Possible refugia in the Alexander Archipelago of southeastern Alaska during the late Wisconsin glaciation

P.E. Carrara, T.A. Ager, and J.F. Baichtal

Abstract: The interpretation of the extent of late Wisconsin glaciation in southeastern Alaska has varied between geologists and biologists. Maps and reports of the region prepared by geologists commonly indicated that late Wisconsin ice extended as a large uniform front west to the edge of the continental shelf. However, the distribution of plants and animals in the region has led many biologists to suggest that there may have been ice-free areas that served as refugia during the late Wisconsin. Based on analyses of aerial photographs, topographic maps, and bathymetric charts, in conjunction with a review of previous literature and reconnaissance fieldwork throughout the region, this study presents data supporting a limited ice extent in the Alexander Archipelago during the late Wisconsin and identifies possible ice-free areas that may have served as refugia. These areas include (1) the Fairweather Ground, (2) the Herbert Graves Island area, (3) the western coast of southern Baranof Island and adjacent continental shelf, (4) Coronation Island and the adjacent continental shelf, (5) the Warren Island area, (6) the continental shelf from west of Heceta Island to Forrester Island in the south, (7) parts of the west coast of southern Dall Island, and (8) lowland areas in southern Prince of Wales Island. The identification of these possible refugia has bearing on the recolonization of the Alexander Archipelago, as they could have served as centers of biotic dispersal upon regional deglaciation and as stepping stones for early humans with a maritime tradition entering the western hemisphere from Asia.

Résumé : Les géologues et les biologistes interprètent de manière différente l'étendue de la glaciation au Wisconsin tardif dans le sud-est de l'Alaska. Les cartes et les rapports portant sur la région, préparés par des géologues, indiquent presque tous qu'au Wisconsin tardif la glace s'étendait selon un large front uniforme vers l'ouest, jusqu'au bord de la plate-forme continentale. Toutefois, la distribution des plantes et des animaux dans la région a conduit de nombreux biologistes à postuler qu'il existait peut-être des secteurs libres de glace qui ont servi de refuge durant le Wisconsin tardif. Basé sur des analyses de photographies aériennes, de cartes topographiques et bathymétriques jointes à une analyse bibliographique de documents antérieurs et des travaux de reconnaissance sur le terrain à travers la région, cet article présente des données qui soutiennent une étendue de glace limitée dans l'archipel Alexander au cours du Wisconsin tardif et identifie des secteurs possiblement libres de glace et qui pourraient avoir servi de refuge. Ces secteurs comprennent : (1) les terrains Fairweather, (2) le secteur de l'île Herbert Graves, (3) la côte ouest du sud de l'île Baranof et la plate-forme continentale adjacente, (4) l'île Coronation et la plate-forme continentale adjacente, (5) le secteur de l'île Warren, (6) la plate-forme continentale de l'ouest de l'île Heceta à l'île Forrester au sud, (7) des parties de la côte ouest du sud de l'île Dall et 8) les terres basses du sud de l'île Prince-de-Galles. L'identification de ces refuges possibles a une influence sur le rétablissement de colonies dans l'archipel Alexander car il est envisageable que ces refuges aient servi de centres de dispersion biotique lors de la déglaciation et de chemin pour les premiers humains qui auraient eu une tradition marine, pénétrant dans l'hémisphère ouest en provenance d'Asie.

[Traduit par la Rédaction]

Introduction

The Alexander Archipelago of southeastern Alaska extends for 500 km from Cross Sound southeast to Dixon Entrance (Fig. 1). The region extends about 200 km from the Coast Mountains of the Alaska mainland, which contain many peaks higher than 2200 m in elevation, west to the outer islands. The narrow strip of coastal mainland is isolated from the rest of North America by the heavily glaciated mountains. The Alexander Archipelago includes about 16 000 km of coastline and more than 2000 islands, including seven of the 10 largest in the United States. In many instances, deep, wide glacial channels separate these islands. Several of the islands contain rugged mountain ranges that exceed 1000 m in elevation and support small glaciers and snowfields (e.g., Admiralty, Baranof, and Chichagof).

The climate of the Alexander Archipelago is characterized by a wet maritime regime of mild, wet winters and cool, wet summers. From about September to March, the Aleutian

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Fig. 1. General location map of the Alexander Archipelago of southeast Alaska showing many of the place names discussed in the text and areas of figures presented in this paper.

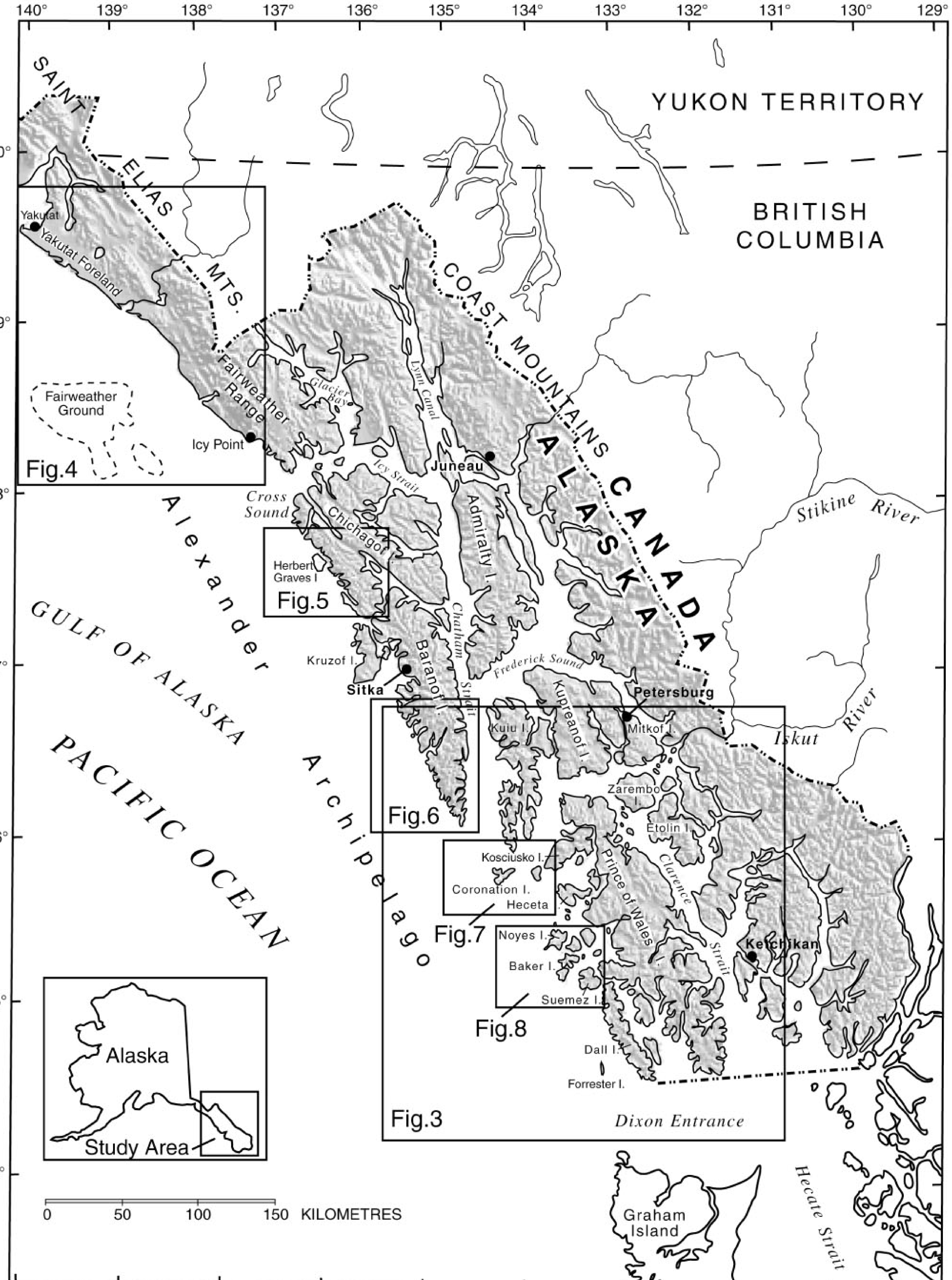
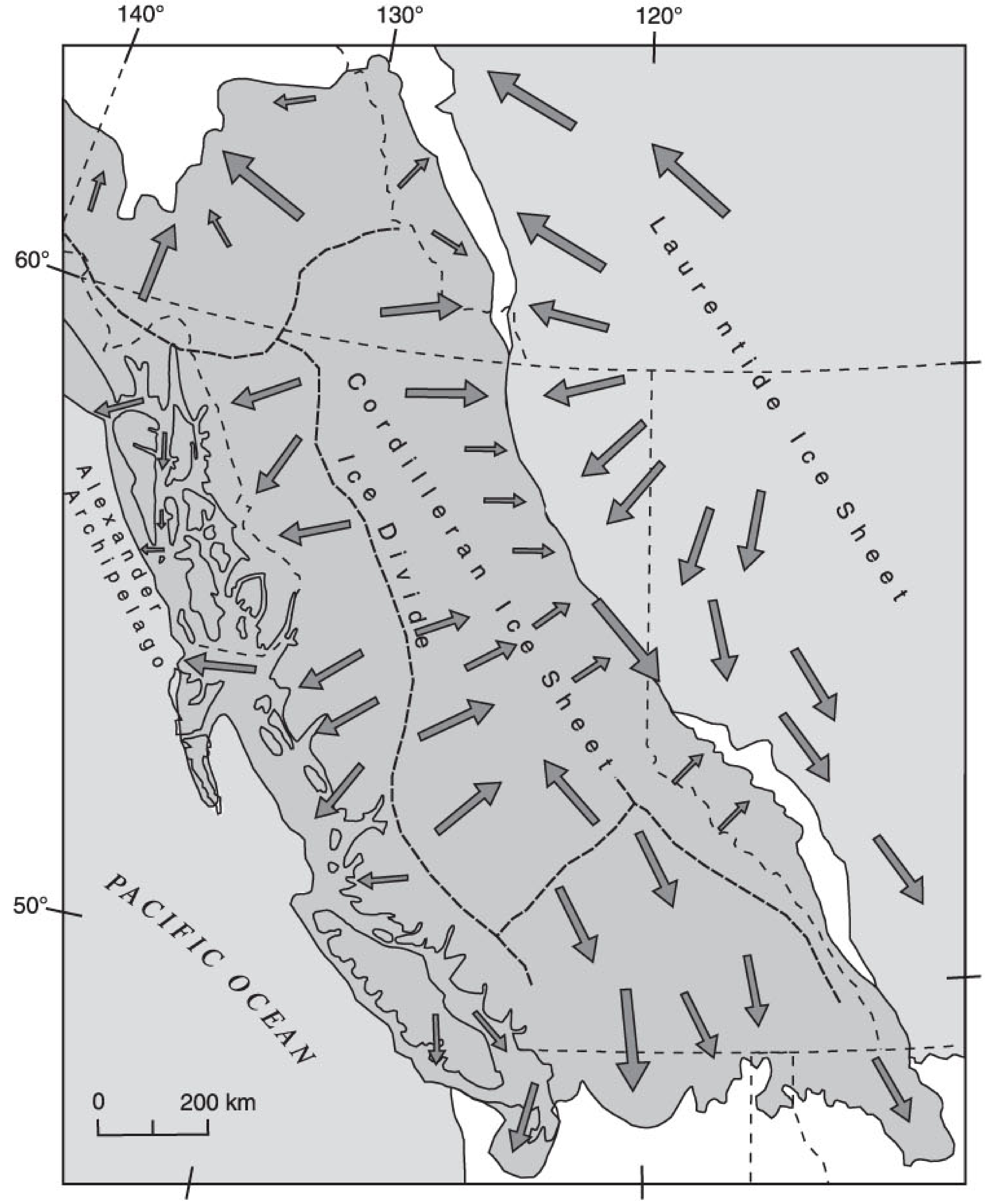


