundance become enhanced. This is exemplified in Figure 4.11 where one or more different decisions between Participant 1 and 2 result in significantly different IRD signals for the same core section (especially at 15-20 cm, 40-45 cm and 95-100 cm depth).

4.4.4. A protocol to improve consistency between users when undertaking the Grobe (1987) IRD method

A few clear suggestions are provided below which if implemented may help to improve the consistency of the Grobe (1987) method.

1. Crucially, only one observer should count the gravel clasts of cores in any given study. Also following guidelines by McKay et al. (2022), these counts should be validated by another user. This should avoid large discrepancies, even between experienced users, such as those between Participant 1 and 2.
2. Screen brightness should be maximised to facilitate maximum visibility of all clasts, whilst remaining comfortable.
3. Gravel classification should be determined based on the length of clasts (the longest visible axis).
4. Clasts should be counted from the base of the core section upward (from bottom to top), following the law of superposition.
5. Clasts should be counted in only the first sampling interval in which they appear. Failing to adhere to this rule may result in overcounting and also may result in the reported number of clasts being biased by the grid location.
6. All clasts close to the 2 mm threshold should be measured using a measuring tool. We draw the analogy that when conducting clast-fabric analysis, clast size would not simply be “eyeballed” but rather measured. Discretion should be used, as there is no need to measure clasts which are clearly longer than 2 mm.

4.4.5. Final considerations

It is well accepted that the core diameter can impact gravel counting as an IRD proxy (McKay et al., 2022). The results from this study add further uncertainties given that some users consistently count higher or lower than each other. Our findings further add to the existing observation that clast counting on X-radiographs cannot be used to quantify IRD as a proportion of weight or volume such as can be achieved using sieving or X-ray CT (Cederström et al., 2021), however, manual clast counts serve as a fairly consistent *proxy* for clast percentage abundances, and therefore, potentially IRD totals.

By adhering to the above protocol, more consistency will be delivered between different users. However, one very important takeaway from this study is that without one consistent observer, clast counts may only be considered semi-quantitative between studies. Overall, we call for more transparency when undertaking this particular analysis, whereby the specific rules users’ implement should be clearly stated when implementing the Grobe method.

In addition, more clarity must be provided in the literature as to what constitutes a clast in an X-radiographic sediment core image and what does not constitute a clast, for example, as observed in the discrepancies between Participant 1 and 2. This will be more common in sediments with many ambiguous features with a radiodensity higher than that of the surrounding sediment matrix, increasing the propensity for inaccuracies. This emphasises the need for greater clarification and potentially standardisation of how different objects appear on sediment core X-ray images.

Finally, the results of this study strengthen the case for the use of automated strategies to determine IRD and pursuing further research into how these different techniques may be improved to work better in different (glacio)marine settings across the globe. Many of these methods (e.g. Reilly et al., 2019; McDonald et al., 2022) are significantly quicker to implement, with manual counting averaging 22 minutes and 8 seconds for a 92 cm long diamicton facies, and 16 minutes and 31 seconds for a 100 cm long laminated facies. In the meantime, however, the framework provided here will go some way to minimise the inconsistencies in the manual clast-counting technique, which will in turn help to improve training for machine learning models based on manually counted datasets (e.g. Jasper et al., 2024).

4.5. Conclusions

In a participatory study of 14 individuals, the manual clast-counting IRD method (Grobe, 1987) was found to be a highly variable measure of IRD in two different sediment facies. Participants were observed to have relatively strongly correlated results with only 1 count comparison returning a statistically non-significant result using Spearman's rank correlation. Although the phasing (or frequency of clasts per cm) was strongly correlated between nearly all users, there was significant variability between users counts, with some users consistently counting more clasts than others. There was internal consistency between users indicating that some users are more conservative counters than others for various reasons ($\rho = 0.887$). The factors that result in this user variation include different approaches when: users attempt to determine the size of clasts (by either measuring using a ruler, reference filter or estimation), clasts overlap on X-radiographs (Hogan et al., 2016), clast appear in more than one sampling interval (1 cm slice), users attempt to differentiate between non-clastic high radiodensity objects and low-radiodensity clasts, and potentially differences in users' screen brightness and eyesight.

Expertise does not play a significant role between users, with statistically significant count correlations observed between both experienced and inexperienced participants in this study. Two experts in the field were also observed to have very different outputs of IRD on the same images. Manual clast counting is also observed to be quick compared to other traditional IRD quantification techniques (taking ~ 22 minutes and 8 seconds and 16 minutes and 31 seconds for 92 cm and 100 cm long core sections respectively). It is therefore significantly slower and more labour intensive than newer automated sediment core X-ray imaging routines.

A new framework is presented for researchers to follow in order to increase count consistency. These include selecting one observer for each study, counting from the base of the core upward (following superposition), counting clasts in the first interval they appear if they overlap several sampling grids, using the maximum comfortable screen brightness and measuring (rather than estimating) the long axis of clasts near the 2 mm threshold. We also call for more research on how gravel clasts can be differentiated in XR imagery from other marine geological / biogenic materials that are denser than the typical surrounding matrix.

Overall, these results suggest that XR clast counting, when applied manually, should only be considered a semi-quantitative measure of IRD abundance. Innovations in automated approaches to quantify IRD, in particular artificial intelligence, provide exciting new approaches which may act to mitigate the observer biases discovered in this study.

Chapter 5: Constraining the Timing of Marine Ice Sheet Instability in The Minch, NW Scotland

5. Introduction

5.1. Chapter aims and importance

This chapter attempts to constrain the behaviour and timing of the Minch Ice Stream (MnIS), during the transition from full ice stream (with ice shelf) to tidewater glacier system. This is achieved using a suite of new ^{14}C dates on a mixture of micro- and macro-fossils, part of a robust multi-proxy palaeo-environmental approach combining geomorphology, sedimentology and foraminifera analyses. Subsequently the extent of the ice shelf in the Minch is constrained during the final ice-sheet stability phase and ice-stream/tidewater-glacier-ocean interactions are explored at an important time period during the last glacial cycle (Heinrich Stadial 1).

Constraining the timing and nature of ice-stream retreat and ice-shelf extent helps to advance our understanding of the timescales on which the marine ice sheet instability operates. The MnIS is a particularly well-suited ice stream for this study as it is one of two unambiguous examples of palaeo-ice streams to have undergone the marine ice sheet instability (IPCC, 2021b). Furthermore, constraining the Minch Ice Shelf extent during the final stable phase of the MnIS, will allow better insights into how ice-shelf size affects ice stream buttressing capacity. Furthermore, this will also help to understand whether the MnIS was a more appropriate analogue for sectors of the West Antarctic Ice Sheet, with large extensive ice shelves, or sectors of the Greenland Ice Sheet with smaller, less extensive ice shelves.

5.2. Methods and materials

5.2.1. Sedimentology

Sedimentological analyses were conducted using traditional and innovative techniques including: qualitative, quantitative, destructive and automated non-destructive techniques. One core was analysed from the East Minch (JC123-021PC) and one from the West Minch (JC123-033PC) to understand ice-sheet dynamics across the Inner Minch strait (Figure 5.1). These include analyses of sediment structure, colour, particle-size analysis (PSA), clast abundance ($> 2\text{ mm}$) for identification of ice-rafted debris (IRD) and automated greyscale analysis (sediment radiodensity and heterogeneity). All of these proxies were analysed in order to reconstruct the processes driving sedimentation and ultimately determine the origin of sedimentation (proximal / distal glaciomarine or marine) and make palaeo-glaciological reconstructions.

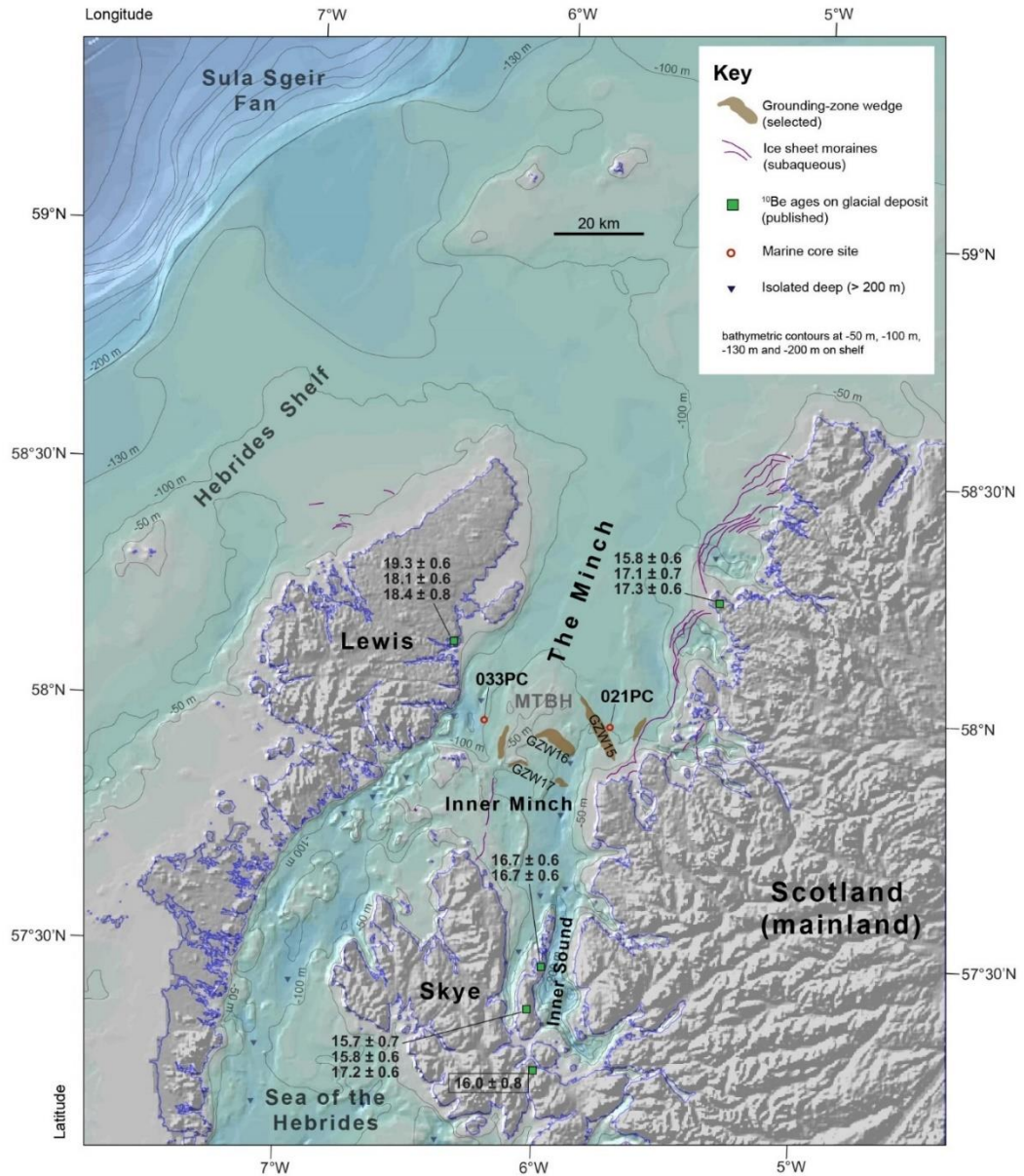


Figure 5.1. Minch palaeo-ice Stream setting and associated grounding zone wedges in the Central Minch (Bradwell et al., 2021). Timing of onshore glacial conditions evidenced by ^{36}Cl radionuclide dates (Small et al., 2012; Bradwell et al., 2019, 2021).

5.2.1.1. Destructive sedimentological methods

5.2.1.1.1. Fine particle-size analysis (< 2 mm)

Laser particle size analysis (LPSA) was conducted using the Bettersizer S3 Plus (JC123-021PC) and Beckman Coulter LS230 (JC123-033PC) particle analysers at the University of Stirling to analyse the fine sediment particle-size distributions (< 2 mm). Samples were added to a solution with deionised water (4 x sediment volume) and 3 ml of Sodium Hexametaphosphate. Samples were left on a shaker tray for 24 hours and dispersed using a magnetic stirrer. Samples were then added to

LPSA systems and 3 ‘runs’ were calculated using laser diffraction technology with the average of all 3 runs used to represent the fine sediment fraction. Fine-particle sizes (< 2 mm) were measured in order to understand the energy of sedimentation and to track proximity to the ice margin, with finer particles settling farther from the source. Particle-size analysis can also be useful for identifying past ice-shelf presence as finer material dominate with distance from the ice shelf, meanwhile, coarser sediment dominates during ice-shelf disintegration and removal (Smith et al., 2019; Gilbert and Domack, 2003).

5.2.1.1.2. Sediment shear strength

Sediment strength was considered based on undrained torsional shear strength measurements. This was measured in 10 cm intervals upcore using a hand-held torvane. These data can be used to differentiate sediments of similar physical properties deposited in differing glacial settings (e.g. subglacial, sub-ice-shelf and iceberg calving diamicton units (Boyd et al., 2007; Smith et al., 2019, 2023)).

5.2.1.2. Non-destructive sedimentological methods

5.2.1.2.1. Sediment core image analysis

Optical linescan (OLs), X-radiographic (XR) and X-ray computed laminography (CL) images were acquired in 2022 at BOSCORE, Southampton using the Geoscan V linescan camera and the Geotek ScoutXcan (X-ray images). X-ray images reveal many structures not visible to the naked eye and were evaluated for the presence of IRD via the counting of clasts or grains (> 2 mm) (sensu Grobe, 1987; Chapter 4).

5.2.1.2.2. Automated sediment characterisation using greyscale analyses

X-ray computed laminography (CL) images were utilised to extract greyscale properties using the methodology outlined in McDonald et al. (2022) (Chapter 2). The freely available ‘Sediment Characteristics’ plugin was used for FIJI/ImageJ to extract the mean and standard deviation (SD) of grey values (GV) in pixel intervals downcore, this provides the highest resolution of any analysis of IRD currently available (~ 0.066 mm downcore intervals). The mean GV provides a measure of sediment radiodensity as work undertaken in partnership with Geotek Ltd. shows a high degree of correlation with gamma bulk density (Figure 5.2) and the GV SD provides a measure of sediment heterogeneity which can in some cases be used as a proxy for clast or IRD abundance (McDonald et al., 2022). These techniques are combined to determine sediment density and IRD abundance (a proxy for iceberg abundance or calving frequency) and ultimately to discriminate different sedimentary facies.

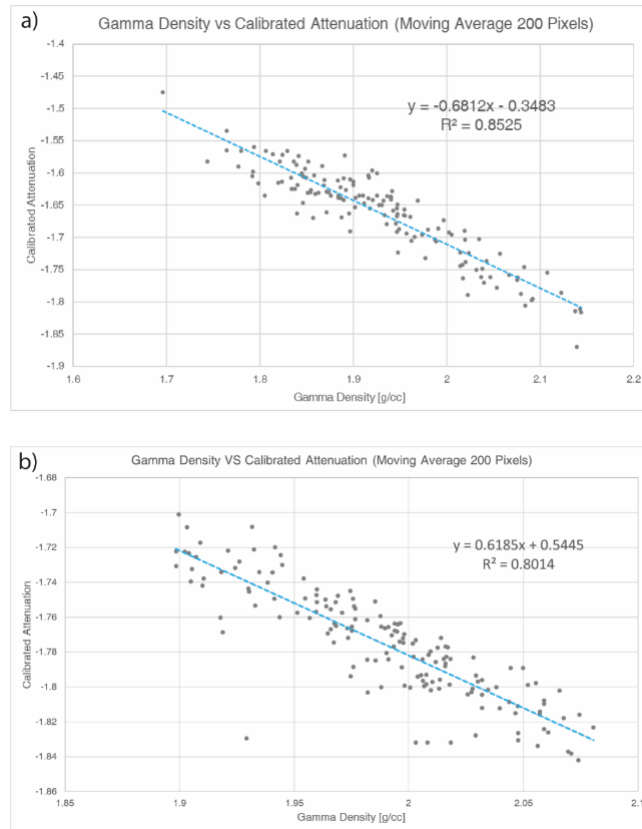


Figure 5.2. Relationship between gamma density (g/cc) and X-ray mean attenuation. Data extracted from X-radiographs on glaciomarine sediments from cores JC123-031PC and JC123-069VC (see Bradwell et al., 2019, 2021 for core locations and descriptions). This figure was produced by researchers at Geotek ltd.

5.2.2. Micropalaeontological techniques

5.2.2.1. Foraminifera abundance and species identification

Bulk sediment was extracted from sediment cores and sieved through a mesh size of 63 μm . Foraminifera were 'picked' in order to provide an overall count and distribution of species. Sampling of 5 cm^3 samples downcore (50 cm intervals) allowed for an initial understanding of foraminifera abundances which was useful for targeting specific horizons for AMS ^{14}C dating. In core JC123-033PC where foraminifera were extremely rare, 20 cm^3 samples were taken to provide an estimate of general species assemblages and abundances below 300 cm. Foraminifera abundances and species assemblages were implemented to better constrain palaeo-environmental conditions during sedimentation, for example: sediment sources, oceanographic conditions (water temperature / turbidity / bottom current velocity), and whether perennial floating-ice margins were present (following findings from such authors as Smith et al., 2019; Jennings et al., 2020; Peters et al., 2020; Smith et al., 2023).

5.3. Results

5.3.1. East Minch sediment core facies descriptions and interpretations (JC123-021PC)

Initial sedimentation in the East Minch (core JC123-021PC) consists of laminated muddy-silt with occasional sandy lenses (Figure 5.3). This unit is subdivided into two lithofacies associations (LfA1a and LfA1b), with unit LfA1a being deformed, the deformation is in keeping with water escape rather than iceberg turbate, mass flow or other processes (Lowe, 1975). Unit LfA1b therefore preserves the true undisturbed nature of this basal sediment. LfA1 consists of clast poor sediment, evidenced by low GV SD (mean GV SD ~ 300) and gravel counts. Foraminifera were absent in 20 cm³ of sediment, strongly suggestive of a proximal glaciomarine and possibly sub-ice-shelf environment (Korsun and Hald, 1998; Majewski et al., 2018; Jennings et al., 2020; Smith et al., 2023). Additionally, the mud-sand laminae (occasionally lenticular) and low (but present) IRD abundances suggest that this sediment was deposited when the grounding-line of the MnIS was *moderately* proximal to the core site (i.e. within 5 km; *sensu* Smith et al., 2019; O'Regan et al., 2021).

The transition at the base of LfA2 is a granulated unit, with the main facies comprising a clast-rich, crudely stratified sandy diamicton (Figure 5.3). In the East Minch, LfA 2 is composed predominantly of red sand layers interspersed with less stratigraphically extensive grey / blue layers (Figure 5.3). Stratified diamictons are typical of many glaciomarine environments including: grounding-line proximal settings beneath ice shelves where rainout dominates; following ice-shelf collapse (proximal and distal); within iceberg calving bays; and in debris-dominated mass flows (Hogan et al., 2016; Furze et al., 2018; Smith et al., 2019; Vermassen et al., 2020). The stratified nature of sedimentation suggests a likely source from meltwater plumes either by suspension settling or variations in sediment source (Ó Cofaigh and Dowdeswell, 2001; Furze et al., 2018). High shear strengths (2 – 4 kg/cm²) and barren foraminifera ($n = 0$ in 20 cc) suggest a proximal, high-energy environment with abundant iceberg rafting or ice-shelf rainout (as seen in the IRD counts) (Smith et al., 2019; Smith et al., 2021).

Initial sediment interpretations were undertaken by Bradwell et al. (2021) based solely on non-destructive analyses – X-radiographic images, geophysical properties and sub-bottom acoustic profiles. They preferred an explanation of LfA1 and LfA2 as evidence of an oscillating ice stream margin with either iceberg-rafting or an ice shelf. Our results confirm the findings of Bradwell et al. (2021) and suggest that these basal units record an oscillation or an advance of the Minch Ice Shelf, similar to Holocene sediments recovered beneath the present-day Thwaites Ice Shelf, in the Amundsen Sea Basin (Clark et al., 2024 – core KC04).

The increasing shear strengths, granulated transitional unit at the base of LfA2 and crudely stratified nature of the foraminifera-barren diamicton, probably indicate a proximal sub-ice-shelf setting (Smith et al., 2019). An alternative explanation is that the association of a foraminifera barren, silty-mud laminated unit capped with a crudely stratified diamicton indicates a transition from a

moderately proximal sub-ice-shelf regime, followed by ice-shelf collapse, similar to palaeo-ice shelf sediments reported in Lancaster Sound, NE Canada (Laurentide Ice Sheet) (Furze et al., 2018 – core 2011804-0010PC). However, we retain the sub-ice-shelf interpretation as similar stratified diamicton units with granulated transitional units have been recovered from contemporary ice-shelf settings (Smith et al., 2019; Reilly et al., 2019; O'Regan et al., 2021; Jennings et al., 2022).

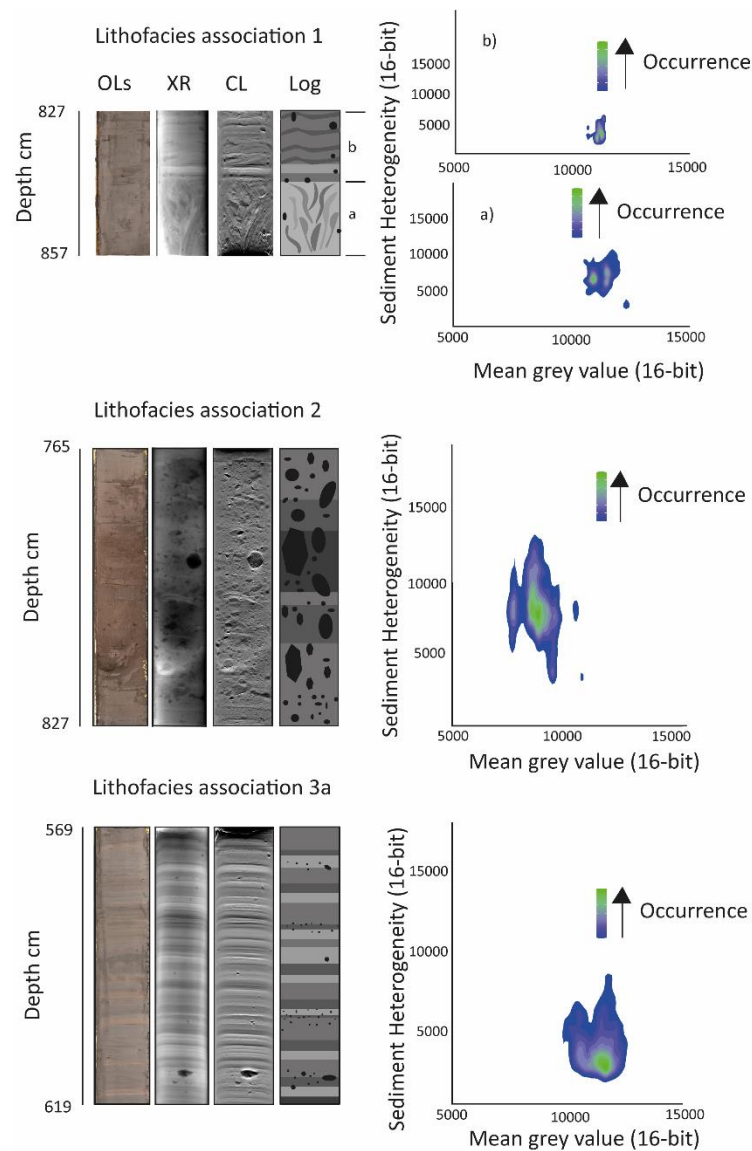


Figure 5.3. Sediment packages sourced from the eastern Central Minch (Core JC123-021PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies.

