Ecosystem development in the Girdwood area, south-central Alaska, following late Wisconsin glaciation

T.A. Ager, P.E. Carrara, and J.P. McGeehin

Abstract: Pollen analysis of two cores with discontinuous records from a peat bog near Girdwood, in south-central Alaska, provides the basis for reconstructing the first radiocarbon-dated outline of postglacial history of vegetation in the upper Turnagain Arm area of Cook Inlet. Pollen data from clayey silt underlying peat at one site indicate that the earliest known vegetation in the Girdwood area was shrub–herb tundra. Tundra vegetation developed by ∼13 800 cal years BP, soon after local retreat of glacial ice from the maximum position of the Elmendorf glacial advance (∼15 000 – 11 000 cal years BP). By ∼10 900 cal years BP, the tundra vegetation became shrubbier as *Betula nana*, *Salix*, and Ericales increased, and scattered *Alnus* shrubs began to colonize Turnagain Arm. By ∼9600 cal years BP, *Alnus* thickets with Polypodiaceae ferns became the dominant vegetation. By ∼6600 cal years BP, birch trees (*Betula neoalaskana*, *B. kenaica*) from the Anchorage and Kenai lowlands began to spread eastward into eastern Turnagain Arm. Mountain hemlock (*Tsuga mertensiana*) began to colonize the Girdwood area by ∼3400 cal years BP, followed soon after by Sitka spruce (*Picea sitchensis*), both Pacific coastal forest species that spread westward from Prince William Sound after a long migration from southeastern Alaska. For at least the past 2700 cal years, Pacific coastal forest composed mostly of *Tsuga mertensiana*, *Picea sitchensis*, and *Alnus* has been the dominant vegetation of eastern Turnagain Arm.

Résumé : Une analyse de pollens de deux carottes dont les données sont discontinues, prélevées dans une tourbière à proximité de Girdwood, dans le centre-sud de l'Alaska, fournit une base pour la reconstruction des premières grandes lignes de l'historique post-glaciaire de la végétation dans la partie supérieure de la région du bras Turnagain du bras de mer Cook, tel que déterminé par datation au radiocarbone. À un site, les données sur le pollen provenant d'un silt argileux sous la tourbe indiquent que la première végétation connue dans la région de Girdwood était une toundra arbustive et herbacée. La végétation de toundra s'est développée vers ∼13,800 années calibrées avant le présent (années cal. BP), peu après le retrait local de glace de la position maximale de l'avancée glaciaire Elmendorf (∼15,000–11,000 années cal. BP). Vers ∼10,900 années cal. BP, la toundra est devenue plus arbustive alors que les quantités de *Betula nana*, de *Salix* et d'Ericales augmentaient et que des arbustes *Alnus* dispersés commençaient à coloniser la péninsule Turnagain. Vers 9600 années cal. BP des taillis *Alnus* avec des fougères de Polypodiaceae constituaient la végétation dominante. Vers 6600 années cal. BP, des bouleaux (*Betula neoalaskana*, *B. kenaica*) des basses terres d'Anchorage et de Kenai commençaient à se répandre vers l'est dans la péninsule Turnagain orientale. La pruche subalpine (*Tsuga mertensiana*) a commencé à coloniser la région de Girdwood vers 3400 années cal. BP, suivi de près par l'épinette de Sitka (*Picea sitchensis*), deux espèces de la forêt côtière du Pacifique qui se sont étendues vers l'ouest du golfe du Prince William après une longue migration du sud-est de l'Alaska. Pour les 2700 dernières années calibrées au moins, la forêt côtière du Pacifique était composée principalement de *Tsuga mertensiana*, *Picea sitchensis* et de *Alnus* a constitué la végétation dominante de bras Turnagain orientale.

[Traduit par la Rédaction]

Introduction

Pollen analysis of Quaternary peat deposits and fine-grained sediments is a valuable method for reconstructing past vegetation changes on time scales of centuries to many thousands of years. Late Quaternary pollen records have been used to develop vegetation histories for many areas of Alaska (e.g., Ager 1983; Ager and Brubaker 1985; Heusser 1985; Anderson and Brubaker 1993; Anderson et al. 2004), but the Turnagain Arm area of upper Cook Inlet, south-central Alaska (Fig. 1), has received little attention. The vegetation history of Turnagain Arm is of interest because it now has Pacific coastal forest at the east end, boreal forest at the far west end, and a mixture of the two vegetation types in between. In this paper, we reconstruct the history of these vegetation types in the region by providing the first radiocarbon-dated pollen records to be published from eastern Turnagain Arm. We then discuss these new records within a larger regional context of topographic and climatic influences.

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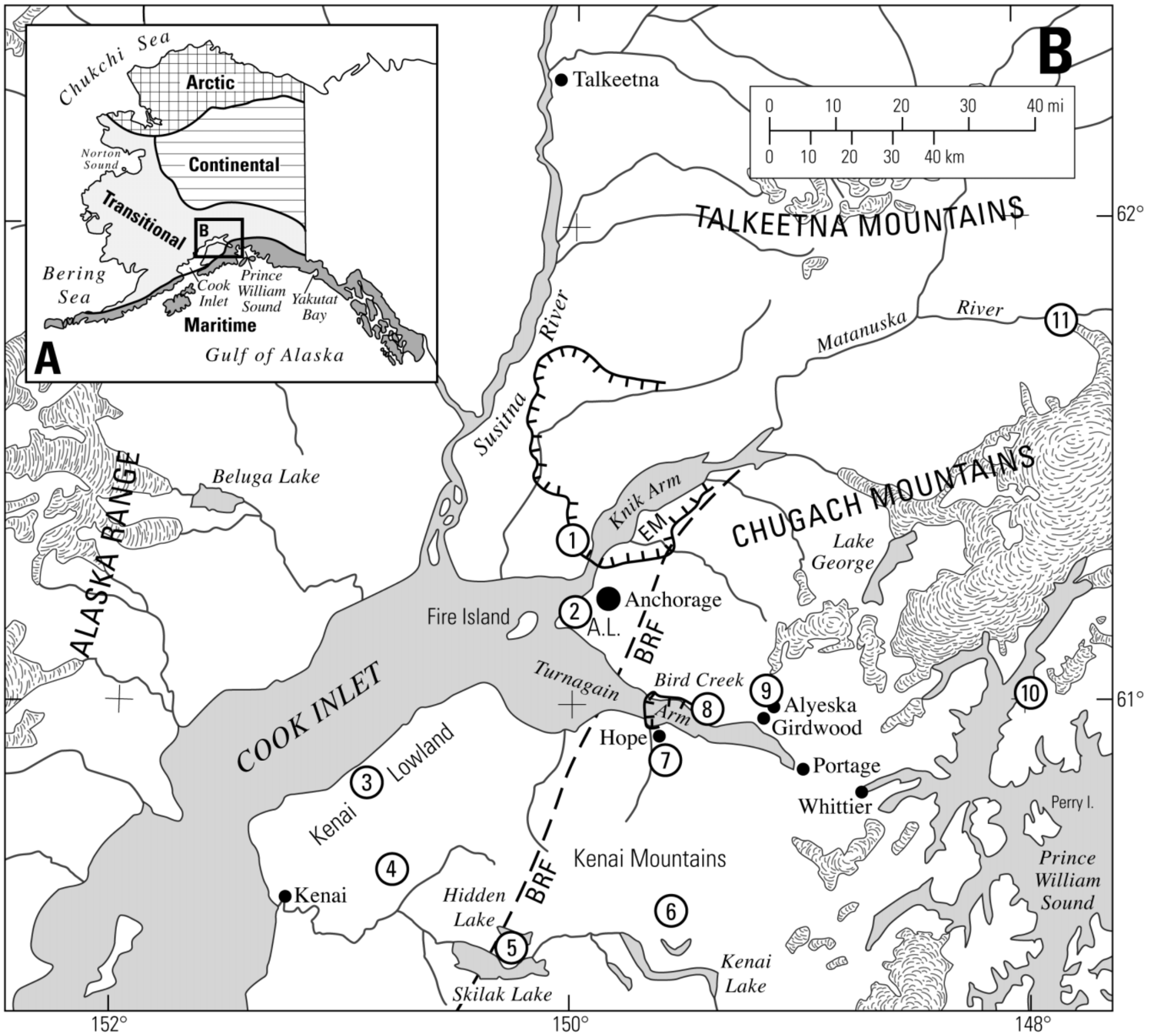
Fig. 1. (A) Inset map of Alaska showing present-day climate zones (modified from Péwé 1975). (B) Map of upper Cook Inlet, south-central Alaska, showing Turnagain Arm, western Prince William Sound, the northern Kenai Peninsula, the western Chugach Mountains, and northern Kenai Mountains. Also shown are communities where climate data used in this study were recorded (Kenai, Anchorage, Hope, Girdwood, Alyeska, Portage, and Whittier (Table 1)). Numbered circles show locations of important sites from which pollen data and (or) radiocarbon dates relevant to this study were obtained: (1) Lake Lorraine (Kathan et al. 2004); (2) Point Woronzof peat section and nearby Earthquake Park peat core (Ager and Brubaker 1985; Ager and Carrara 2006); (3) Swanson Fen (Jones et al. 2009); (4) Paradox Lake (Anderson et al. 2006); (5) Hidden Lake (Ager 1983); (6) Tern Lake peat bog (Ager 2001); (7) Hope area peat bog (Ager and Carrara 2006); (8) Bird Creek peat bog (Ager and Carrara 2006); (9) Girdwood area peat bog (Heusser, 1960; this paper); (10) Golden peat deposit, northwestern Prince William Sound (Heusser 1983a); (11) Matanuska Glacier peat exposures and pond sediments (Williams 1986; Yu et al. 2008). Approximate maximum positions of Elmendorf glacial advances in the Anchorage – lower Susitna Valley and western Turnagain Arm areas are shown by arcuate hachures (Reger et al. 1995; Reger et al. 2007). The type Elmendorf moraine near Anchorage is shown by the letters EM. Broken line shows position of the Border Ranges fault (BRF) that separates the Chugach Mountains from the Anchorage Lowland (A.L.), and the Kenai Mountains from the Kenai Lowland.