Fig. 2. Map of the late Wisconsin Cordilleran ice sheet as depicted by previous reconstructions. Note that the Alexander Archipelago of southeast Alaska is shown as covered by the ice sheet, which is shown as extending as a large uniform front west to the edge of the continental shelf. Arrows indicate ice-flow direction. Map is modified from Capps 1931, p. 4; Coulter et al. 1965; Flint 1971, p. 465; Péwé 1975, p. 16; Denton and Hughes 1981, fig. 2-2; Prest 1984; Dyke and Prest 1987; Clague 1989; and Clague et al. 2004.

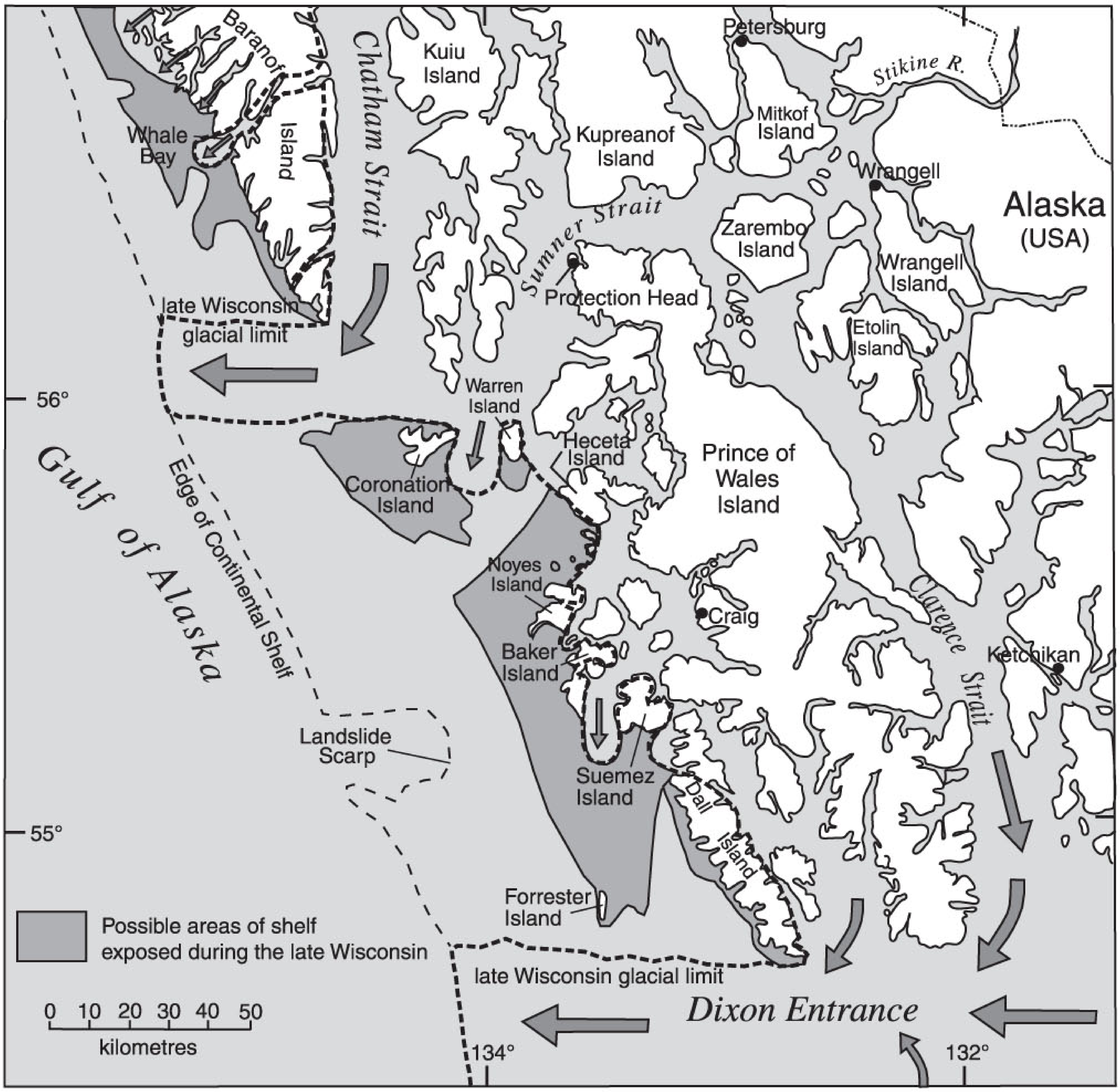


Low, a semipermanent low-pressure system in the Gulf of Alaska, directs an almost continuous series of storms across the region. These storms are blocked from intruding farther inland by the Coast Mountains, resulting in heavy precipitation in the archipelago. From April through August, the Aleutian Low is displaced by the North Pacific High that exerts a moderating influence on the climate, as precipitation generally decreases during this period. However, mean annual precipitation exceeds 300 cm in many areas and is estimated to reach 1000 cm in some places, such as the higher elevations on southern Baranof Island (O'Clair et al. 1997).

During the late Wisconsin glaciation (ca. 26 000 to 13 000 ^{14}C years BP), the Cordilleran ice sheet covered large areas of the Canadian and Alaskan Cordillera (Clague 1989). This ice sheet consisted of a complex of interconnected valley and piedmont glaciers and ice caps, which merged to form the ice sheet. During this time, the ice sheet covered most of British Columbia, southern Yukon Territory, and southern Alaska (Fig. 2). It also flowed onto the plains of Alberta, where it merged with the western edge of the Laurentide ice sheet and sent large lobes into the northwestern United States that filled lowlands from Puget Sound to western Montana (Prest 1984; Clague 1989). The ice sheet stretched more than 2000 km from Washington state to the southern Yukon Territory, and reached altitudes of 2000 to 3000 m over present-day British Columbia, where it was about 900 km in width. At its maximum, the Cordilleran ice sheet was approximately the size of the present-day Greenland ice sheet (Clague 1989).

During the late Wisconsin glaciation, the western margin of the Cordilleran glacier complex formed vast ice fields and large glaciers along the crest of the Coast Mountains. As

Fig. 3. Map of the southern Alexander Archipelago showing restricted late Wisconsin Cordilleran ice limit (note: limits of local glaciers not shown) and areas of the inner continental shelf that may have been subaerially exposed and ice-free and served as refugia at this time (after Carrara et al. 2003). Arrows indicate ice-flow direction.



these glaciers flowed west to the Pacific Ocean, they were joined by local glaciers originating on the higher elevations of the islands of the Alexander Archipelago (Mann and Hamilton 1995), including Admiralty, Baranof, Chichagof, and Prince of Wales islands. This extensive volume of ice was channeled into deep troughs (present-day fjords) that were occupied by major outlet glaciers. Many of these outlet glaciers were 10 to as much as 60 km (Dixon Entrance) wide as they flowed through the Alexander Archipelago to the ocean. Such outlet glaciers occupied Icy Strait, Chatham Strait, Frederick Sound, Clarence Strait, and Dixon Entrance (Mann 1986) (Fig. 1).