LfA3 is comprised of laminated red and blue-grey sediment with low clast counts and low sediment heterogeneity (Figure 5.3; Figure 5.4). LPSA distributions indicate a near absence of sand-sized material $> 150 \mu\text{m}$ (interpreted as IRD) as sediment is principally muddy-silt with a normal PSA distribution (Figure 5.5). Shear strengths are consistently low throughout this sediment package (< 1

kg / cm²). Further upcore, laminae become more wispy and less well defined, IRD becomes more abundant, shear strengths gradually lower and foraminifera abundance and foraminifera diversity increase (we identify this transition by defining three sub-units LfA3a, LfA3b and LfA3c – Figure 5.3; Figure 5.4; Figure 5.5). This indicates a slowly retreating ice margin in a distal glaciomarine setting. Foraminifera abundances are low in LfA3, however, sufficient benthic foraminifera were recovered for radiocarbon dating (Figure 5.5). Three radiocarbon dates were recovered from this facies (Figure 5.5), indicating deposition between 17.16 (+/- 0.26) ka cal BP to 16.64 (+/- 0.27) ka cal BP (Table 5.1).

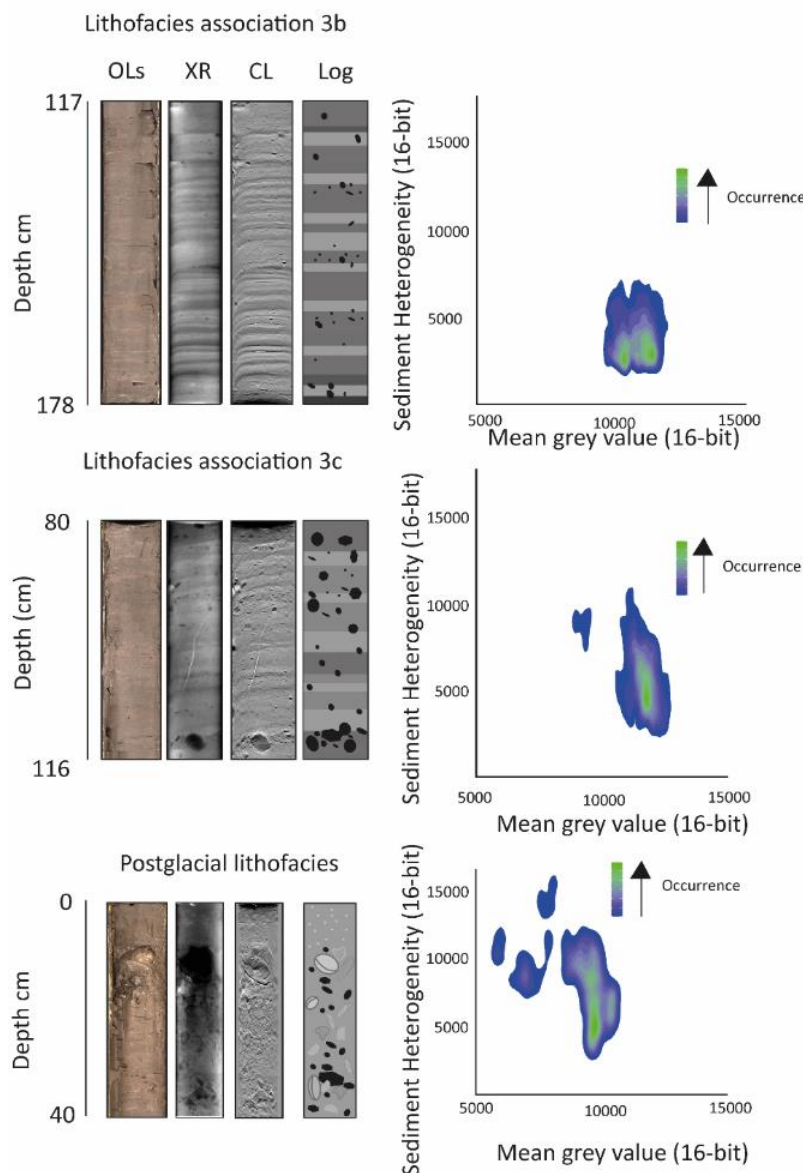


Figure 5.4. Sediment packages sourced from the eastern Central Minch (Core JC123-021PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies.

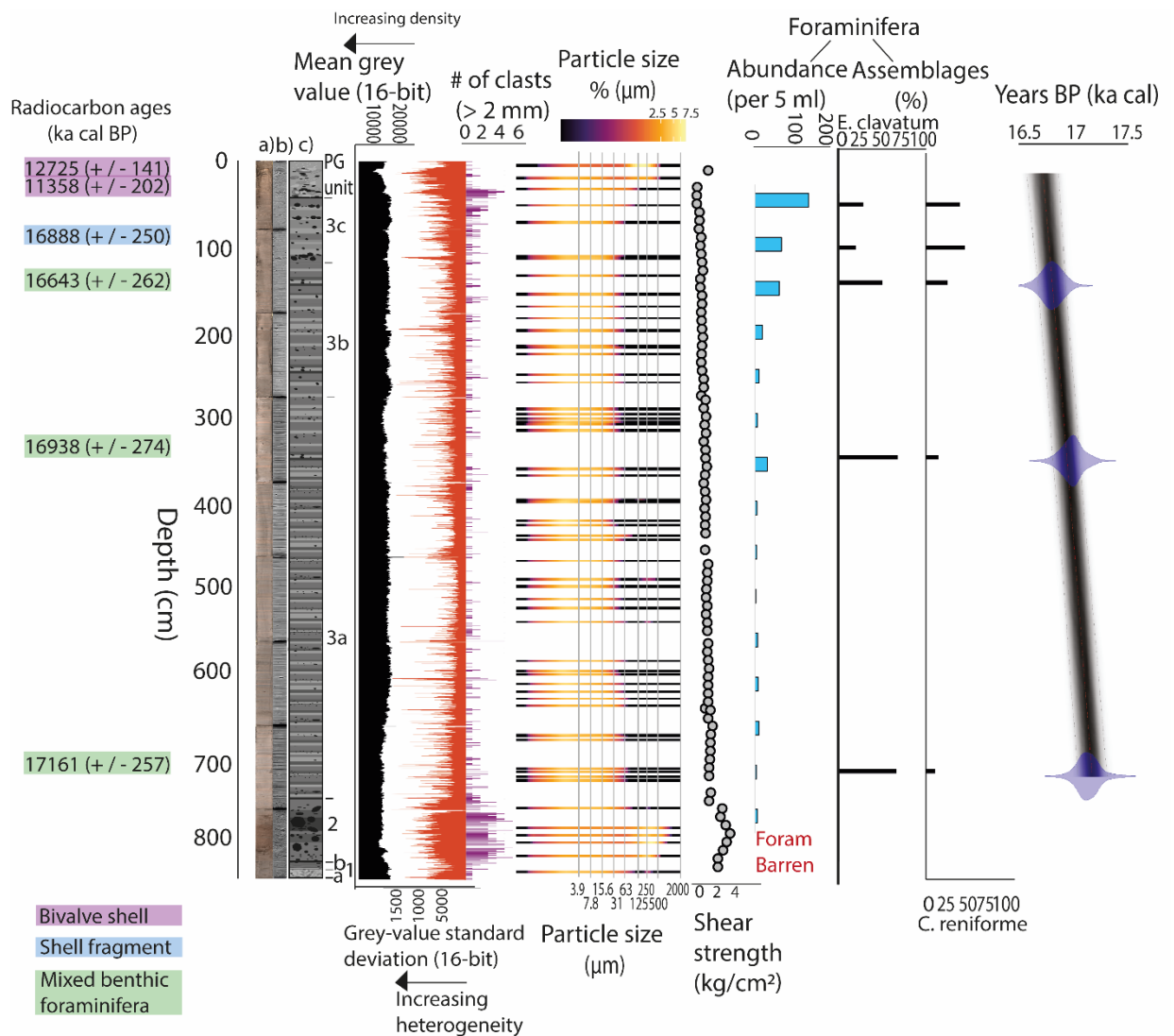


Figure 5.5. Sediment stratigraphy and associated palaeoenvironmental proxies in core JC123-021PC. Sediment core linescan optical images, X-ray images and sediment logs on left. X-radiographic grey value extractions in black and red downcore area plots – black = mean X-ray grey value from X-radiographic images, a proxy for density; red = grey value standard deviation sampled from X-ray computed laminography – a measure of sediment heterogeneity and a proxy for iceberg rafting) (McDonald et al., 2022). X-ray Clast counts (> 2 mm) in purple bars, a proxy for iceberg rafting, note correlation with grey value standard deviation (Grobe, 1987). Laser particle size analysis (Betttersizer S3 Plus) output displayed on heatmap, brighter colours indicate increased percentages of the sediment. Sediment shear strength in grey bullet points. Foraminiferal abundances and assemblages displayed 2nd and 3rd from the right, note assemblages on bars are measured in 50 cm intervals downcore (relative to 5 cc of sediment); assemblages are resampled with higher abundances at 5 targeted horizons. Radiocarbon dates calibrated using RBAcon (Blaauw & Christen 2011). Note samples correspond to both core stratigraphy (top to bottom) and years BP (ka cal) (left to right).

The foraminifera assemblages in LfA3 are predominantly *E. clavatum* and *C. reniforme*, indicating cold water conditions (possibly as low as 1 °C) and a glaciomarine setting without cover from perennial sea ice or a floating-ice shelf (Hald et al., 1994; Jennings et al., 2020), contradictory to previous interpretations by Bradwell et al. (2021) who favoured a sub-ice-shelf depositional environment. Indeed, the frequency of IRD is in keeping with proposed short-ice-shelf sediments (Smith et al., 2019; Vermassen et al., 2019, 2020). IRD may be present in sub-ice-shelf sediments via other feeding glaciers, supraglacial debris or because the core site is potentially within 5 km of the grounding line (Smith et al., 2019; Jennings et al., 2022). However, in these cases, evidence of debris filtering – a reduction of IRD in the middle or toward the top of the laminated unit – is typically observed (Smith et al., 2021), or foraminiferal species which do not tolerate ice shelves are absent (e.g. *E. clavatum*; Jennings et al., 2023).

In JC123-021PC laminae, with the transition from LfA3a to LfA3c an increase in the abundance of IRD is observed, despite only a minor decrease in sedimentation rate (Figure 5.5). Therefore, due to the geomorphological evidence of ice shelves (GZW and tabular iceberg scours; Bradwell et al., 2021), finely laminated clast-poor, and increasing upcore non-ice-shelf foraminifera (Jennings et al., 2020), we reappraise this unit as having formed within ~ 5-10 km of the grounding line (after Smith et al., 2019), adjacent to the MnIS ice shelf (eastern MnIS). The laminae formation mechanism is explored in detail in Chapter 6.

Overlying LfA3 is a postglacial facies spanning ~40 cm with two ¹⁴C dates at 12.73 +/- 0.14 cal ka and 11.36 +/- 0.20 cal ka BP at depths of 13 cm and 25 cm, respectively (both excluded from the Bayesian model). This upper unit comprises shelly muds with gravel lag units and a well-sorted sandy cap.

5.3.2. West Minch sediment core facies descriptions and interpretations (JC123-033PC)

Sedimentation in the West Minch (core JC123-033PC) is similar to that of the East Minch (021PC), however, subtle differences in the sediment stratigraphy point to differences in environmental conditions. At the base of core JC123-033PC, at a depth of 767 – 805 cm, a laminated, silty-mud unit was recovered (with occasional sand), with a moderate number of clasts (LfA1) (Figure 5.6). A stratified mud-sand diamicton unit (LfA2) is observed at 707 – 767 cm. These units suggest an oscillating ice margin in a similar manner to those identified in the East Minch (LfA 1 + 2), forming the large GZW15 in the West Minch. Foraminifera in these core JC123-033PC units comprise a low abundance of temperate and glaciomarine species, suggesting reworking either from subglacial or bottom-current processes.

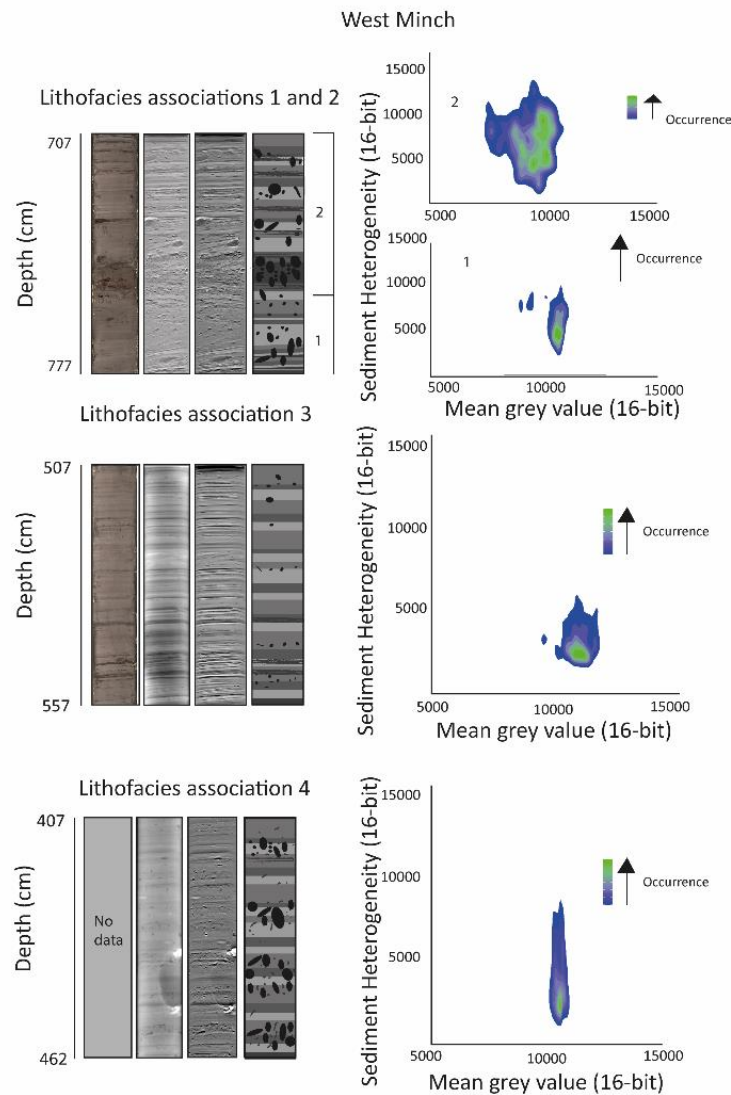


Figure 5.6. Sediment packages sourced from the western Central Minch (Core JC123-033PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies.

LfA3 in the West Minch comprises finely laminated glaciomarine muddy-silt, with decreasing laminae thickness upcore and moderately stable, intermediate shear strengths – suggesting a stable or slowly retreating ice margin, possibly from GZW15. Sandy layers (stratified or laminated), lower in the sediment stratigraphy (part of an upcore transition from a stratified diamicton) is characteristic of Greenlandic sub-ice-shelf facies (Jennings et al., 2022). Clasts are extremely rare in this unit (LfA3: 505 – 707 cm), and sediment heterogeneity is very low (Figure 5.7). Foraminifera in core JC123-033PC (LfA 1 – 3) are also in exceptionally low abundances with ~ 0-13 tests per 20 cc, these values are lower than fossil foraminifera abundances recovered from beneath the extant Petermann Ice Tongue (Figure 5.7; Jennings et al., 2020). One very small unidentified shell was recovered from the top of LfA3 at 510 cm (mass = 0.7 mg) which returned a radiocarbon date of 16.39 (+/- 0.56) ka cal BP.

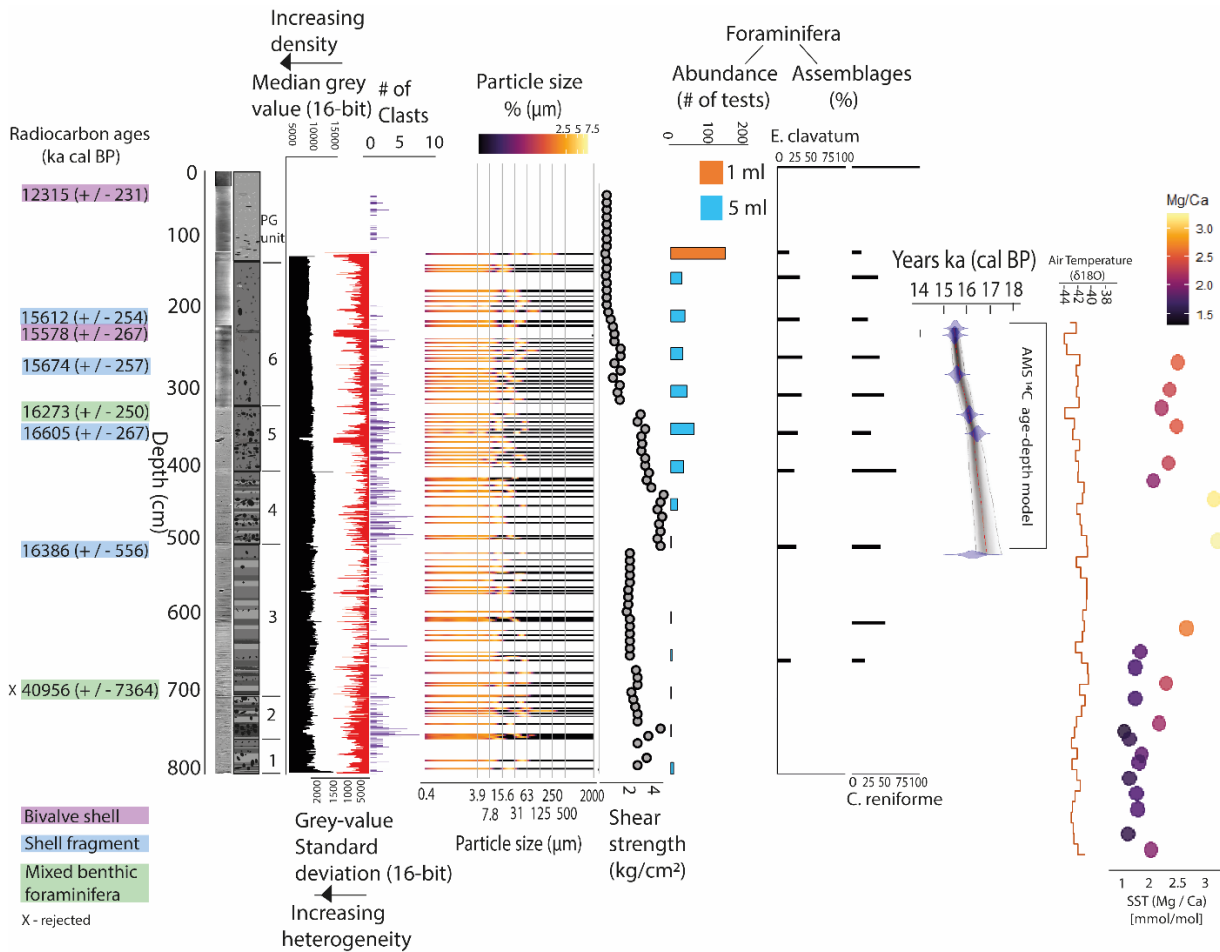


Figure 5.7. Sediment stratigraphy for West Minch (JC123-033PC). Sediment stratigraphy and associated palaeoenvironmental proxies in core JC123-033PC. X-ray images and sediment logs on left. X-radiographic grey value extractions in black and red downcore area plots – black = mean X-ray grey value from X-radiographic images, a proxy for density; red = grey value standard deviation sampled from X-ray computed laminographs, a measure of sediment heterogeneity and a proxy for iceberg rafting) (McDonald et al., 2022). Clast counts (> 2 mm) in purple bars, a proxy for iceberg rafting, note: correlation with grey value standard deviation (Grobe, 1987). Laser particle size analysis (Bettersizer S3 Plus) output displayed on heatmap; brighter colours indicate increased percentages of the sediment. Sediment shear strength in grey bullet points. Foraminiferal abundances and assemblages displayed 2nd and 3rd from the right, note assemblages on bars are measured in 50 cm intervals downcore (5 cc of sediment); abundances are resampled with higher abundances. Radiocarbon dates calibrated using R Bacon (Blaauw & Christen, 2011). Note: samples correspond to both core stratigraphy (top to bottom) and years BP (ka cal) (left to right). Air temperature (proxy – $\delta^{18}\text{O}$) as presented in Greenland ice core (NGRIP). Summer sea-surface temperature (Mg / Ca – *G. bulloides*) sourced from Porcupine Seabight (MD 01-2461) (Peck et al., 2008).

