Pleistocene Glaciation of British Columbia

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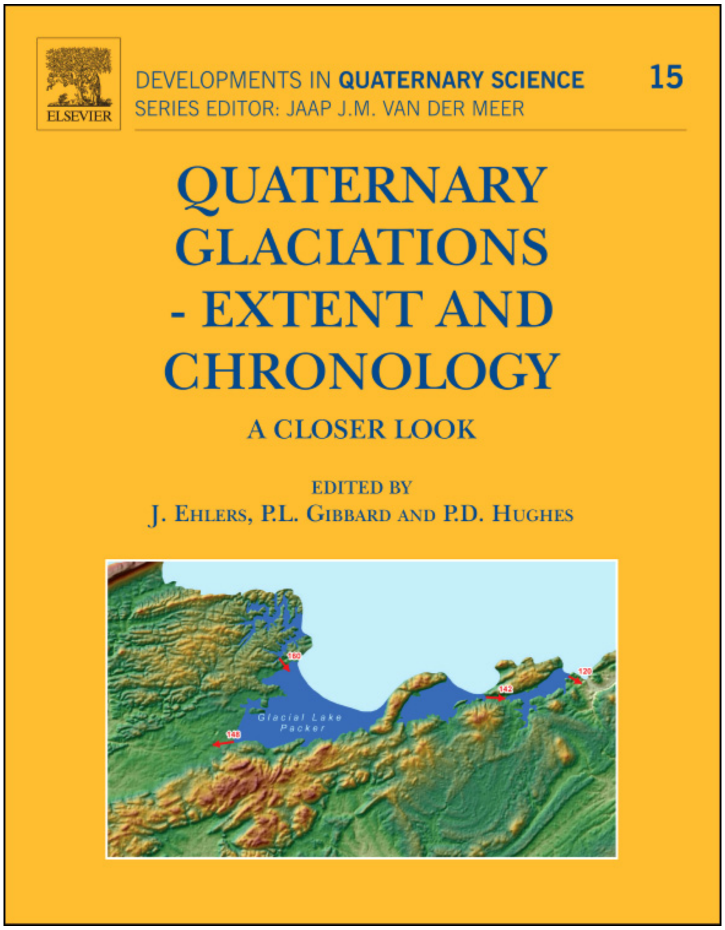

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Chapter 44

Pleistocene Glaciation of British Columbia

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44.1. INTRODUCTION

British Columbia lies within the mid-latitudes of the North Hemisphere adjacent to the Pacific Ocean, which is the moisture source for present and past glaciers in the region. The region is dominated by northwest-trending mountain ranges, rolling plateaus, and, on the west, coastal lowlands. The highest peaks in British Columbia are in the St. Elias Mountains (Mt. Fairweather, 4671 m a.s.l.), the southern Coastal Mountains (Mount Waddington, 4016 m a.s.l.), and the southern Rocky Mountains (Mount Robson, 3954 m a.s.l.).

The high mountains of British Columbia today support valley and cirque glaciers and some ice caps. The total current ice cover in British Columbia is about 26,000 km^2, which is probably close to the minimum value for the entire Quaternary.

Most of our knowledge of glaciation in British Columbia comes from the last period of ice-sheet glaciation (the Late Wisconsinan; approximately coincident with Marine Isotope Stage (MIS) 2). Patchy stratigraphical evidence exists for earlier Pleistocene glaciations, but much of the record for these evidence was eroded by Late Wisconsinan glaciers or buried beneath their deposits. Thus our understanding of Pleistocene glaciation in the region may be biased by temporal filtering of events. Nonetheless, the record of the last Cordilleran ice sheet is well preserved, within the range of radiocarbon dating, and readily interpretable. From this record, we now understand that a true ice sheet, formed by coalescence of glaciers over the interior of the province, was a rarely achieved during the Pleistocene. Through nearly all the Pleistocene, the plateaus of interior British Columbia were not covered by an ice sheet; instead, glaciers were confined to high mountains and intermontane valleys. The style of glaciation over these long periods was alpine; the signature of long-lasting alpine glaciation is strong in all high mountain ranges in British Columbia (Fig. 44.1).

The development of the Cordilleran ice sheet is, of course, rooted in alpine glaciation. The current paradigm for establishment of the ice sheet involves its inception in an extended alpine phase that, either progressively or more likely episodically, leads to establishment of a continuous ice cover over the interior of the province during an ice-sheet phase (see below).

44.2. CHARACTER AND EXTENT OF CORDILLERAN ICE SHEET

The Cordillera of western Canada was repeatedly enveloped by a continental ice sheet, known as the Cordilleran ice sheet, during the Pleistocene and latest Pliocene (Flint, 1971; Clague, 1989; Jackson and Clague, 1991). At its maximum extent, the Cordilleran ice sheet and its satellite glaciers covered almost all of British Columbia, as well as southern Yukon Territory and southern Alaska. It extended south into the northwestern conterminous United States (Fig. 44.2). The ice sheet, to a considerable extent, was confined between the high mountain ranges bordering the Canadian Cordillera on the west and east, but large areas on the east flank of the Rocky Mountains and west of the Coast Mountains were also covered by ice. Glaciers in several bordering mountain ranges, such as the Olympics, Cascade, and Mackenzie Mountains and the Queen Charlotte Range, were more or less independent of the ice sheet, even at times of maximum ice cover.