In several places along the coast, deep submarine glacially scoured troughs indicate that glaciers reached the western edge of the continental shelf. For instance, the glacier that occupied Chatham Strait excavated a deep (350 m), wide (20 km) trough that extends to the edge of the continental shelf (Fig. 3). Bathymetric contours indicate that a prominent submarine fan is present on the ocean floor west of this trough (Carrara et al. 2003). In addition, the glacier that extended into the Dixon Entrance trough is also known to have extended to the edge of the continental shelf (Barrie and Conway 1999).

Despite knowledge of the broad form of the Cordilleran ice sheet just discussed, the westernmost extent of much of the late Wisconsin Cordilleran ice in southeastern Alaska is poorly known because much of the evidence is now submerged on the continental shelf. In addition, the thick rain forest vegetation prevalent in the area and the general logistical difficulties due to rainy weather and lack of roads hinder investigations. Other problems include the lack of sea-floor imagery with detailed topography and seismic data on the shelf to show the extent and thickness of glacial deposits. Small-scale maps and reports of the region commonly show or imply late Wisconsin ice extending as a large uniform front west to the edge of the continental shelf (Capps 1931, p. 4; Coulter et al. 1965; Flint 1971, p. 465; Péwé 1975, p. 16; Denton and Hughes 1981, fig. 2-2; and Prest 1984). The map by Coulter et al. (1965) was based primarily on unpublished glacial-geologic mapping, much of it of a reconnaissance nature, and aerial photograph analysis by the six coauthors who formed the Alaska Glacial Map Committee of the US Geological Survey (USGS). In the region of southeastern Alaska, Coulter et al. (1965) did not map glacial limits. However, their map displays late Wisconsin ice-surface contours that indicate a uniformly sloping surface high enough to cover the highest summits in the area and extend to the edge of the continental shelf.

Recent glacial-geologic studies suggest that although the late Wisconsin glaciation was extensive in the Alexander Archipelago, some areas may have been ice free at this time (Carrara et al. 2003; Kaufman and Manley 2004). This paper discusses areas of southeastern Alaska that may have been ice free during the late Wisconsin. The importance of ice-free areas in this region is that they may have served as refugia for plants and animals during the late Wisconsin and as "stepping stones" for human migration along the coast of North America during the late Pleistocene (Heusser 1960, 1989; Dixon et al. 1997; Dixon 1999, 2001).

Evidence for a limited ice extent in southeastern Alaska during the late Wisconsin

The presence of ice-free areas, including refugia, during the late Wisconsin glaciation along the coasts of southeastern Alaska and southwestern British Columbia based on the distribution of plants and animals has been previously suggested by a number of authors. The presence of late Wisconsin refugia seems to be best documented for the Queen Charlotte Islands region (McCabe and Cowan 1945; Banfield 1962; Foster 1965; Randhawa and Beamish 1972; Warner et al. 1982; Heusser 1989; Fedje and Josenhans 2000; Hetherington et al. 2003; Lacourse et al. 2005; Reimchen and Byun 2005; Wigen 2005). Clague et al. (1982) concluded that possible refugia in the Queen Charlotte Islands region included (1) a shallow offshore platform bordering eastern Graham Island (Fig. 1) that was probably exposed during the late Wisconsin glaciation by sea-level lowering, (2) nunataks in the mountains of Graham and Moresby Islands, and (3) headlands, islands, and inter-fjord ridges along the west coast. Recently, Reimchen and Byun (2005) concluded a refugium existed on the continental shelf off the central coast of British Columbia.

The limited extent of late Wisconsin glaciation and possible refugia in the Queen Charlotte Islands suggests that the Alexander Archipelago, with a similar topography and climate, may also have had an incomplete ice cover. Indeed, the distributions of plants and animals in this region have led several investigators to suggest that there may have been ice-free areas that served as refugia during the late Wisconsin glaciation and as centers for biotic dispersal upon deglaciation (Hultén 1937; Heusser 1960, 1989; Harris 1965; Klein 1965; Worley and Jaques 1973; Worley 1980; Wheeler and Guries 1982; Kondzela et al. 1994; Heaton et al. 1996; Cook et al. 2001; Fleming and Cook 2002; Heaton and Grady 2003).

In southeastern Alaska, 108 mammal species or subspecies currently inhabit the region. Of these, 27 are endemic to southeastern Alaska and an additional 11 have ranges that are largely confined to the region (MacDonald and Cook 1999; Cook et al. 2001). The endemic mammals occur most frequently on the outer islands, including Baranof, Chichagof, Coronation, Forrester, and Warren islands, whereas the islands lying closer to the mainland are often occupied by mainland mammals (Klein 1965). The endemism is attributed to the glacial history and the complex geography of the region that isolated the fauna. The high degree of endemism and its increase toward the outer islands has been interpreted as suggesting that refugia existed in some areas of the exposed continental shelf and the outer islands of the Alexander Archipelago (see discussion in Heusser 1989).

Brown bears (*Ursus arctos*) are an example of a mammal that may have survived the late Wisconsin glaciation in refugia in the Alexander Archipelago. Differences in mitochondrial DNA (mtDNA) sequences suggest that brown bears in the Alexander Archipelago make up a distinct clade and are more closely related to present-day polar bears (*Ursus maritimus*) than brown bears on the mainland (Heaton et al. 1996). Based on this and other evidence Heaton et al. (1996) concluded that brown bears and possibly other large mammals may have inhabited the archipelago continuously for at least 40 000 years and that habitable refugia were present throughout the late Wisconsin glaciation (Heaton et al. 1996; Heaton and Grady 2003).

Although brown bear population densities vary depending on the productivity of the environment (Alaska Department of Fish and Game 2006), any viable population of brown bears would require an extensive foraging area. In areas of low productivity, such as on Alaska's North Slope, bear densities are as low as one bear per 775 km^2. In areas with abundant available food, such as Admiralty Island in the Alexander Archipelago, densities can be as high as one bear per 2.6 km^2. In central Alaska, both north and south of the Alaska Range, bear densities tend to be intermediate, about one bear per 40–60 km^2 (Alaska Department of Fish and Game 2006). Although the area used by an individual bear may overlap that of other bears, any viable population of brown bears probably requires several thousand square kilometres.

Ermine (*Mustela erminea*) also provide an example of mammals that may have survived the late Wisconsin glaciation in refugia in the Alexander Archipelago. Differences in mtDNA sequences indicate three distinct lineages of ermine in southeastern Alaska (Fleming and Cook 2002). Two of these lineages have a wide distribution (including outside of southeastern Alaska); however, the "island" lineage is found only on Prince of Wales, Suemez, and Heceta islands in southeastern Alaska, and Graham Island in the Queen Charlotte Islands. Because of the island lineage's restricted distribution and its degree of divergence from the other two lineages, Fleming and Cook (2002) concluded that it has been isolated for a prolonged period of time and probably survived the late Wisconsin glaciation in coastal refugia.

Chum salmon (*Oncorhynchus keta*) provide further evidence suggesting that refugia may have existed in the Alexander Archipelago during the late Wisconsin glaciation (Kondzela et al. 1994). The genetic variation of this species is clustered regionally, such that populations from Prince of Wales Island are more like each other than elsewhere in southeast Alaska or coastal British Columbia. This information was interpreted as suggesting that the present-day populations of chum salmon are likely to have been derived from late Wisconsin populations that existed along the outer shores of the present-day continental shelf and used stream channels in refugia that are now underwater (Kondzela et al. 1994).

Shore pine (*Pinus contorta* var. *contorta*) presently occupies a wide range of climatic and soil conditions along the Pacific coast from northern California to southeastern Alaska (Wheeler and Guries 1982). This subspecies played a significant role in the forest succession of the Pacific Northwest, as its pollen is abundant in the early postglacial parts of many pollen records in southeastern Alaska and coastal British Columbia (Heusser 1960). In the Alexander Archipelago, shore pine was the dominant early postglacial tree species (Heusser 1960; Klein 1965). The early arrival of shore pine (by 11 900 ^{14}C years BP) and mountain hemlock (*Tsuga mertensiana*) at a site on Pleasant Island in the Glacier Bay region has been interpreted as suggesting an expansion from refugia in the Alexander Archipelago (Hansen and Engstrom 1996). In addition, five alleles, found nearly exclusively in *Pinus contorta* var. *contorta*, suggest that it has been a separate entity for a considerable period of time (Wheeler and Guries 1982) and is best explained by a "multiple north-coast refugia" model that includes portions of the Alexander Archipelago.

Subalpine fir (*Abies lasiocarpa*) currently exists as isolated (disjunct) stands on Dall (Harris 1965), Prince of Wales (Worley and Jaques 1973), Heceta, and Kosciusko islands. This species inhabits the interior of British Columbia and only in several locations extends westward through the Coast Mountains into the coastal region (Heusser 1989). As the isolated stands are about 150 to 250 km west of the main range of this species, it is suggested that they may have survived during the late Wisconsin glaciation in refugia within the Alexander Archipelago.