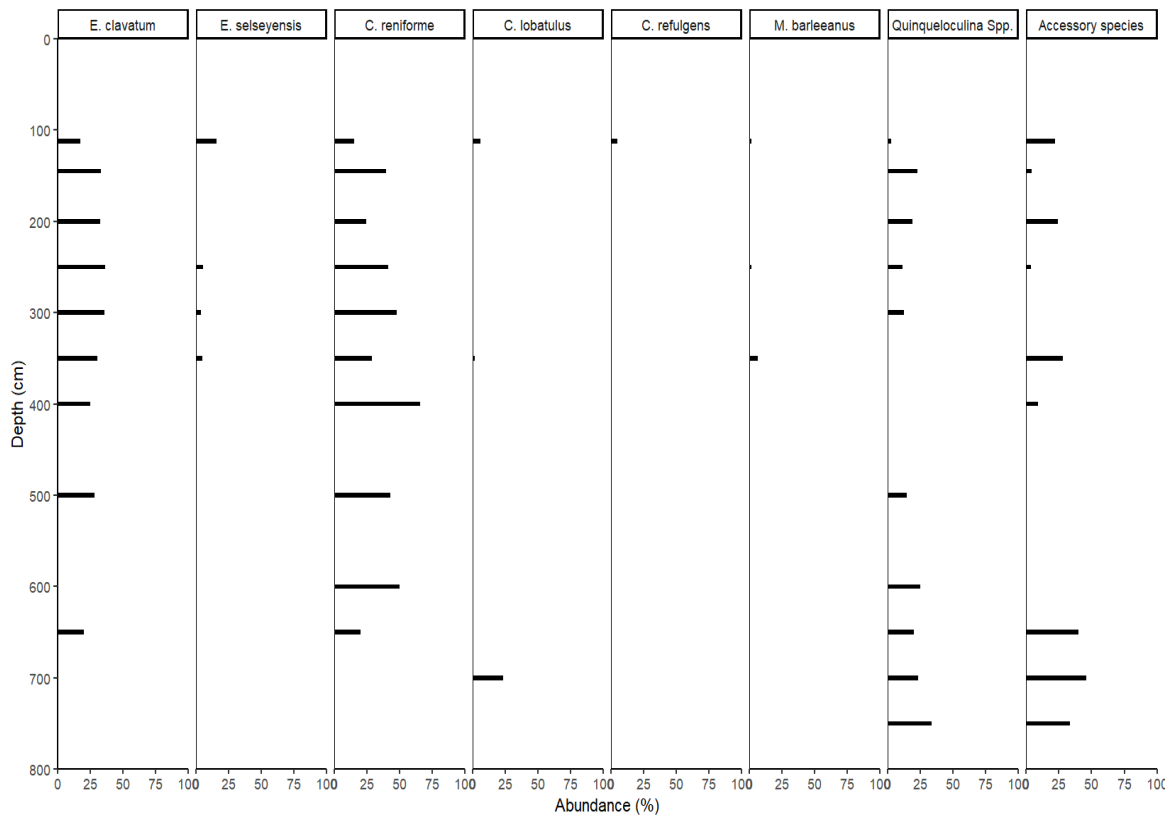


Figure 5.8 Foraminifera assemblages for core JC123-033PC. Samples taken every 50 cm upcore from 800 cm to 150 cm with one further sample recorded at 110 cm.

Very clast-poor, foraminifera barren, laminated glaciomarine sediments indicate possible ice shelf cover (Jennings et al., 2022; Smith et al., 2023). Furthermore, we favour an interpretation of ice-shelf cover rather than dense sea-ice cover (multiyear landfast sea ice) over the site of core 033PC during this time for two main reasons:

- a) The nearby presence of GZWs, suggesting a floating-ice shelf (Batchelor and Dowdeswell, 2015; Normandeau et al., 2017).
- b) The sediment stratigraphy is very similar to that observed in sediment cores recovered from beneath contemporary ice shelves from Antarctica and Greenland (Smith et al., 2019; Jennings et al., 2022).

We note, however, that distinguishing between dense sea ice and ice shelves in the Quaternary record remains challenging due to the lack of recognised diagnostic criteria. This makes distinction between the two environments difficult.

Overlying the finely laminated unit (LfA3) is a muddy-silt sediment package with abundant gravel clasts and diffuse laminations (LfA4). Gravels occur in a rhythmic pattern, over a typical vertical interval of 2-3 cm, suggesting seasonal break-up of sea ice (Dowdeswell et al., 2000; Figure 5.9). However, there is an alternative explanation: that increased meltwater plumes overload the sediment

package with finely laminated sediment in summer (rather than coarse IRD), and in winter the reduction of melting results in less intense meltwater plume activity and a relative increase in IRD (Cowan et al., 1997). The varying abundance of IRD can be explained by both increased distance from the source of meltwater plumes (more diffuse laminae) and the collapse of the Minch Ice Shelf, with an abrupt transition from clast-poor to clast-rich sedimentation (Figure 5.7; Figure 5.9). Foraminifera in this facies comprise cold-water glaciomarine species of low abundances (*E. clavatum* and *C. reniforme*) (Figure 5.7; Figure 5.8).

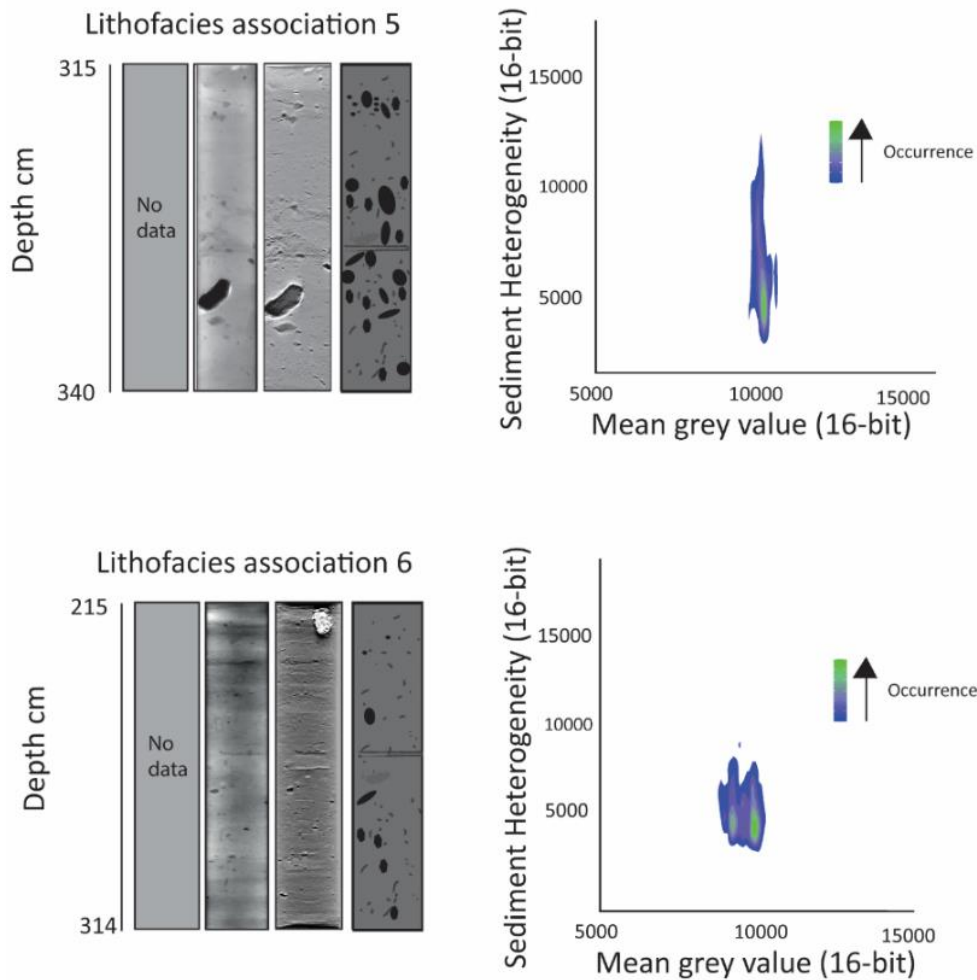


Figure 5.9. Sediment packages sourced from the western Central Minch (Core JC123-033PC). Scatter plot style heatmaps indicate the X-radiograph mean grey value (radiodensity) against X-ray grey value standard deviation for each lithofacies.

LfA5 is inherently similar to LfA4 and probably relates to the ice-shelf breakup or collapse event. LfA5 is also rich in IRD, with higher shear stresses, but the IRD are not rhythmic in nature. AMS ^{14}C dated unidentified shell fragments within LfA5, at 350 cm depth, returned a radiocarbon date of 16.61 $\pm$ 0.27 ka cal BP. Near the top of LfA5, the sedimentation rate drops dramatically (Figure

5.7; Figure 5.8). More temperate foraminifera are observed in this facies, concurrent with a reduction in sedimentation rate and continued ice-margin retreat (Figure 5.7; Figure 5.8).

LfA5 is overlain by a very diffusely laminated clast-moderate to clast-poor mud with shells (LfA6). Clast abundance decreases gradually upcore. AMS age-depth modelling shows that sedimentation rates increase significantly to ~ 1 cm per year in this unit. Foraminifera also shift back to predominantly cold water glaciomarine species. The high sedimentation rates, diffuse laminations and high gravel clast counts suggest that this unit may be glaciomarine. However, its association with the overlying unit and wider association with other seismo-stratigraphically linked sediment packages suggest that it may be bottom-current reworked glaciomarine sediment. This unit is particularly interesting because our dating evidence places it between 15.7 and 15.6 ka cal BP, in the same time period as the Wester Ross Readvance (Ballantyne & Small, 2019; Figure 5.7) – a major ice-sheet oscillation in NW mainland Scotland.

LfA6 is overlain by LfA7; a postglacial mixed unit containing mud – sandy unit. Interpreted as a shell-rich bottom current reworked sediment with temperate foraminifera including *C. lobatulus* a species diagnostic of high energy bottom currents and sandy substrates (Mackensen, 1987; Figure 5.7; Figure 5.8).

Table 5.1. Atomic Mass Spectrometry (AMS) ^{14}C radiocarbon dates, core depths, description of sample type and integrity. Note: not all radiocarbon dates are reported in this study, as some are rejected based on erroneous dating with regard to the core stratigraphy, while others are recovered from sediment cores which are not investigated in this chapter. Calibration = Marine20 (Heaton et al., 2020).

Core	depth (cm)	Radiocarbon Age (^{14}C years BP)	1 σ (years)	Calibrated Age (cal yr BP)	Age Range 2 σ (years)	Sample type	Outcome
JC123-021PC	13	11,386	41	12,725	282	Bivalve shell	Rejected (likely reworked)
JC123-021PC	25	10,367	40	11,358	403	Bivalve shell	Accepted
JC123-021PC	90	14,631	51	16,888	499	Broken shell fragment	Excluded from Bayesian model (likely reworked)

JC123-021PC	140	14,430	49	16,643	523	Mixed benthic foraminifera	Accepted
JC123-021PC	340	14,673	63	16,938	548	Mixed benthic foraminifera	Accepted
JC123-021PC	700	14,864	67	17,161	514	Mixed benthic foraminifera	Accepted
JC123-033PC	43	10,977	39	12,315	462	Bivalve shell	Accepted
JC123-033PC	211	13,639	47	15,612	507	Broken shell fragment	Accepted
JC123-033PC	220	13,614	50	15,578	508	Bivalve shell	Accepted
JC123-033PC	271	13,685	50	15,674	514	Broken shell fragment	Accepted
JC123-033PC	325	14,117	49	16,234	499	Mixed benthic foraminifera	Accepted
JC123-033PC	350	14,401	51	16,605	533	Broken shell fragments	Accepted
JC123-033PC	510	14,233	202	16,386	1112	Broken shell fragment	Accepted
JC123-033PC	700	38,032	3,874	40,956	14,728	Mixed benthic foraminifera	Rejected (likely reworked)

5.4. Discussion

5.4.1. Chronology of ice stream retreat

Previous work, by the BRITICE-CHRONO consortium, inferred that glaciomarine sedimentation in the Inner Minch last occurred between ~18.5 and 17 ka as the ice stream rapidly retreated (Bradwell et al., 2021; Clark et al., 2022). This inference came from tying Terrestrial Cosmogenic Nuclide (TCN) dating with the offshore geomorphological (and sedimentological) evidence. Our new AMS ¹⁴C chronology from two sediment cores, either side of the MTBH in the Minch indicates that glaciomarine sedimentation was still ongoing at 16.6 ka, around ~0.4 to 1.5 ka later than previously estimated. These findings extend the operational time of the Minch ice stream by up to 1500 years and thus increase the rate of ice-stream demise significantly – perhaps by an order of magnitude

5.4.2. Sequence of events from ice-stream stability to collapse

18 – 17.2 ka cal BP: Initial retreat and stabilisation around the MTBH

The Minch Ice Stream underwent punctuated retreat in the North Minch between ~ 20-18 ka cal BP (Bradwell et al., 2019). A series of GZWs in the central Minch display the hallmarks of episodic retreat apparently unrelated to climate forcing at this time (Bradwell et al., 2019, 2021). The mid-trough bedrock high (MTBH) probably facilitated ice-stream stability soon after this, evidenced by large and more numerous GZWs here (Bradwell et al., 2019, 2021), and supported by high-resolution numerical modelling (Gandy et al., 2018).

A major ice-stream stabilisation around the MTBH is preserved sedimentologically in LfA1 and LfA2 in the East Minch. The stable grounding line around the MTBH likely formed an ice rise with ice shelves flanking either side, like that at the margin of the Brunt Ice Shelf, (see Thomas, 2017) (Figure 5.10). The oscillations reconstructed here are strikingly similar to oscillations identified throughout the Holocene beneath Antarctic ice shelves (see Clark et al., 2024). These oscillations were probably triggered by internal dynamic forcings such as ice-shelf thickening, dense sea-ice build-up, increased calving or ice-velocity increases.

During this time in the West Minch, the Sea of Hebrides and Little Minch strait *may* have already become free of grounded ice. We make this inference on the presence of a small number of temperate foraminifera species (e.g. *Ammonia Falsobeccarii*, *Lagena sp.* and *B. Marginata*) in the lowermost glaciomarine units of core JC123-033PC (in the West) but these species are not observed in the corresponding facies in the eastern core JC123-021PC. A very small weight of these foraminiferal tests (< 1 mg) returned an anomalous (rejected) radiocarbon date from LfA3 of 40,956 (+ / - 14.7) ka cal BP. Whether this is due to reworking (glacial or bottom currents) or old carbon contamination remains unclear.

We also suggest that the mud-sand stratified diamicton unit (LfA2) may record the unzipping of the western MnIS from the Lewis ice cap. While a section of the ice stream remained grounded and oscillating on the MTBH (situated on GZW 17), the farthest most western sector was unzipping. This is further supported by the configuration of the GZW ('GZW 15') in the W Minch containing a SW – NE orientation. Therefore, potentially validating high-resolution modelling which suggests rapid MISI-style retreat in the West Minch due to the significantly overdeepened bed (Gandy et al., 2018). The western corridor of the Sea of the Hebrides and W Inner Minch possibly allowed temperate foraminifera advection via warmer-water bottom currents from the SW, in-turn influencing glacial retreat. Additionally, this is consistent with the findings of Callard et al. (2018) who suggest the southern margin of the Sea of the Hebrides began to open around 20.2 ka cal BP “at the latest”.

17.2 - 16.6 ka cal BP: Major ice stream stability and slow retreat

Around 17.2 ka cal BP (+ / - 0.26) distal ice stream (~ 5 km from grounding line) sedimentation is observed, with the grounding line likely retreating *slowly* from GZW15. The trigger for this retreat remains unclear. The sediments deposited in the East Minch at this time were probably deposited adjacent to, but not beneath, a short ice shelf. Our ^{14}C chronology indicates sedimentation of ~ 1 - 3 cm per year, which is in keeping with estimates from contemporary glaciomarine systems (Elverhøi et al., 1989; Cowan et al., 1997).

The East Minch Ice Stream slowly retreated ca. 5 km in 0.6 ka under these conditions (~ 17.2 – 16.6 ka cal BP), shown by decreasing lamination clarity, decreasing sediment shear strengths and increased foraminifera abundances. We can assume that the Minch Ice Stream was transitioning from GZW 15 to GZW 16 in the East Minch during this time. The combination of proximal ice-shelf sediments with *E. clavatum* and persistent IRD throughout the entire laminated sediment package suggest a limit on ice shelf extent here in the East Minch (Smith et al., 2019; Jennings et al., 2020; Jennings et al., 2022).

The geomorphological evidence of an ice shelf is overwhelming with several GZWs and large, wide U-shaped tabular iceberg scours which cut through LfA3 in the stratigraphically tied JC123-022VC (Bradwell et al., 2021), combined with the sediment stratigraphy and very low clast abundances (as recorded elsewhere, such as Smith et al., 2019; Jennings et al., 2022). However, JC123-021PC core site was not covered by a perennial floating-ice margin (landfast sea ice or ice shelf) at this time as indicated by the combination of sedimentological and micropalaeontological evidence (Figure 5.5). This is further validated by the presence of rhythmic silt-sized IRD, which is not typical of sub-ice-shelf sedimentation. We attribute this to windblown fines settling through seasonal sea-ice melt (Figure 5.3; Figure 5.4). We can therefore assume that although an ice shelf was present in the Minch at this time, it was not extensive enough to cover the core site. This places a limit on the length of the ice shelf at this time to a maximum of 10 km – a similar extent to the proposed Porcupine Bank Ice Shelf in the Malin Sea, inferred by subaqueous ridges produced by an ice-shelf grounding on Porcupine Bank associated with a nearby GZW ~ 10 km inland (Peters et al., 2016).

In the West Minch, it is not possible to constrain the extent of the ice shelf at any time, and laminated sediments (LfA3) in core 033PC may indeed be deposited in a sub-ice-shelf cavity, despite the laminae containing rare IRD throughout their stratigraphic profile, unlike typical sub-ice-shelf units. Laminated sub-ice-shelf sediments can occasionally contain rare IRD, if the core site was fairly proximal to the grounding line during deposition (see unit 4 in Smith et al., 2021).

Constraining ice-stream behaviour in the western part of The Minch is challenging, owing to the lack of dateable material in the available cores. AMS ^{14}C dates were only recovered at the top of the ice-shelf stability unit and in the ice-shelf collapse muddy IRD unit. But what is clear, is that the ice shelf

which was stabilised over the MTBH (the central portion supplying sediment to the West Minch core site and the intact East Minch section) collapsed roughly synchronously at ~16.6 cal BP (Figure 5.10), triggering rapid retreat.

16.6 – 16 ka cal BP: Ice-shelf removal and runaway retreat

Around 16.6 ka, the MnIS which was stabilised around the MTBH crossed a threshold from multi-centennial stability (or very slow retreat) to a phase of rapid retreat. The loss of the ice shelf played a critical role in destabilising the ice stream, as originally proposed by Bradwell et al. (2019, 2021). Our new AMS ^{14}C dates confirm that this occurred later than previously estimated at ~16.6 ka cal BP rather than ca. 18.5-17.0 ka BP. We find evidence of this ice-shelf collapse in an increase in IRD recovered in core JC123-033PC (LfA 4 and 5). At 350 cm in core JC123-033PC, after ice-shelf collapse, a significant increase in foraminifera abundance is observed (Figure 5.7; Figure 5.8). The presence of more temperate species, for example *M. Barleaanus*, suggests sea-ice reduction and/or open water conditions with increased organic matter (Corliss, 1991). After the initial ice-shelf loss, the fingerprint of seasonal-sea-ice is observed in the West Minch with rhythmic IRD signals. The effect of this sea ice on stabilising (or retarding) Minch Ice Stream losses was negligible as shoreward retreat ensued at a rapid rate.

When considering the significant overlap between the retreat chronology from the central Minch at 16.6 ka cal BP and median TCN radionuclide dates recovered from boulders on Raasay and Skye (16.0 – 16.7 ka cal BP), it suggests that retreat of the Minch ice stream was indeed rapid – akin to marine ice-sheet-instability-style runaway retreat (Gandy et al., 2018). Our new suite of AMS ^{14}C dates suggests that this retreat occurred later (and faster) than previous estimates (cf. Bradwell et al., 2019, 2021).

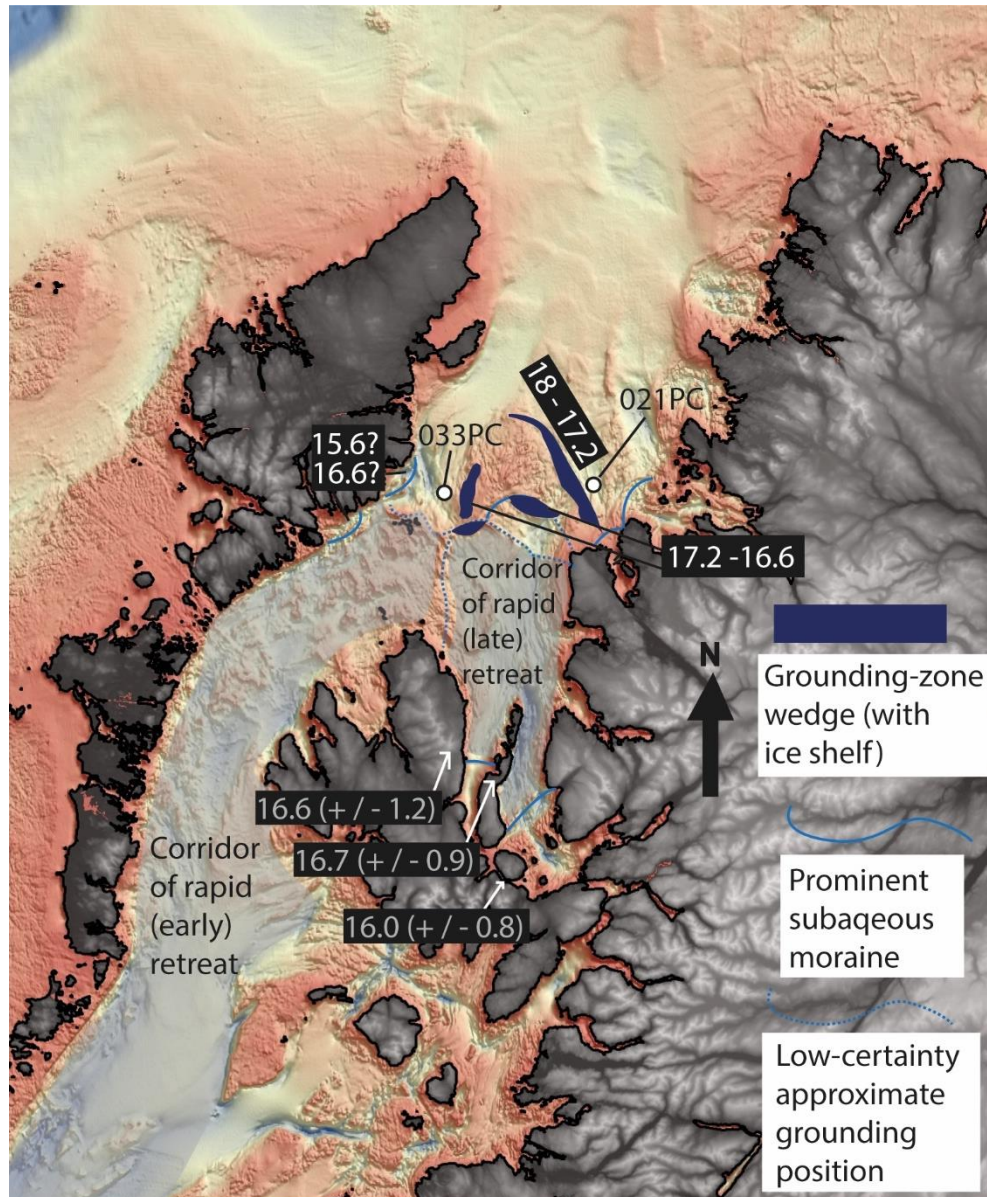


Figure 5.10. Central / Inner Minch retreat chronology constrained via our new suite of AMS ^{14}C dates. Dates in grey text are sourced from cosmogenic radionuclide ^{36}Cl ages from the Isle of Skye and Isle of Raasay (Stone et al., 1998; Small et al., 2012; Ballantyne and Small, 2018; Bradwell et al., 2021).