The last Cordilleran ice sheet attained its maximum size in British Columbia where it was up to 900 km wide and reached to 2000–3000 m elevation over the plateaus of the interior (Wilson et al., 1958). When fully formed, the ice sheet in British Columbia probably had the shape of an elongate dish, with gentle slopes in the interior region and steeper slopes at the periphery. It closely resembled the present-day Greenland ice sheet at such times. More commonly, the interior of the ice sheet had an irregular, undulating surface, with several ice divides that shifted through time. These ice divides were subordinate to the main divide along the axis of the Coast Mountains.

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FIGURE 44.1 Glaciated landscape, southern Coast Mountains, British Columbia. The erosional landforms visible in this photograph are typical of a landscape sculpted by alpine glaciation and include cirques, arêtes, horns, and U-shaped valleys. Although this area was also covered by the Cordilleran ice sheet for up to a few thousand years during the Late Wisconsinan, alpine glaciers and mountain ice caps were much more important in shaping the landscape during the Quaternary (Province of British Columbia).

In western British Columbia, ice streamed down fjords and valleys in the coastal mountains and covered large areas of the Pacific continental shelf. At these times, parts of the British Columbia continental shelf were exposed due to eustatic lowering of sea level driven by the growth of continental ice sheets on land. Some lobes at the western margin of the ice sheet extended to the shelf edge where they calved into deep water. Glaciers issuing from the southern Coast Mountains and Vancouver Island Ranges coalesced over the Strait of Georgia to produce a great outlet glacier that flowed far into Puget Lowland in Washington State (Waitt and Thorson, 1983). Glaciers streaming down valleys farther to the east likewise terminated as large lobes in eastern Washington, Idaho, and Montana (Waitt and Thorson, 1983).

On the east, ice flowed from the British Columbia interior and the Rocky Mountains and locally coalesced with ice originating in the Keewatin sector of the Laurentide ice sheet over the Rocky Mountain Foothills (Clague, 1989). These ice masses coalesced only rarely, at times of maximum glaciation, most recently about 17,000 years ago (Jackson et al., 1999). At other times, an ice-free zone (the "Ice-free corridor") existed between the Cordilleran and Laurentide ice sheets.

44.3. GROWTH AND DECAY OF CORDILLERAN ICE SHEET

The Cordilleran ice sheet nucleated in the high mountains of British Columbia (Figs. 44.3A and 44.4A). Small mountain ice fields grew, and valley glaciers advanced when climate deteriorated early during each glaciation (Fig. 44.3B; Kerr, 1934; Davis and Mathews, 1944; Fulton, 1991). With continued cooling and an increase in precipitation, glaciers expanded and coalesced to form a more extensive cover of ice in mountains (Fig. 44.4B). The glaciers advanced out of the mountains and across plateaus and lowlands (Fig. 44.4C), eventually coalescing to form an ice sheet that covered most of British Columbia and adjacent areas (Figs. 44.3C and 44.4D). During this period, which spanned thousands of years, the major mountain ranges remained the principal sources of ice, and ice flow was controlled by topography. Ice thickened to such an extent during the final phase of glaciation that one or more domes became established over the interior of British Columbia, with surface flow radially away from their centres. This full continental ice sheet phase of glaciation was rarely achieved. The transition into this final phase was accompanied by a local reversal of ice flow in the Coast Mountains, as the ice divide shifted from the mountain crest eastwards to a position over the British Columbia interior (Stumpf et al., 2000). A comparable westward shift and reversal of flow may also have occurred locally in the Rocky Mountains. The flow reversals resulted from the build-up of ice in the interior to levels higher than the main accumulation areas in the flanking mountains.

The model outlined in the preceding paragraph provides a framework for conceptualising the growth of the Cordilleran ice sheet, but the actual history of the ice sheet is more complicated (Clague, 1989). Ice did not build up in a uniform, monotonic fashion; rather, periods of growth were interrupted by intervals during which glaciers stabilised or receded.