Methods

Possible refugia and the limits of the western margin of the late Wisconsin Cordilleran ice sheet were identified by reconnaissance fieldwork throughout much of the region, analyses of National Aeronautics and Space Administration (NASA) false-color, aerial photographs (1 : 60 000 scale), USGS topographic maps (1 : 63 360 and 1 : 250 000 scales), National Ocean Atmosphere Administration (NOAA) bathymetric charts, (at a variety of scales including as large as 1 : 20 000 and 1 : 40 000), and previous literature. In addition, a digital database of southern southeast Alaska containing more than 100 000 depth soundings was contoured and analyzed (Carrara et al. 2003).

Evidence of glaciation, or lack thereof, noted on aerial photographs and topographic maps included the identification of various features such as (1) glacially scoured U-shaped valleys versus stream-eroded V-shaped valleys, (2) the presence or absence of glacially eroded features (e.g., cirques, arêtes), (3) the presence or absence of features of glacial deposition (e.g., moraines, eskers, kames), (4) the presence or absence of glacially streamlined forms (e.g., drumlins, roches moutonées), (5) glacially smoothed and rounded ridges and passes versus sharp-crested ridges and passes, and (6) the presence of strong structural lineations that might have been buried beneath till had the area been glaciated. Fieldwork augmented these observations and noted the presence, or lack thereof, of smaller-scale features (e.g., erratics and glacially striated and polished rock surfaces).

The bathymetric data proved to be quite useful. The concentration of depth soundings on the NOAA charts was generally higher within several kilometres of the coast. On those charts at 1 : 20 000 scale, 15 to 20 soundings per square kilometre were common, whereas on charts at 1 : 40 000 scale, 10 to 15 soundings per square kilometre were common. These data combined with the digital database of southern southeast Alaska (Carrara et al. 2003) allowed us to distinguish a variety of features on the ocean floor, including glacial troughs, areas of hummocky (till?) ocean floor versus areas of smooth, relatively featureless (unglaciated?) ocean floor that were indicated by areas of similar depths or gradually increasing depths to the west approaching the continental shelf edge, and possible paleo-stream channels. In addition, seamounts, and large submarine landslides and fans could also be distinguished.

Possible refugia in southeast Alaska

Many of the high mountains of Admiralty, Baranof, Chichagof, and Prince of Wales islands appear to have been above the level of Cordilleran and local glacial ice during the late-Wisconsin glaciation, as indicated by their sharp-crested ridges and summits. However, it is doubtful that low-altitude forms of plants and small mammals survived on these ridges and summits (Klein 1965), as they would have been subjected to harsh climatic conditions.

It is more likely that refugia in southeast Alaska were confined to (1) unglaciated ocean-facing slopes and forelands (Dahl 1946), (2) the outer islands of the Alexander Archipelago (Worley 1980), and (3) parts of the inner continental shelf exposed by either the lowering of sea level by an estimated 125 m, relative to present (Bard et al. 1990), or a forebulge effect. However, because of the complex interaction of eustatic sea-level fluctuations, isostatic rebound (and forebulge effects), and tectonic movements in southeastern Alaska, the exact areas of the continental shelf that were subaerially exposed by sea-level lowering during the late Wisconsin cannot be identified with certainty. Indeed, our estimates of areas of possible refugia may be a minimum if these areas were affected by a forebulge.

Evidence for the existence of a crustal forebulge in southeastern Alaska is limited at this time, but it is likely that a forebulge formed along the western margin of the Alexander Archipelago and the adjacent inner continental shelf during the late-Wisconsin glaciation. The best evidence comes from a sediment core obtained in lower Sitka Sound during the 2004 oceanographic cruise of the R/V Maurice Ewing, in which one of the authors (Ager) participated. A core (EW0408-40 JC) was obtained in 216 m of water in a glacially scoured trough between Baranof and Kruzof islands. The upper 9 m of the 11.72 m core consists of late-glacial marine mud, but the lower 2.72 m consists of lacustrine deposits containing freshwater diatoms interbedded with at least 10 tephras from the late-glacial eruptions of Mt. Edgecumbe and other volcanoes on Kruzof Island around 11 400 to 10 600 ^{14}C years BP (Riehle et al. 1992). Sitka Sound was filled with glacial ice during the late Wisconsin, but it is likely to have been deglaciated by 13 000 ^{14}C years BP. The freshwater deposits indicate that the floor of Sitka Sound stood above the eustatic sea-level position of about 65 m below present sea level 11 000 ^{14}C years BP (Fairbanks 1989; Bard et al. 1990). The position of those freshwater deposits is now more than 225 m below present sea level indicating a minimum of 160 m of subsidence of the sea floor in lower Sitka Sound following deglaciation. It is suggested that the most likely cause of such a major local subsidence is the rapid collapse of a crustal forebulge that apparently existed along the western edge of Baranof Island, and perhaps all along the western Alexander Archipelago. The transition from freshwater to marine deposits in the core occurred between about 11 000 and 10 500 ^{14}C years BP, about the time when a crustal forebulge collapse was under way on the shelf between the Queen Charlotte Islands and the British Columbia mainland (Hetherington et al. 2003).

In the discussion that follows, evidence for likely refugia in southeastern Alaska is presented. Possible refugia may have existed in and near the following areas: the Fairweather Ground, the Herbert Graves Island area, the west coast of southern Baranof Island and adjacent continental shelf, Coronation Island and the adjacent continental shelf, the Warren Island area, the continental shelf from west of Heceta Island to Forrester Island in the south, parts of the west coast of southern Dall Island, and lowland areas in southern Prince of Wales Island.

Fairweather Ground

Although the Fairweather Ground is somewhat north of the Alexander Archipelago, it is briefly discussed here as it is directly west of the Icy Point – Lituya Bay area that may have had a restricted ice cover during the late Wisconsin (see discussions in Worley 1980; Mann 1986; and Molnia 1986). The Fairweather Ground is a submarine bank, about 100 km west of the Alaska mainland (Fig. 1), with depths about 120 m shallower than the surrounding shelf. Approximately 5000 km^2 of the Fairweather Ground and ocean floor between the Fairweather Ground and the Alaska mainland is <125 m in depth, and much of this area was likely exposed by the lowering of sea level during the late-Wisconsin glaciation. This shallow area extends from Lituya Bay west to the edge of the Continental Shelf (Fig. 4). Submersible observations indicate that shallow areas of the western ground, especially the northern part, were smoothed and contoured by glaciers at some time in the past (H.G. Greene, Moss Landing Marine Laboratories, personal communication, 2001). Two sets of grooves, one from the northeast and the other from the east, were distinguished. However, the western edge of west Fairweather Ground appears to be unglaciated as it contains a series of sedimentary rock pinnacles 20 to 30 m high formed by subaerial erosion (H.G. Greene, Moss Landing Marine Laboratories, personal communication, 2001).

