Plate 2.1 (a–c) Simulation of zones of basal freezing and melting beneath the European ice sheet at the LGM, and comparison with geological reconstruction of the basal freezing and melting zones. (a) Basal freezing (blue) and melting (red) for a ‘cold’ surface temperature simulation. (b) The same for a ‘warm’ surface temperature simulation. Note the zones of melting along simulated ice streams. (c) The inferred probable maximum zone of basal freezing at the LGM in yellow, and inner zone of sustained freezing in black (from Kleman & Hättestrand, 1999). Clearly the model in (b) is the better fit.
Plate 2.2 A section through the simulation model through the last glacial cycle from the central-western continental shelf of Norway (left) to northern Germany. It shows the zones of basal freezing (turquoise) and zones of basal melting (red).
Plate 2.3 The distribution of eskers in the area of the European ice sheet.
Plate 9.1 Hydrofracture caused by pressurized groundwater at the margin of the Saalian ice sheet in northwest Germany. The fracture dissects outwash sediments and is filled with sand injected from below.
Plate 10.1 Modeled groundwater flow velocity vectors and equipotential lines in the two major aquifers in the study area at present and under the Last Glacial Maximum ice sheet. Ice movement was from northeast to southwest. Inactive cells are marked black. Note the complete reorganization of the groundwater flow field between glacial and interglacial (present) conditions.
Plate 23.1 Sea-ice extent (all coloured areas) and ice concentration anomalies (see colour bar) for September of 2002 and 2003. Ice concentration anomalies are referenced to means for the period 1988–2000. Median ice extent based on the same period is shown by the red line. (Courtesy of National Snow and Ice Data Center, Boulder, CO.)
Plate 23.2 Large-scale trends in observed winter sea-ice motion (SIM) and summer sea-ice concentration (SIC) (top) and regressions on the prior winter AO index (bottom). Results are based on the period 1979–1998. Areas with negative and positive SIC trends of at least 5% over the record period are indicated by yellow/red and blue, respectively. The numbers indicate the largest negative trends. (Adapted from Rigor et al., 2002.)
Plate 23.3 Estimated age of sea-ice in September of 1986 and 2001 (in years, see colour scale at bottom). Open water (OW) is shown in dark blue, and the oldest ice is shown as white. The years that younger ice was produced in the Beaufort and Chukchi seas are also shown. (Adapted from Rigor & Wallace, 2004.)
Plate 26.1 Location map of the M’Clintock Channel Ice Stream (a) and satellite imagery of the bedform imprint on Victoria Island (b). The late glacial imprint of the ice stream occupies present day M’Clintock Channel and infringes on western Prince of Wales Island and eastern Storkerson Peninsula (thin red lines). Landsat satellite imagery in (b) shows the margin of the late glacial ice stream imprint on Storkerson Peninsula. However, older flow patterns (thin black lines) indicate that the ice stream may have been much bigger during the Last Glacial Maximum, extending eastward and occupying Hadley Bay.
Plate 26.2 Map of the inferred surface current-driven iceberg drift directions from the Canadian Arctic Archipelago (solid arrows) and concurrent hypothesized drift of Russian pack ice (broken arrows) during glacial intervals (modified from Bischof & Darby, 1997). The expanded M’Clintock Channel Ice Stream is shown in red and it can be seen that icebergs issued from this region would enter Fram Strait relatively rapidly compared to present day conditions (Bischof & Darby, 1997). The box indicates the area shown in Plate 26.1a.
Plate 27.1 Ice velocity of Petermann Gletscher, northwestern Greenland measured from Radarsat-1 interferometric synthetic-aperture radar (InSAR) data. Grounding line inferred from double difference InSAR is white. Ice flow is to the north. Bounding box of calculation of bottom melt rates is dotted white. Inset shows velocity V (red, in m yr⁻¹, left scale), thickness H (blue, in m, left scale) and bottom melt rate B (black, in m yr⁻¹, right scale) calculated over the glacier width, versus the distance (in km) from the grounding line.
Plate 30.1 Bathymetry of the mid-Norwegian shelf showing cross-shelf troughs and intervening banks. (Modified from Ottesen et al., 2002.)
Plate 30.2 Multibeam swath bathymetric image of sediment drifts and intervening channels on the western Antarctic Peninsula continental margin. (Modified from Dowdeswell et al., 2004b.)
Plate 32.1 Modelled modern-day mass balance fields on the Greenland Ice Sheet and in the western Arctic, using degree-day methodology and climate fields from the NCAR Community Climate System Model (CCSM), v.2.0, with climate fields provided by B. Otto-Bliesner (personal communication, 2003). (a) and (b) show the precipitation and temperature maps that go into the calculation of mass balance fields. (c), (d) and (e) plot annual accumulation, ablation, and mass balance, all in m yr⁻¹ water-equivalent. (f) shows ice sheet thickness (m). Model resolution is 1/6° latitude by 1/2° longitude.