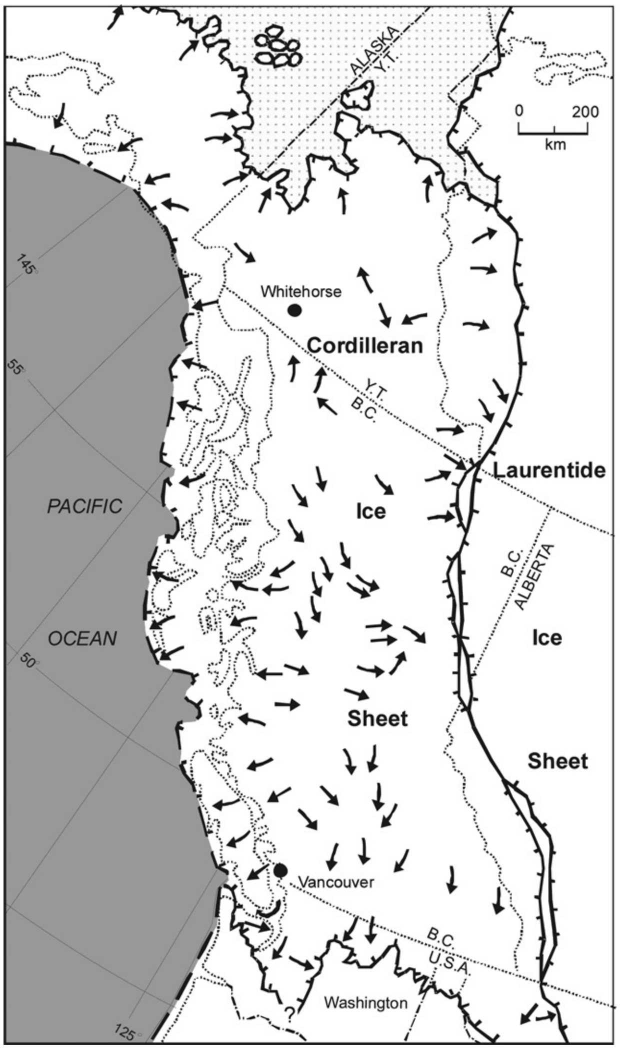

FIGURE 44.2 The Cordilleran ice sheet about 17,000 years ago at the maximum of the last glaciation. The upper surface of the ice sheet reached up to 2000–3000 m a.s.l. Arrows indicate directions of ice flow.

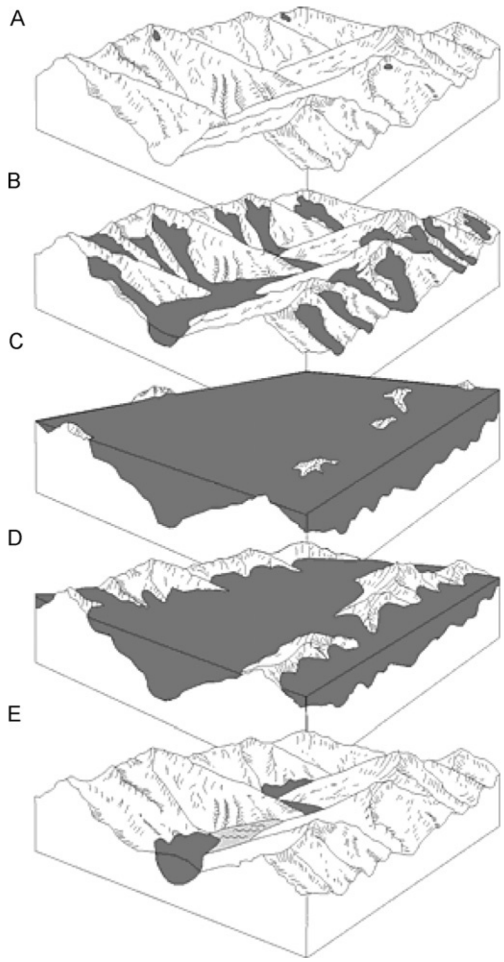

FIGURE 44.3 Schematic diagram showing growth and decay of the Cordilleran ice sheet. (A). Mountain area at the beginning of a glaciation. (B). Development of a network of valley glaciers. (C). Coalescence of valley and piedmont lobes to form an ice sheet. (D) Decay of ice sheet by downwasting; upland areas are deglaciated before adjacent valleys. (E). Residual dead ice masses confined to valleys. (Modified from Clague, 1989, fig. 1.13).

Most glacial cycles terminated with rapid climate warming. Deglaciation was characterised by complex frontal retreat in peripheral glaciated areas and by downwasting accompanied by widespread stagnation throughout the Cordilleran interior (Fulton, 1967). The western periphery of the ice sheet became unstable due, in part, to the global rise in sea level that occurred at such times. The British Columbia continental shelf was rapidly freed of ice, as glaciers calved back to fjord heads and valleys. Frontal retreat also occurred elsewhere along the periphery of the ice sheet, for example, in northern Washington and southern Yukon.

A different style of deglaciation has been documented for areas of low and moderate relief nearer the centre of the ice sheet. Deglaciation in these areas occurred mainly by downwasting and stagnation and proceeded through four stages (Fulton, 1967): (1) active ice phase—regional flow continued but diminished as ice thinned (Fig. 44.3D); (2) transitional upland phase—the highest uplands became ice free but regional flow continued in valleys; (3) stagnant ice phase—ice was confined to valleys but was still thick enough to flow; and (4) dead ice phase—ice tongues in valleys thinned to the point that they no longer flowed (Fig. 44.3E). Geomorphological evidence for this pattern of deglaciation is widespread and convincing: successively lower and younger lake sediments in valleys; flights of ice-marginal channels over vertical ranges of hundreds of metres; and ice-stagnation features at a range of elevations and in a variety of geomorphological positions.