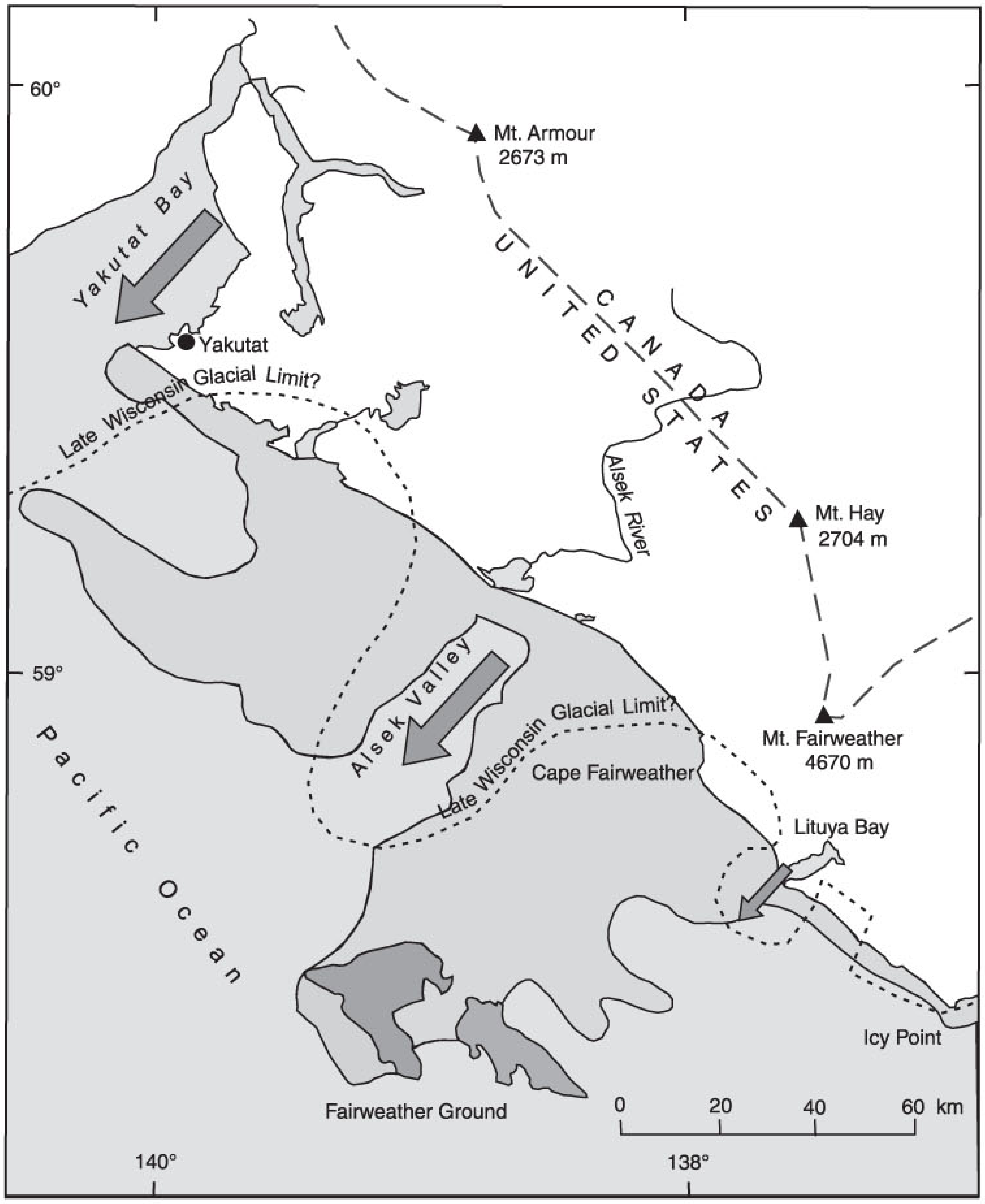
Herbert Graves Island

Herbert Graves Island is a small (about 26 km^2) island off the west coast of Chichagof Island (Figs. 1, 5). Aerial photographs and the topographic map of the island do not display features that indicate the island was overrun by either Cordilleran or local glacial ice. In addition, topographic maps of the island and surrounding area indicate that ice from the interior of Chichagof Island flowed through several valleys opposite Herbert Graves Island but terminated several kilometres east of the island. This ice flowed west through low divides into the heads of the Black River and Goon Dip River valleys (Fig. 5). However, as noted by Reed and Coats (1941, p. 11) the Black River valley changes abruptly from a broad, glacial U-shaped valley to a narrow, V-shaped valley about 2 km east of the western edge of Chichagof Island, as does the Goon Dip River valley (Fig. 5). This change in valley morphology indicates a restricted glacial cover and suggests that the area around Herbert Graves Island and the adjacent continental shelf to the west may have been ice-free and possibly served as a refugium during the late Wisconsin. In addition, aerial photographs of the island show strong structural lineations trending northwest to southeast (Fig. 5), approximately perpendicular to any ice flow direction. If ice from Chichagof Island flowed farther west and had overwhelmed Herbert Graves Island, these lineations should have been obscured by till.

Baranof Island

Baranof Island (Figs. 1, 6) is one of the largest (4065 km^2) islands in the Alexander Archipelago. This large outer island contains a high mountainous divide with elevations ranging from about 600 m to as much as 1625 m. The higher peaks on the island presently support small glaciers and ice fields. Topographic maps of Baranof Island indicate that the sharp-crested divide was high enough in most places to contain the ice of the large outlet glacier in Chatham Strait. Ice from Chatham Strait did flow west through the low pass in the divide at Gut Bay to feed the glacier in Whale Bay (Fig. 6). The bathymetric chart shows a deep glacial trough extending about 8 km southwest from the mouth of Whale Bay onto the continental shelf. The divide was not breached again for another 45 km to the south, where ice from Chatham Strait flowed through a low divide into Puffin Bay Fjord. Hence, the outlet glacier in Chatham Strait was largely confined to this strait, where it flowed due south to the southern tip of Baranof Island. At this point, the glacier then flowed sharply to the west to the outer edge of the continental shelf (Fig. 3). From Whale Bay south to near the southern end of the island, the western side of Baranof Island supported only local mountain glaciers. These glaciers headed in cirques on the island's divide and flowed to the southwest. South of Whale Bay, the terrain along the western coast has a strong structural trend to the northwest. Here, streams, lakes, and ridges are

Fig. 4. Map of the Fairweather Ground area (dark shading) showing those areas of the continental shelf (shaded) that are <125 m below present sea level; some of which may also have been refugia during the late Wisconsin glaciation. Arrows indicate ice-flow direction. Possible late Wisconsin glacial limit (dashed line) modified from Mann (1986) and Molnia (1986).



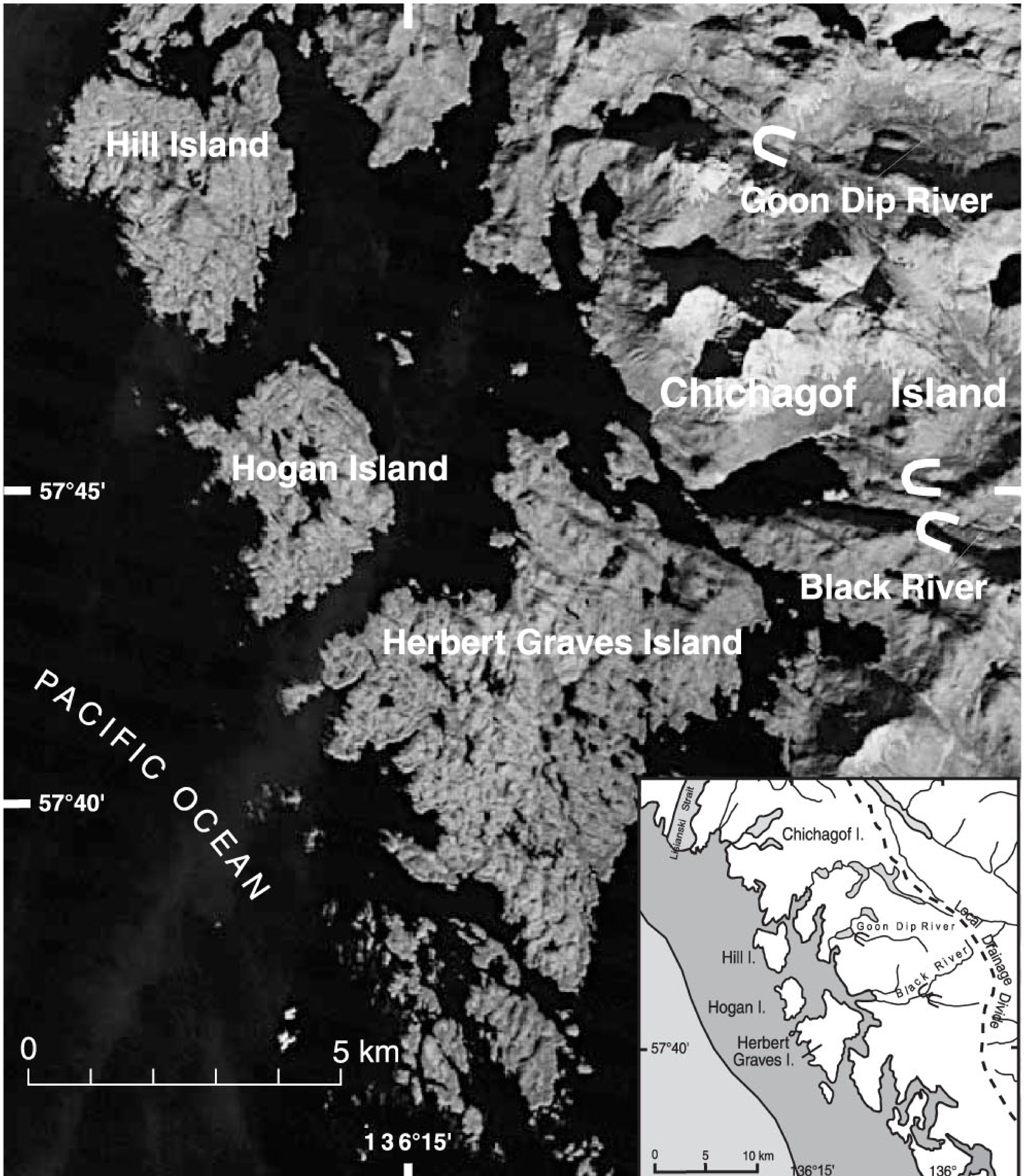
aligned to the northwest. Many of the valleys have V-shaped profiles. Local mountain glaciers flowing southwest from the divide were blocked and diverted northwest by ridges 300 to 580 m in height, protecting this area from glaciation.

In the summer of 2000, fieldwork in the area south of Whale Bay, near Sandy Bay and Still Harbor (Fig. 6), failed to identify any glacial deposits such as till, outwash, large granitic erratics from the Coast Mountains, or local erratics that should have been present had the area been overridden by the western margin of the Cordilleran ice sheet. In addition, glacially striated and polished rock surfaces are absent in these areas. These observations suggest that the western part of Baranof Island in the vicinity of Whale Bay south to near the southern end of the island and the adjacent continental shelf, about 510 km^2 (Carrara et al. 2002), may have served as a refugium during the late Wisconsin. Heusser (1989) also concluded that Baranof Island was likely to have had an ocean-side refugium.