Plate 32.2 Modelled air temperature, mass balance and ice thickness fields on the Greenland Ice Sheet and in the western Arctic for 2200. All plots are difference maps from the reference modern-day (2000) conditions shown in Plate 32.1. (a) Difference in air temperature, 2200 − present (°C). (b & c) Difference in snow/ice ablation and accumulation rates, 2200 − present (m yr⁻¹ water-equivalent). (d) Difference in ice sheet thickness, 2200 − present (m). Model resolution is 1/6° latitude by 1/2° longitude.
Plate 38.1 Four ice sheet-scale reconstructions using inversion protocols by (a) Boulton et al. (1985), (b) Dyke & Prest (1987a), (c), Boulton & Clark (1990a,b) and (d) Kleman et al. (1997). The emphasis in (a) and (b) is on post-LGM configuration changes, whereas in (c) and (d) it is on ice-sheet evolution through the last glacial cycle, with an emphasis on events pre-dating the LGM. (Panel (a) is reproduced with permission from the Geological Society, London. Panel (b) is modified from Dyke & Prest (1987a). Panel (c) is reprinted by permission from Nature, 346, 813–817 (1990), copyright 1990 Macmillan Publishers Ltd. Panel (d) is modified from Kleman et al. (1997).)
Plate 38.2 A visualization of the differences between four ice-sheet reconstructions, focusing on particular time–space data domains and the data types used in the inversion procedures. Coloured items mark the primary data domains; thick red line marks the deglacial landforms; green, blue and purple mark glacial ‘events’ reflected by till lineations pre-dating the final decay phase; red diamonds schematically illustrate radiocarbon dates (which always reflect ice-free conditions); orange colour represents a ‘stretching’ of the deglacial landform record for inferences about older non-deglacial events.
Plate 38.3 The genetic and inversion problems in glacial geomorphology are associated with fundamentally different suites of assumptions, scale and generalization considerations, as well as methodological issues.
Plate 38.4 Details from the Glacial Map of Canada (Prest et al., 1968). (a) The southwestern sector of Keewatin displays a ‘classic’ glacial landscape where abundant eskers parallel a single coherent system of till lineations. Fields of ribbed moraine occur in the proximal part of the till lineation swarm, and probably mark areas that changed from cold-based to warm-based (wet-bed) conditions (Hättestrand & Kleman, 1999). This type of landscape is thought to have formed in marginal wet-bed zones of substantial width during ice-sheet decay (Kleman et al., 1997). (b) Eskers cutting obliquely across the convergent head zone of the Dubawnt lineation swarm in Keewatin. The lineations were probably formed by a short-lived ice stream (Stokes & Clark, 1999). The eskers indicate that a major change in flow direction occurred between the ice-stream phase and the deglaciation stage. (c) An intersection zone in central Quebec–Labrador where two different glacial landscapes, with opposing flow directions, occur in close contact. The southwest-orientated landscape in the lower left-hand
half of the map displays a full suite of deglacial meltwater features aligned parallel to the lineation system, leading us to regard it as being formed during the last deglaciation. The NNE-orientated Ungava Bay swarm in the northeastern half, in contrast, almost entirely lacks eskers, leading us to believe that the lineations formed underneath central portions of the ice sheet during an earlier flow phase (Jansson et al., 2003). The apparent ice divide is probably entirely fictitious and instead denotes only the up-glacier boundary of wet-bed conditions of the southwardflow, during the last deglaciation. (d) An isolated patch of relict N–S and NNE–SSW orientated lineations southwest of the Dubawnt lineation swarm. The patch is probably an erosional remnant of a lineation system formed during a glacial event that predated the LGM (Kleman et al., 2002). Hence, its present extent is governed by subsequent Dubawnt ice-stream erosion to the north and sheet-flow erosion to the south. Eskers from the last deglaciation cut the relict north–south trending lineations in the patch at almost right angles. (e) A landscape without eskers on the northwestern flank of the Keewatin sector. Because lineations and aligned striae yield few clues to their age or the duration of flow, these landscapes are difficult to treat in inversions models. If they are part of a cold-based deglaciation landscape (which, typically, lacks eskers), the distribution of glacial-lake shorelines, spillways and drainage channels may give only the solid guidance for decay reconstruction in such areas (Borgström, 1989; Jansson, 2003). Reproduced with the permission of the Minister of Public Works and Government Services Canada, 2004 and Courtesy of Natural Resources Canada, Geological Survey of Canada.