5.4.3. Elucidating the triggers of ice-shelf removal and retreat

During Heinrich Stadial 1, the Minch ice stream underwent three main behavioural phases: ice-stream frontal oscillations (pre-17.2 ka cal BP); multi-centennial stability – or a period of very slow retreat – (17.2 – 16.6 ka cal BP); followed by rapid retreat (16.6 ka cal BP). Our results therefore confirm inferences of dynamic ice-stream retreat, we also confirm that early retreat is initially divorced from climate forcing (18-16.6 ka), but the final ice-shelf collapse event (16.6 ka cal BP) is synchronous with increased ocean warming (via increased Atlantic Meridional Overturning

Circulation), but not rising Northern Hemisphere air temperatures. Our new suite of AMS ^{14}C dates indicate that the observed events occurred during Heinrich Stadial 1.

5.4.3.1. Ice-stream retreat via internal dynamics modulated by topography in the East Minch

Zooming in on Heinrich Stadial 1 (17.5 – 14.6 ka BP), our results allow an investigation into the relative roles of different factors on ice-stream stability. These factors include the role of topography / water depth, the role of ice shelves / sea ice and the role of sea-surface temperatures. Stabilisation phases occurring over the MTBH suggest that seafloor topography played a critical role in ice stream stabilisation, as proposed by others (Gandy et al., 2018; Bradwell et al., 2019). The events discussed in this chapter occur during a potential ‘purge’ phase of the BIIS (Alley and MacAyeal 1994; Hubbard et al., 2009; Clark et al., 2022). Certainly, the marine components of the BIIS, including the Minch Ice Stream, were retreating asynchronously with climate forcing (Clark et al., 2022). According to our new data, stability of the Minch Ice Stream occurred over the MTBH at ca. 17.5-16.6 ka. We infer that the MTBH acted as an ice-stream sticky spot – and potentially allowed an ice rise to form – with ice shelves spanning the deeper water and depositing facies 1-3 either side of this topographic high – similar to the conditions at the margin of the Brunt Ice Shelf, Antarctica, today (Thomas et al., 2017) – albeit on a smaller scale.

This study has presented a higher resolution investigation into Minch Ice Stream behaviour on centennial to millennial timescales. Our evidence suggests that this stabilisation (or very slow retreat phase) persisted for ca. 600 years (17.2 – 16.6 ka cal BP). The collapse of the Minch ice shelf (or shelves) has been proposed as a trigger for wider ice-stream collapse (Bradwell et al., 2019). However, the precise trigger for ice-shelf collapse has so far remained elusive.

Interestingly our new suite of AMS ^{14}C radiocarbon dates constrain the rapid retreat of the Minch Ice Stream to have occurred synchronously with warming NE Atlantic waters. This evidence is recorded in core MD01-2461 recovered from Porcupine Seabight off SW Ireland (Peck et al., 2008). However, for the ice shelf collapse event at 16.6 ka cal BP no evidence of ocean warming is recovered in sediment cores until MnIS retreat is underway, but there could be other ecological factors limiting the distribution of these foraminifera in ice-proximal settings, such as ice shelf / sea-ice cover, ice-stream proximity, water turbidity etc. (Forwick et al., 2010; Jennings et al., 2020). This highlights the importance of generating well constrained local palaeoclimatic proxies.

There is possible evidence of an early opening of the Sea of the Hebrides and the West Minch with warm water advection through the Little Minch / Sea of Hebrides, indicated by temperate foraminifera in lower stratigraphically positioned glaciomarine sediments (LfA1-2 and the lower sections of LfA3). The presence of these foraminiferal assemblages in the lowermost units of JC123-033PC could be evidence of the early opening of a marine corridor in the West Minch. However, the radiocarbon date of ~ 40 ka cal BP is anomalous and suggests that the warm water foraminifera

sampled were possibly the result of subglacial reworking. This separation of the Outer Hebrides ice mass from the main Scottish Ice Sheet could be in part due to ice starvation, as most ice was fed into the Minch ice stream from the ice accumulation centres in the west Scottish Highlands, or could be due to the reverse bed-slope in this sector of the shelf (as proposed by Gandy et al., 2018).

Bed topography and the presence of a short ice shelf appear to have played the most critical role in stabilising the Minch Ice Stream from 17.2 to 16.6 ka cal BP. However, the wider oceanographic conditions in the NE Atlantic Ocean during Heinrich Stadial 1 suggest that ocean warming may have been the trigger that prompted the MnIS ice shelf to collapse, causing the ice stream to pass a critical threshold from stability to rapid runaway retreat.

5.4.4. Wider implications

5.4.4.1. Reconstructing ice shelf or ice tongue extent in the palaeo-record

The extent of ice shelves may exert significant challenges when elucidating ice-shelf presence in the palaeo-record. This is because the current ice-shelf geomorphology and sedimentology models are adopted from large ice shelves and extensive ice tongues (> 50 km long) (Smith et al., 2019; Jennings et al., 2022). However, our data validates the suggestion by Smith et al. (2019), that smaller ice shelves / ice tongues may be identified via a greater abundance of clasts in their laminated sediment packages (distal units). However, a multi-proxy approach is necessary to provide certainty to these conclusions.

With smaller ice tongues there is a significantly greater chance of proxies leading to competing interpretations. For example, near typical glaciomarine margins (< 5 km) foraminifera are typically very low in abundance (< 100 in 10cm³ of sediment) or even absent due to high sedimentation rates, challenging environmental conditions or carbonate dissolution (Görlich et al., 1987; Korsun et al., 1995; Korsun and Hald, 1998), as is the case with sub-ice-shelf / ice-tongue environments (Jennings et al., 2020). Additionally, species capable of surviving near the ice margin are often those capable of tolerating sub-ice-shelf conditions e.g. *Textularia earlandi* and other agglutinated foraminifera (cf. Korsun et al., 1995; Bowser et al., 2005; Jennings et al., 2020). On the contrary, *E. Clavatum*, is a foraminifer which persists in low latitude regions (unlike many sub-ice-shelf tolerant species such as *S. horvathi*) and can be used as a strong indicator of a lack of ice-shelf cover. This is because this foraminifer is tolerant of ice-proximal conditions (Korsun and Hald, 1998), but not ice-shelf conditions (Jennings et al., 2020). Therefore, an absence of *E. Clavatum*, can be combined with other multiproxy evidence (e.g. finely laminated clast-poor sediments, and GZW / corrugation ridges) as a potential indicator of ice-shelf cover. Therefore, *E. clavatum* can play a critical role in deciphering between ice shelf and non-ice-shelf cover.

To further complicate this issue, however, foraminifera and sea-ice biomarkers (regularly used to differentiate seasonal sea ice and ice shelves) may have a high propensity to be advected beneath

smaller ice tongues (Pudsey et al., 2006; Stoltenberg et al., 2025). Given these complexities, small ice tongues may be indistinguishable in the palaeo-record from non-ice-shelf glaciomarine regimes if geomorphological evidence (GZW, wide U-shaped iceberg scours, corrugation ridges) is not preserved. Here, we have provided a constraint on ice shelf size in the Minch, albeit only in the East Minch. Therefore, significantly more knowledge is required from marine-terminating glaciers and ice streams with smaller ice tongues where data has not yet been collected, for example, from sectors of the NW Greenland Ice Sheet (Enderlin and Hawat, 2013).

5.4.4.2. Marine ice sheet implications

These results have significant implications for contemporary ice streams such as those draining the Antarctic and Greenlandic Ice Sheets. These results suggest that bed topography can result in significant stabilisations of an ice stream in keeping with numerical modelling studies (Drouet et al., 2013; Van den Akker et al., 2025). However, localised ocean warming effects (such as increased bottom current intensities), as possibly observed with initial retreat in the West Minch, may promote periods of retreat. Similarly, a combination of factors such as ocean warming and exposure to deeper waters may trigger marine ice sheet instabilities as is observed in The Minch.

It should also be noted that the rapid retreat observed from the Inner Minch to the fjords of Skye occurred during Heinrich Stadial 1, and under subtle ocean warming, over a reverse bedslope in relatively shallow water by Antarctic standards (but very deep UK continental shelf waters at > 200 m). There are significant implications for contemporary ice streams, as those which terminate in relatively shallow water (e.g. marine-terminating sectors of NE Greenland – Zoller et al., 2023) may be susceptible to rapid ice stream retreat (and even collapse) especially in a world containing accelerating oceanic and atmospheric warming.

One takeaway from this study is that even small ice shelves can play an important role in stabilising ice streams. Recently many Antarctic and Greenlandic ice shelves have lost a significant proportion of their extents in recent years (Rack and Rott, 2004; Rignot et al., 2004; Christie et al., 2022; Millan et al., 2023). These results suggest that in certain circumstances ice streams can maintain fairly stable grounding positions for centuries with only small ice shelves. The implication here is that if current anthropogenic warming can be controlled and limited, the ice streams and marine-terminating outlet glaciers of contemporary ice sheets may not necessarily undergo immediate MISI style retreat, rather retreat may be punctuated by lengthy standstills (multi-centennial scale stabilisations).

5.5. Conclusions

The results of this study constrain, at high-resolution, the timing and behaviour of the Minch ice stream before, during and after its collapse. The MnIS underwent two main stable phases when its grounding-zone was positioned in the central Minch: one remains poorly constrained, occurring *before* 17.2 ka cal BP; the other was a ~ 600-year stable phase from 17.2 to 16.6 ka cal BP. The first

phase is characterised by an oscillating ice margin with clast-poor muddy-silts capped by stratified diamicton units. These units, typically barren of foraminifera, likely formed in a sub-ice-shelf cavity. More distal glaciomarine units characterise the 600-year stable (or slow retreat) phase. These sediment packages contain low-clast abundance strongly laminated muddy-silt with low abundances of *E. clavatum* and *C. reniforme*.

In the East Minch, the length of the Minch Ice Shelf has been determined based on combined geomorphological, sedimentological and micropalaeontological evidence to show that the ice shelf between 17.2 ka cal BP and 16.6 ka cal BP could not have extended more than 10 km. Despite its short extent, when the ice shelf was removed, rapid, runaway ice-stream retreat ensued. This is evidenced by a lack of grounding-line features inshore and also a significant increase in IRD in the West Minch (core JC123-033PC).

Constraining rates of ice stream retreat in glaciomarine systems is challenging. However, our work suggests that retreat was indeed rapid, with ^{14}C and TCN ages overlapping in their uncertainties, between 16.6 ka cal BP and 16.7 - 16.0 ka cal BP. We place the period of final rapid ice-stream retreat, or collapse, around 16.6 ka and no later than 16.0 ka cal BP. Although air temperatures were cold during this time (Heinrich Stadial 1), sea-surface temperatures in the NE Atlantic Ocean were already warming, perhaps acting as the trigger for the Minch Ice Shelf removal and ultimate ice-stream demise.

Chapter 6: A Multiproxy Analysis of Laminated Glaciomarine Sediments **– Evidence from The Minch, NW Scotland (Last British-Irish Ice Sheet)**

6.1. Introduction

Laminated sediments are near-ubiquitous components of glaciomarine sediment archives and have been observed at the margins of both past and present ice sheets (Domack, 1990; Dowdeswell et al., 2000; Ó Cofaigh and Dowdeswell, 2001; Domack et al., 2005; Maddison et al., 2005; Furze et al., 2018; Bradwell et al., 2021; Ó Cofaigh et al., 2025). Laminated glaciomarine packages can form in all glaciomarine settings, including polar and temperate, proximal to *moderately* distal, ice shelf and tidewater glacier margins (Mackiewicz et al., 1984; Powell et al., 1984; Philipps, 1991; Domack et al., 2005; Maddison et al., 2006; Smith et al., 2017, 2019, 2023; Jennings et al., 2022).

The wide range of depositional settings has one of two potential implications which must be considered when attempting to pin-down the process controlling laminae deposition, either:

1. Laminated glaciomarine sediments are deposited via one common mechanism which is inherent to all glaciomarine regimes (e.g. suspension settling – Ó Cofaigh and Dowdeswell, 2001; Figure 6.1).
2. Laminated glaciomarine sediments are deposited via several different mechanisms and these different processes leave similar, but subtly different laminated sediment records (cf. Maddison et al., 2005; Furze et al., 2018; Figure 6.1).

Early studies into laminated sediments highlighted distinct silt–sand couplets in moderately proximal glaciomarine settings indicating formation via suspension settling of sediment-laden meltwater plumes – known as plumites (Mackiewicz et al., 1984; Cowan and Powell, 1990). Ó Cofaigh and Dowdeswell (2001), in a landmark review addressing the deposition and characteristics of laminated glaciomarine sediments, highlight two main modes of deposition: suspension settling from meltwater plumes with i) absent shorefast sea ice; ii) shorefast sea ice cover and turbidity current deposition.

Meltwater plume suspension-settled sediments are characterised by planar, parallel laminae in the sand–silt fraction, which are occasionally rhythmically bedded and grade upwards (Mackiewicz et al., 1984). Laminae may become flocculated within the water column during settling, therefore the lowermost lamina within a couplet may be poorly sorted (Cowan and Powell, 1990; Figure 6.1). Laminae also exhibit sharp basal contacts but may have gradational boundaries at the top of individual lamina. Coarseness of laminae decreases with distance from the source (Powell, 1983, 1984; Lemmen, 1990; Cowan et al., 1999).

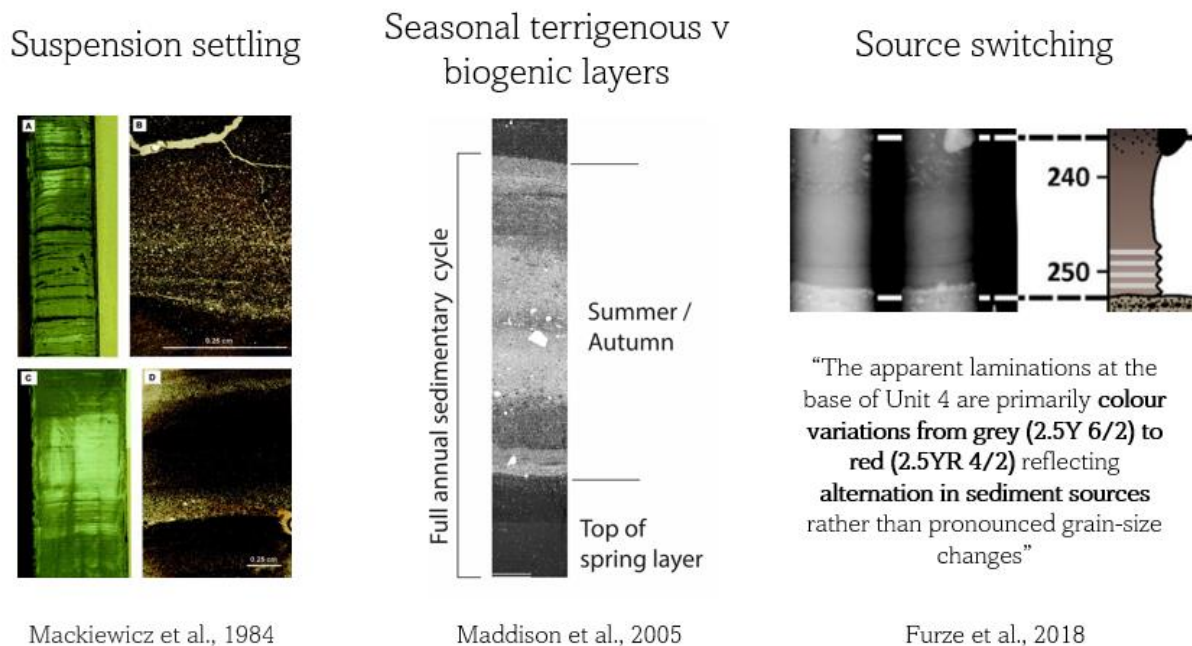


Figure 6.1. Characteristic laminated glaciomarine sediments. Figures adapted from Ó Cofaigh and Dowdeswell, (2001) Mackiewicz et al. (1984); Maddison et al. (2005) and Furze et al. (2018).

Suspension-settling plumites deposited under shorefast sea ice are principally differentiated based on the sparsity of ice-rafted debris (IRD) and stratigraphic associations, such as being bounded by diamicton units (Dowdeswell et al., 2000), and share a similarity with ice-shelf sediments (Chapter 1; Smith et al., 2019; Jennings et al., 2022).

Turbidity current sedimentation contains massive or graded mud–sand units, and have irregular occurrence within the sediment record, possibly with load casts, flame structures and convoluted bedding (Ó Cofaigh and Dowdeswell, 2001). They are common in ice-proximal settings and may arise from highly pressurised, sediment-rich subglacial conduits (Gilbert, 1983; Ó Cofaigh and Dowdeswell, 2001) or remobilised secondary deposits of precursor sediments (Mackiewicz et al., 1984; Cowan and Powell, 1991). Turbidites often co-occur with laminae which are argued to have formed via suspension settling, particularly in proximal glaciomarine settings (Vermassen et al., 2020).

A second depositional model for glaciomarine laminae which form in West and East Antarctica comprises seasonally alternating biogenic (diatom ooze) v terrigenous (IRD) laminae (Leventer et al., 2002; (Maddison et al., 2005). Laminae deposited within these settings are distinct from other glaciomarine laminae and have a seasonal mode of deposition (e.g. laminae identified at Mertz Ninnis trough, East Antarctica; Maddison et al., 2005).

These ‘glaciomarine varves’ are characterised by increased Summer / Autumn terrigenous input, rich in ice-rafted debris (IRD) (terrigenous laminae), while the other laminae within these sediment

packages comprises Spring diatom blooms (biogenic laminae). Occasionally mixed, partly biogenic and partly terrigenous, laminae do occur under certain circumstances (Pike et al., 2001, Leventer et al., 2002; Maddison et al., 2005). Varves which form through this model comprise lamina couplets comprising colour-banded orange–brown pure diatom ooze dominated by *Hyalochaete* and *Chaetoceros* spp., with resting spores, and grey-brown or blue-grey terrigenous quartz-rich mud–silt with an abundant mixed diatom flora (Stickley et al., 2005).

A third model focuses on inferred palaeo-sub-ice-shelf sediments recovered from Lancaster Sound, Canadian Arctic Archipelago (Furze et al., 2018). These sediments comprise clast-free, colour-banded finely laminated laminae reflecting local variations in sediment sources, likely variable meltwater efflux flowing over red and grey bedrock. However, the inference that there is no grain-size change in these sediments is speculative, as they are fine clays / silts, and differentiating these sediment sizes can be challenging (or impossible) optically. However, the distinct red–grey colour-banding does suggest a different mechanism than suspension settling.

Laminated sediments are common around the former British-Irish Ice Sheet (BIIS) margin, for example, in the Irish Sea (Eyles and Eyles, 1984; Scourse and Furze, 2001; Scourse et al., 2019), Malin Sea (Peters et al., 2016; Tarlati et al., 2020), North Sea (Roberts et al., 2019) and The Minch, NW Scotland (Bradwell et al., 2019, 2021). Around the BIIS, sediments are almost unanimously thought to have formed via suspension settling (typically citing Ó Cofaigh and Dowdeswell, 2001). One exception is the study by McDonald et al. (2022) (Chapter 2), where varying energies and sources (marine v terrestrial) were proposed to have influenced laminae of varying radiodensity which formed near the margin of The Minch Ice Stream during deglaciation. Despite the common inference that laminae which formed around the BIIS are suspension settling derived, many of the sedimentary examples are distinctly colour-banded (suggesting varying sources – see examples in Callard et al., 2018; Roberts et al., 2019) and have no *unambiguous* evidence of size sorting and are therefore similar to sediments formed via alternating meltwater plume sources (after Furze et al., 2018).

This chapter attempts to elucidate the factors which underpin laminated sediment formation in The Minch, NW Scotland. Whether that be meltwater-plume-derived suspension settling (Dowdeswell et al., 2000); seasonally alternating biogenic diatom ooze v terrigenous (IRD) laminae (Cowan et al., 1997); meltwater-plume source switching (Furze et al., 2019); or another mechanism. Laminated sediments of The Minch, NW Scotland are well suited to analyse the relationships between different laminae's physical and chemical properties as they are interpreted to have formed beneath (or in association with) an ice shelf – resulting in low IRD (Bradwell et al., 2019, 2021). Because of their low IRD content, physical properties such as mean X-ray grey value (density), colour and elemental composition are less affected by IRD than IRD-rich laminated glaciomarine sediments.

6.2. Methods

6.2.1. Methodological approach

This study uses a multiproxy suite of sediment core imaging properties (colour and X-radiographic grey value), geochemistry (elemental composition and Fe mineralogy) as well as particle size to characterise and interpret different laminated facies. To evaluate the mode of deposition for laminated glaciomarine sediments, different coloured laminae (red, blue-grey and dark-brown – which we hereby refer to as ‘dark’) were compared statistically based on their optical colour (visual categorisation – red, blue-grey or dark, and RGB extracted using ImageJ). Colour was quantified by the equation “colour = red/blue” (R/B) to give a single quantitative statistic. Particle-size analysis was undertaken (median particle size (μm)), as well as X-ray fluorescence (XRF) elemental composition (Fe, Ti, Ca, St and Fe/Ca), X-ray mean grey value (density) and iron mineralogy.