The first areas to become ice-free were those near the periphery of the ice sheet, for example, British

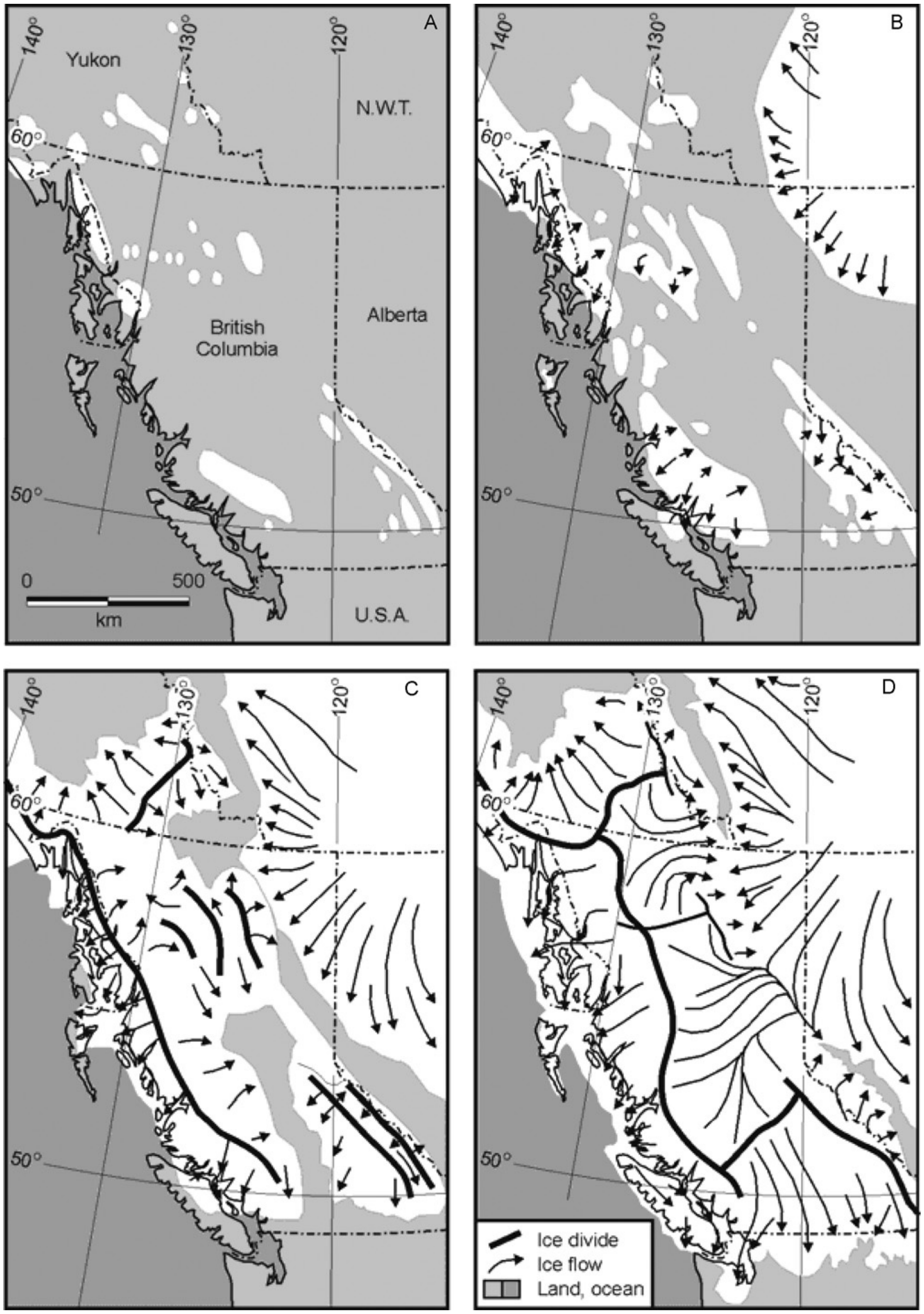

FIGURE 44.4 Schematic maps of ice cover in British Columbia during the growth phase of the last glaciation, about (A) 35,000, (B) 30,000, (C) 25,000, and (D) 18,000 years ago. Ice distributions are inferred from limited data and should only be considered approximations. (Modified from Clague et al., 2004, fig. 4).

Columbia's continental shelf and the plateaus of the northwestern United States (Clague, 1989). Active glaciers probably persisted longest in high mountain valleys, but they may have coexisted with large masses of dead ice on the plateaus of the Cordilleran interior. In general, retreat in the interior proceeded from both southern and northern peripheral areas towards the centre of the ice sheet. In detail, however, the pattern of retreat was complex, with uplands in each region becoming ice-free before adjacent valleys.

Decay of the Cordilleran ice sheet at the close of the last glaciation, and probably during the terminations of earlier glaciations, was interrupted repeatedly by glacier readvances (Alley and Chatwin, 1979; Clague, 1984, 1989; Clague et al., 1997; Friele and Clague, 2002; Kovanen, 2002; Lakeman et al., 2008). Most readvances affected relatively small areas and may not have been synchronous from one region to another.