Plate 38.5 (a) Relict surfaces lacking glacial landforms, such as the Tjeuralako Plateau, northern Sweden, are interpreted to mark sustained frozen-bed conditions under one or more successive ice sheets. Cosmogenic dating (10Be) of exposed bedrock on this plateau yielded an exposure age of 45 kyr, indicating inheritance from one or more previous ice-free intervals, and negligible erosion by the last ice sheet (Stroeven et al., 2006) (b) In Fennoscandia, periglacially formed surfaces, such as this striated boulder surface (A) at Tjóolma, The Ulteis plateau, Sweden, occur preferentially on uplands with clear erosional boundaries (Kleman, 1992) to younger glacial landscapes (B) comprising fluting and drumlinization from the last ice sheet. An erratic perched on surface (A) yielded an exposure age (10Be) of 7.4 kyr, whereas bedrock exposed on the same surface yielded exposure ages of 32.7 and 35.2 kyr (Fabel et al., 2002; Stroeven et al., 2006). (c) The Stúdan–Nípsjállat upland in the southern Scandinavian mountains comprises marginal moraines older than the last ice sheet, and a >200 m-deep weathering mantle, indicating negligible erosion by the last ice sheet. (d) Relict surfaces and glacially eroded surfaces display an archipelago-like pattern west of Kiruna, northern Sweden. The flow pattern indicated by lineations is consistent with the pattern expected for thick overriding ice and polythermal bed conditions, but inconsistent with the flow pattern expected from a thin-ice scenario comprising nunataks and ice-tongues in valleys. Modified from Kleman et al. (1999). (e) Frozen-bed extent under the Fennoscandian Ice Sheet, as inferred for three time periods. Approximate LGM extent, largely based on the distribution of ribbed moraine, inferred to have formed during transition from frozen-bed to thawed-bed conditions, shown as light grey shading. Approximate extent during Younger Dryas, after onset of major ice streams in Finland, is shown as medium grey. Black mark zones with abundant pre-Late Weichselian glacial and non-glacial landforms, and stratigraphic and cosmogenic dating evidence for non-erosive frozen-bed conditions under the last ice sheet. (f) Hughes (1981b) hypothesized that terrestrial core areas would comprise a frozen-bed core, a patchy transition zone to mostly thawed-bed conditions, lenticular frozen-bed patches in ice-stream headlands, and ice stream corridors with sharp thermal boundaries to intervening ice-stream ridges. The collective evidence from the Fennoscandian and Laurentide ice sheet areas (Dyke et al., 1992; Kleman et al., 1999) confirms all essential aspects of this hypothesis.