Turnagain Arm is an east–west-trending glacial fjord that has been largely filled with sediments since deglaciation (Fig. 1B). It is bordered along most of its length by the Chugach Mountains to the north and the Kenai Mountains to the south (Fig. 1B). Beyond the western flanks of the Chugach and Kenai mountains, near where Turnagain Arm joins with the main trough of Cook Inlet, the fjord is bordered to the north by the Anchorage Lowland and to the south by the northern Kenai Lowland (Fig. 1B). During the late Wisconsin glacial interval, ice expanding from the Alaska Range and the Kenai, Chugach, and Talkeetna mountains converged in Cook Inlet to cover much of the region several times (Fig. 1B; Karlstrom 1964; Schmoll and Yehle 1986; Reger and Pinney 1997; Schmoll et al. 1999; Reger et al. 2007).

Reconstructing the history of terrestrial ecosystem development following deglaciation of Turnagain Arm is also of interest because the region is one of climate transition, and a strong precipitation gradient exists today between northwest Prince William Sound and the Anchorage Lowland

Table 1. Climate data for upper Cook Inlet and northwest Prince William Sound, south-central Alaska.

Station:	Kenai	Anchorage	Hope	Girdwood	Alyeska	Portage	Whittier
Latitude	60°34′N	61°10′N	60°55′N	60°56′N	60°58′N	60°49′N	60°46′N
Longitude	151°15′W	150°01′W	149°38′W	149°10′W	149°08′W	148°58′W	148°41′W
Elevation (m)	27	34	46	6	76	12	18
Record length	1949–2009	1952–2009	1979–2009	1955–1978	1963–2009	1973–1995	1950–2009
Mean January temperature (°C)	–10.8	–9.4	–7.6	–6.8	–6.5	–5.4	–2.8
Mean July temperature (°C)	12.7	14.7	14.1	13.5	13.8	12.9	13.7
Mean annual temperature (°C)	1.1	2.3	2.5	2.5	3.0	2.4	4.5
Mean January precipitation (cm)	2.6	1.9	4.7	9.7	20.3	22.4	47.0
Mean July precipitation (cm)	4.7	4.8	4.7	6.0	6.6	7.5	26.8
Mean annual precipitation (cm)	47.8	40.4	55.8	105.5	175.8	198.8	499.9

(Fig. 1B; Table 1). It is likely that this gradient also existed in the past and may explain the distribution of present and past vegetation types in upper and lower Turnagain Arm.

The only pollen records that have been previously published from the Turnagain Arm area include an analysis of an undated peat core collected near Girdwood (Heusser 1960; Fig. 1B, site 9; Fig. 2, Heusser site) and a dated vegetation history from a peat bog near Hope, west of Girdwood (Ager and Carrara 2006; Fig. 1B, site 7). Late Quaternary pollen records with at least some radiocarbon age control have been published for sites in the Anchorage Lowland (Point Woronzof area; Fig. 1B, site 2; Ager and Brubaker 1985; Ager and Carrara 2006); the northern Kenai Lowland (Swanson Fen; Fig. 1B, site 3; Jones et al. 2009; and Paradox Lake, Fig. 1B, site 4; Anderson et al. 2006); the western flank of the Kenai Mountains (Hidden Lake; Fig. 1B, site 5, Ager 1983); and in the central Kenai Mountains, near Tern Lake (Fig. 1B, site 6; Ager 2001). In addition, several dated and undated pollen records have been described from Prince William Sound, east of Turnagain Arm (Heusser 1955, 1960, 1983*a*, 1985). The longest published pollen record with radiocarbon age control from Prince William Sound is from Golden (Fig. 1B, site 10; Heusser 1983*a*). In the interior, northeast of Anchorage, pollen data from an exposure of peat and from lake sediments near Matanuska Glacier provide information about the approximate timing of initial postglacial colonization of the upper Matanuska Valley, first by tundra and then by boreal forest vegetation (Fig. 1B, site 11; Williams 1986; Yu et al. 2008).