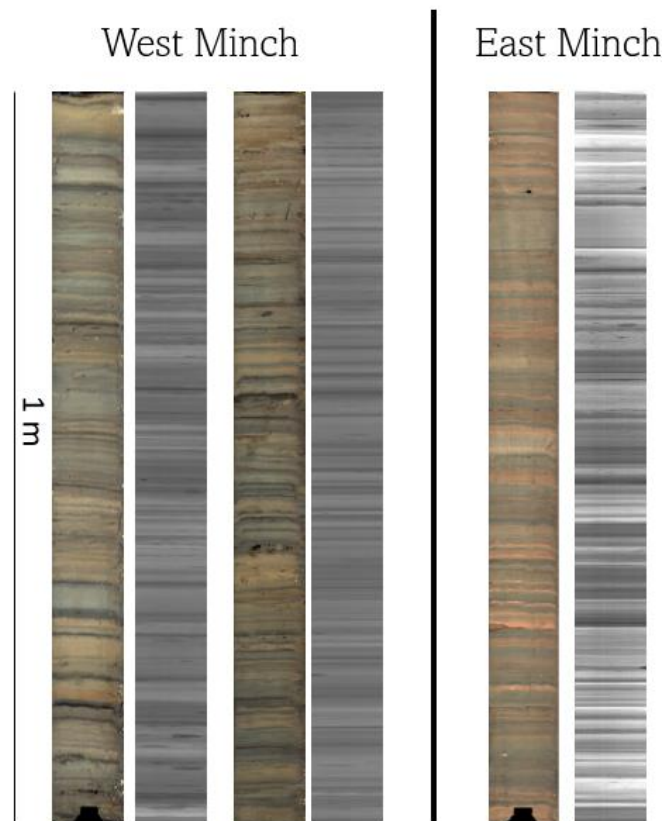


Figure 6.2. Sediment core images used in this chapter. Two sediment core sections with ITRAX optical images (left) and ITRAX X-radiograph images (right) (histogram window applied to improve visibility, but was not used for data analysis). Cores: JC123-031PC-section-7 (left); JC123-031PC-section-4 (middle); JC123-020PC-section-7 (right). Note: strong red colouration within core JC123-020PC-section-7 (East Minch).

6.2.1.1. Sediment physical and chemical properties – colour, X-ray grey value (density), X-ray fluorescence analysis

Sediment colour and X-ray mean grey values were captured using “ITRAX corescanner” images acquired at BOSCORF, Southampton, UK. ITRAX images were optically and density calibrated after Francus et al. (1999) and the scanning resolution was mm-scale. To extract the colour and X-ray mean grey values a script (adapted from McDonald et al., 2022; Chapter 2) was written and run in FIJI/ImageJ. This allowed a like-for-like comparison with ITRAX XRF geochemistry which was measured at the same resolution. These results were compared for the whole core sections of cores JC123-020PC-section-7, JC123-031PC-section-4 and JC123-031PC-section-7 (see Figure 6.2 for core images).

6.2.2. Laminae specific investigations: particle-size analysis, colour, X-ray grey value (density) and elemental composition

12-19 laminae were investigated for laminae specific investigations per core section, this allowed an investigation into how particle size relates to colour and density. Particle size was analysed using the Bettersizer S3 Plus and the corresponding colour (RGB) and mean X-ray grey value were manually extracted using FIJI/ImageJ. These results and the corresponding ITRAX XRF chemistry (Fe, Ti, Ca, Sr and Fe/Ca) were compared to understand the typical elemental abundances of each coloured laminae.

6.2.2.1. Fe mineralogy (Mössbauer spectroscopy)

To analyse the iron mineralogy within laminae Mössbauer spectroscopy was undertaken. Mössbauer spectroscopy measures the recoilless absorption of gamma rays within a sample, whereby the radioactive source is adjusted using the doppler effect (Vandergrift and Fulze, 1998). Different iron-bearing minerals can therefore be identified based on the specific energies required for recoilless absorption. These analyses were done to understand whether sediment was derived from the same source (thus had the same chemical signature), or different sources (different chemical signatures between red and blue layers). Two laminae (one red and one blue) from core JC123-020PC-section-7 were analysed using Mössbauer spectroscopy to assess whether different Fe minerals were present. These analyses were performed by Emily Bonsall on the University of Stirling’s Mössbauer Spectrometer.

6.3. Results

The relationship between laminae colour and radiodensity is weak (Pearson’s $r = -0.231, 0.142, 0.371$) but statistically significant ($p < 0.001$) indicating that colour and density are related, but the predictive power between the variables is low (Figure 6.3). The relationship also varies in direction and strength depending on the sediment core section analysed. In the East Minch core (JC123-

020PC) there is a negative relationship and in the West Minch core there is a positive relationship (JC123-031PC) (Figure 6.3).

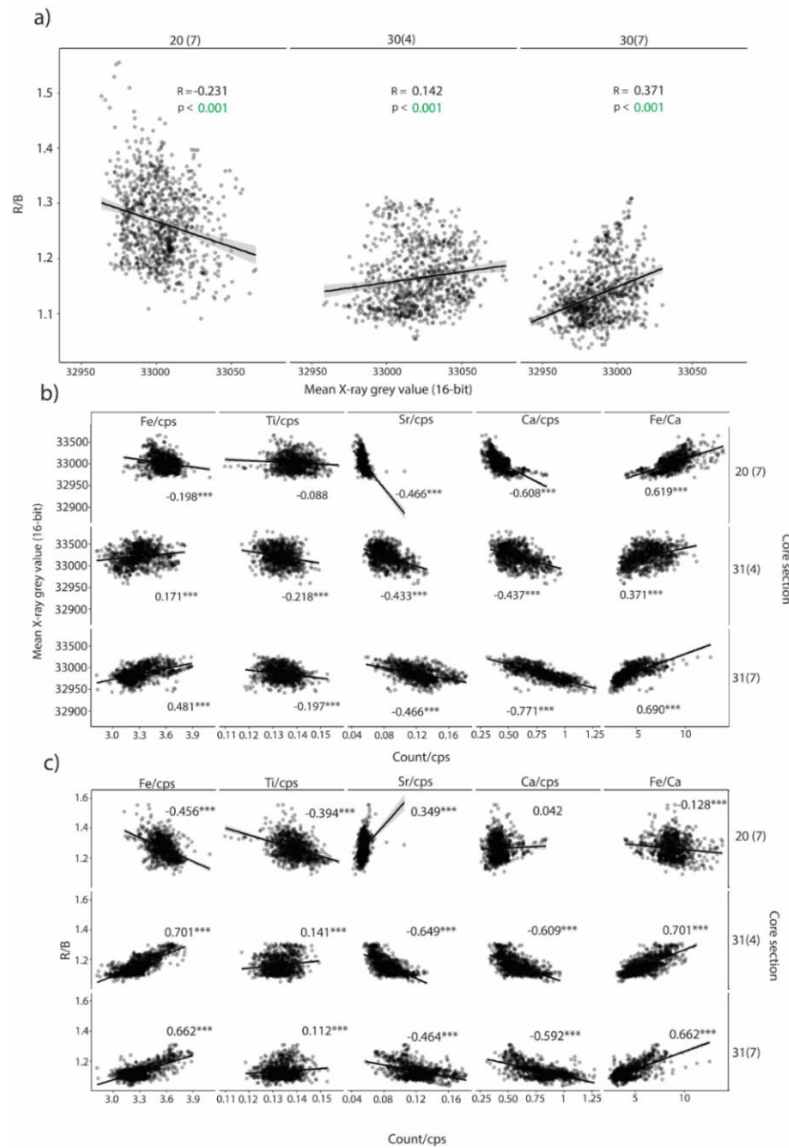


Figure 6.3. Panel a) colour (R/B) v mean grey value (16-bit) for each core section. Panel b) elemental composition v mean grey value (16-bit) for each core section. Panel c) elemental composition v colour (R/B) for each core section.

No statistically significant difference was observed between red and blue laminae when comparing the median particle size of both using the Mann-Whitney U Test (Figure 6.4). Similarly weak associations were observed when comparing the correlation between colour (R/B) and median particle size (μm) (Figure 6.4). Dark laminae were too small in number to be investigated using Mann-Whitney U Test (< 5 for JC123-031PC-section-4 and JC123-031PC-section-7). However, from a visual assessment, it is clear that they are typically coarser grained than red and blue laminae (Figure 6.4). This is validated by quantitative colour analysis (R/B) whereby darker (low R/B) layers appear to skew the Pearson's correlation coefficient between R/B and particle size in core JC123-

031PC-section-3 to a stronger correlation than would be apparent between red and blue layers alone ($r = 0.404$; $p = 0.086$) (Figure 6.4).

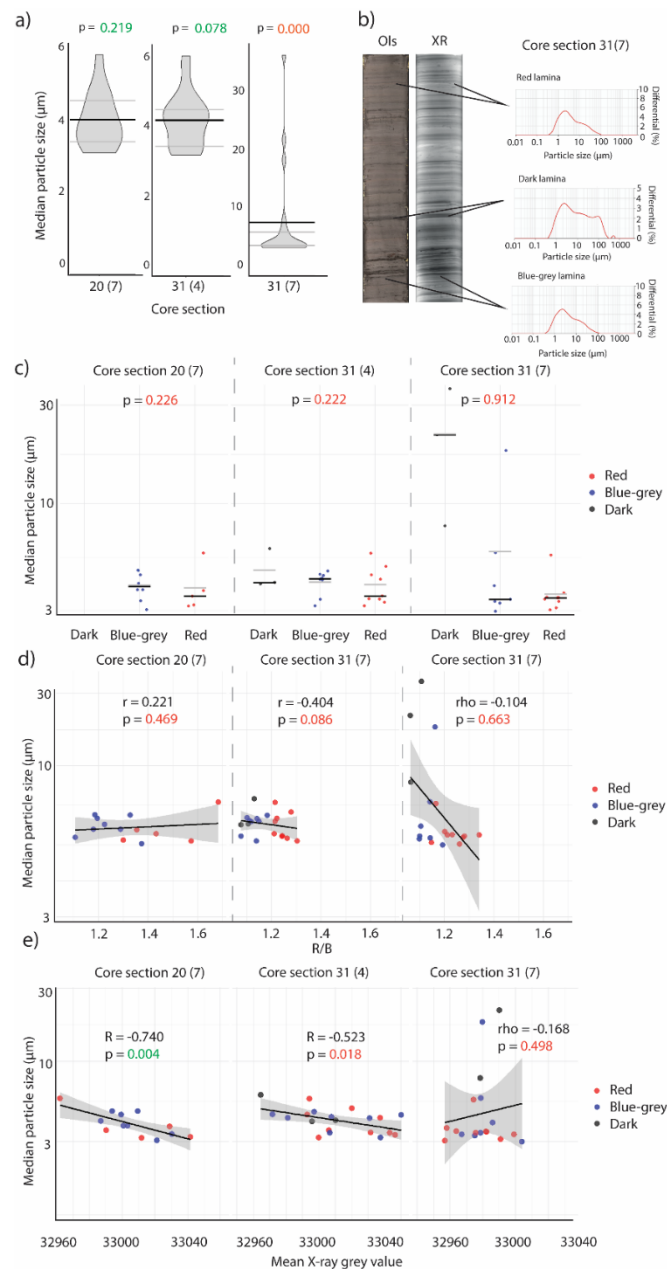


Figure 6.4. Particle-size analysis results for core JC123-020PC-section-7; JC123-031PC-section-4 and JC123-031PC-section-7 – labelled 20(7), 31(4) and 31(7) respectively. Panel a) Distributions of particle-size analysis results for core JC123-020PC-section-7; JC123-031PC-section-4 and JC123-031PC-section-7. Statistics refer to p-value results using Shapiro-Wilk test for normality. Panel b) Core images for core JC123-031PC-section-7 (core length = 40 cm), relevant particle-size distributions for representative red, blue-grey and dark laminae are presented. Panel c) relationship between laminae colour (R/B) and associated particle size for each core section. Panel d) relationship between laminae media particle size (μm) and associated particle size for each core section.

When compared to mean X-ray GV and colour, elemental composition typically returns strong, statistically significant relationships (Figure 6.3). Elements which are typically indicative of a terrigenous source – Ti and Fe generally share positive or negative directionality with each other when compared against colour (R/B) and Mean X-ray GV. The same can be said for elements which are typically indicative of a marine source (Ca and Sr). The exception here is Ti in JC123-031PC when compared to mean X-ray GV which shares negative directionality with Ca and Sr, different from Fe which is positively associated with mean X-ray GV. For this reason, we select Fe normalised by Ca to best represent chemistry of varying sources.

Strong statistically significant relationships are observed between mean X-ray GV and Fe/Ca in JC123-031PC-section-4 and JC123-031PC-section-7 ($r = 0.619$; $p < 0.001$ and $r = 0.690$; $p < 0.001$), whereas a weaker (moderate), statistically significant relationship is observed for JC123-031PC-section-4 ($r = 0.371$; $p < 0.001$; Figure 6.3). When comparing Fe/Ca with colour, both the strength and direction of the relationship (positive / negative) varies between the East and West Minch cores (Figure 6.3), with a weak statistically significant negative relationship in the East Minch ($R = -0.128$; $p < 0.001$) and statistically significant relationships in the West Minch ($R = 0.701$; $p < 0.001$ and $R = 0.662$; $p < 0.001$). Different Fe mineralogy is observed when comparing red and blue laminae of the East Minch. The signals produced by the Mössbauer spectroscopy clearly differ, with a signal characteristic of hematite observed in red laminae and other currently unidentified iron oxides present in blue laminae (Figure 6.5).

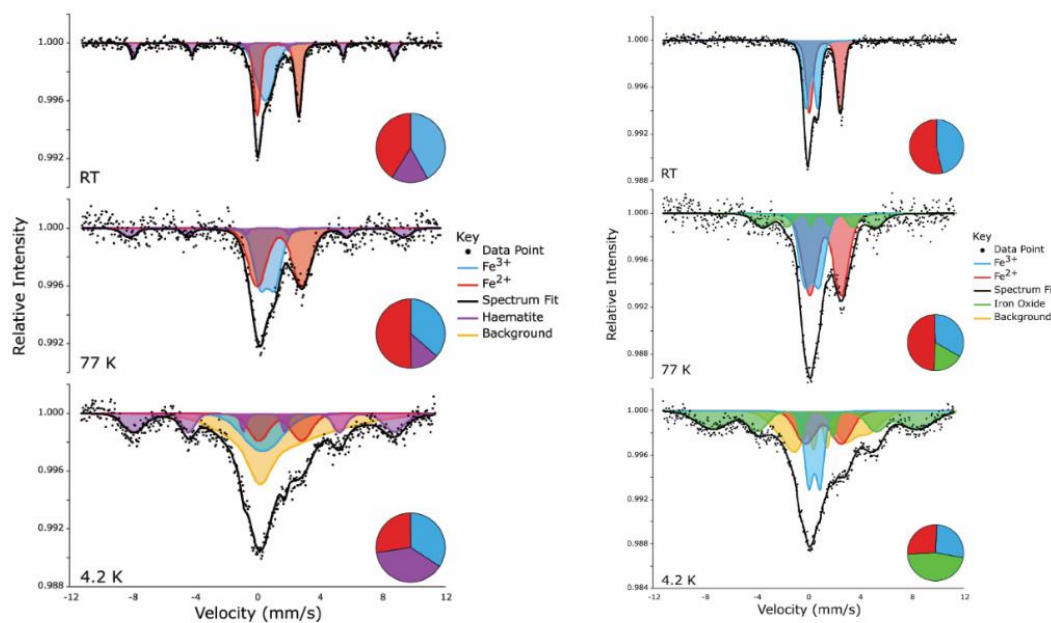


Figure 6.5. Fe mineralogy measured using Mössbauer spectroscopy at room temperature (RT), 77 K and the lower temperature (4.2 K). Right panel = red layer; left panel = blue-grey layer. This figure was produced by Emily Bonsall, University of Stirling.

6.4. Discussion

6.4.1. Laminae colour and density – characteristics influenced by a multitude of factors

Our high-resolution investigation of fine-grained laminae indicates that sediment colour is impacted by multiple factors. Despite a statistically significant relationship between density (mean X-ray GV) and colour (R/B), the relationship varies in direction and strength when analysing the association between colour and density between the West (where there are weak to moderate, positive relationships) and East Minch (where there is a weak, negative relationship) (Figure 6.3). This suggests laminae colour is not directly related to the factors that control laminae density and vice versa. This is probably because both physical properties (colour and density) are the result of variations in multiple factors (elemental composition, mineralogy, particle size etc.), which in different concentrations can alter colour or density in different ways.

Our results indicate that geochemistry (elemental composition and mineralogy) is strongly associated with laminae colour and density and likely plays a significant role in determining both. Conversely, there is no statistically significant difference between the colour of red and blue laminae based on visual classification (Figure 6.4). Additionally, weak and statistically non-significant relationships are observed between quantitative colour (R/B) and median particle size (μm). This suggests that particle size is not a driver of laminae colour, for red v blue-grey laminae (Table 6.1). The exception is dark-coloured laminae, particularly in core 031PC-section-7. This potentially indicates a different depositional mechanism for dark, sand-rich laminae, which are clearly coarser than red and blue laminae (Figure 6.4). We infer that these mud, silt and sand layers which are either normally or bimodally distributed are turbidites, typical in glaciomarine settings proximal to the grounding line (Vermassen et al., 2019, 2020; Jennings et al., 2022).

The density (mean X-ray GV) of laminae is strongly associated with particle size in core sections JC123-020PC-section-7 and JC123-031PC-section-4, but not in JC123-031PC-section-7. The discrepancy may be affected by the fact that mean X-ray GV is a proxy for bulk density and there are a number of factors which contribute to the density of sediment from particle size, chemistry, compaction etc (Cremer et al., 2002; McCave and Hall, 2006; Hodell et al., 2017; Reilly et al., 2017; Penkrot et al., 2018).

6.4.2. The depositional mechanism behind laminated glaciomarine sedimentation in The Minch, NW Scotland

As particle size is (generally) strongly associated with laminae density and not colour; and colour and density are not strongly correlated (low Pearson's / Spearman's rank correlation coefficients), we rule out suspension settling (in the style of Ó Cofaigh and Dowdeswell, 2001) as the primary mode of deposition. If particle size *was* the major control on laminae formation there would be a strong relationship between particle size and colour as well as density. This is because suspension

settling requires slow settling of clays and silts, meanwhile, sands settle out of the water column more quickly resulting in sand–silt–mud couplets. Finally, the sediments in this study have fundamentally different properties from those observed in suspension-settling derived laminae. We observe well-sorted, normally distributed muddy-silts with very little or no sand, rather than sand v mud-silt ‘couplets’ with sharp basal contacts and gradational upper boundaries (Ó Cofaigh and Dowdeswell, 2001).

Elemental chemistry is the major control on laminae colour and density, therefore, it is key to understand whether these laminae are formed via biogenic v terrigenous sedimentation (glaciomarine varves) (Maddison et al., 2005) or meltwater-plume source switching (Furze et al., 2018). Ca typically represents marine-derived sediment (Crowdace and Rothwell, 2015), however, large sectors of the Inner Minch seafloor are comprised of Jurassic marine sedimentary bedrock as well as other *potential* sources of inorganic calcium within eroded Quartz veins or Plagioclase Feldspars from Lewisian Gneiss basement rock which is common around The Minch (Fyfe et al., 1993). As we do not observe a clear relationship between colour and size (as would be expected with biogenic (diatom bloom) v terrigenous (IRD) layers), we do not infer a Quaternary marine source for Ca or Sr layers, as they share fundamental characteristics with red layers (particle size and structure) and therefore, likely share an identical depositional process, potentially indicating they formed via meltwater plume source switching after Furze et al. (2018).

6.4.3. Wider supporting evidence and implications

The colour of sediment laminae under the Furze (meltwater plume) source switching model reflects the local geology (Furze et al., 2018). Indeed, brighter, red colouration was observed in the laminated units of East Minch sediment cores (JC123-020PC and JC123-021PC), than cores recovered from the West Minch (e.g. JC123-031PC and JC123-033PC). This is also validated by elevated R/B values in East Minch laminae (Figure 6.2; Figure 6.4). The East Minch is within an ice-flow path which incorporates Torridonian Sandstone, suggesting red layers are predominantly composed of mud-silt derived from weathered and eroded Torridonian Sandstone.

The strong red colouration is likely the result of hematite, identified using Mössbauer spectroscopy (Figure 6.5). This may be derived from smaller outlet glaciers of the former Minch Ice Stream, flowing through Loch Ewe and Little Loch Broom. Whereas darker layers of different iron mineralogy (possibly other Fe oxides, such as goethite or lepidocrocite) may be sourced from meltwater plumes emanating from (perhaps) the main Minch Ice Stream outlet. In the West Minch, a lithological source is harder to pin-down but the colouration may be the result of different subglacial or englacial sources of the Minch Ice Stream.

Table 6.1. Relationships between laminated sediment properties.

Proxy	Measurement	Relationship with laminae colour	Relationship with laminae density	In keeping with source switching model?	In keeping with terrigenous v biogenic seasonal glacio- marine varves?	In keeping with suspension settling method?
Elemental composition (Fe/Ca)	(Fe/Ca)/cps.	Strong – weak and variable in direction (positive or negative) depending on location.	Strong – moderate. Elemental composition is a major control on sediment density.	Yes – the variable nature of relationships between colour and density, often with strong associations, suggests that location and chemistry play a key role in laminae appearance.	Yes – strong associations between elemental composition and the colour / density is in keeping that laminae are comprised of different materials (e.g. summer terrigenous IRD layers and biogenic spring layers (e.g. Stickley et al., 2005).	No, but Possible – if finer or coarser material are comprised of different chemistry / structure.
Particle size	Median particle size (μm).	Red v blue laminae (no effect); dark layers distinctly	Variable (strong – low).	Yes – no statistically significant difference (or	No – IRD rich, 'terrigenous' units should be	No – distinct differences between coarse and

		independent (coarser).		correlation) between distinct red and blue layers.	identifiable based on coarse sediment input.	fine layers should be observed.
Fe mineralogy	Counts.	Distinct difference between red and blue laminae.	Unknown (possibly minor due to the strong impact of particle size and elemental composition on density).	Yes – distinctly different mineralogy between red and blue laminae.	Possibly, however, more research would be required to understand the exact source and whether the blue layers can represent biogenic laminae.	No – distinctly different source based on mineralogy and chemistry.