44.4. GLACIAL EROSION AND DEPOSITION

The ice sheet and the alpine glaciers from which it formed modified the late Tertiary landscape of British Columbia (Mathews, 1989). Mountain areas are dominated by erosional glacial landforms, whereas plateaus, coastal lowlands, and intermontane valleys record both the erosional and depositional effects of glaciers (Clague, 1989). In high mountains, classic alpine forms were created, including cirques and over-deepened valley heads, horns, and comb ridges. Most mountain valleys are typical glacial troughs. Some valleys in the westernmost Cordillera extend into fjords, which attain water depths of up to 750 m. Much of the sediment produced by glacial erosion was transported beyond the periphery of the ice sheet. Large amounts of sediment, however, were deposited in valleys, on coastal lowlands, and on the plateaus of the Cordilleran interior as proglacial and ice-contact sediments, mainly during the advance and recessional phases of the last glaciation. Deposits of older glaciations are less common, because they have been extensively eroded by the last Cordilleran ice sheet. Even in areas where these older deposits are present, they are covered by younger sediments and, consequently, are poorly exposed.

44.5. CRUSTAL DEFORMATION

Growth and decay of the Cordilleran ice sheet triggered crustal movements that were dominantly isostatic in origin (Clague, 1983; Clague and James, 2002; Hetherington et al., 2004). The crust was displaced downward during periods of ice-sheet growth. Initially, the depression was localised beneath the mountain ranges that were loci of glacier growth. The area of crustal subsidence grew larger as glaciers advanced out of mountains and into lowlands. At times of maximum ice cover, the entire area of the ice sheet was displaced downward.

The amount of isostatic depression during times of maximum ice cover depended primarily on the thickness and extent of the ice sheet, the length of time over which it formed, and the structure and composition of the crust and mantle (James et al., 2000). Isostatic depression was greatest beneath the centre of the ice sheet and decreased west of the Coast Mountains and Strait of Georgia towards the continental margin and south into Washington state.

Elevated glaciomarine sediments and shoreline features along the British Columbia and northern Washington coasts provide evidence for isostatic depression at the end of the last glaciation (Clague et al., 1982a; Thorson, 1989). The elevation of the late-glacial marine limit differs in relation to distance from former centres of ice accumulation and time of deglaciation. In general, the marine limit is highest (ca. 200 m a.s.l.) on the British Columbia mainland coast and drops towards the west, southwest, and south. Many mainland fjords, however, were deglaciated after much of the local isostatic rebound had occurred, and consequently, the marine limit in those areas is relatively low. Late-glacial shorelines on Haida Gwaii (Queen Charlotte Islands) were lower than at present, indicating that glacioisostatic depression there was less than the coeval global (eustatic) lowering of sea level (Clague et al., 1982b; Clague, 1983; Josenhans et al., 1997; Barrie and Conway, 2002; Hetherington et al., 2004).

Rapid deglaciation at the end of each glaciation triggered isostatic adjustments that were opposite in direction to those that occurred during ice-sheet growth (Fig. 44.5; Clague, 1983; Clague and James, 2002). Material moved laterally in the mantle from extraglacial regions towards the centre of the decaying ice sheet. Areas at the periphery of the ice sheet, which were deglaciated earliest, rebounded first. The total amount of uplift in these areas, however, was less than at the centre of the ice sheet where ice thicknesses generally were greater. As deglaciation progressed, the zone of rapid isostatic uplift migrated in step with receding glacier margins (Clague, 1983). The rate of uplift in each region decreased exponentially with time, and rebound was largely complete within several thousand years of deglaciation (Clague et al., 1982a; James et al., 2000).

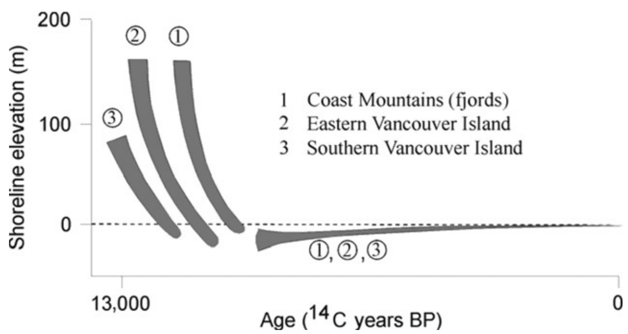

FIGURE 44.5 Generalised patterns of sea-level change on the British Columbia coast since the end of the last glaciation. Deglaciation and isostatic rebound occurred later in the Coast Mountains than on Vancouver Island. (Modified from Muhs et al., 1987, fig. 10).

44.6. STRATIGRAPHICAL RECORD AND CHRONOLOGY

Scattered evidence of Early and Middle Pleistocene glaciations has been reported throughout British Columbia, but reconstructions are sparse and correlations difficult. Near Merritt in southern British Columbia, two sequences of glaciolacustrine sediments separated by a palaeosol are reversely magnetised and thus are older than 780 ka (Fulton et al., 1992). At a site along the Fraser River north of Lillooet, a reversely magnetised till overlies a normally magnetised sequence of glaciofluvial sediments (Lian et al., 1999). This sequence may date to the early part of the Matuyama Chronozone at about 2.6 Ma.