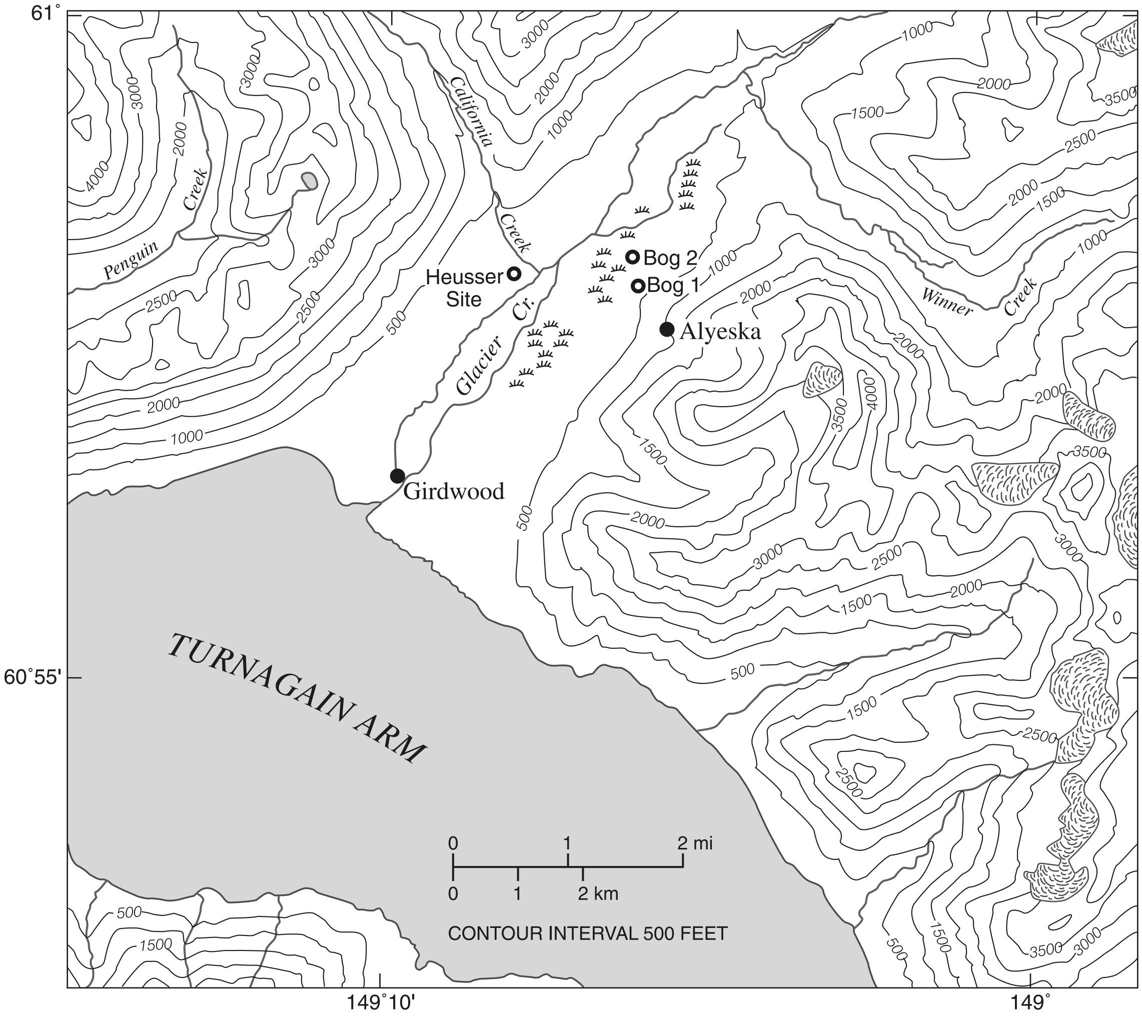
Glacial history

The Cook Inlet region has undergone multiple glaciations during the late Tertiary and Quaternary (Karlstrom 1964; Péwé 1975; Hamilton and Thorson 1983; Schmoll and Yehle 1986; Reger et al. 1995; Reger and Pinney 1997; Schmoll et al. 1999; Reger et al. 2007). Present-day glaciers and icefields cover substantial areas of the Chugach and Kenai mountains of south-central Alaska (Molnia 2008; Fig. 1B); but during past glacial intervals, glaciers occupied vastly greater areas, covering most of the Cook Inlet region and the mountain ranges of south-central Alaska and extending southward onto the continental shelf (Schmoll and Yehle 1986; Molnia 1986; Kaufman and Manley 2004). For the purposes of the present study of postglacial ecosystem development, the most relevant major glacial events in the Cook Inlet occurred during the late Wisconsin glacial interval ~30 000 – 11 000 cal years BP (Reger et al. 2007).

Four significant glacial advances during the late Wisconsin have been recognized in the Cook Inlet region (Karlstrom 1964; Reger and Pinney 1997; Reger et al. 2007). The initial interpretations of the Naptowne (late Wisconsin) glacial advances in the Cook Inlet region as defined by Karlstrom (1964) have been refined and reinterpreted by other researchers in light of additional mapping, radiocarbon dating, and stratigraphic studies in the region (e.g., Reger et al. 1995; Reger and Pinney 1997; Schmoll et al. 1999; Reger et al. 2007). For the purposes of this paper, we follow the terminology of late Wisconsin glacial events in upper Cook Inlet as summarized by Reger et al. (2007). The four recognized late Wisconsin glacial advances covered successively smaller areas of the Cook Inlet region, and the later three glacial advances appear to have been of much shorter duration than the earliest, most extensive ice advance. Reger et al. (2007) retain Karlstrom's original nomenclature for three of the original four names for the earliest three Naptowne glacial advances: the Moosehorn (the oldest, most areally extensive, and longest enduring), the Killey, and the Skilak. The fourth Naptowne glacial advance has been renamed the Elmendorf advance, after the prominent Elmendorf moraines that cover part of the northern Anchorage Lowland, the lower Susitna Valley, and the lower Matanuska Valley (Fig. 1B). Karlstrom's chronology for these glacial events has been updated in light of extensive field investigations in the region during the past several decades, as summarized in Reger et al. (2007).

Our investigations focus on the development of terrestrial ecosystems following glacial retreat from the maximum ice positions achieved during the Elmendorf glacial advance. Major glacial recession during the waning stages of the preceding Skilak stade was accompanied by flooding of much of Cook Inlet, including Turnagain Arm, by marine waters. During the following Elmendorf stade, glaciers readvanced into Turnagain Arm from tributary valleys in the Chugach and northern Kenai mountains (Fig. 1B). The trunk glacier in Turnagain Arm flowed westward to reach maximum positions near Hope ~15 100 cal years BP and occupied another somewhat later terminal position near Bird Creek (Fig. 1B; Kachadoorian et al. 1977; Reger and Pinney 1997; Schmoll et al. 1999; Ager and Carrara 2006; Reger et al. 2007). Retreat of glacial ice of the Elmendorf stade from its maximum terminal positions probably began sometime before 14 100

Fig. 2. Map of part of upper Turnagain Arm, south-central Alaska, showing the Girdwood area, Glacier Creek, and the site (bog 1) where a small peat bog within a bedrock basin was cored for this investigation. Another core was obtained from bog 2, but the results of the pollen analysis have not been included in this paper. The radiocarbon ages from the bog 2 core are shown in Table 2. Also shown is the location of a slope bog site near California Creek where Heusser (1960) collected an undated peat core for pollen analysis. Contour interval is 500 feet (~152.4 m).



cal years BP, based on radiocarbon ages of organic sediments at the base of sediment cores from Lake Lorraine, a kettle lake on the Elmendorf moraine west of Knik Arm in upper Cook Inlet (Fig. 1B, site 1; Kathan et al. 2004). Other radiocarbon-dated deposits providing minimum ages for the retreat of glacial ice from the Elmendorf moraine near Anchorage have yielded similar ages (Schmoll et al. 1999). The final retreat of glacial ice from Turnagain Arm and its tributary valleys set the stage for the beginnings of postglacial terrestrial ecosystem development in the deglaciated parts of the Chugach and Kenai mountains. Reconstructing by means of pollen analysis the sequence of vegetation changes following deglaciation is the subject of this paper.

Paleoclimates

A broad outline of postglacial climates of south-central Alaska can be reconstructed from a variety of published evidence. The transition from arid, full-glacial climates to a somewhat warmer, wetter climate may have begun as early as 16 400 cal years BP in the Kenai Peninsula region, as inferred from pollen evidence (Ager and Brubaker 1985). Increases in marine biological productivity in paleoceanographic records from the Gulf of Alaska indicate warmer ocean waters during the late glacial (Bølling–Alleröd) climatic warming (~14 700 – 12 900 cal years BP; Barron et al. 2009). This was followed by a climatic cooling event (Younger Dryas: ~12 900 – 11 700 cal years BP), which caused some vegetation responses in coastal sites, most notably a drop in fern spore percentages (Peteet and Mann 1994). Other evidence for Younger Dryas cooling includes a drop in marine biological productivity, an increase in sea ice in the Gulf of Alaska (Barron et al. 2009), and a negative ~2‰ $\delta^{18}O$ in a lacustrine record near Matanuska Glacier (Fig. 1B, site 11; Yu et al. 2008). During the early Holocene, warmer climates beginning as early as ~11 000 cal years BP are inferred from various climate proxies (Kaufman et al. 2004), including a rapid expansion of alders across south-central Alaska beginning ~9600 cal years BP (Ager and Brubaker 1985), lower lake levels in the Kenai lowlands (Anderson et al. 2006; Reger et al. 2007), and a regional climate reconstruction for the Holocene based on a pollen–climate transfer function that indicates warmer, drier climates (Heusser et al. 1985). A regional cooling trend began after ~9000 cal years BP, but convincing evidence of early Holocene glacial expansion has not been found in south-central Alaska (Barclay et al. 2009). However, evidence for glacial advances as early as ~8400 and ~7400 cal years BP in the mountains of western Canada (Menounos et al. 2009) suggests that correlative events may have also occurred in south-central Alaska during the early Holocene. During the late Holocene, evidence for Neoglacial ice expansions as early as 4000 cal years BP has been documented in south-central Alaska, with later advances beginning near 3300, 2200, and 1400 cal years BP, as well as several Little Ice Age advances within the past 800 cal years (Barclay et al. 2009). Additional evidence for late Holocene climate trends towards cooler, wetter conditions is based on a pollen–climate transfer function developed for the Gulf of Alaska coastal region (Heusser et al. 1985).