Typically studies cite glaciomarine laminae as evidence of suspension settling (in the style of Mackiewicz et al., 1984; Cowan et al., 1999; Ó Cofaigh and Dowdeswell, 2001) without considering alternative modes of deposition (e.g. Reilly et al., 2019; Syring et al., 2020b; Ó Cofaigh et al., 2021; Jennings et al., 2022; López-Quirós et al., 2024). Researchers interpreting fine laminae of differing colour (e.g. red / brown v blue / grey) devoid of sharp basal contacts and gradational upper boundaries should strongly consider the Furze et al. (2018) model of switching meltwater plume sources. As we suggest in this study, meltwater plume sources may arise from different glaciers emitting meltwater plumes, or different sectors of the outlet glaciers and ice streams emitting meltwater plumes from different sub / englacial channels (see Figure 4 in How et al., 2017). Therefore, we urge greater care when interpreting colour-differentiated, finely laminated glaciomarine sediments.

6.5. Conclusions

A multiproxy investigation of laminated sediments recovered in seabed sediment cores from The Minch, (NW Scotland), highlights a laminated glaciomarine sedimentation mechanism via alternating meltwater plume sources and not meltwater plume suspension settling or biogenic v

terrigenous sources. This conclusion is derived from the fact that elemental composition (and mineralogy) has the strongest correlations with laminae colour and density. Meanwhile distinct differences in Fe mineralogy was observed between red and blue-grey laminae.

Red colouration is significantly more pronounced in the East Minch, where laminae are found to contain hematite, suggesting a potential Torridonian Sandstone source (potentially from outlet glaciers feeding from Loch Ewe or Little Loch Broom). Blue-grey laminae which contain other iron oxides may be sourced from meltwater plumes from the main Minch Ice Stream outlet. In the West Minch a precise source is harder to elucidate, but alternating subglacial or englacial sources may result in the more diffuse (but still pronounced) colouration observed.

We infer that suspension settling from sediment-laden meltwater plumes was not a dominant controlling factor on laminae formation due to distinct elemental chemistry and mineralogical differences between different coloured laminae. The other factor ruling out suspension settling deposition is that particle size does not have a strong association with laminae colour and density between red and blue-grey laminae. Furthermore, for the same reasons, laminae in The Minch, NW Scotland were not seasonally deposited via terrigenous (IRD dominant) and biogenic (diatom bloom) sedimentation as is observed across the Antarctic Margin.

Overall, the results of this chapter provide greater insights into the processes which underpin laminated glaciomarine sediment deposition in the palaeo-record. This work also allows greater insights behind what information can be deciphered from laminated glaciomarine sediment archives, for example:

- i) laminae are not annually deposited.
- ii) Laminae are derived from differing sediment-laden meltwater sources.
- iii) The colour of laminae can potentially be used to trace meltwater sources.

Finally, these findings will allow a more nuanced and critical insight into how glaciomarine laminated sediments are formed and what glaciological information can be derived from them.

Chapter 7: Synthesis and Future Work

7.1. Introduction

This thesis contains five data chapters which aim to broaden insights of how glaciomarine sediment archives are used and can be interpreted. Specifically, to obtain ultra-high resolution palaeoenvironmental information such as iceberg rafting (by quantifying ice-rafted debris – IRD), ice-shelf and ice-sheet dynamics – ultimately broadening our understanding of how ice sheets impact sea levels. In order to achieve these outcomes, new insights have been acquired with the objective of refining interpretations of glaciomarine sediments and the ways of characterising them. This synthesis chapter consolidates and elaborates on the findings of this thesis by considering the wider academic and geographical context of this work.

7.2. Is there a need for automated sediment characterisation in glaciomarine sedimentology?

The findings of Chapter 4 highlight a strong need for automated characterisation of glaciomarine sediments, in a manner which minimises human bias. Chapter 4 indicates that different researchers cannot accurately quantify the abundance of clasts within X-ray images of glaciomarine sediment core sections by on-screen clast counting. There is a wider implication associated with this finding – namely, that mismatches may occur when different researchers interpret clast-poor, clast-moderate and clast-rich units, which may result in differing interpretations of sediment packages between studies.

7.3. How can glaciomarine sediment and ice-rafted debris (IRD) be quantified using automated image analysis?

The highest resolution IRD technique to date has been developed (Chapter 2). This was achieved using a new type of imagery for the Quaternary Sciences (X-ray computed laminography – CL). Since the publication of this chapter, CL images have been adopted by other Quaternary scientists to identify biogenic structures and trace fossils (Dorador et al., 2024). However, our specific IRD proxy has not yet been adopted by other researchers.

This may be in part due to the requirement of X-ray Computed tomography (CT) images which are expensive or CL images to successfully implement the method. CL images are not yet widely used by the Quaternary Science community and CL-capable scanners are still rare. Additionally, there are many established X-ray CT algorithms which are used widely (e.g. Reilly et al., 2017; Bartels et al., 2018; Reilly et al., 2019). Our review of the strengths and weaknesses of this technique in relation to other IRD proxies may help to improve the appreciation of the applicability of this method in quantifying IRD and characterising glaciomarine sediments.

As highlighted in this thesis, X-radiographic greyscale variation of sediments can be used to differentiate ice-proximal diamicton, ice-shelf adjacent and seasonal sea ice sediments. It is possible that Machine Learning (ML) can achieve the same outcomes and possibly advance the field of glacial sedimentology further by identifying subtle sedimentary associations which humans cannot. ML has already been adopted to elucidate sand and gravel-sized IRD from background sedimentary structures (Jasper et al., 2024). In future, ML could also be used to better characterise sediments from environments that humans find challenging to differentiate, for example, sub-ice-shelf v multiyear landfast sea ice sediments and laminated glaciomarine sediments of different formation mechanisms. To achieve this, a database of sediments from contemporary settings could be compiled to allow for comparison of sediments from past glacial settings. ML has the benefit of not being confined to human biases and may therefore be a very important tool in the future of sedimentology.

7.4. Ice-rafted debris (IRD) – how can our current understanding of the strengths and limitations of different IRD techniques be refined?

Chapter 3 demonstrates that X-radiographic (XR) manual clast counting, X-ray CL grey-value standard deviation (GV SD) and (in some cases) sieving are the best suited methods to analyse IRD within glaciomarine sediment cores as they have the highest detection levels. Laser particle size analysis is not appropriate for IRD quantification in glaciomarine settings as the detection level is too low. However, GV SD may not be an appropriate method for analysing sediment cores with high levels of deformation or bioturbation, as GV SD also considers any non-IRD related heterogeneity in the output (McDonald et al., 2022). For studies in settings such as continental shelf breaks or deeper oceans, where bioturbation is more common than ice-proximal settings, sieving or XR grain / clast counting may be more appropriate than GV SD.

To further advance the methodological comparisons of IRD techniques, such as performed in Chapter 3 and the wider literature (e.g. Andrews, 2000; Bartels et al., 2018; McKay et al., 2022), further research could be undertaken. For example, an expanded study using the same methods and the same sediment core with larger sieving samples (~ 10 g per sample) could be undertaken. This would allow greater insight into whether the larger sample size elevates IRD percentages in glaciomarine settings, as has been suggested by other authors on the Antarctic margin (McKay et al., 2022).

As there have only been a few studies focusing on direct comparisons of IRD quantification methods (Andrews, 2000; Bartels et al., 2018; McKay et al., 2022), there remains a lack of direct comparisons of existing techniques from a variety of oceanographic and glacial settings. An expanded study could, therefore, focus on other sediment cores from different glaciomarine settings, for example, fjordic and contemporary glacier margins or deeper ocean settings (such as in the Ruddiman Belt, North Atlantic Ocean – Ruddiman, 1977; Hemming et al., 2004) to understand how different glacial settings and oceanographic processes may affect IRD proxies.

7.5. Can the marine ice sheet instability be constrained over marine and terrestrial boundaries? Can a trigger for ice-stream collapse be elucidated within the timeframe?

The timing and nature of marine ice sheet instability during the final embers of the Minch Ice Stream has been constrained. Two main stable phases were identified: the first is poorly constrained but occurred before 17.2 ka cal BP where an oscillating margin was present; followed by retreat and the re-stabilisation of a stable ice-stream margin with a short ice shelf(ves) which persisted for ~ 600 years (17.2 – 16.6 ka cal BP). Despite the radiocarbon-poor nature of sediments in this region (Bradwell et al., 2021; Chapter 5), advances in small sample Atomic Mass Spectrometry (AMS) ^{14}C allowed for the dating of very small sample mixed benthic foraminifera samples and shell fragments (to a minimum of 0.7 mg). The results allow higher resolution insights into ice-shelf extent, ice-stream behaviour and the timing of retreat. The only factor which remains somewhat elusive is the trigger of ice-shelf and ice-stream collapse.

Our refined ice-limits are in keeping with the ‘optimal’ model from the BRITICE-CHRONO consortium (Clark et al., 2022). This model suggests an early opening of the West Minch, while the remaining sectors of the Central to Inner Minch maintained a fairly stable ice shelf / ice stream (Figure 7.1). This is suggested based on the combination of grounding zone wedge orientations, sedimentological (and potentially) foraminifera results. This excludes the potential ‘maximum’ model from having occurred based on empirical data (Figure 1.9 in Chapter 1).

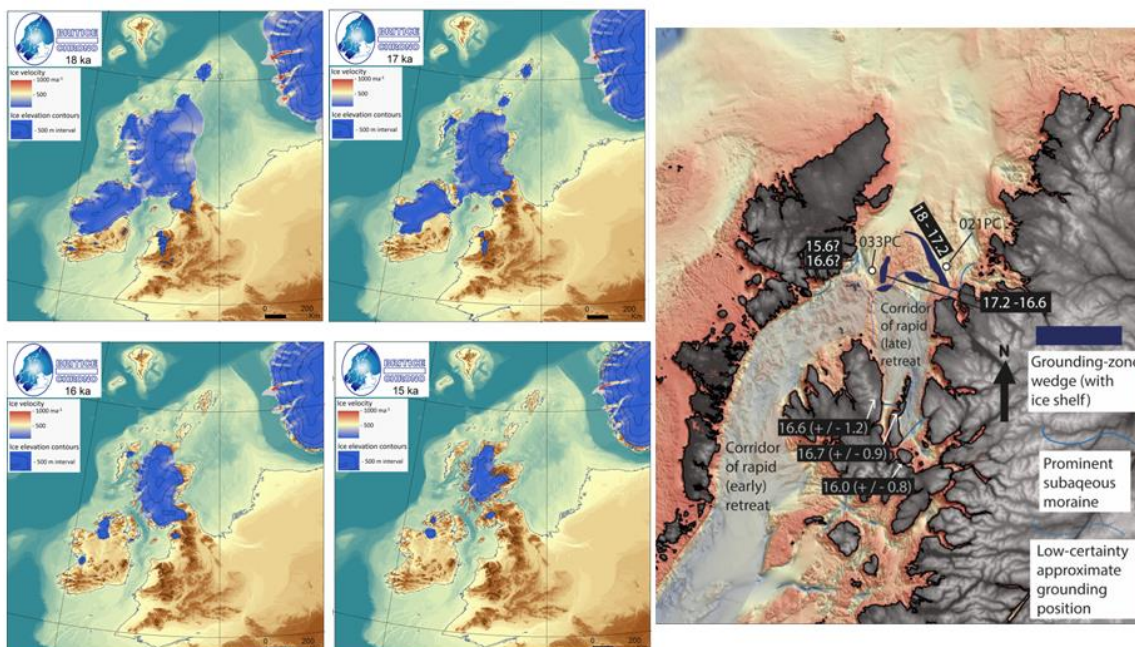


Figure 7.1. BRITICE-CHRONO British-Irish Ice Sheet limits from 18 – 15 ka (Clark et al., 2022). Minch Ice Stream (NW British-Irish Ice Sheet sector) ~18 – 16.6 / 16.0 ka cal BP (Chapter 5; Stone et al., 1998; Small et al., 2012; Ballantyne and Small, 2018; Bradwell et al., 2021).

This finding highlights the importance of ice stream mass balance, topography and warm water advection on the stability of ice margins. Ice-stream inputs (e.g. precipitation and associated ice accumulation) are critically important to consider when reconstructing the stability of marine-based ice stream sectors. Contemporary ice margins which have multiple feeding regions such as the NE Greenland ice stream margins (e.g., Zachariæ, Nioghalvfjærdsfjorden and the Storstrømmen glaciers) may be susceptible to readjustment and alterations at the margin due to the loss of significant feeding sectors under a broader scenario of ice sheet mass loss. For example, recent deceleration of ice loss has occurred in NE Greenland due to an increase in precipitation between 2011 and 2013 (Wang et al., 2023). A reduction in precipitation could result in increased mass loss and subsequently ice starvation at the margin, in a similar manner to the collapse of the West Minch.

Our new chronology places Minch Ice Stream collapse within a period of wider oceanic warming across the northern Atlantic Ocean, suggesting this is a possible trigger (Chapter 5). Although this is a *potential* trigger, no clearcut evidence for ocean-warming-driven retreat was evident in foraminifera assemblages, however, the lack of warmer-water (temperate) foraminifera species could be attributed to other palaeoecological factors e.g. ice-shelf cover, low salinity or turbidity of meltwater-laden seawater near the ice margin (Chapter 5). To identify a precise trigger, additional sedimentological analysis of NW Scotland waters outwith the proximity of the ice margin could be collected. For example, alkenone palaeothermometry (Filippova et al., 2016; Tierney and Tingley, 2018) undertaken on a distal sediment core (e.g., JC123-011VC), could provide insight into local sea-surface temperatures during this time.

7.6. Reconstructing ice-shelf extent in the palaeo-record

For the first time in the British Isles, the general extent of an ice shelf has been reconstructed without the association of ice-shelf ridges (as achieved by Peters et al., 2015, 2016). This was attained by combining geomorphological, sedimentological and micropalaeontological (foraminifera) evidence in The Minch, NW Scotland (Chapter 5). Until recently, it was unclear whether large ice shelves (such as those observed in W Antarctica) or only smaller ice shelves (or tongues) existed around the British-Irish Ice Sheet (BIIS).

Recent work from Kirkham et al. (2025) has suggested large ice shelf presence around the BIIS, inferred from toothcomb multi-keeled iceberg scours in the North Sea. Alternatively, a smaller ice shelf was also suggested to ground on the Porcupine Bank, West of Ireland ~ 10 km in length (Peters et al., 2015, 2016). Our results are in keeping with the work of Peters et al., (2015, 2016) suggesting that similar, short ice shelves, existed during the later stages of BIIS evolution in The Minch (Chapter 5). This is validated, not only from the combination of existing geomorphological and sedimentological evidence (Bradwell et al., 2019, 2021; Chapter 5), but from an additional analysis comparing the curvature coefficient (polynomial quadratic function) of iceberg scour in the Minch to those of the bed of Pine Island Bay (Figure 7.2). This finding suggests that with regard to ice-shelf

extent, the Minch Ice Stream was analogous to Greenlandic regimes – for example, the Greenland ice tongues (Enderlin and Howat, 2013), Zacharie Istrom, NE Greenland (Hill et al., 2017) and recently collapsed sectors of the Jakobshavn Isbrae or Kangerlussuaq glacier (Hill et al., 2017; Vermassen et al., 22020). There is also some similarity with or depleted West Antarctic ice shelves or those in Lützow-Holm Bay, East Antarctica (Kondo and Sugiyama, 2017).

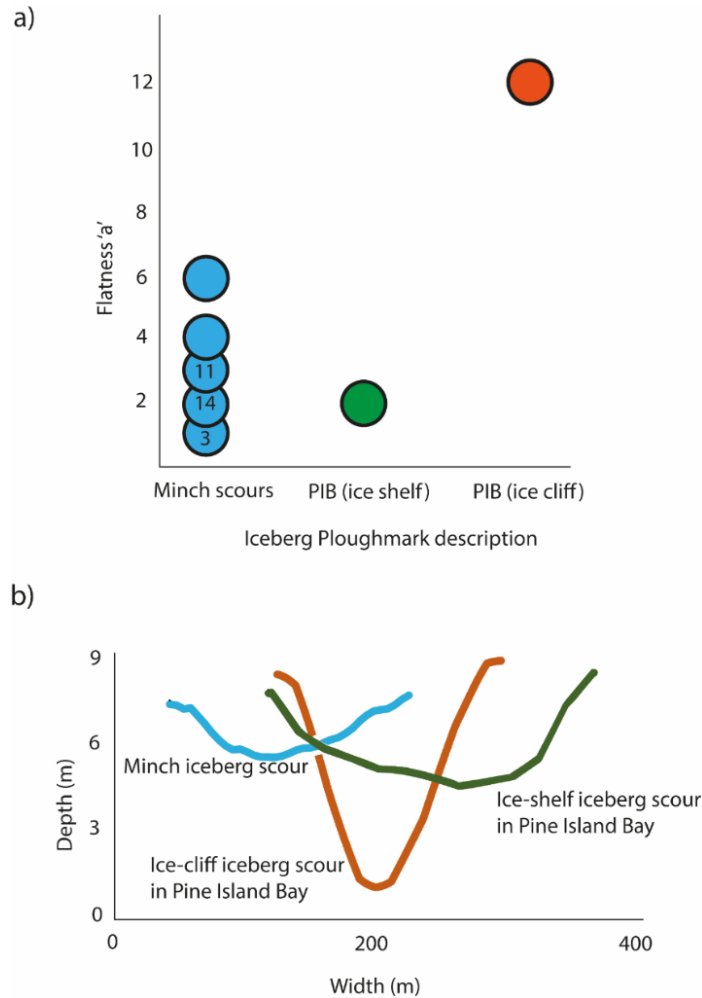


Figure 7.2. Iceberg scours and associated curvature coefficients ('a' in the polynomial quadratic function) used to emphasise flatness (U- or V-shaped). Minch iceberg scours share a close association with those calved from iceberg scours. Pine Island Bay examples sourced from Wise et al. (2017).

Iceberg scours with U-shaped cross-profiles, but relatively small widths (~ 100 – 200 m) compared to the larger multi-keeled examples (e.g. Dowdeswell and Ottesen, 2013; Kirkham et al., 2025) may be useful diagnostic criteria for shorter ice shelves. Examples of margins which calve large ice islands are the sizeable Petermann Ice Shelf (NW Greenland) (e.g. PII-2010) and during the collapse of the Larsen Ice Shelf (e.g. A68a). It is possible, therefore, that large ice shelves are required for the formation of multi-keeled iceberg scours, as implied by the work of Kirkham et al. (2025). Therefore, it is likely that many smaller, but still large, tabular icebergs can be used to infer small ice shelf presence (~ 5 – 10 km) – those which are similar in size to the Minch Ice Shelf and Porcupine Bank

Ice Shelf (and associated U-shaped iceberg scours) (Chapter 5; Peters et al., 2015, 2016; Bradwell et al., 2019, 2021).

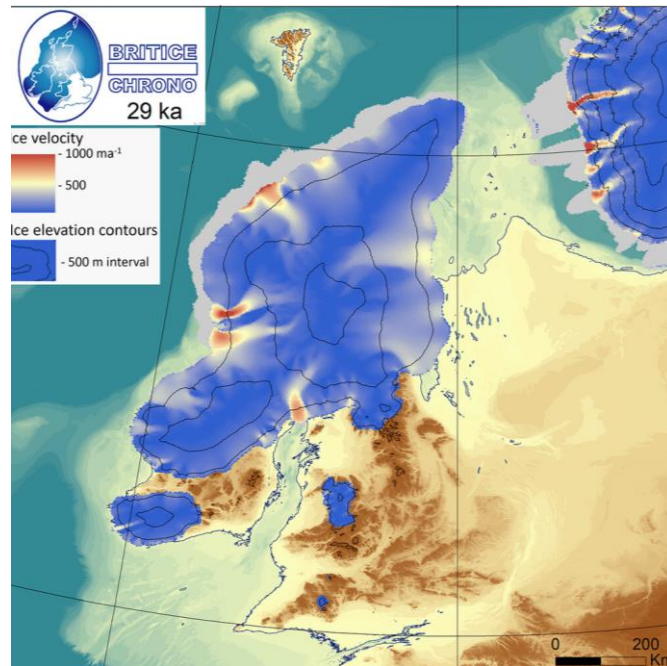


Figure 7.3. British-Irish Ice Sheet limits at 29 ka BP as reconstructed by the BRITICE-CHRONO model (Clark et al., 2022). Note: large ice shelves surrounding the North-Western ice sheet sectors which currently lack geological evidence.

More broadly, ice-shelf reconstructions from the BIIS suggest that the BIIS is a highly adaptable analogue for sectors of all major ice sheets, West Antarctica, East Antarctica and Greenland, with regard to ice-marginal dynamics at different times. To fully understand the sectors of the BIIS which were more analogous to Greenland or Antarctica further research constraining ice-shelf extents is required. Future work should aim to apply the methods utilised in Chapter 5 to track ice-shelf extent at the MnIS margin and the BIIS more broadly throughout the evolution of the ice sheet. This would allow deeper insight into interactions between floating ice-margin extent and stability and also help to draw appropriate modern analogues at different times during ice stream / sheet evolution.

7.7. Marine ice sheet sedimentology – how can laminated sediments advance insights into ice-stream stability?

This thesis has elucidated the depositional mechanism of laminated glaciomarine sediments in distal ice-stream / ice-shelf settings, using sediments which formed at the margin of the Minch Ice Stream (Chapter 6). As laminated glaciomarine sediments form in distal settings, but not > 10 km of the ice margin due to the depletion of sediment-charged meltwater plumes (Smith et al., 2019; Chapter 5), laminae can be used to infer distance from the boundary between grounded and floating ice (grounding line), and ice-stream stability.

Laminae thickness is inherently tied to grounding line proximity (Ó Cofaigh and Dowdeswell, 2001; Smith et al., 2019), thus allowing ice-stream stability or retreat to be inferred based on laminae thickness (Stickley et al., 2005). Although foraminifera may be extremely rare or absent in laminae which form beneath ice shelves, a potential method to infer sedimentation rates is presented by tracking laminae thickness upcore. With consistent laminae thicknesses inferring stability and a reduction in laminae thicknesses suggesting ice-stream retreat.