Plate 38.6 (a) Two chronological domains are defined: the extramarginal domain, to which all currently available dating methods pertain (radiocarbon, OSL, cosmogenic and amino-acid racemization techniques), and the subglacial, which is not accessible by any current absolute dating methods. The chronology of the deglacial envelope is currently defined mainly by a scatter of radiocarbon and OSL dates of widely varying spatial density. Through ancillary data, e.g. pollen, a specific dating often can be related to climatic evolution, but only rarely can any direct link to ice-dynamics be established. (b) In the subglacial dating domain, only relative ages are readily available. The relative age of flow events is established through cross-cutting relationships (Clark, 1993). Through analysis of landform assemblages and relative ages, inferences about ice dynamics can be made, but only rarely can any information pertaining to climate be gained. (c) Ice-stream landscapes have a substantial but yet largely unrealized potential for absolute dating of subglacial events, and may prove to be the only realistic tool for that purpose.

Plate 38.7 Palaeo-ice streams in the northwestern Canadian Arctic. Prime data sources are Prest et al. (1968) and morphological mapping using Landsat MSS and TM imagery (Kleman, unpublished data); thin black lines show till lineations mapped from MSS imagery; blue lines show major ice streams of type 1; green lines show type 2 ice streams; red lines show ice streams of type 3; grey lines show unclassified ice streams. See text for description of ice-stream types. Grey shading shows areas displaying relic non-glacial morphology and areas inferred to have been the sites of frozen-bed interstream ridges in the last ice sheet.

Plate 38.8 (a) Domains of landform formation in a time–distance diagram. Eskers form close to the ice margin in a time-transgressive fashion. Ribbed moraine is inferred to form during transition from a frozen bed to a thawed bed (Kleman & Hättestrand, 1999). Glacial lineations form wherever the bed is thawed and subglacial sediments are available. (b) The three swarm types we recognize are event swarms, ice-stream swarms and the deglacial envelope. The latter is defined by eskers and other meltwater landforms and may or may not be associated with till lineations. Swarms are simplified and spatially delineated map representations of many individual landforms.

Plate 38.9 (a) A swarm is spatially defined by longitudinal continuity lines, aligned to a visually coherent system of flow traces, and transverse up–downstream boundaries. The latter are drawn transverse to continuity lines, if necessary in a stepped fashion. Those elements which allow definition of a swarm can be any geological features that reflect ice-flow direction (e.g. striae, flutes, till fabrics, glaciotectonic folds, etc.). (b) An example of an event swarm underlying the deglacial envelope. The angular difference between the flow indicators in the event swarm and the deglacial envelope will differ depending on location, and may be small or non-existent at some locations.

Plate 38.10 (a) Glacial landforms in Keewatin. Till lineations interpreted in Landsat MSS data. Striae observations are from Lee (1959). Eskers are redrawn from the Glacial Map of Canada (Prest et al., 1968). Letters A–D mark patches of lineations, and striae observations, indicative of older ice flow from a dispersal centre in northern Keewatin or the central Arctic. The trunk of the Dubawnt Ice Stream is marked by E. Overridden end moraines in southeastern Keewatin are from Kleman et al. (2002). (b) The deglacial envelope is shown by yellow colour and the swarm formed by older flow from the northeast is shown in purple. Green colour marks the Dubawnt ice stream swarm. X–Y marks the location of the transect shown in Plate c. (c) The three Keewatin swarms schematically illustrated in a time–distance diagram. The Dubawnt swarm is interpreted as a short-lived ice-stream event during the Late Wisconsinan deglaciation. The deglacial envelope formed time-transgressively during the entire post-LGM time. The northeast swarm (purple) probably represents a pre-LGM event with small ice volume and a very northerly dispersal centre.