Present-day climate

Turnagain Arm lies within two major climate zones of Alaska: the maritime zone in upper (eastern) Turnagain Arm and the transitional climate zone in lower (western) Turnagain Arm (Fig. 1). The transitional zone separates the maritime zone of the outer coast of southern Alaska from the continental zone of interior Alaska. Climate data from several meteorological stations in upper Cook Inlet and northwest Prince William Sound (Fig. 1B) are summarized in Table 1 (West Regional Climate Center 2009). The climate data indicate that Turnagain Arm has a strong precipitation gradient, far drier in the west than in the east. For example, the mean annual precipitation (MAP) in the Anchorage Lowland is 40.4 cm; whereas at Portage in upper Turnagain Arm, MAP is 198.8 cm (Table 1). This precipitation gradient is consistent with the mapped climate zone boundaries that meet within Turnagain Arm, with the relatively dry transitional climates of upper Cook Inlet in the west and wetter, more maritime climates in the east (Fig. 1A; Péwé 1975). The drier climate of upper Cook Inlet is largely the result of substantial precipitation shadows formed by the Kenai and Chugach mountains. The Gulf of Alaska is the major source of abundant precipitation that falls mostly along the mountainous southern and eastern coasts of Kenai Peninsula and the coasts of Prince William Sound (Péwé 1975). MAP for Whittier in northwest Prince William Sound, where maritime climate prevails, is 499.9 cm (Fig. 1; Table 1).

Temperature differences are less dramatic between upper Cook Inlet and upper Turnagain Arm and northwest Prince William Sound (Table 1). The climate data indicate that cooler summer temperatures and warmer winter temperatures occur where the maritime influences are greatest. Upper Turnagain Arm is separated from northwest Prince William Sound by a low mountain range, which partly blocks moisture from entering upper Turnagain Arm, as shown by the differences in precipitation between Whittier and Portage (Table 1). However, the low pass through the range near Portage (Fig. 1B) is only 240 m in elevation, and this allows some moisture-laden air masses from the east and southeast to penetrate the coastal mountain barrier. Wind regimes are highly complex in this region because of the mountainous terrain and the interactions between maritime air masses in the Gulf of Alaska region and continental and transitional air masses from the interior (Shulski and Wendler 2007). Prevailing wind directions during the months when most wind-dispersed pollen and spores are released (April–July) are generally from the south in Cook Inlet. However, prevailing winds during those months are generally from the east and east-southeast in Prince William Sound and eastern Turnagain Arm (Western Regional Climate Center 2009). These wind patterns favor the dispersal of boreal forest pollen and spore types from Kenai Lowland into western Turnagain Arm, and coastal forest pollen and spore types from Prince William Sound into eastern Turnagain Arm.

Present-day vegetation

The distribution of present-day vegetation types of Turnagain Arm mirrors the strong precipitation gradient. Vegetation in the areas bordering Prince William Sound and upper Turnagain Arm (Fig. 1B) is North Pacific coastal rainforest with large expanses of *Alnus* thickets. Coastal forest vegetation reaches its northwestern limits in Cook Inlet (Heusser 1960, 1983*a*, 1983*b*, 1985; Hultén 1968; Viereck and Little 1975, 2007; Pojar and MacKinnon 1994). The southern and southeastern coastal regions of Alaska were extensively glaciated during the late Wisconsin, and most of the vegetation within those regions was destroyed by cold climate and burial by advancing glaciers. It is highly likely, however, that some tundra and shrub vegetation persisted in the region on nunataks and within some unglaciated parts of the Kenai Lowland, northwestern Kenai Mountains, and perhaps on subaerially exposed portions of the continental shelf (Molnia 1986; Kaufman and Manley 2004). Alpine zone- and subalpine zone-adapted shrubs, herbs, mosses, and lichens are the most likely kinds of plants to have survived glaciation within refugia in south-central Alaska. If unglaciated areas did serve as refugia for plants, they would have provided the nearest seed sources that expedited the initial revegetation of adjacent, newly deglaciated areas.

Many of the plant species that colonized coastal south-central Alaska in postglacial time came from distant seed sources in southeastern Alaska, a migration that appears to have required thousands of years to spread for hundreds of kilometres along the coast (Heusser 1960, 1983*a*, 1983*b*, 1985; Ager 1983, 2000, 2001; Peteet 1986). Pollen records from sites along the coast between southeastern and south-central Alaska indicate that this slow recolonization of largely deglaciated landscapes by coastal plant species probably resulted from topographic bottlenecks (e.g., Malaspina and Bering glaciers) in the narrow band of coastal lowlands and foothills between Yakutat Bay and Prince William Sound (Fig. 1A; Heusser 1960, 1985; Peteet 1986; Molnia 1986). Large areas of the present-day coastal lowlands along the Gulf of Alaska east of Prince William Sound apparently were submerged under marine waters until isostatic rebound and tectonic uplift resulted in gradual emergence, leaving limited areas of emergent lowlands for forest establishment (Molnia 1986; Shennan 2009).

The dominant coastal tree species in the lands surrounding upper Turnagain Arm today are Sitka spruce (*Picea* *sitchensis*) and mountain hemlock (*Tsuga mertensiana*). In some valley bottom alluvial settings, black cottonwood (*Populus trichocarpa*) forms locally significant stands. In Prince William Sound to the east, a more diverse coastal forest of Sitka spruce, mountain hemlock, with western hemlock in some areas (*Tsuga heterophylla*), and rare stands of yellow-cedar (*Chamaecyparis nootkatensis*) along the northern coast of the sound have become established (Viereck and Little 1975, 2007; Hennon and Trummer 2001). Western hemlock and yellow-cedar are not known to grow today in Turnagain Arm (Viereck and Little 1975, 2007). Sitka alder (*Alnus crispa* ssp. *sinuata*) is the dominant large shrub species; but willow (*Salix* spp.), heaths (Ericaceae, *Empetrum*), and devil's club (*Oplopanax horridus*) are also common.

Trees rarely grow above ~500–520 m in the Turnagain Arm area. The elevation limit of forest vegetation varies with slope angle, slope aspect, and local avalanche history. Snow avalanches destroy wide swaths of forest on steep valley slopes and result in a deeply scalloped upper tree line. *Alnus* and Polypodiaceae ferns colonize avalanche tracks in this region. Stunted *Tsuga mertensiana* trees usually form the upper treeline in this area. *Alnus* and *Salix* shrubs predominate above treeline up to ~700 m. At higher elevations, shrub tundra and alpine tundra vegetation communities grow in favorable sites, interspersed with bedrock, rocky soils, and snowfields.

At the west end of Turnagain Arm, in the Anchorage Lowland and the northern Kenai Lowland (Fig. 1B), the predominant vegetation is boreal forest, composed primarily of white spruce (*Picea glauca*), black spruce (*Picea mariana*), Alaska paper birch (*Betula neoalaskana*), Kenai birch (*Betula kenaica*), balsam poplar (*Populus balsamifera*), and aspen (*Populus tremuloides*), along with shrub species of alder (*Alnus crispa* ssp. *crispa*, *A. crispa* ssp. *sinuata*, *A. tenuifolia*) and willow (*Salix* spp.).

A transition zone exists today between the boreal forest vegetation of the Anchorage and Kenai lowlands in western Turnagain Arm and the coastal forest vegetation of eastern Turnagain Arm. The boundaries between these vegetation types are gradual and therefore are difficult to define or map. The transition zone vegetation consists of a mixture of coastal forest and boreal forest plant species. The most common trees within this transition zone are hybrid spruce (e.g., Lutz spruce, *Picea* × *lutzii*), which commonly occur where populations of Sitka spruce and white spruce come into proximity (Viereck and Little 2007). Other common trees in this transition zone are *Betula neoalaskana*, *B. kenaica*, *Populus trichocarpa*, and *P. balsamifera*.

Methods

Several peat cores from the Girdwood area were obtained from two bogs (Fig. 2), using a Russian peat corer (Aaby and Digerfeldt 1986) during the 1996, 1997, 2002, and 2003 field seasons. Preliminary pollen analysis of cores collected during the 1996 and 1997 site visits indicated that those initial records preserved only late Holocene histories, and therefore additional peat cores were collected in subsequent field seasons. Preliminary pollen analysis and radiocarbon dating of the 2002 and 2003 cores indicated that they contained more complete postglacial records than the earlier cores and were therefore selected for detailed pollen analysis and radiocarbon dating. The resulting vegetation history was reconstructed from two cores from the same bog (Fig. 2, bog 1). A third peat core of late Holocene age was collected from another nearby bog (Fig. 2, bog 2). Pollen analysis and radiocarbon dating of that core was completed; but since its record largely duplicates the late Holocene part of the record from bog 1, core 1, it is not presented here. The radiocarbon ages of dated samples from bog 2, core 3, are included in Table 2 to allow comparison with the chronology for bog 1, core 1.