Coronation Island

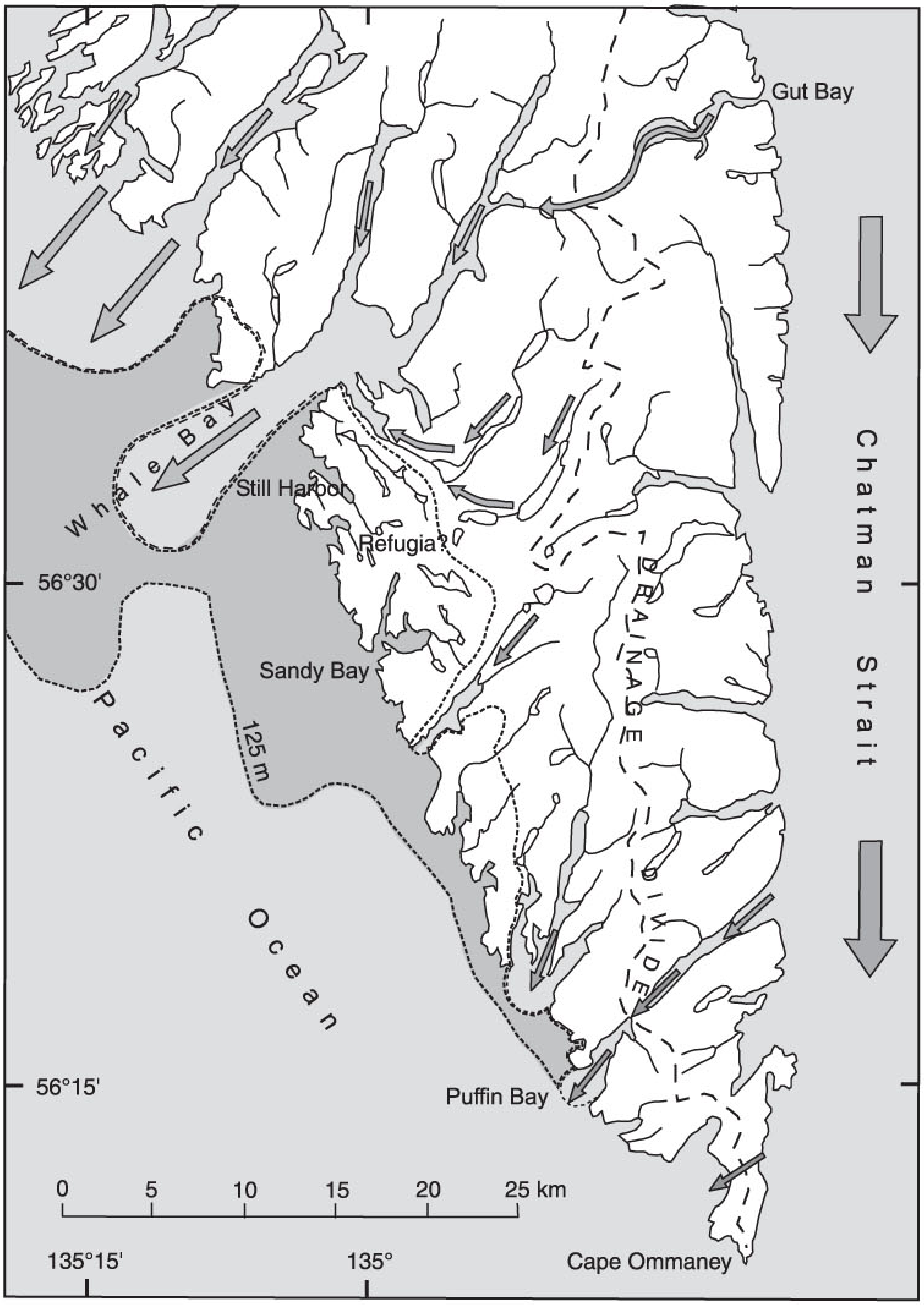
Coronation Island, about 70 km^2 in area, is one of the outermost islands in the Alexander Archipelago and lies about 50 km southeast of the southern end of Baranof Island across Chatham Strait (Figs. 1, 3). The highest point on the island is Needle Peak at an elevation of about 600 m. Although the large outlet glacier in Chatham Strait was only about 10 to 15 km to the northwest of Coronation Island, aerial photographs and the topographic map of the island do not display features that indicate the island was overrun by Cordilleran ice. There are several drowned amphitheaters suggesting that

Fig. 5. Part of 1986 NASA satellite image mosaic in bands 2, 4, and 5, of the Herbert Graves Island area. Note the strong lineations to northeast in bedrock of Herbert Graves, Hogan, and Hills islands. U symbol marks location where valleys on the western side of Chichagof Island change from U-shaped valleys to V-shaped valleys.



the island supported local glaciers at some time in the past (Wisconsin?). The bathymetric chart indicates a trough (>55 m deep) in Windy Bay (Fig. 7), on the west side of the island; however, the trough shallows several kilometres to the west, indicating that the glacier, if present, was not extensive. The chart also suggests a relatively smooth, featureless ocean floor south and west of the island extending about 20 km to the edge of the continental shelf. Hence, the unglaciated ocean-facing slopes and forelands on Coronation Island and the adjacent continental shelf to the south and west, an area of about 750 km^2, (Carrara et al. 2002), may have been a refugium during the late-Wisconsin glaciation.

Fig. 6. Map of the southern Baranof Island area. Dotted line represents areas of island and continental shelf that were likely ice-free during the late Wisconsin and may have served as refugia. Darker shaded area represents that part of the continental shelf <125 m below present sea level. Arrows indicate ice-flow direction.

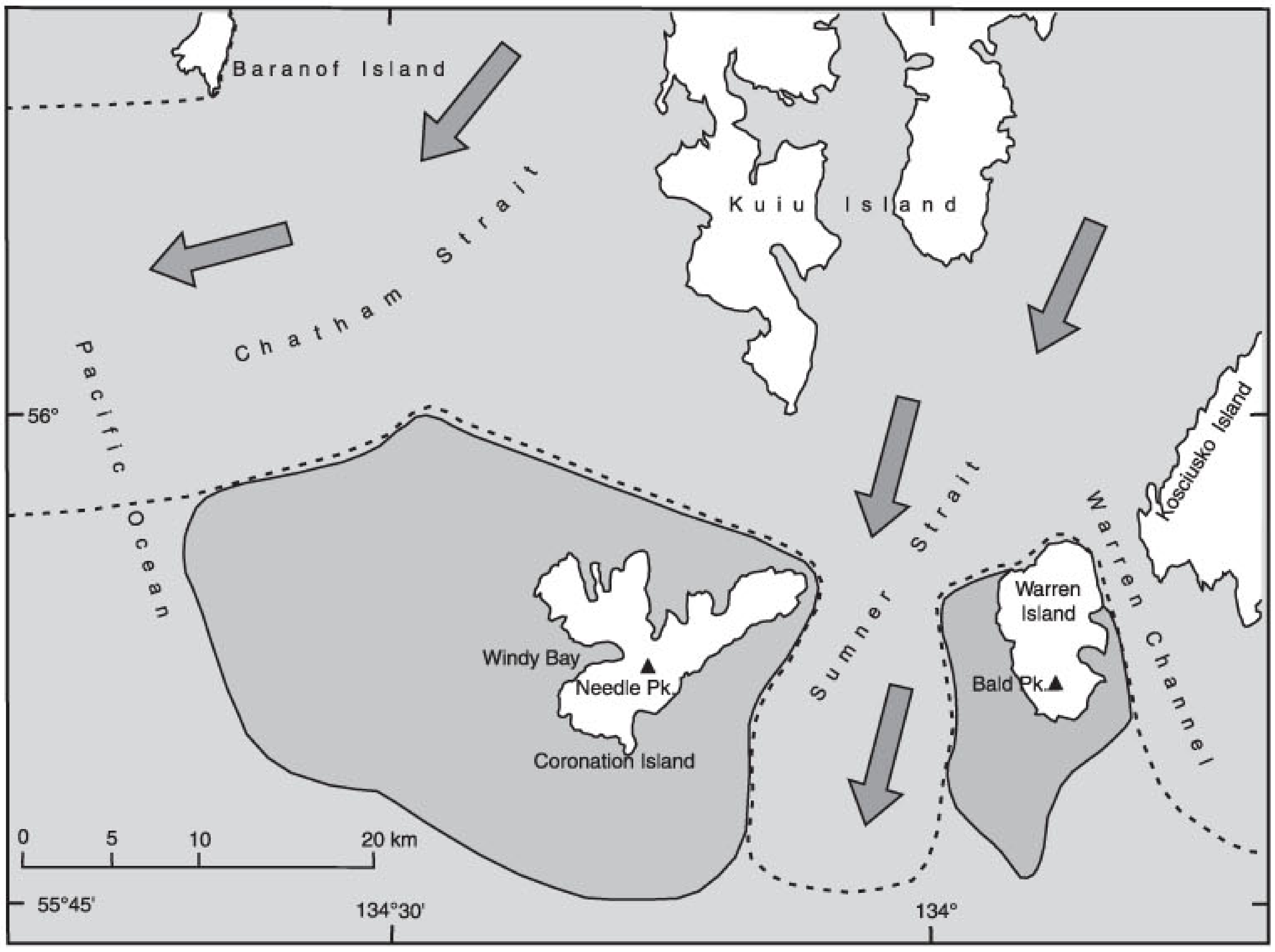


A brown bear skeleton that yielded a radiocarbon age of 11 630 ± 120 ^{14}C years BP was found in Colander cave on the western side of Coronation Island (Heaton 2002; Heaton and Grady 2003). Brown bear are not presently found on the island (MacDonald and Cook 1999), and the presence of brown bear soon after deglaciation may indicate the presence of nearby refugia from where brown bear could have migrated. As brown bears are omnivores, eating a wide assortment of plants and animals, their presence suggests the existence of an established ecosystem with a variety of plants and presumably other animals (Wigen 2005).