Glacial deposits are interstratified with lavas and pyroclastic sediments on the flanks of Quaternary volcanoes in British Columbia, allowing some older glaciations to be dated. Two basalts overlying tills in the Clearwater River area of east-central British Columbia have been dated by the potassium–argon method to 0.5 and 0.27 Ma (Hickson et al., 1995). At Dog Creek south of Williams Lake, a striated bedrock surface is covered with basalt, which in turn is overlain by a sequence of glacial sediments that is capped by another basalt flow (Mathews and Rouse, 1986). The older basalt has been dated to 2.84 Ma, and the younger one to 1.06 Ma (Graham Andrews, personal communication, 2010). Till in the Stikine River area underlies a basalt flow dated at 330 ka (Spooner et al., 1995).

Volcanic rocks erupted beneath or against glaciers can also provide information on the age of glaciation, but the extent of these glaciers can be difficult to ascertain. Ice-contact volcanic rocks in the Garibaldi Lake area have been dated to 0.75, 0.6, 0.45, 0.13, and 0.090 Ma (Kelman et al., 2002), and others in the Clearwater River area have yielded ages of 1.9, 1.6, and 0.27 Ma (Hickson et al., 1995). In northwest British Columbia, glaciovolcanic eruptions have been documented at >1.1, 0.9, 0.75, 0.43, 0.085, and <0.040 Ma (Spooner et al., 1996; Edwards et al., 2002, 2011; Harder and Russell, 2007). Some of these glacial events have been inferred to be of ice-sheet scale, suggesting that the Cordilleran ice sheet formed and decayed many times during the Pleistocene. The Early and Middle Pleistocene record of glaciation in British Columbia is beginning to approach in completeness that of the marine isotopic record, although the extent of these glaciations remains unclear.

Some subsurface glacial deposits in British Columbia have been assigned a late Middle Pleistocene or early Late Pleistocene age, but because they have not been dated, questions remain as to whether they record MIS 4, MIS 6, or even older glaciation. Some units underlie deposits that are likely Sangamonian (MIS 5) and thus record MIS 6 or older glaciation. One of these units, originally described by Armstrong (1975) in the Fraser Lowland, is Westlynn drift. It comprises a complex sequence of till, glaciofluvial, glaciomarine, and possibly glaciolacustrine sediments. An unnamed till, underlying deposits correlated to MIS 5 on southern Vancouver Island, has been correlated to Westlynn drift by Hicock (1990) and Lian et al. (1995). Bobrowsky and Rutter (1992) describe deposits of an "Early advance" below what they interpreted to be Sangamonian fluvial deposits in the Northern Rocky Mountain Trench in northeast British Columbia. Other till sheets, without stratigraphical relationship to MIS 5 deposits, could also correlate to Westlynn drift, for example two tills beneath MIS 2 till along the Fraser River north of Lillooet (Ryder, 1976).

Glacial deposits assigned to MIS 4 and consisting of till and glaciofluvial and glaciolacustrine sediments have been identified in many parts of British Columbia (Table 44.1). They include the Okanogan Centre Drift in south-central British Columbia (Fulton and Smith, 1978), deposits of the Early Portage Mountain advance in the Northern Rocky Mountain Trench (Bobrowsky and Rutter, 1992), Muchalat River Drift on north-central Vancouver Island (Howes, 1981, 1983), Dashwood Drift (Fyles, 1963) and Mapleguard sediments (Hicock and Armstrong, 1983) on southeast Vancouver Island, and Semiahmoo Drift in the Fraser Lowland (Hicock and Armstrong, 1983). These units are not well dated, although in some cases they appear to be conformably overlain by radiocarbon-dated MIS 3 deposits. There is evidence of extensive MIS 4 glaciation, probably of ice-sheet scale, from an ODP core off the west coast of Vancouver Island. The core records glaciomarine sedimentation similar to that of MIS 2 (Cosma et al., 2008). In addition, an episode of glaciovolcanism in northern British Columbia record probable ice-sheet glaciation during MIS 4 (Edwards et al., 2011).

Deposits and landforms of the MIS 2 Fraser glaciation are ubiquitous and well constrained by radiocarbon ages, allowing robust reconstruction (Table 44.1). Glacier advance in southwestern BC is recorded by a diachronous sheet of outwash termed Quadra Sand. (Clague, 1976; Clague et al., 2005). The unit is up to 50 m thick and is exposed along the margins of the Strait of Georgia and in adjacent mountain valleys. Numerous radiocarbon ages on plant and animal fossils recovered Quadra Sand range from about 29 ^{14}C ka BP at the northern end of the Strait of Georgia to 17 ^{14}C ka BP near Victoria on southeastern Vancouver Island. The outwash was deposited on isostatically depressed braidplains and in deltaic and shallow marine environments. Brackish-water diatoms have been found in laminated silt within Quadra Sand at an elevation of 14 m a.s.l. at Vancouver, indicating isostatic depression of the order of 100 m at 24.6 ^{14}C ka BP (Clague et al., 2005). A similar amount of isostatic depression has been inferred on the west coast of Vancouver Island at ca. 16.5 ^{14}C ka BP (Ward et al., 2003).