The peat samples and a few basal samples of mineral sediments from bog 1, cores 1 and 2, were processed to extract pollen and spores in the United States Geological Survey Cenozoic Palynology Laboratory in Denver, Colorado, following preparation techniques modified from Doher (1980). Pollen and spore assemblages were analyzed with a binocular microscope, usually at magnifications of 400× and 630×.

Fossil pollen and spores were identified by comparison with specimens from a collection of modern reference slides of Alaskan and Pacific Northwest pollen and spore types housed at the United States Geological Survey in Denver and by consulting a published pollen flora for Alaska (Moriya 1978). More than 300 pollen grains were identified and tabulated for each sample. Percentages of each pollen taxon were calculated from the pollen sum shown on the pollen diagrams while spore percentages were calculated from the pollen + spore sum. Pollen and spore types shown on the pollen diagrams follow regional botanical taxonomic nomenclature (Hultén 1968; Pojar and MacKinnon 1994; Viereck and Little 2007). Pollen zone boundaries were determined by visual inspection. These zone boundaries delineate the core positions where significant changes in the percentages of dominant pollen and spore types occur. Such changes in pollen and spore percentages are interpreted to reflect important past ecological changes in the Girdwood area.

Radiocarbon samples were obtained from the cores by selecting peat fractions that appeared to be free of rootlets. A few samples of clayey silt obtained from the base of cores 1 and 2 from bog 1 contained little visible organic material. One clayey silt sample (Table 2, WW4328) contained fine rootlets that were separated from the mineral sediments by sieving. The oven-dried rootlets were submitted for accelerator mass spectrometry (AMS) radiocarbon dating based on the (incorrect) assumption that the rootlets represented remains of plants that grew at the time of deposition of the clayey silt unit. The resulting age of 4750 ± 130 cal years BP (sample WW4328 in Table 2) indicates that the rootlets represent root penetration by much younger plants. The reported age is clearly too young given the other ages from bog 1 cores and the associated pollen zones. Therefore, sample WW4328 was not used to develop the chronology for the Girdwood area vegetation history.

In order to date the basal clay–silt sediment unit that overlies bedrock in cores 1 and 2, two samples (Table 2, WW5127 and WW5128) were processed to concentrate pollen residues for AMS radiocarbon dating. Processing the samples followed pollen sample preparation methods for un-

Table 2. Radiocarbon ages and median calibrated ages from Girdwood peat cores 1, 2, and 3.

Core	Depth (cm)	Material	^{14}C age (years BP)[a]	Lab No.	Calib. 2σ range[b]	Median calib. age (years BP)
GW1-1	40–45	Peat	410±40	WW3423	530–310	420±110
GW1-1	65–70	Peat	1690±50	WW3424	1720–1410	1565±155
GW1-1	75–80	Peat	3180±40	WW3425	3480–3330	3405±75
GW1-1	90–95	Peat	4685±55	WW2332	5590–5330	5450±140
GW1-1	114–115	Peat	5780±40	WW4322	6680–6480	6580±100
GW1-1	162–163	Peat	6735±45	WW4327	7680–7510	7595±85
GW1-1	169–170	Pollen	11820±40	WW5127	13800–13560	13680±120
GW1-1	174–175	Rootlets	4255±40	WW4328	4880–4620	4750±130
GW1-1	174–175	Pollen	11935±40	WW5128	13920–13700	13810±110
GW1-2	85–86	Peat	5825±35	WW5203	6740–6530	6635±105
GW1-2	125–126	Peat	8600±40	WW4719	9680–9500	9590±90
GW1-2	130–131	Peat	9570±40	WW5142	11110–10730	10920±190
GW2-3	60–65	Peat	1090±50	WW2333	1140–920	1030±110
GW2-3	100–105	Peat	1795±45	WW2334	1870–1600	1735±135
GW2-3	130–135	Peat	2220±50	WW2335	2350–2120	2235±115
GW2-3	165–170	Peat	3960±65	WW2336	4650–4150	4400±250

[a] The quoted age is in radiocarbon years before present (BP) using the Libby half life of 5568 years and following the conventions of Stuiver and Polach (1977). Values for δ^{13}C used to adjust the ages are the assumed values of –25 δ^{13}C (‰) according to Stuiver and Polach (1977).

[b] Calibrated ages are median values representing 2σ ranges in calibrated years before present (cal years BP) using the internationally ratified Intcal04 data base (Reimer et al. 2004) and Oxcal 3.1 calibration software (Bronk Ramsey 2001).

consolidated mineral sediments modified from those described in Doher (1980). Modifications of the processing methods to produce pollen residues for AMS radiocarbon dating include intensive ultrasonic cleaning of sieves and laboratory glassware to reduce the chances of sample contamination and avoidance of chemical treatments that might alter the results of the radiocarbon age determinations. The resulting pollen residues yielded dry sample weights of 6.8 mg (WW5127) and 6.6 mg (WW5128). Sample combustions yielded ~2.2 mg carbon per sample (~32% carbon), of which only 1 mg per sample was used for dating. We consider that the resulting ages, 13 680 ± 120 cal years BP and 13 810 ± 110 cal years BP (Table 2), are reasonable in the context of the known regional glacial history and other ages from upper Cook Inlet peat cores (Schmoll et al. 1999; Ager and Carrara 2006; Reger et al. 2007). Selected peat samples from the cores were oven-dried and sent to the United States Geological Survey Radiocarbon Laboratory to be prepared for AMS radiocarbon dating by one of the authors (JPM). Sample locations, sample depths, radiocarbon dates, calibrated two sigma (2σ) age ranges, and median calibrated radiocarbon ages (with uncertainties) are presented in Table 2. Median calibrated radiocarbon ages are also shown at the right margins of the pollen diagrams, near the stratigraphic positions from which they were collected (Figs. 3, 4).

Results

The vegetation history for the Girdwood area has been reconstructed based on radiocarbon dated pollen records from two peat cores. The results of pollen and spore analysis of the longest records from the area (Girdwood bog 1, cores 1, 2) are presented in two pollen and spore percentage diagrams (Figs. 3, 4). Gaps (unconformities) exist in each of the two peat cores, as indicated by the sequence of radiocarbon ages (Table 2). The vegetation history is reconstructed from a composite record derived from both cores. Some gaps in the record remain. Since unconformities are not often obvious when visually inspecting peat cores, analysis and dating of multiple cores from a given area are sometimes necessary to reconstruct the most complete history possible.

Girdwood bog 1, core 1 (Fig. 3)

Pollen zone GW1-4 (162–178 cm core depth; ~13 400 to ~13 800 cal years BP)

The age of the upper boundary of this zone can only be approximated because the uppermost radiocarbon age from within the zone does not coincide with the upper zone boundary. An unconformity separates the top of this pollen zone from the base of the overlying pollen zone GW1-3. Part of the missing record spanning ~5800 cal years in this core is preserved in Girdwood bog 1, core 2, as described later in the paper. The sediment in the lower part of the core is clayey silt, which is probably derived from local till mantling glacially scoured bedrock. The clayey silt directly overlies bedrock. The pollen assemblages in pollen zone GW1-4 differ substantially from the assemblages seen above 162 cm core depth. The assemblages are dominated by pollen of *Betula* (25%–32%). It is likely this pollen was derived from dwarf birch (*B. nana*) rather than birch trees (e.g., *B. neoalaskana*). *Salix* (20%–30%), Cyperaceae (20%–30%), and Polypodiaceae fern spores (23%–60% of the pollen + spore sum) constitute the other dominant pollen and spore types in this zone. Minor taxa include Ericales, *Rubus*, *Sanguisorba*, Poaceae, *Artemisia*, Asteroideae, *Heracleum* and other Apiaceae, Ranunculaceae, and *Cryptogramma* fern spores. These pollen assemblages are interpreted to represent shrubby tundra vegetation of *Salix*, dwarf *Betula,* Ericales, Cyperaceae, Poaceae, and Polypodiaceae, with a diverse assortment of herbaceous plant types. This suggests that tundra vegetation first developed on recently deglaciated lands in the Girdwood area (Fig. 2). The relative abundance of ferns

Fig. 3. (Parts 1 and 2) Pollen and spore percentage diagram for Girdwood bog, core 1, south-central Alaska. Lithology column shows peat deposits overlying ∼13 cm of clay–silt, with bedrock below. Horizontal layers shown as xxxxx represent tephra layers of late Holocene age. Radiocarbon ages (median calibrated years BP) are shown in the far right column. The horizontal cylindrical object shown in the lithology column represents tree-size wood.