Warren Island

Warren Island, about 50 km^2 in area, is about 15 km east of Coronation Island (Figs. 3, 7). The highest point on Warren Island is Bald Peak (675 m). Bathymetric charts indicate deep glacially scoured troughs along the west and east sides of Warren Island. During the late Wisconsin, a lobe of ice

Fig. 7. Map of the Coronation and Warren islands area. Darker shaded area indicates areas of the continental shelf <125 m below present sea level, which may have served as refugia during the late Wisconsin. Arrows indicate ice-flow direction. Dotted line represents possible late Wisconsin glacial limit.



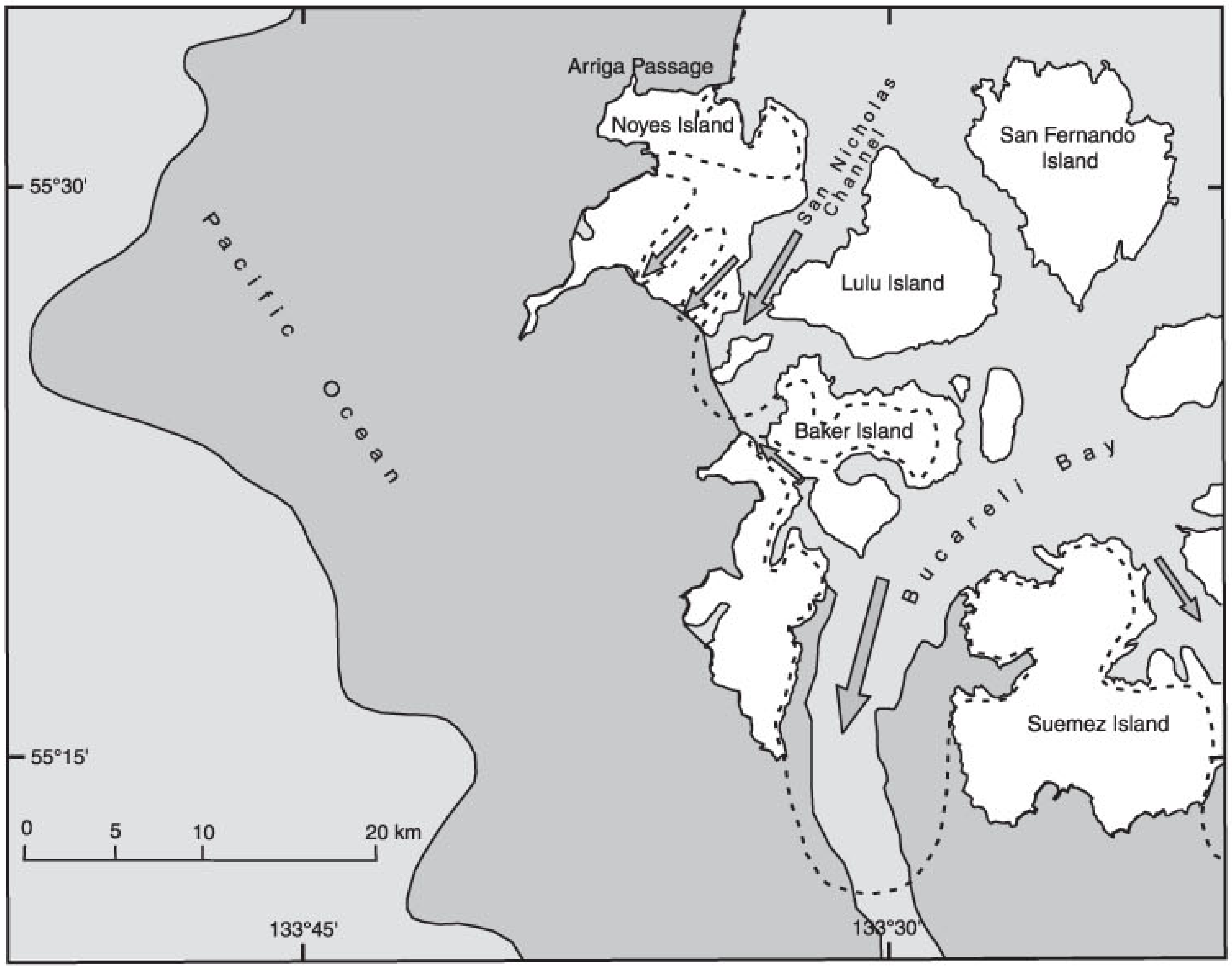
flowed into the deep (>275 m) Sumner Strait trough that separates Warren Island from Coronation Island. To the east of Warren Island, a lobe of ice flowed into the deep (>180 m in places) Warren Channel. However, south of Warren Island a broad, shallow (<90 m) shelf extends outward about 10 km; to the west, this shelf narrows in width to about 4 km. The topographic map of the island suggests that it was not overrun by continental ice as the divide of the island does not appear to have been breached by ice from the east. The topographic map does show several features that may be drowned valleys on the eastern side of the island. These valleys head in large amphitheaters and suggest that the island may have supported local glaciers during the late Wisconsin. These observations support the presence of unglaciated ocean-facing slopes and forelands on Warren Island and the adjacent continental shelf to the south and west that may have served as a refugium during the late Wisconsin.

Area from west of Heceta Island to Forrester Island

A large area of the continental shelf (2500 km^2), stretching for more than 100 km from west of Heceta Island to Forrester Island in the south (Fig. 3), and ranging from about 15 to 40 km west to east, may have served as a refugium during the late Wisconsin. Most, but not all, of Heceta Island appears to have been covered by Cordilleran ice, although the island appears to have been near the western edge of the late-Wisconsin glacial limit (Fig. 3). Bathymetric charts indicate a deep (180 m) channel along the south-southeastern side of the island; however, this channel shallows and ends abruptly to the west and suggests the presence of a moraine (terminal?) on the ocean floor south of the central part of the island. Furthermore, a late-Wisconsin terminal position is suggested by uniformly shallow water depths, immediately east of a chain of small islands stretching from southeastern Heceta Island in the north to Noyes Island in the south (Fig. 3). Hence, ocean-facing slopes and forelands on the western side of Noyes, Baker, and Suemez islands and the adjacent continental shelf may have served as refugia.

Noyes (85 km^2), Baker (105 km^2), and Suemez (135 km^2) islands are three outer islands to the west of Prince of Wales Island (Figs. 1, 3). Analyses of aerial photographs and topographic maps of Noyes Island indicate that glacial ice was banked up against the north and east sides of the island as it flowed through St. Nicholas Channel (Fig. 8). Two valleys on the southern part of the island were invaded by overflowing ice from St. Nicholas Channel and these glaciers flowed to the southwest side of the island. However, the rest of the island does not appear to have been crossed by Cordilleran ice, at least during the late Wisconsin. The bathymetric chart of the area indicates that St. Nicholas Channel reaches a depth of 115 m. However, this channel and the ocean floor adjacent to the two through-flowing valleys on the southern part of the island do not extend into the ocean floor south of Noyes Island. A deep, narrow channel in Arriaga Passage to the north of the island appears to have been formed subaerially. Several U-shaped valleys indicate that the island supported local glaciers in the past. The bathymetric chart shows a relatively smooth, featureless ocean floor extending west for as much as 30 km to the edge of the continental shelf. This could be, at least in part, a result of postglacial

Fig. 8. Map of the Noyes, Baker, and Suemez islands area. Darker shaded area indicates areas of continental shelf <125 m below present sea level, which may have served as refugia during the late Wisconsin. Arrows indicate ice-flow direction. Dotted line represents possible late Wisconsin glacial limit.



marine sediment accumulation. However, even with up to 20 m of marine mud, deep glacial troughs would be discernable on bathymetric maps.

Analyses of aerial photographs and topographic maps of Baker Island suggest that continental ice from the lobe in Bucareli Bay, east of the island (Fig. 8), flowed through a low valley to the western side of the island. The highest point on the floor of this through-flowing valley is about 30 m. The rest of the island divide does not appear to have been breached by ice from the east. Several drowned valleys on the island indicate that the island supported local glaciers in the past. The bathymetric chart of the area indicates a deep (>275 m in places) glacial trough in Bucareli Bay. However, to the west, the bathymetric charts indicate a smooth, featureless ocean floor extending about 30 km to the edge of the continental shelf.

Analysis of aerial photographs and topographic maps of Suemez Island suggest that parts of the island were inundated by continental ice, both from the lobe in Bucareli Bay along the west side of the island and a small lobe along the east side of the island. Ice from these lobes appears to have flowed into the interior of Suemez Island, such that only the higher parts may have been above the ice level. It is doubtful that a refugium of any significant size existed on the island.

Forrester Island lies in the far southwestern part of the Alexander Archipelago about 30 km west of Dall Island (Fig. 3). The island is only about 8 km long (north to south) and about 2 km at its widest point. The central ridge, which trends north to south, culminates at an elevation of 410 m. The island shows no signs of prior glaciation (Worley 1980). A search of the island for the deepest and oldest peat section yielded a radiocarbon age of only 6470 ± 160 ^{14}C years BP from the basal peat of a section about 2.75 m deep (Worley 1980). The young radiocarbon age and the low floral diversity led Worley (1980) to suggest that Forrester Island may have been tectonically uplifted above sea level in postglacial time and hence to discount the probability of the island having been an important refugium during the late Wisconsin. However, the amount of uplift (> 500 m = 410 m height of the island + 125 m lowering of sea level during the late Wisconsin) required to raise the island above present sea level during postglacial time seems unlikely.