TABLE 44.1 Quaternary stratigraphic framework for selected areas of British Columbia

	GEOLOGIC-CLIMATE UNITS	^{14}C years ka BP (not to scale)	FRASER LOWLAND (Armstrong, 1891, 1984; Hicock and Lian, 1995) lowland → mountains	North-Central Vancouver Island (Howes, 1981)	Northern Vancouver Island (Howes, 1983)	South-Central British Columbia (Fulton and Smith, 1978)	Southern Rocky Mountain Trench (Clague, 1975)	Northern Rocky Mountain Trench (Bobrowsky and Rutter, 1992)
HOLOCENE	Postglacial	5, 10	Fraser River sediments, Salish sediments; Sumas Stade	Postglacial sediments	Postglacial sediments	Postglacial sediments	Postglacial sediments	Postglacial sediments
PLEISTOCENE – LATE WISCONSINAN (MIS 2)	Fraser Glaciation	11, 14, 15, 17, 19	Capilano sediments; Ft. Langley interval; Vashon Stade; Port Moody Interstade; ? Coquitlam Stade ?	Gold River Drift	Port McneilDrift	Kamloops Lake Drift	Younger Drift; Interdrift sediments; Older drift	Late Portage Mountain
PLEISTOCENE – MIDDLE WISCONSINAN (MIS 3)	Olympia nonglacial interval	25, 36, 50, Not calibrated	Quadra Sand; Cowichan Head Formation			Bessette Sediments	'Interglacial' Sediments	Fluvial and lacustrine sediments
PLEISTOCENE – EARLY WISCONSINAN (MIS 4)			Dashwood and Semiahmoo Drift	Muchalat River Drift	Older Drift	Okanagan Centre Drift		Early Portage Mountain
PLEISTOCENE – SANGAMONIUM (MIS 5)			Muir Point Formation and Highbury Sediments			Westwold Sediments		Fluvial sediments
PLEISTOCENE – MIS 6 or OLDER			Westlynn Drift					Early Advance

Advance outwash deposits are present in interior valleys in British Columbia, but they are generally not well dated. They comprise thick glaciofluvial gravel, conformably overlain by glaciolacustrine sediments deposited in proglacial lakes (Ryder, 1976, 1981; Fulton and Smith, 1978; Howes, 1981; Clague, 1986, 1987). The limited number of radiocarbon ages that bear on the age of these deposits constrain growth of the last Cordilleran ice sheet growth and support the conceptual model outlined above (Fig. 44.4). Glaciers sourced in the mountains of Vancouver Island were advancing 25 ^{14}C ka BP, prior to the island being overtopped by the Cordilleran ice sheet flowing from the east (Howes, 1981). Ice sourced in the high mountains of British Columbia advanced onto the Interior Plateau after 25 ^{14}C ka BP, and parts of the interior remained ice-free until after 19 ^{14}C ka BP (Clague et al., 1980). Glaciomarine sedimentation on the continental slope off central Vancouver Island began about 25 ^{14}C ka BP (Cosma et al., 2008).

The Fraser Lowland and adjacent mountain valleys have been the subject of detailed Quaternary stratigraphical research for a half century. Late Pleistocene events have been detailed at higher resolution here than in other areas of British Columbia (Armstrong et al., 1965; Armstrong, 1975, 1981; Armstrong and Clague, 1977; Clague, 1980, 1981, 1989; Clague et al., 1980, 1988, 1997; Hicock and Armstrong, 1981, 1983, 1985; Hicock et al., 1982, 1999; Miller et al., 1985; Saunders et al., 1987; Hicock and Lian, 1995, 1999; Lian et al., 2001; Kovanen, 2002; Ward and Thomson, 2004). The Fraser glaciation in this region has been divided into the Coquitlam, Vashon, and Sumas stadials (Table 44.1). Nonglacial sediments of the Sisters Creek Formation, radiocarbon dated from 19 to 18 ^{14}C ka BP, separate deposits of the Coquitlam and Vashon stadials (Hicock and Lian, 1995). Similar deposits beneath Vashon till in the eastern Fraser Lowland have been radiocarbon dated from 20 to 19 ^{14}C ka BP (Ward and Thomson, 2004). The Coquitlam and Vashon stadials have been linked to Heinrich events (Hicock et al., 1999), and the former has been correlated to the Evans Creek stadial, an alpine glacier advance in the Cascade Range in Washington State (Armstrong et al., 1965; Hicock et al., 1999; Riedel et al., 2010).

Deposits of the Coquitlam stadial have been identified at seven sites and have maximum and minimum ages of 21.3 and 18.7 ^{14}C ka BP. It was initially proposed to be a brief advance of valley glaciers from the Coast Mountains and a piedmont glacier flowing down the Strait of Georgia (Hicock and Armstrong, 1981). Subsequent work suggested that ice during the Coquitlam stadial was more extensive, with westward flow across the entire Fraser Lowland (Hicock et al., 1999; Hicock and Lian, 1999). Recent work in the Chehalis River watershed indicates that glacier cover during the Coquitlam stadial was not this extensive (Ward and Thomson, 2004). The lower Chehalis River valley was not glaciated until the Vashon stadial, after 19 ^{14}C ka BP.