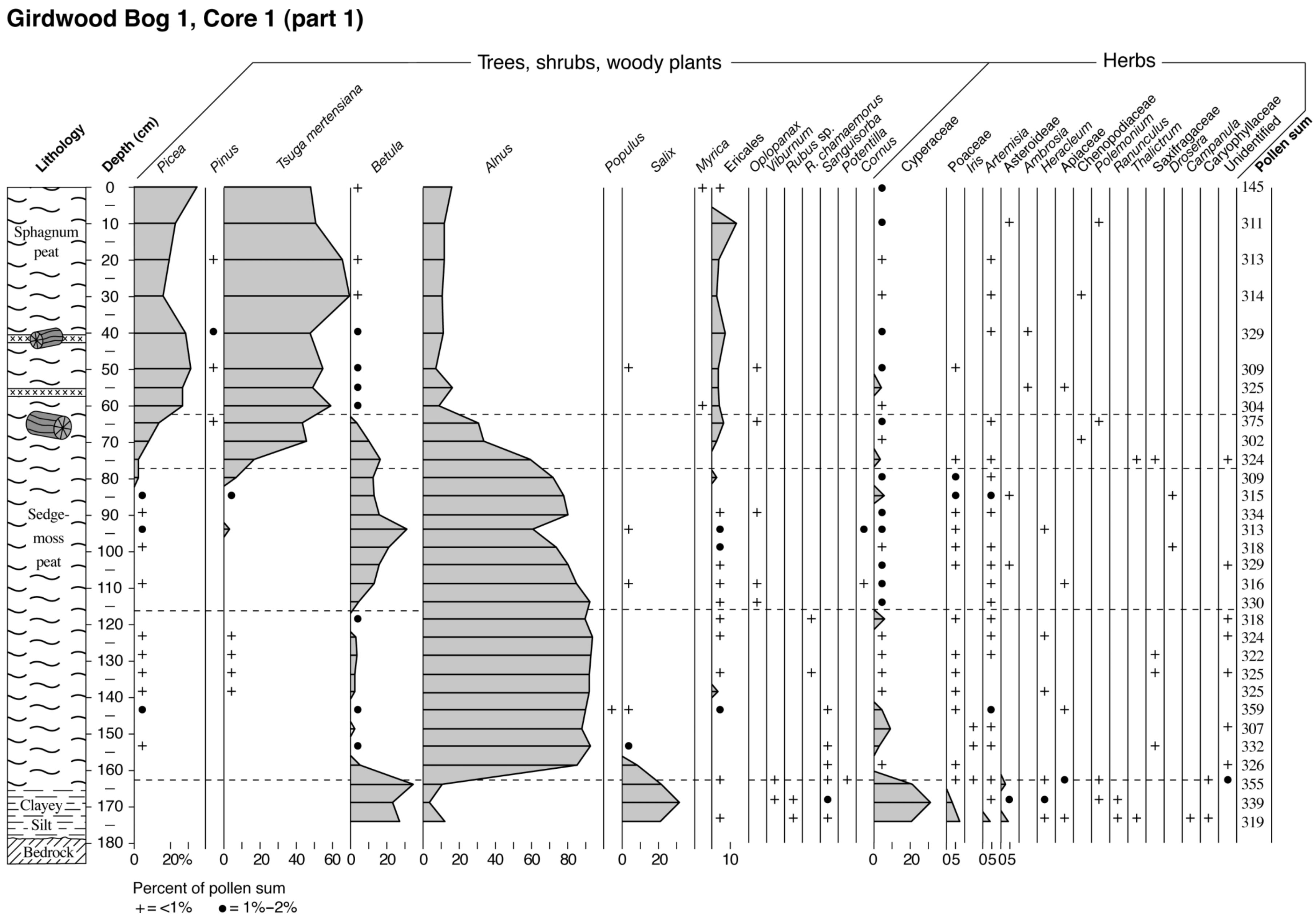
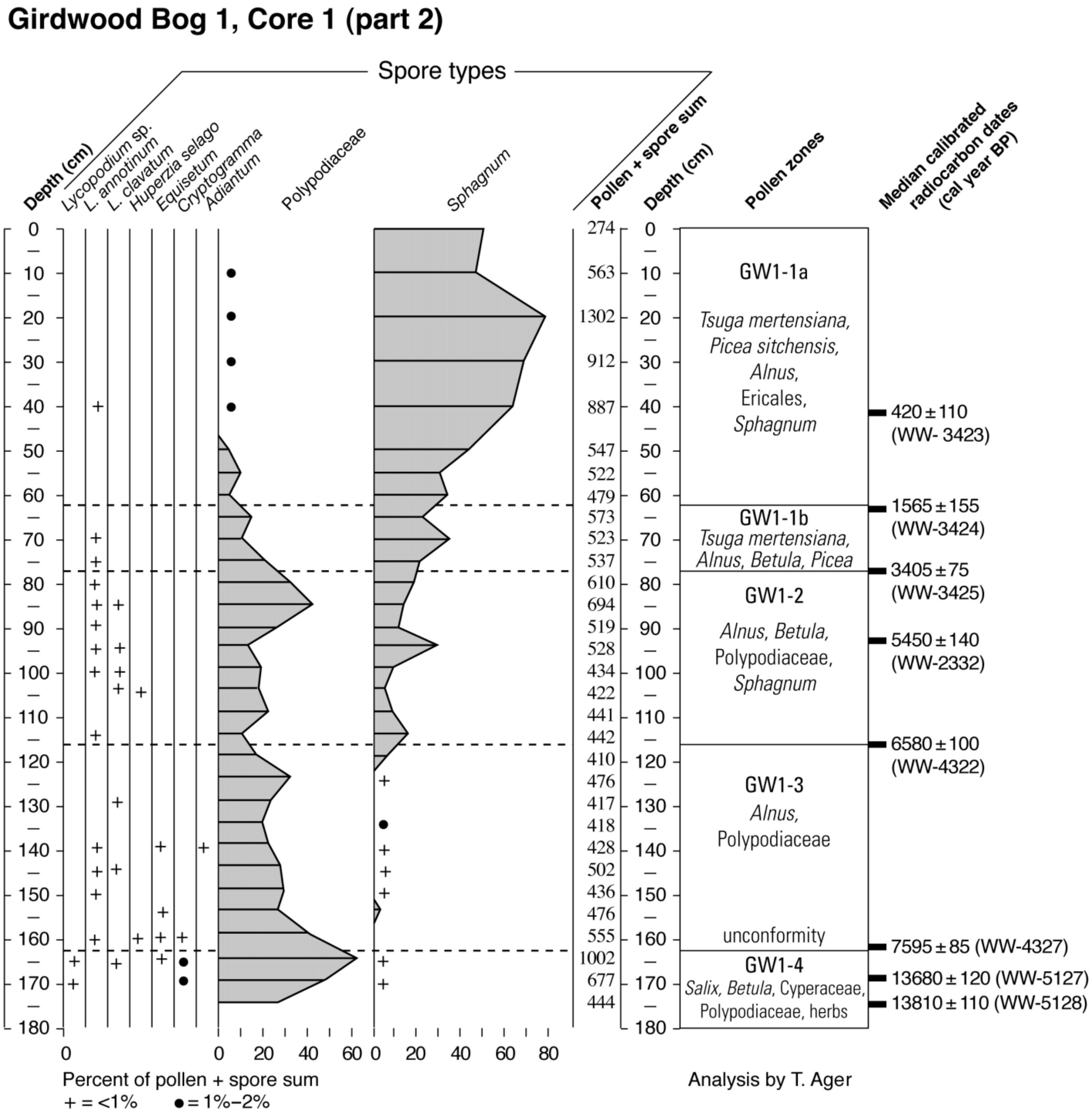


Fig. 3 (*concluded*).



suggests moist conditions consistent with the present-day climate in eastern Turnagain Arm. Ferns are important colonists following deglaciation or disturbance by avalanches in the moist to wet coastal regions of south-central and southeastern Alaska.