Hence, it is suggested that a large area of the continental shelf from west of Heceta Island to Forrester Island and incorporating the ocean-facing slopes and forelands of Noyes and Baker Islands and all of Forrester Island may have served as a refugium during the late-Wisconsin glaciation.

Dall Island

Dall Island (655 km^2) is about 90 km long (northwest to southeast) and about 15 km across at its widest point (Fig. 3). The drainage divide culminates at an elevation of about 760 m, although the highest point is Thunder Mountain (950 m) along the west side of the island. Aerial photographs and topographic maps of the island indicate the presence of numerous fjords and glacial valleys indicating that the island had been substantially glaciated during the late Wisconsin. The northern one-third of the island was overrun by ice from Prince of Wales Island to the east. The southern part of the island supported local glaciers. Bathymetric charts indicate steep ocean floor off the west coast of the island; for most of the length of the island the 90 m (50-fathom) contour is less than several kilometres offshore. Deep major channels are absent along the west coast, indicating that major outlet glaciers did not cross the island.

Several lines of biological evidence suggest that refugia may have been present on or near Dall Island. As discussed earlier, isolated stands of subalpine fir on the island (Harris 1965) could have been derived from refugia within the region. A brown bear skeleton, which yielded a radiocarbon age of 11 715 ± 120 ^{14}C years BP, was found in Enigma cave on Dall Island (Heaton 2002; Heaton and Grady 2003). Brown bears are not found on the island today (MacDonald and Cook 1999), and the presence of a brown bear soon after deglaciation may indicate the presence of nearby refugia. Together these data suggest that the unglaciated ocean-facing slopes and forelands along the west side of Dall Island and narrow strips of adjacent continental shelf exposed by a lowering of sea level may have formed a series of refugia in the region.

Prince of Wales Island

Prince of Wales Island is the largest island (6675 km^2) in the Alexander Archipelago (Fig. 1). Although not an outer island, Prince of Wales Island contains several fossil localities that provide important information regarding the extent and duration of the late-Wisconsin glaciation. Radiocarbon ages have been obtained from bones of late Pleistocene and Holocene animals recovered from caves in the northwestern part of the island (Heaton et al. 1996; Baichtal et al. 1997; Dixon et al. 1997; Heaton and Grady 2003). The radiocarbon ages have been processed by several different laboratories and are uncorrected for those animals with a marine diet (correction of about 600 years) so that there may be some discrepancy in the ages. Nonetheless, the 100+ finite radiocarbon ages form an almost complete sequence from about 40 000 – 10 000 ^{14}C years BP (Heaton and Grady 2003). Although till of apparent late-Wisconsin age is present at the mouth of On Your Knees cave, near Protection Head (Fig. 3), the radiocarbon ages are important in that they indicate that this part of northern Prince of Wales Island could not have been covered by glacial ice during much of the late Wisconsin. A gap in the radiocarbon ages occurs between about 17 100 and 14 500 ^{14}C years BP, corresponding to the time of maximum ice extent (about 16 000 – 15 500 ^{14}C years BP) on the Queen Charlotte Islands and adjacent continental shelf (Blaise et al. 1990), and probably indicates the time when the cave entrance was covered by glacial ice. As the source of Cordilleran ice on Prince of Wales Island was from the north and northeast and apparently of limited duration, some areas in the southern part of the island may have been free of Cordilleran ice and supported only local glaciers and ice caps on the higher reaches during the late Wisconsin (S.M. Karl and T.D. Hamilton, US Geological Survey, personal communication, 2001). In addition, Sainsbury (1961) noted till of two different ages in east-central Prince of Wales Island. Although he was unsure of the ages of these tills, he concluded that the younger till was deposited by local glaciers and not Cordilleran ice (Sainsbury 1961). Hence, some lowland areas on the southern part of Prince of Wales Island may have served as a refugium.

Fossil remains of brown bear, a species not present on Prince of Wales Island today, have been found in several caves in the northern part of the island. At On Your Knees cave, radiocarbon ages of 39 400 ± 3100, 35 365 ± 800, 31 700 ± 1900, and 26 820 ± 700 ^{14}C years BP were obtained on the remains of brown bears (Heaton and Grady 2003), clearly indicating the presence of this species on the island prior to the late-Wisconsin glaciation (Heaton et al. 1996). Radiocarbon ages of the remains of brown bears found in other caves on the island range from 12 295 ± 120 to 7205 ± 65 ^{14}C years BP (Heaton et al. 1996; Heaton 2002; Heaton and Grady 2003). The presence of brown bears on the island before and soon after regional deglaciation may indicate the presence of nearby refugia.

Caribou are a good indicator of the possible presence of nearby refugia in the Prince of Wales Island area. Radiocarbon ages obtained on the remains of caribou recovered from caves on northern Prince of Wales Island indicate they were present before and after the late-Wisconsin glaciation (Heaton and Grady 2003). In addition, caribou persisted on the nearby Queen Charlotte Islands until the early 1900s (Banfield 1962).

The dispersal of mammals from refugia to recently deglaciated terrain may have been facilitated by the presence of sea ice. Ringed seals (*Phoca hispida*) are an indicator of sea ice, and their remains, which appear to have been scavenged, are quite abundant in On Your Knees cave (Heaton 2002; Heaton and Grady 2003). Approximately 25 radiocarbon ages of ringed seal bones range from about 24 150 ± 490 to 13 690 ± 240 ^{14}C years BP (with some gaps) (Heaton 2002; Heaton and Grady 2003) and suggest that the area around northwestern Prince of Wales Island supported sea ice and, therefore, may have facilitated the seasonal movement of large mammals during this time.

Refugia and early humans

The presence of early humans in the Alexander Archipelago (Prince of Wales Island) is demonstrated by radiocarbon ages of 9880 and 9730 ^{14}C years BP on a human mandible and pelvis (marine reservoir corrected to ca. 9200 ^{14}C years BP) (Dixon et al. 1997; Dixon 1999; Heaton and Grady 2003). In addition, a bone tool believed to be from a black bear (*Ursus americanus*) rib yielded a radiocarbon age of 10 300 ^{14}C years BP (Dixon 1999; Heaton and Grady 2003). In the Queen Charlotte Islands, a small stone tool assemblage from caves includes points dating to 10 600 ^{14}C years BP (Fedje and Mackie 2005) and artifacts from a submerged site indicate the presence of humans by ca. 9300 ^{14}C years BP (Josenhans et al. 1997). Prehistoric inhabitants of both the Alexander Archipelago and Queen Charlotte Islands would more than likely have been confined to the coastal regions, which contained abundant sea life, and to the mouths of major rivers, which supported large salmon runs.

The Alexander Archipelago, including Prince of Wales and surrounding islands, experienced a complex array of eustasy and glacio-isostatic crustal adjustments during the late Wisconsin, similar to those reported in the Queen Charlotte Islands to the south (Hetherington et al. 2003). It appears that the mainland and the islands east of Clarence Strait (Fig. 3) were subjected to substantial isostatic subsidence under the weight of glacial ice. Deglaciated by ca. 13 000 ^{14}C years BP, shorelines near Ketchikan rose to a height of at least 54 m above present-day sea level.

On Prince of Wales and surrounding islands, the oldest uplifted shell-bearing marine sediments have been dated to between 9700 and 9200 ^{14}C years BP and are found only about 12.5 m above present-day sea level (Putnam and Fifield 1995). Older shell-bearing glacial marine strata are not exposed above the present shoreline suggesting that, as has been reported in the Queen Charlotte Islands (Hetherington et al. 2003), a glacial forebulge developed under Prince of Wales and the surrounding islands. If this assumption is correct, then as previously mentioned, areas of possible refugia could be much more extensive in area than previous estimates (Carrara et al. 2003) and those proposed in this paper. Although several archeological sites dating from the early Holocene are present on the outer islands of the archipelago (see discussion in Dixon 1999), much of the possible earlier evidence of human occupation along the outer coast is likely now below sea level. Evidence of early postglacial human occupation may exist farther to the east, near the Alaska mainland, where the continental ice was much thicker and isostatic rebound greater. There, late Pleistocene and early Holocene marine deposits are found high above present-day sea level (Mann 1986; Mobley 1988).

Conclusions

Several areas in the Alexander Archipelago of southeastern Alaska may have been ice-free during the late-Wisconsin glaciation and served as refugia for various species of plants and animals. The probable refugia in southeast Alaska were confined to (1) unglaciated ocean-facing slopes and forelands of some of the islands (Dahl 1946), (2) the outer islands (Worley 1980), and (3) parts of the inner continental shelf exposed by the lowering of sea level by an estimated 125 m, relative to present (Bard et al. 1990), or raised by a glacial forebulge. These areas include (1) the Fairweather Ground, (2) the Herbert Graves Island area, (3) the western coast of southern Baranof Island and adjacent continental shelf, (4) Coronation Island and the adjacent continental shelf, (5) the Warren Island area, (6) the continental shelf from west of Heceta Island to Forrester Island in the south, (7) parts of west coast of southern Dall Island, and (8) lowland areas in southern Prince of Wales Island. These areas would have served as centers of biotic dispersal upon deglaciation and as “stepping stones” for early humans, with a maritime tradition, entering the western hemisphere from Asia.

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