Further research comparing the upcore thicknesses of tightly constrained laminated glaciomarine packages (East Minch LfA3 in Chapter 5) with poorly constrained laminated glaciomarine packages (for example West Minch LfA3 in Chapter 5) could potentially allow a stronger understanding of stability or distance from the grounding line in foraminifera barren laminae. The tracking of laminae thickness upcore could then be used to infer the duration of glacial stability even where datable material is absent. However, further research would need to be undertaken to validate this hypothesis as sediment coarseness within meltwater plumes may also be impacted by other factors such as the trapping of sediment particles in the freshwater-saltwater boundary (Mackiewicz et al., 1984), the density of underlying bedrock, the flocculation of silt particles (McCave and Hall, 2006), meltwater stream power, water depth or other factors.

Chapter 8: Thesis Conclusions

- i) To develop a new, ultra-high resolution technique for quantifying ice-rafted debris. The method should remove or significantly minimise user bias from the process. [Chapter 2]

This research has developed a new ultra-high-resolution technique for quantifying IRD. This technique utilises a new type of imagery for the Quaternary Sciences (X-ray Computed Laminography). The method aims to minimise human error by excluding human decision making. CL imagery has fewer imaging artifacts than the traditional X-radiography method (e.g. beam hardening, cupping and striping). This allows for quantitative image analysis with only minimal image preparation (for example using histogram equalisation and beam hardening correction).

A new freely available plugin for the open-access image analysis software FIJI/ImageJ was developed. The ‘Sediment Characteristics’ tool extracts the mean, median, mode and standard deviation of grey Horizontally acquired grey values at pixel intervals downcore. The grey value standard deviation (GV SD) can be used as a proxy for ice-rafted debris. This resulting output closely relates to the percentage area coverage of clasts.

Glaciomarine sediment packages can be classified based on the combination of X-ray mean radiodensity and X-ray GV SD (Chapter 2; Chapter 5). Initially, this was demonstrated by grouping sediments into clast-free, clast-poor and clast-rich by comparing the output of horizontal mean GV and GV SD against the percentage area coverage of clasts against Folk’s classification (Chapter 2). A subsequent analysis characterised sediments using mean X-ray GV and GV SD against qualitative descriptions (e.g., diamicton, clast-free to clast-poor laminated sediment and rhythmically bedded clast-rich / clast poor units) (Chapter 5). These classifications can be useful in determining the sedimentary environment of different glaciomarine sediments (e.g. ice-stream proximal iceberg / ice-shelf rainout) pro-ice-shelf, iceberg calving bay with seasonal sea ice) (Chapter 5).

- ii) To investigate and quantify the strengths and weaknesses of different IRD techniques (e.g., sieving, laser particle size analysis, clast counting on X-ray images, and a new ultra-high resolution automated method). [Chapter 3]

Strong statistically significant relationships are generally observed when comparing the outputs of sieving ($> 63 \mu\text{m}$, $> 250 \mu\text{m}$), LPSA ($> 63 \mu\text{m}$), XR clast counting and GV SD. Sieving and LPSA ($> 250 \mu\text{m}$) are the only comparisons which did not register statistically significant relationships, this occurred when comparing these techniques to XR clast counting ($> 2 \text{ mm}$) as LPSA and sieving at higher thresholds have low IRD detection.

Sieving ($> 63 \mu\text{m}$, $> 250 \mu\text{m}$), XR clast counting and GV SD are the most appropriate methods for detecting IRD in glaciomarine sediments. However, each method has its weaknesses; for example,

sieving is destructive; X-ray clast counting is imprecise between different users (Chapter 4); and GV SD considers non-IRD related sediment heterogeneity within the output. Laser particle size analysis is found to be unsuitable for measuring IRD in glaciomarine settings as the small sampling volumes detects unrepresentatively very low IRD volumes.

- iii) To quantify the user variability in the technique most commonly used to determine the presence of past icebergs from sediment core archives – i.e. manual clast counting on X-radiographs (Grobe, 1987). [Chapter 4]

A participatory study of 14 individuals suggests that X-radiographic manual clast counting has significant variability between users. Different users' gravel counts (> 2 mm) were found to be consistently strongly correlated with 181 / 182 comparisons returning statistically significant results using Spearman's rank correlation. However, significant variability was observed between users counts – with some users consistently counting more clasts than others.

When comparing individuals counts on two different images there was strong internal consistency. The reason that some users count consistently higher (or lower) than other users can be attributed to different decision making when: clasts overlap on X-radiographs (Hogan et al., 2016); clast appear in more than one sampling interval (1 cm slice); encountering non-clastic high radiodensity objects and low-radiodensity clasts; as well as potential differences in users' eyesight capabilities and screen brightness. Interestingly, expertise does not play a significant role in users' ability to accurately implement the technique as statistically significant count correlations were observed between both experienced and inexperienced participants.

Ultimately, the results of Chapter 4 highlight the need to drive toward automated approaches in sediment characterisation and IRD quantification.

- iv) To devise a refined and fully transparent protocol for better implementing clast counting for the quantification of IRD. [Chapter 4]

Given the observed inter-participant variability but intra-participant consistency of clast counting on X-ray images to quantify IRD (after Grobe, 1987), a refined framework has been developed to increase transparency and consistency when undertaking X-ray clast counting between studies. This framework aims to ensure internal consistency within any given study, by ensuring one participant completes all counting within any study, while the results should be validated by another user. To increase consistency between studies, a systematic approach of counting clasts which appear in multiple centimetre-intervals should be counted only in the first section in which they appear (from the base of the core upward – following the law of superposition). The long axis of all clasts should be used, and the user should increase screen brightness to the maximum comfortable setting. Finally, clasts close to the 2 mm threshold should be measured with a tool or a reference object to ensure consistency.

This new framework will help to minimise user biases when undertaking manual clast counting in future. This will prove useful for ensuring more robust IRD quantifications and consistency between studies. Manual clast counting (and other aspects of manual sediment quantification / segmentation) will become increasingly important for training machine-learning algorithms which will allow automated approaches to quantify IRD and classify glaciomarine sediments in the future.

- v) To refine the timing and behaviour of the MnIS (NW Scotland) from the final stable ice-stream phase to tidewater glaciers phase. [Chapter 5]

Two main stable ice-stream phases were reconstructed in the Central Minch. The first was a poorly-constrained oscillating ice-stream margin (with floating ice-shelf cover), occurring *before* 17.2 ka cal BP. The second was a ~ 600-year stable phase from 17.2 to 16.6 ka cal BP with a short (5 – 10 km) floating-ice shelf, with a very slowly retreating ice-stream margin over a multi-centennial timescale.

In the East Minch, the length of the Minch Ice Shelf has been determined based on combined geomorphological, sedimentological and micropalaeontological evidence. Despite the ice shelves short extent, when the ice shelf was removed, rapid, runaway ice-stream retreat ensued. This is evidenced by a lack of grounding-line features inshore and also a significant increase in IRD in the West Minch (core JC123-033PC).

Constraining rates of ice stream retreat in glaciomarine systems is challenging due to the lack of datable material. However, our work suggests that Minch Ice Stream retreat was indeed rapid and likely collapsed, with offshore AMS ^{14}C (in the Central Minch) and TCN ages (~ 40 km inland) overlapping in their uncertainties, between 16.6 ka cal BP and 16.7 – 16.0 ka cal BP. We place the period of final rapid ice-stream retreat, or collapse, around 16.6 ka and no later than 16.0 ka cal BP.

- vi) To elucidate the nature and extent of the Minch ice shelf(ves) during the final stable phase before collapse. [Chapter 5]

New insights into The Minch Ice Shelf reveal that two related (but not necessarily connected) ice shelves flanked The Minch while the ice-stream was stabilised around a topographic high (Mid-trough Bedrock High). The configuration of the ice-stream / ice-shelf system in The Minch was likely similar to that of the modern-day Brunt Ice Shelf W Antarctica, but on a much smaller scale.

The extent of The Minch Ice Shelf has, for the first time, been constrained to 5 – 10 km. This was achievable in the East Minch and was inferred by combining grounding-zone positions with sediment core signatures and allows a powerful new approach for past ice-shelf reconstructions.

- vii) To identify, if possible, the trigger for ice shelf / ice-stream removal (collapse) in the Central Minch. [Chapter 6]

The retreat of the MnIS was asymmetric, with early collapse of the western sector, and maintenance of a functional ice stream in the East Minch. Ice-stream partitioning was attributed to a starvation of

ice in the western sector as the Outer Hebrides Ice Cap and British-Irish Ice Sheet separated. Furthermore, an unzipping of ice in the Sea of the Hebrides would allow for (warm) water advection through the Little Minch enhancing ice stream destabilisation.

The trigger for the final collapse of the remaining Minch Ice Stream is not clearcut. However, ice-shelf / ice-stream collapse was broadly synchronous with warming North Atlantic Ocean waters (but not air temperatures) during Heinrich Stadial 1. Therefore, ocean warming may have been a potential trigger for the demise of the Minch Ice Stream, however, more research would be required to validate this. An expanded study using supplementary evidence from nearby sediment cores undertaking alkenone palaeothermometry could help to understand whether local sea-surface temperatures in The Minch were rising around 16.6 ka cal BP.

One component which played a critical role in ice-stream (in)stability in The Minch, is topography (e.g. Gandy et al., 2018; Bradwell et al., 2019, 2021). A significant stabilisation (or oscillating margin with very slow retreat) over the MTBH, followed by rapid retreat once the ice stream margin entered deeper waters inland has been reconstructed. This suggests that topography itself could be the trigger for ice shelf / ice stream destabilisation – with the ice stream retreating at an anomalous (slow) rate across the MTBH followed by rapid retreat (perhaps exacerbated by ocean warming) once the ice-stream had retreated beyond this major topographic / bathymetric high.

Either way, a collapsing ice shelf and ice stream during the latter stages of Heinrich Stadial 1 would not be unprecedented and would be in keeping with a ‘purging’ of the British-Irish Ice Sheet (Clark et al., 2022). A collapsing Minch Ice Stream during this time does suggest either externally driven retreat, for example, ocean current warming (without the influence of rising atmospheric temperatures) or internally driven retreat (marine instability) or both. The implications of which could be extremely important for projecting the future contribution of Greenlandic and West Antarctic ice sheet sectors to global sea levels.

- viii) To identify the main physical and geochemical characteristics of laminated sediments in glaciomarine settings. This should help to elucidate the depositional mechanism of laminated glaciomarine sediments in The Minch, NW Scotland and elsewhere. [Chapter 6]

An analysis of sediment geochemistry (ITRAX XRF), and physical properties (colour, density and particle size) concluded that laminated glaciomarine sediments from three different core sections located in different ice-stream sectors were controlled principally by geochemistry. This finding implies that colour-banded laminations in glaciomarine settings are derived from meltwater plumes from different sources (either different outlet glaciers or different meltwater plume conduits).

This can be inferred because of i) weak associations between particle size and sediment colour; ii) strong correlations between elemental composition and sediment colour and X-ray density; iii)

distinct Fe mineralogical differences in red and blue-grey laminae; iv) distinct difference between sediment – the brightness of red laminae was measured between the East Minch (brighter red layers) and the West Minch (less bright red layers). In the East Minch, laminae contain hematite. In this region, Torridonian Sandstone is present and indicates potential sedimentary source from Loch Ewe or Little Loch Broom. Blue-grey layers contain other Iron Oxides and may be derived from sediment-laden meltwater plumes from the Minch Ice Stream. In the West Minch there is no clear source, however, we suggest that alternating subglacial or englacial sources may be the source for these laminae.

9. Appendices

Appendix A Supplementary Information for Automated Characterisation of Glaciomarine Sediments using X-ray Computed Laminography

This work has been published in *Quaternary Science Advances*, in the following: McDonald, N., Bradwell, T., Callard, S.L., Toney, J.L., Shreeve, B. and Shreeve, J., 2022. Automated characterisation of glaciomarine sediments using X-ray computed laminography. *Quaternary Science Advances*, 5, p.100046. <https://doi.org/10.1016/j.qsa.2021.100046>.

This Appendix file (Appendix A) includes:

1. **Supplementary Figures (A1 + A2).**
2. **Process of Operations**
3. **Supplementary Codes (Sediment characteristics script + Area fraction script).**
4. **Appendix A References**

1. **Supplementary Figures**

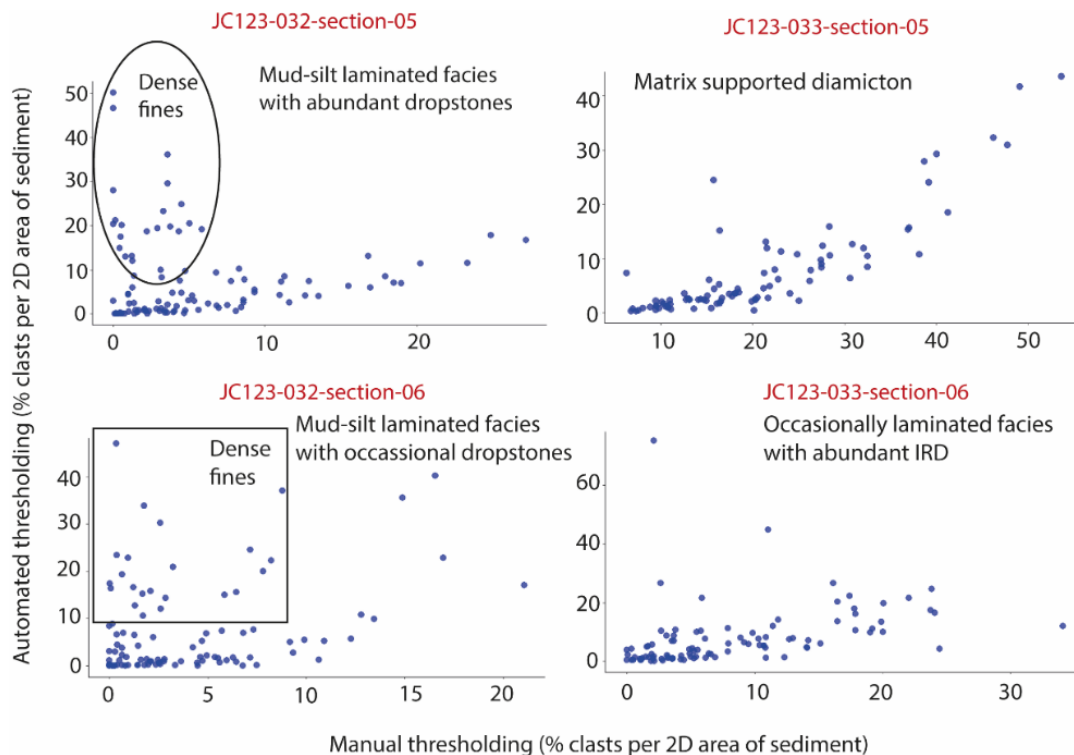


Figure A1. Manual and automated thresholding characterised by % of clasts per area (cm depth intervals x width of sampling region). Overestimation/underestimations in automated methods resulting from density variations in sediment matrices.

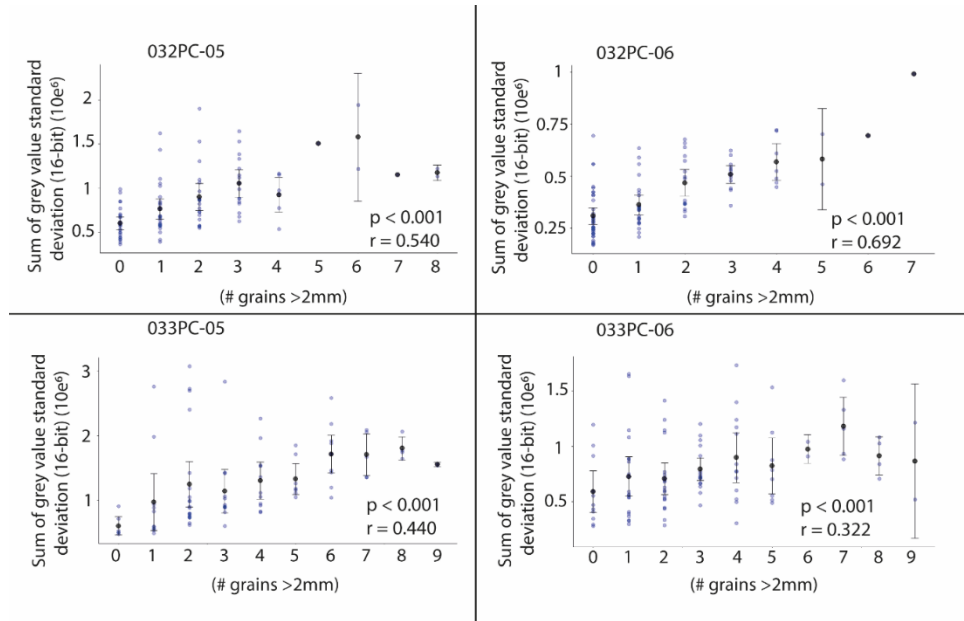


Figure A2. Scatter plots of X-ray grey value (16-bit), expressed as sum of standard deviation (or sediment heterogeneity), per 1 cm downcore area vs. grain counts (>2 mm) per 1 cm downcore (Grobe, 1987); with associated Pearson's rank correlation coefficients shown (r). Means (black dots) and associated standard error bars plotted to highlight general trend around raw data values (blue).

2. Process of operations

The following is a process of operations designed to provide more clarity to those methods outlined in the study. The following process description is specifically aimed to assist those who are not particularly familiar with FIJI/ImageJ, allowing a more accessible approach to the coding element of this study.

Stage 1: Preliminary stage: Downloading programmes and importing data

FIJI/ImageJ is freely available for download online at (<https://imagej.net/software/fiji/downloads>).

Data may be imported by selecting (File > Import) or simply opening data. However, data may be pre-prepared in software specifically designed for X-radiographic image visualisation and preparation.

Stage 2: Beam-hardening correction

The beam-hardening correction is undertaken using Geotek's own user-friendly software (Gquickview), normally provided with the acquisition of Geotek X-radiography data. This manual iterative approach is undertaken between Gquickview, FIJI/ImageJ and Microsoft Excel. The use of these 3 different programs plays to the strengths of each, whilst making the process as user-friendly as possible.

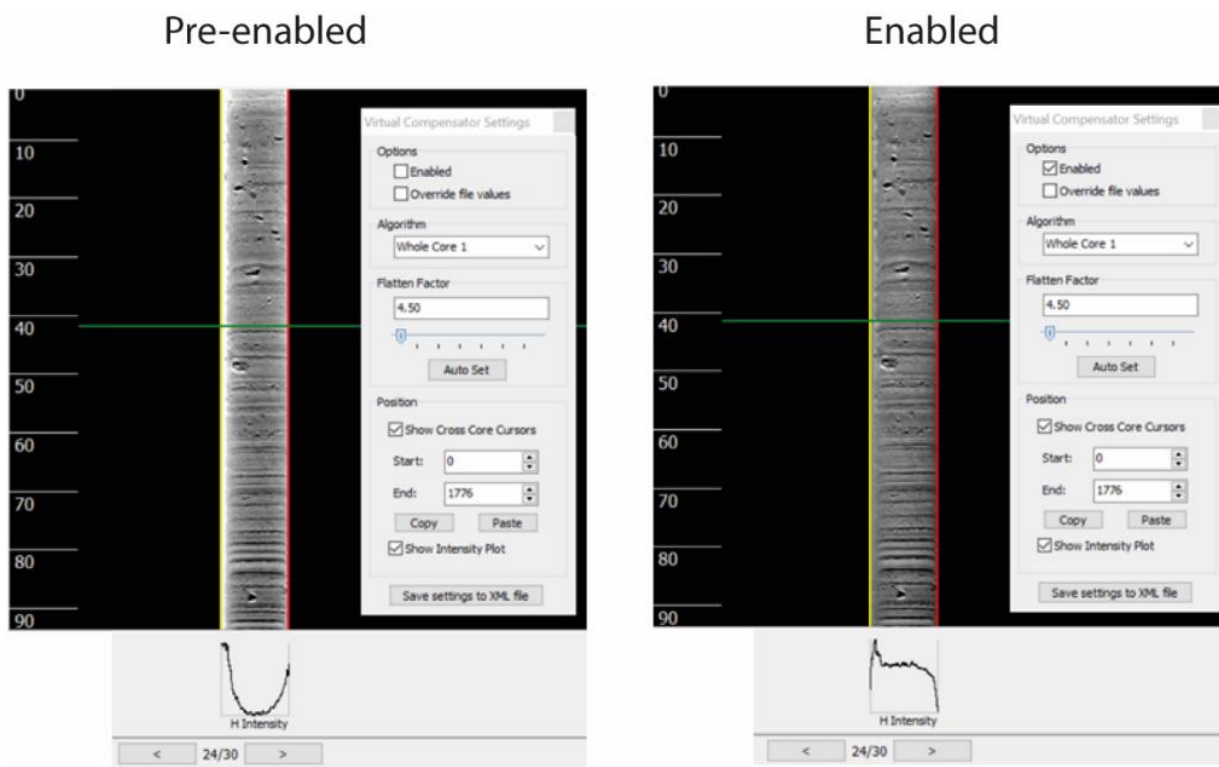


Figure A3. Beam-hardening correction using Geotek's Quickview interface's Virtual Compensator. Left: Core JC123-032-section-05 before correction; Right: JC123-032-section-05 once corrected.

For split cores, the beam-hardening correction is applied using Geotek's Quickview programme (View > Virtual Compensator > Half Core). The user then adjusts the 'Flatten Factor' and toggles the start and end positions of the 'Cross Core Cursors' (if necessary) until the 'Intensity Plot' appears flat over homogenous sections of the core. As non-homogenous (e.g. clastic or deformed) sections of the core can skew the intensity plot, it is important to select a fairly homogenous section of the core. Data are then exported to FIJI/ImageJ, where all grey values within the image are selected using the 'Area Selection Tool' (rectangle in the top left of the main panel). The selection tool can be dragged over the whole image and plotted – Analyse > Plot Profile (CTRL + K).