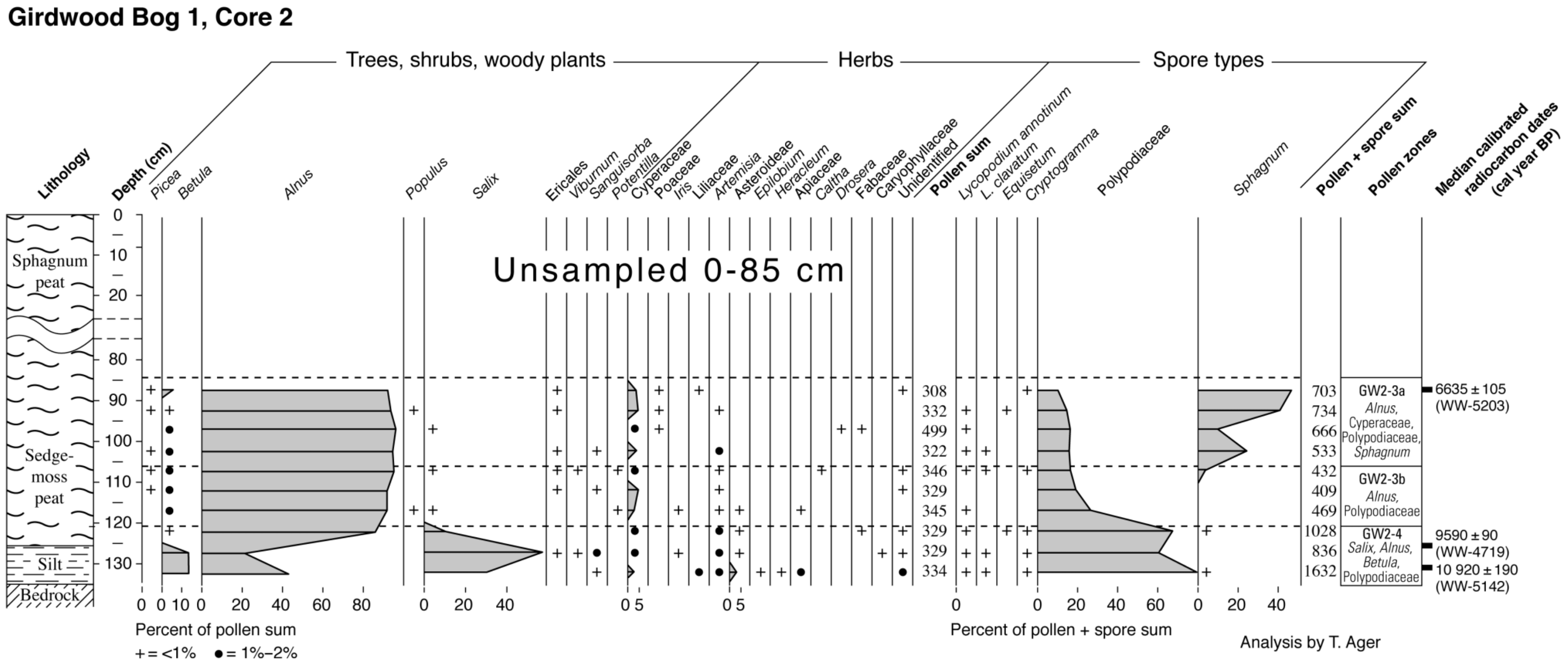
Pollen zone GW1-3 (117–162 cm core depth; ~6600 to ~7600 cal years BP)

Pollen assemblages within this zone are heavily dominated by *Alnus* (83%–92%) and Polypodiaceae type fern spores (20%–40% of the pollen + spore sum). *Sphagnum* spores are uncommon. Pollen grains of *Picea* are present in small amounts (<2%) and probably represent wind-transported pollen from boreal spruce forests in western Turnagain Arm and vicinity. Cyperaceae is present in small amounts (<1%–9%). Minor taxa include *Betula*, Ericales, *Sanguisorba*, Poaceae, *Artemisia*, and Saxifragaceae. This pollen zone is interpreted to represent *Alnus*-dominated vegetation with associated abundant Polypodiaceae ferns and open bogs and meadows supporting Ericales and herbs.

Pollen zone GW1-2 (77–117 cm core depth; ~3400 to ~6600 cal years BP)

This pollen zone is dominated by pollen of *Alnus* (62%–92%), *Betula* (12%–30%), and spores of Polypodiaceae (13%–42%) and *Sphagnum* moss (6%–30%). This pollen evidence from this core indicates that *Alnus* thickets with Polypodiaceae ferns formed the dominant vegetation type in the upper Turnagain Arm area from ~6600–3400 cal years BP. However, pollen evidence from core GW1-1 indicates that the *Alnus*–

Fig. 4. Pollen and spore percentage diagram for Girdwood bog, core 2, south-central Alaska. Lithology column at left shows peat deposits overlying ∼10 cm of clay–silt on top of bedrock. Radiocarbon ages (median calibrated years BP) are shown in the far right column.



Polypodiaceae vegetation dominated in this area at least as early as ~7600 cal years BP. The relative abundance of *Betula* pollen, however, likely represents Alaska paper birch (*Betula neoalaskana*) and Kenai birch (*B. kenaica*; Viereck and Little 2007). These arboreal birches are two of the few boreal forest tree taxa that have colonized limited areas of upper Turnagain Arm during the Holocene in any abundance. We did not attempt to differentiate birch pollen types in this investigation because of the widespread hybridization of birch species in the Cook Inlet region (Viereck and Little 2007). Some stands of small-diameter birch trees grow in the Girdwood area today, but are more common west of Girdwood. Some of the birch pollen in this pollen zone may be from dwarf birch (*Betula nana*), which also grows on boggy sites in the area today (Viereck and Little 2007). Another shrub birch species, resin birch (*Betula glandulosa*), could possibly have contributed small amounts of its pollen to the birch pollen sum, via long-distance wind transport from other areas of upper Cook Inlet in which it grows. That species has not been documented from the present vegetation in the upper Turnagain Arm area (Viereck and Little 2007).

Pollen subzone GW1-1b (62–77 cm; ~1560 to ~3400 cal years BP)

This subzone is dominated by pollen of *Tsuga mertensiana* (18%–45%), *Alnus* (28%–60%), *Betula* (4%–18%), and increasing amounts of pollen of *Picea*, probably *P. sitchensis*, which rises from 3% to 15% within the subzone. Polypodiaceae spores (12%–20%) and *Sphagnum* moss spores (20%–35%) are also well represented. Minor taxa include Ericales, Cyperaceae, *Artemisia*, and *Lycopodium annotinum*. Subzone GW1-1b represents a late Holocene vegetation transition from *Alnus* thickets with Polypodiaceae ferns, arboreal *Betula*, and bog communities to a mixture of coastal *Tsuga mertensiana* – *Picea sitchensis* forest with bogs and alder thickets with ferns.

Pollen subzone GW1-1a (0–62 cm core depth; present day to ~1560 cal years BP)

This subzone is characterized by predominance of *Tsuga mertensiana* pollen (50%–70%), along with *Picea* pollen (18%–31%). We assume that most of the spruce pollen is derived from *Picea sitchensis*, the only species of spruce that grows today near Girdwood. However, long-distance wind transport of conifer pollen is a common occurrence; and therefore some *Picea* pollen in the Girdwood records may be derived from white spruce (*Picea glauca*), black spruce (*Picea mariana*), and common hybrids between white spruce and Sitka spruce. Some of these hybrids are classified as Lutz spruce (*Picea* × *lutzii*; Viereck and Little 2007). Also present in this subzone are pollen of *Alnus* (8%–13%), Ericales (3%–12%), and abundant spores of *Sphagnum* (30%–70% of the pollen + spore sum). Minor pollen taxa include *Pinus*, *Betula*, Cyperaceae, and *Artemisia*. This subzone represents late Holocene coastal forest vegetation dominated by *Tsuga mertensiana* and *Picea sitchensis*, but with significant expanses of *Alnus* thickets, probably growing in avalanche scars and in the shrub zone near and above altitudinal tree limit. Pollen of Ericales, Cyperaceae, herbs, and an abundance of *Sphagnum* spores in this subzone represents local bog vegetation.