Plate 38.11 Glacial swarms (1–3) in northern Fennoscandia. The spatial distribution is based on Kleman et al. (1997). The age assignments are based on Lagerbäck & Robertsson (1988) and Kleman et al. (1997). Geomorphological maps (a)–(c) are redrawn from...
Hättestrand (1997), and show three areas with increasing swarm complexity. Area (a) represents a classic last deglaciation landscapes with eskers and lineations (Swarm 3). Only a few large older drumlins with a transverse direction (in the southeastern corner) have survived the deglaciation wet-based ice flow. In area (b), the last deglaciation envelope (Swarm 3) is represented only as a swarm of lateral meltwater channels, and overprints an older wet-based deglaciation landscape (Swarm 1; with lineations, eskers and end moraines) of an Early Weichselian age. Frozen-bed conditions during the last deglaciation have prohibited formation of subglacial landforms. The third area, (c), is similar to (b), but an event swarm of small drumlins (Swarm 2) overprints the old deglaciation landscape, and is in turn overprinted by the deglacial eolane from the last deglaciation, only manifested by meltwater channels (Swarm 3). The intermediate Swarm 2 lacks any meltwater channels and is therefore interpreted to have formed within the interior of the ice sheet, far from the meltwater system at the ice margin. The area interpreted to have deglaciated under cold-bed conditions is interpreted from the distribution of preserved pre-Late Weichselian landforms (indicating a minimum of subglacial erosion), and areas where the deglaciation meltwater system consists of lateral meltwater channels rather than eskers (indicating a minimum of subglacial meltwater (Kleman & Hättestrand, 1999)).

Plate 41.1 Location of the Dubawnt Lake Ice Stream on the north-western Canadian Shield and location of major drainage basins in red (centre). Mapping from digital satellite imagery (Landsat ETM+) indicates that the subglacial bedforms (drumlins and megascale glacial lineations) mimic the expected ice velocity of an ice stream, which speeds up in the onset zone (d), reaches a maximum in the main trunk (b) and decreases at the divergent terminus (a). Each image (a, b, d) is approximately 10 km wide. The overall pattern is shown in (c) where red/orange colours indicate areas of long bedforms and green through to blue show shorter bedforms.

Plate 41.2 (A) Potential sticky spot formed during or in response to ice-stream shut-down. Ice flow is from bottom right to top left, characterized by elongated drumlins and megascale glacial lineations. Bedform mapping in (B) illustrates that the lineaments have been modified by the formation of ribbed moraines. The association between ribbed moraine formation and zones of cold-based ice suggests that this area may be indicative of localized basal freeze-on as the ice-stream shuts down.

Plate 44.1 Three independent estimates of Greenland Ice Sheet thickening/thinning rates: (a) for the past few decades derived from comparison of ice discharge with snow accumulation, (b) for 1978–1988 derived from comparison of Seasat and Geosat radar-altimeter data, and (c) for 1993/1994–1998/1999 derived from repeated aircraft laser-altimeter surveys. The altimetry data have been corrected for estimated rates (ca. 5 mm yr\(^{-1}\)) of isostatic uplift of the underlying bedrock. (From Thomas et al., 2001.)

Plate 44.2 (a) Calculated increase of ice lens formation at the surface of the Greenland Ice Sheet for a 1 K warming. (b) Difference between surface-elevation change and local mass change for a 1 K warming (in ice equivalent thickness).

Plate 44.3 Distribution of accumulation rate in Greenland based on snow pit and firn core observations. (From Bales et al., 2001.)

Plate 44.4 Present-day surface-elevation evolution in Greenland (mm yr\(^{-1}\)) averaged over the past 200 yr as derived by ice-sheet modelling. (From Huybrechts & LeMeur, 1999.)