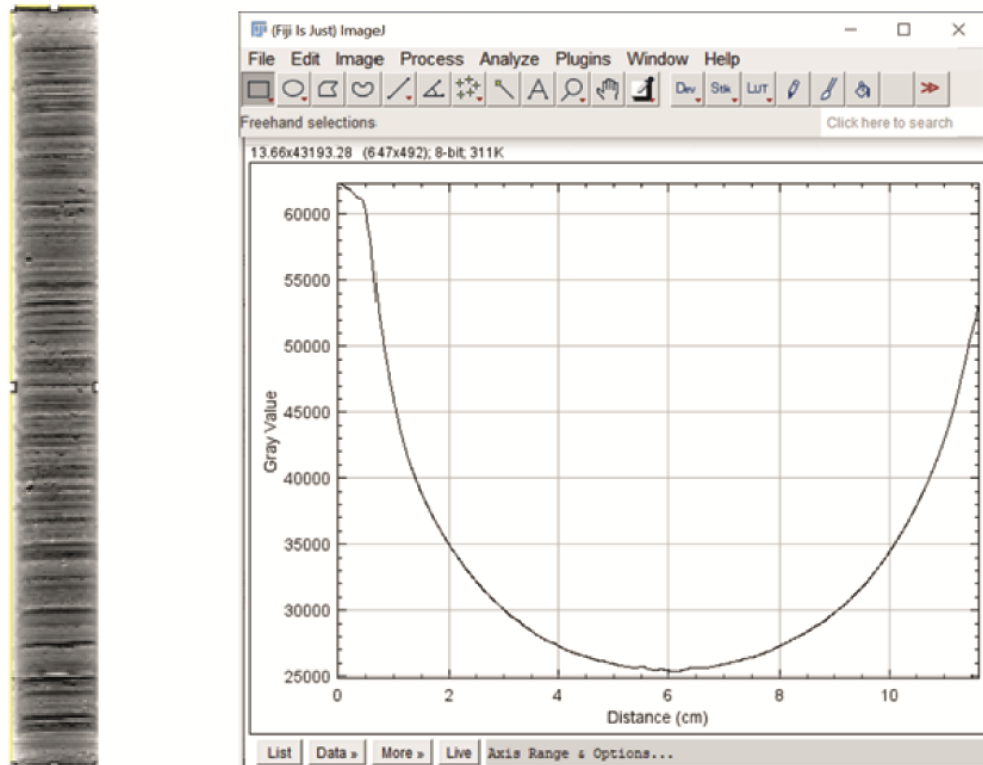


Figure A4. Selection of all core data in FIJI/imageJ using the rectangular selection tool. The ‘data’ tab at the base of the plot allows data values to be exported allowing statistical investigation of the degree of ‘cupping’.

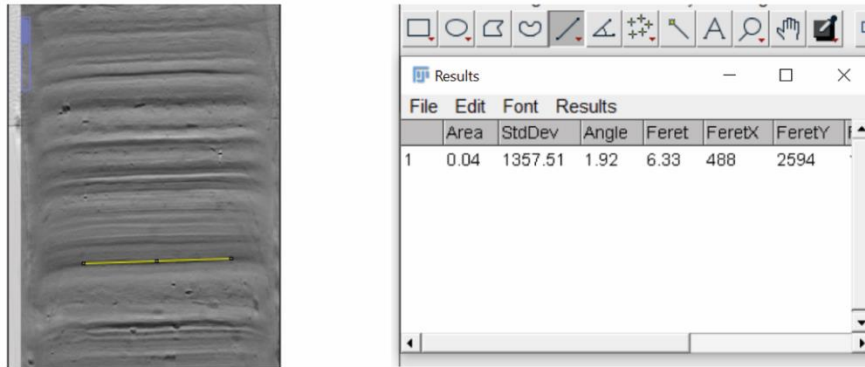
Selecting the data tab at the bottom allows data to be exported; copying and pasting into Microsoft Excel is also possible. In Microsoft Excel, data can be plotted and investigated for cupping or bowing by selecting a polynomial trendline (Insert > Scatter > Trendline > More Options > Polynomial > Display Equation on Chart). This is the authors preferred method as Microsoft Excel allows for data flexibility, however other statistical packages such as R are equally suitable if preferred, but can be more time consuming. If the ‘a’ value in the polynomial function ($y = a^2 + b^2 + c$) is significantly greater than 0 (e.g. 10-50), the analysis should be repeated with a greater degree of beam-hardening correction until the ‘a’ value in the polynomial function is as close to 0 as possible.

Stage 3: Image rotation

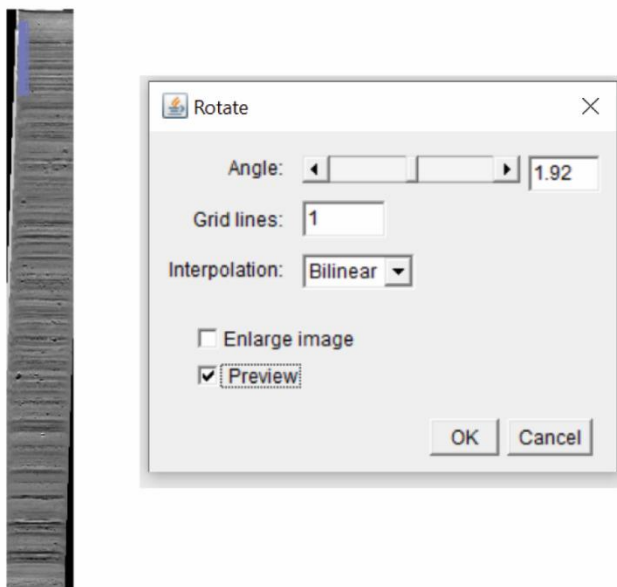
For images with regularly inclined laminae, rotating these is a simple way of preparing them for horizontal analyses. This can be attained very simply in FIJI/ImageJ. First, laminae inclination can be measured using the straight-line tool by drawing over a typical lamina parallel to the plane of inclination, these are then measured to provide a reference angle (Analyse > measure) (CTRL + M). Once the inclination angle is measured, images can be rotated by this reference angle (Image > Transform > Rotate...). The reference angle is then inserted into the ‘Angle’ box. From here images can be cropped to the desired size by selecting the relevant grey values with the area selection tool

and then cropping the image to size (Image > Crop) (CTRL + SHIFT + X). If the angle is greater than rotation allows, cropping into two or more images and running the analysis over these sections before amalgamating the data into a single dataset is possible. Cropping should also take place on all images to negate edge effects.

Stage 1: measure typical laminae inclination angle



Stage 2: rotate



Stage 3: Crop

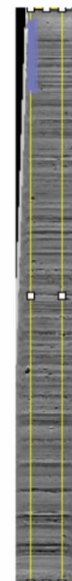


Figure A5. Rotating laminae inclination to horizontal position. Initially laminae are measured for the angle of inclination (underlined in stage 1). Secondly, the image is rotated to account for the laminae inclination angle (returning it to zero), before the image is cropped, whilst maintaining as much information as possible while allowing horizontal examination of core image.

Stage 4: Running the macro / plugin

The plugin can be copied into the 'Plugins' folder in the FIJI/ImageJ directory. From here it can be selected once the image is prepared for use, simply by clicking the 'Sediment Characteristics' plugin

under the 'Plugins' tab. To edit and run the macro, simply select the 'Record Macro' function (Plugins > Macros > Record). The macro can then be copied in and 'created'. Selecting 'Run' on the following screen will run the macro.

Additional methods in this study: Clast map creation

The creation of clast maps may be useful to researchers and has been performed by many using density thresholding and other segmentation routines (Principato, 2005; Bartels et al., 2017; Reilly et al., 2019; O'Regan et al., 2021). Effective segmentation appears more challenging with CL images than 3D CT particularly given that in this study the cores have some very dense laminae, below the density of some clasts in many cases. However, density thresholding can work very effectively to create useful clast maps on massive muds and diamictons (as observed using XR by Principato, 2005). This is achieved by selecting the thresholding function in Fiji/ImageJ (Image > Adjust > Threshold) (CTRL + SHIFT + T). For this to work successfully, images must be converted to 8-bit greyscale images (Image > Type > 8-bit). The user may toggle the threshold until clasts are isolated before selecting 'Apply'. Clast maps can be used for the analysis of clasts with the area fraction code.

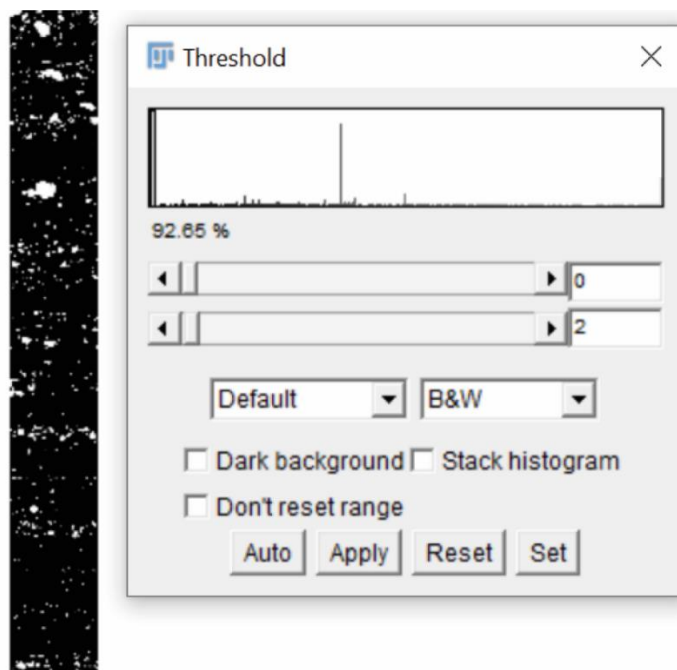


Figure S6. Thresholding of clast maps to isolate clasts or prepare pre-isolated clast maps for analysis.

From our analysis we find the most valuable method of acquiring clast maps is via manual methods. Although more time consuming and subject to human error, this allows very accurate clast maps to be created. This was done using Adobe Illustrator® although free (non-licensed) alternatives are available. We use these data to merely test the strength of our method for quantifying IRD in the approach trialled by Bartels et al. (2017, 2018). Our results also suggest that the grey value standard deviation can be a proxy for the % area of clasts without the need to retrieve clasts maps. Although

more time consuming, we suggest that clast maps may be highly valuable to some researchers as broader spatial analysis tool for of clastic sediments.

Amending scripts for other analyses

It is also possible to add any other built in function using FIJI/ImageJ, simply alter line 4 of the ‘Sediment Characteristics’ script

From:

```
run("Set Measurements...", "mean median standard redirect=None decimal=2");
```

to:

```
run("Set Measurements...");
```

The user will thereby be greeted with the FIJI ‘Set Measurements’ box and may select any analysis available.

3. Supplementary Codes (Sediment characteristics script + Area fraction script)

‘Sediment Characteristics’ script

```
// Sampling interval in pixels = s
```

```
// Number of samples = n
```

```
getDimensions(width, height, channels, slices, frames);
```

```
run("Set Measurements...", "mean median standard redirect=None decimal=2");
```

```
s = 1
```

```
n = height / s
```

```
for(i=0; i<n; ++i)
```

```
{
```

```
makeLine(0, i*s, width, i*s);
```

```
roiManager("Add");
```

```
}
```

```
roiManager("Measure");
```

```
roiManager("Show all");
```

```

'Area fraction' script

// set sampling region

// n = number of samples

// s = sampling interval depth (pixels)

getDimensions(width, height, channels, slices, frames);

run("Set Measurements...", "area_fraction redirect=None decimal=2")

n = 100

s = height / n

for(i=0; i<n; i++)

{

makeRectangle(0, i*s, width, s);

roiManager("Add");

}

roiManager("Measure");

roiManager("Show all with labels");

```

4. Appendix A References

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Appendix B Supplementary information for Quantifying user variability in the traditional X-ray ice-rafted debris (clast) counting technique

The information in this appendix features the information which was provided to participants of the study in Chapter 4.

Section 1. Brief background to study

This study aims to critique the effectiveness of a commonly employed technique for quantifying the presence of icebergs in the past. This method involves counting visible gravel clasts (rocks > 2 mm) from on screen X-ray images of glaciomarine mud. Glaciers and ice sheets pluck rocks (clasts) from land and carry them out to the ocean, when icebergs break-off from glaciers and flow into the sea these clasts can melt out from the iceberg and fall to the seafloor. Glaciologists can therefore identify this process occurring in the past which allows long term records of iceberg rafting which can be useful for tracking climate changes and ocean currents.

The two sediments in this study come from a previously glaciated area located offshore from NW Scotland (The Minch) where a large marine-based glacier once operated. It was similar in size, shape and behaviour to many modern glaciers in West Antarctica and Greenland, which are currently undergoing changes due to climate changes (Bradwell et al., 2019). By studying this previously glaciated region of Scotland we can better understand how West Antarctic and Greenlandic glaciers will respond to modern day climate change.

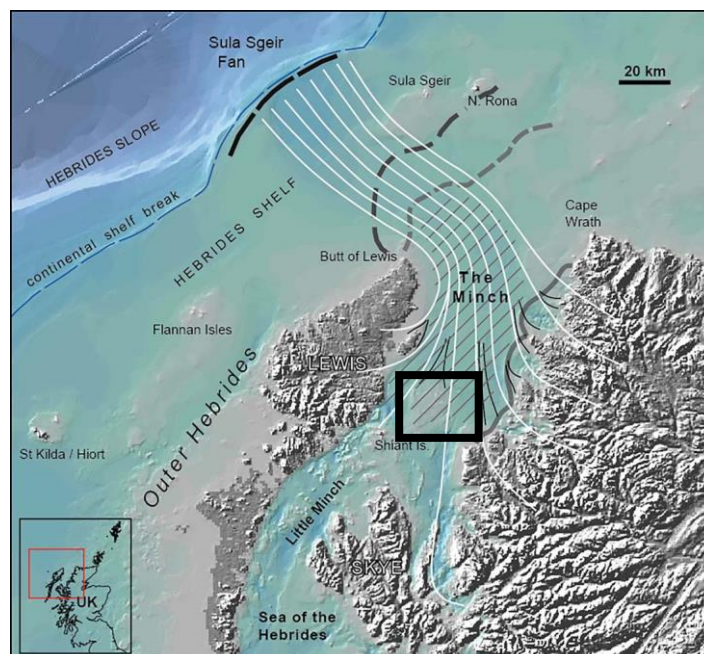


Figure A3. Location of Minch ice stream and general coring locations (Ballantyne and Small, 2018)

This study seeks to validate the effectiveness of one particular method – the counting of clasts in sediment produced by glaciers in the past (Grobe, 1987). Despite this method being over 30 years

years old and newer automated approaches now existing, it is still the most commonly used approach to recreate past icebergs in sediment. I aim to understand how long this technique takes, how variable or similar results are between users and whether expertise or subject specialism affects results. The results of any one individual are not going to be scrutinised, but I am interested to see how the technique holds up when multiple users do the test as no one has validated the user variability of this test, despite the test being incredibly common and playing a crucial role in developing our understanding of past climate changes which in turn drive our current climate projection models.

Section 2. Questionnaire

Please download and save answers to your own device, not on the files in the OneDrive folder in the link provided

1. By which gender do you identify?

Male	Female	Other	Pre
☐ to say	☐	☐	☐

2. Are you currently enrolled as a university student?

Yes	No
☐	☐

3. If so, on what degree are you currently enrolled?

4. Whether you are a student or not, what is the highest level of qualification have you attained to date?

5. Are you experienced in geology / sedimentology / glaciology or a related field? E.g., a qualified geologist, a postgraduate student or beyond in these fields

Yes	No
☐	☐

If so, what is your experience level? (E.g., Current lecturer at a university, PhD student, Master's degree graduate in sedimentology field)

6. Have you ever completed gravel counting (sensu Grobe, 1987) in the past?

Yes	No
☐	☐

Thank you for completing the questionnaire!

Detailed description of task

Icebergs break off the front of glaciers which terminate in the ocean and carry large rocks plucked from the land into the sea. Sediment cores taken from glaciomarine settings therefore provide a long-term record of iceberg fluxes through the rocks within the sediment. X-ray images allow glaciologists to see a larger number of these rocks than would otherwise be visible with the naked eye. The number of gravel clasts (any rock > 2 mm) in X-ray images of glaciomarine sediments is therefore a proxy for the presence of icebergs in the past (Grobe, 1987). Participants are provided with X-ray images of sediment cores from a past glaciomarine setting, which reveal dense clasts carried from icebergs in the past. Participants are asked to identify gravel clasts (a gravel clast is any rock larger than 2 mm) on X-ray images in centimetre intervals down the sediment core image. That is to say, the number of gravel clasts should be totalled for each centimetre 'box' on the images and written down on paper in a list or in the table on the MS Excel spreadsheet (preferred).

On X-ray positive images, like the ones provided, denser material appears darker and thus clasts appear dark relative to the matrix sediment (silt or clay). However, darker laminations or layers (which are not clasts) can exist but these tend to be horizontally expensive and cover the length of the image, but not particularly vertically expansive (see Figure 2).

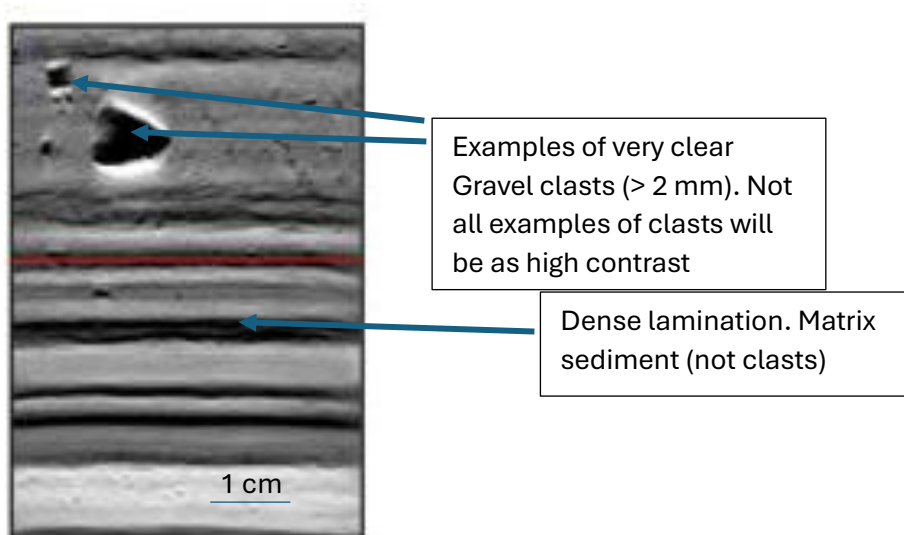


Figure B1. X-ray images showing sediment classification with gravel clasts. (Adapted from McDonald et al., 2022). Images may not be such high contrast, but this displays examples of gravels vs laminations.

Each image is divided into cm intervals which are numbered. Each participant must count the number of gravel clasts they can see (> 2 mm) using the scale bar (> 2 mm) at the side of the image (every 10 cm). The results must be noted down on answer sheets (or on paper).

When ready, each participant may start going through each X-ray image interval by interval (cm by cm box) and counting the clasts they see which are greater than 2 mm (Figure 5). There are two images (Image 1 and Image 2) and answer sheets. The answer sheets do not need to be used (if you do not have MS Excel) you can simply write your answers down on paper, but please label each cm interval if you do so). Participants **must time their experience for each image in minutes and seconds** from start to finish. Below are some images to help with the study, good luck.

Image 1

cm interval	# clasts (> 2mm)
1	2
2	3
3	5
4	1

Figure B2. Example of desired written layout

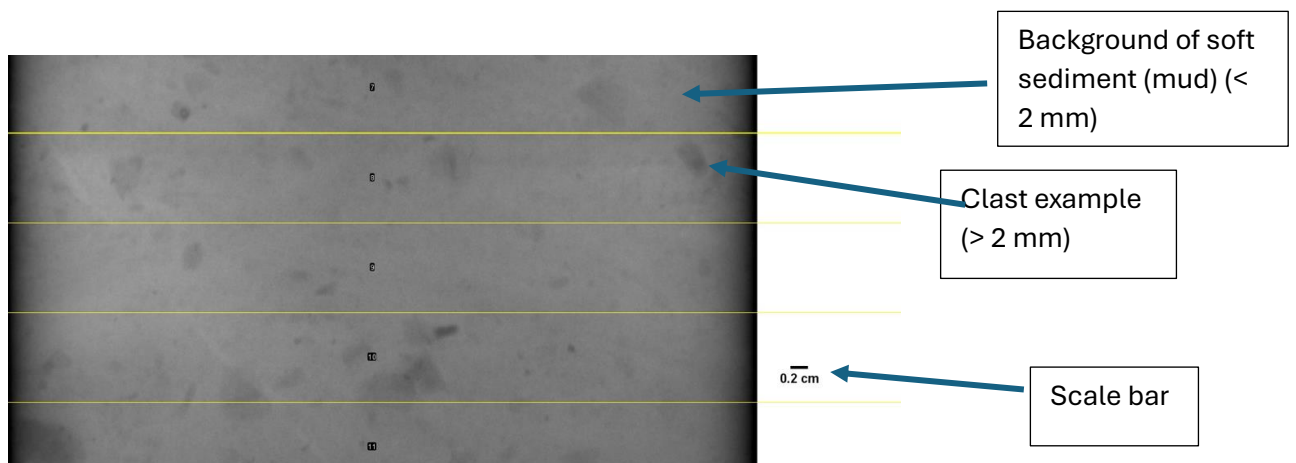


Figure B3. Example of scale bar (on Image 2 provided).

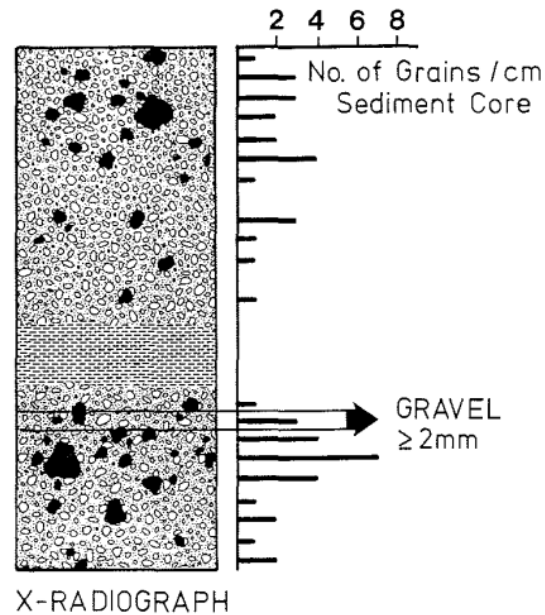


Figure B4. Manual counting method using X-radiographs (Grobe. 1987).

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