Ice cover in British Columbia during MIS 2 was greatest during the Vashon stadial (Fig. 44.6). The Cordilleran ice sheet developed to its maximum size at 14.5 ^{14}C ka BP; at that time, the Fraser Lowland was covered by 2 km of ice and ice reached as far south in the Puget Lowland as Olympia, Washington (Armstrong et al., 1965; Clague, 1981; Porter and Swanson, 1998).

The age of maximum ice cover is known in other areas of British Columbia (Fig. 44.6). Glaciers on Haida Gwaii (Queen Charlotte Islands) reached their limit prior to ~16 ^{14}C ka BP and were retreating by ~15 ^{14}C ka BP (Clague et al., 2004). Ice also was thickest on northern Vancouver Island after ~16 ^{14}C ka BP (Ward et al., 2003; Al-Suwaidi et al., 2006). Ice advanced to the edge of the British Columbia continental shelf ca. 16–17 ^{14}C ka BP and retreated shortly thereafter, based on records from two core sites in the eastern North Pacific Ocean (Blaise et al., 1990; Cosma et al., 2008). Based on these data, it appears that the Cordilleran ice sheet achieved its maximum extent when the Laurentide Ice Sheet was retreating.

Deglaciation was rapid, triggered both by climate warming and by calving at the western margin of the ice sheet. By 13 ^{14}C ka BP, what are now Vancouver, Victoria, and Prince Rupert were free of ice (Fulton, 1971; Armstrong, 1981; Huntley et al., 2001). The entire Strait of Georgia was completely deglaciated shortly thereafter.

Early retreat was followed by a period during which glaciers stabilised at pinning positions at the front of the Coast Mountains and fluctuated about those positions for 1500–2000 year. As an example, the glacier in the Fraser Lowland retreated rapidly eastwards across the Fraser Lowland near Vancouver shortly after 13.0 ^{14}C ka BP but stabilised near Abbotsford, where it advanced and retreated several times between 13 and 10.5 ^{14}C ka BP (Armstrong, 1981; Clague et al., 1997; Kovanen, 2002). These late Glacial advances were of the order of several kilometres to 20 km and were caused by climate and non-climatic factors, including perhaps rapid emergence of the Fraser Lowland. At least one of the advances occurred during the Younger Dryas Chronozone.

Deglaciation in the interior also was rapid. The Cordilleran ice sheet persisted until about 11.0–10.5 ^{14}C ka BP; by 9.5 ^{14}C ka BP, glaciers in the Coast Mountains were probably no more extensive than they are today (Clague, 1981).

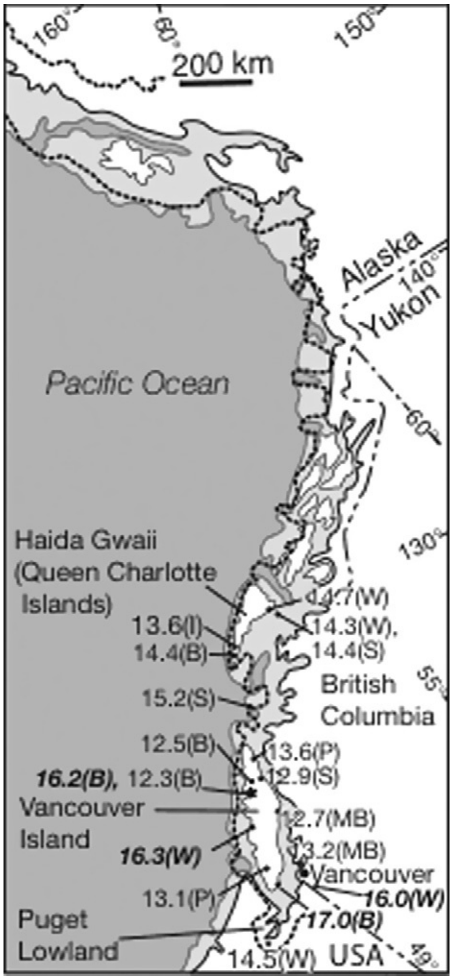

FIGURE 44.6 Time of the Last Glacial Maximum along the British Columbia coast. The continental shelf (<200 m water depth) is shaded light grey. The dotted line delineates the approximate maximum extent of the Cordilleran ice sheet during MIS 2 (Clague, 1989; Blaise et al., 1990; Manley and Kaufman, 2002). Radiocarbon ages (in ^{14}C ka BP) pertaining to maximum extent of the ice sheet are bolded and italicised; limiting minimum radiocarbon ages are shown in plain font (Clague et al., 1982b; 1988; Blaise et al., 1990; Howes, 1997; Nagorsen and Keddie, 2000; Hetherington et al., 2004; Ramsey et al., 2004; Lacourse et al., 2005; Al-Suwaidi et al., 2006). S = shell; W = wood/terrestrial macrofossil; B = bone; P = basal peat; MB = marine mammal bone; I = insect. (Modified from Ward et al., 2003.)

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