Plate 74.1 Velocity of the Northeast Greenland Ice Stream (colour, vectors) displayed over a SAR image mosaic.

Plate 74.2 Interferograms from the fast moving area of the Ryder Glacier displayed as hue-saturation-value images with value (brightness) determined by the SAR amplitude, hue determined by the interferometric phase, and saturation held constant. Each fringe (yellow-red transition) represents 2.8 cm of displacement directed toward or away from the radar. (a) Interferogram for the interval 21–22 September 1995. (b) Interferogram for the interval 26–27 October 1995. The much denser fringes, particularly on the lower portions of the glacier (white box), indicate a dramatic change in velocity over the September observation.

Plate 80.1 Structure of a comprehensive three-dimensional ice-sheet model applied to the Antarctic ice sheet. The inputs are given at the left-hand side. Prescribed environmental variables drive the model, which has ice shelves, grounded ice and bed adjustment as major components. The position of the grounding line is not prescribed, but internally generated. Ice thickness feeds back on surface elevation, an important parameter for the calculation of the mass balance. The model essentially outputs the time-dependent ice-sheet geometry and the coupled temperature and velocity fields. Three-dimensional models applied to the Northern Hemisphere ice sheets are similar, but do not include ice-shelf flow and explicit grounding-line dynamics. (After Huybrechts, 1992.)

Plate 80.2 Present-day vertically averaged ice velocities and basal temperature field as simulated by three-dimensional models applied to the Antarctic (upper pictures) and Greenland (lower pictures) ice sheets. The orange, respectively yellow, colours in the pictures at the right are areas where the basal ice is at the pressure melting point and basal sliding occurs. These fields were obtained from model versions implemented at 10 km resolution spun up over several glacial cycles. Basal temperatures were obtained for a uniform geothermal heat flux of 50.4 W m\(^{-2}\) for Greenland and 54.6 W m\(^{-2}\) for Antarctica. Note that despite what the figures may suggest, the Antarctic ice sheet is about eight times larger than the Greenland ice sheet.

Plate 80.3 Forcing (mean annual air temperature and eustatic sea level) and predicted evolution of key glaciological variables (ice volume, contribution to sea level, freshwater fluxes into the ocean) in typical three-dimensional model experiments over the last few glacial cycles. (Based on the ice-sheet model experiments described in Huybrechts, 2002.)

Plate 80.4 Modelled extent and surface topography of the Antarctic ice sheet at a few selected times during the last glacial cycle. In line with glacial-geological evidence, the most pronounced changes take place in the West Antarctic ice sheet. In East Antarctica, variations in ice-sheet geometry are comparably small. A main characteristic of the model is the late Holocene retreat of the grounding line in West Antarctica, still continuing today. Contour interval is 250 m; the lowest contour approximately coincides with the grounding line. (Modified after Huybrechts, 2002.)

Plate 80.5 Snapshots of Greenland’s ice-sheet evolution at three intervals during the last glacial cycle. According to the model, the ice sheet retreated to a small central dome during the Eemian warm period before expanding over most of the continental shelf at the Last Glacial Maximum. Implied global sea-level changes are between –3 m and +6 m. (Modified after Huybrechts, 2002.)

Plate 80.6 Volume changes of the Greenland and Antarctic ice sheets in greenhouse warming experiments expressed in equivalent global sea-level changes. The climatic forcing was derived from scaling time slices from a high-resolution AGCM (ECHAM4) with a suite of lower-resolution AGCMs. On these short time-scales, the ice-sheet response is entirely dominated by the direct effect of mass-balance changes. The background trend resulting from past environmental changes is shown separately by the thick black lines. The stippled lines refer to the Greenland ice sheet; the full lines are for the Antarctic ice sheet. These experiments were at the base of the polar ice-sheet component to the global sea-level projections of the IPCC Third Assessment Report (Church et al., 2001). (From Huybrechts et al., 2004b.)