Girdwood bog 1, core 2 (Fig. 4)

Pollen zone GW2-4 (120–135 cm core depth; ~9200 (estimated) to ~10 900 cal years BP)

This pollen zone is characterized by relative abundance of *Salix* (31%–58%), *Alnus* (22%–42%), and *Betula* pollen (~12%), along with minor amounts of pollen of *Sanguisorba*, Cyperaceae, *Artemisia*, and Asteraceae, subfamily Asteroideae. The dominant spore type is Polypodiaceae (60%–70%). Minor spore types include *Lycopodium* and *Cryptogramma*. This assemblage zone represents part of the early Holocene during which *Alnus* thickets were becoming well established in upper Turnagain Arm but had not yet become the dominant vegetation type. The relative abundance of *Salix* and Polypodiaceae, along with a variety of herbaceous taxa, suggests that shrub–herb tundra vegetation was common in the area, interspersed with some *Alnus* thickets. The presence of ~12% *Betula* pollen in this zone most likely represents dwarf birch (*Betula nana*), which grows in Turnagain Arm today, often in boggy sites (Viereck and Little 1975, 2007).

Pollen subzone GW2-3b (105–120 cm core depth; ~8000 (estimated) to ~9200 (estimated) cal years BP)

This pollen subzone is dominated by *Alnus* (90%–93%), Cyperaceae (<5%), with minor woody taxa (Ericales, *Potentilla*), and minor percentages of herbs such as *Artemisia* and Asteroideae. Polypodiaceae (15%–25%) is the most abundant spore type, whereas minor spore types include *Lycopodium annotinum*, *L. clavatum*, and *Cryptogramma*. This assemblage represents an early Holocene *Alnus*–Polypodiaceae-dominated landscape in which shrub–herb tundra or open meadow communities are present nearby.

Pollen subzone GW2-3a (85–105 cm core depth; ~6600 to ~8000 estimated cal years BP)

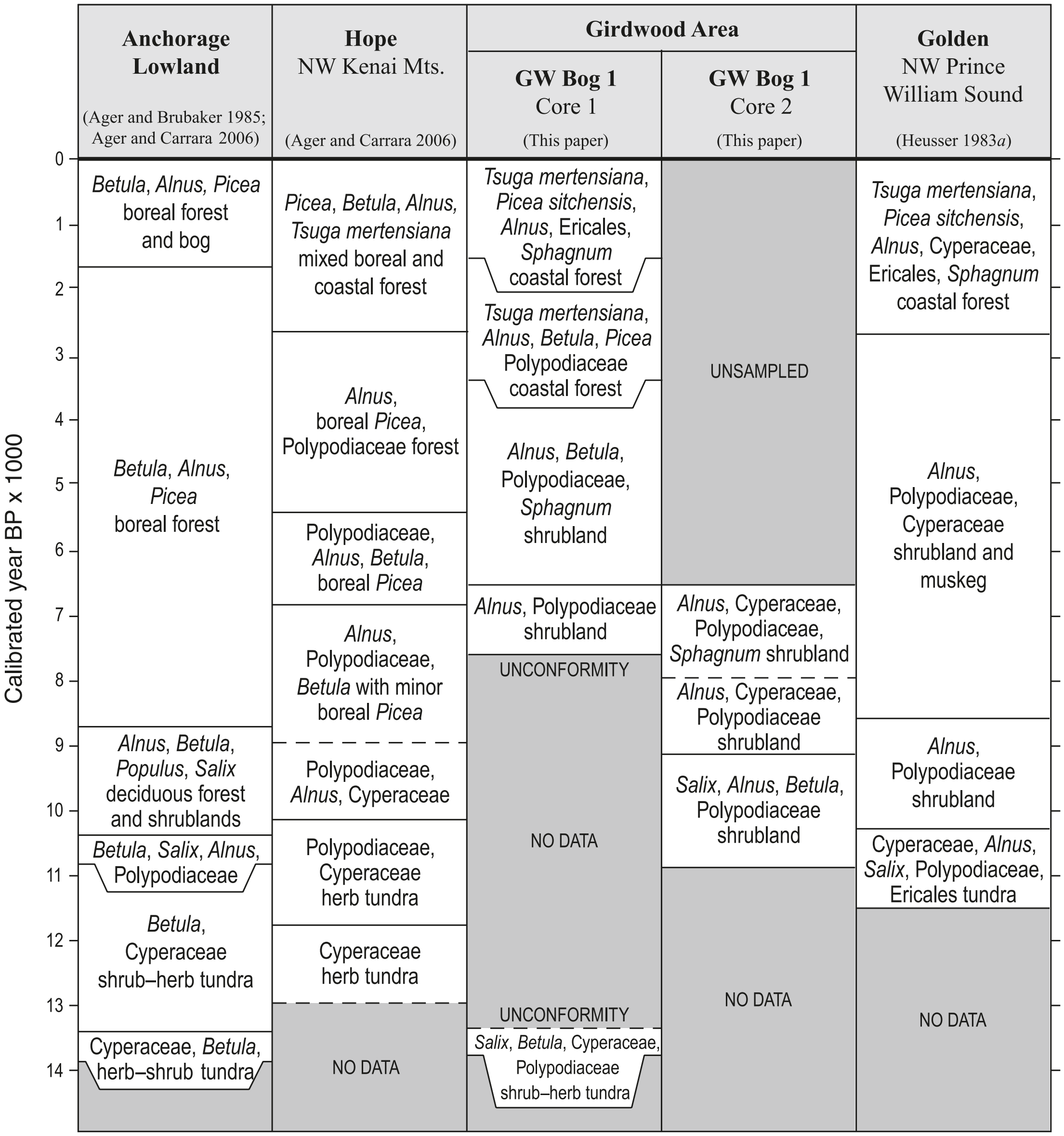
This pollen subzone is characterized by a relative abundance of pollen of *Alnus* (85%–87%) with some Cyperaceae (1.5%–4%). Minor amounts of pollen of woody taxa include *Betula* and Ericales. Herb pollen types present in minor amounts include Poaceae and *Artemisia*. The most abundant spore types include Polypodiaceae (9%–15%) and *Sphagnum* (6%–15%). Minor spore types include *Lycopodium annotinum* and *Cryptogramma*. This pollen subzone is interpreted to represent *Alnus* thickets with ferns that dominated the landscapes of upper Turnagain Arm during much of the early to middle Holocene.

Core depth 0–85 cm was unsampled because we assumed its pollen record would probably duplicate the record from ~0–117 cm obtained from Girdwood bog 1, core 1, which includes pollen zones GW1-1a, GW1-1b, and GW1-2. The distance between coring sites within bog 1 was ~10 m.

Discussion and summary

The discontinuous nature of the pollen records from the Girdwood area cores prevents reconstruction of the entire history of vegetation development in the upper Turnagain Arm area since local retreat of glacial ice from the Elmendorf stade. A gap in the Girdwood area record remains for the interval ~10 900 – 13 400 (estimated) cal years BP, in spite of multiple coring attempts during several field sea-

Fig. 5. Chart comparing vegetation histories based on pollen analysis of peat deposits between the Anchorage Lowland and northwestern Prince William Sound, south-central Alaska. Pollen zone boundaries within columns for each site are shown with solid black lines where the age control is provided by adjacent radiocarbon ages. Broken horizontal lines indicate approximate chronological positions of pollen zone boundaries, where age control is estimated by interpolation from calibrated radiocarbon ages of samples located some distance from the boundaries.



sons. However, a comparison of vegetation histories from two of the Girdwood area cores permits reconstruction of most of the postglacial history (Fig. 5). Comparisons with pollen records from the Anchorage Lowland, the Hope area, and Golden in northwestern Prince William Sound areas (Fig. 1B) can be used to infer the likely nature of the vegetation in upper Turnagain Arm during the missing interval at Girdwood. The radiocarbon-dated pollen record from a peat bog near Hope (Ager and Carrara 2006; Fig. 1B, site 7) provides evidence about the likely vegetation history in Turnagain Arm during the missing interval from the Girdwood area records. The vegetation histories from the Anchorage Lowland, Hope, Girdwood area, and northwestern Prince William Sound sites are summarized in Fig. 5.

The final glacial readvance of the late Wisconsin to fill most of Turnagain Arm (Elmendorf stade of Reger and Pinney 1997; Reger et al. 2007) began to wane in the northern Anchorage Lowland before ~14 100 cal years BP (Schmoll et al. 1999; Kathan et al. 2004). Remnants of Elmendorf stade ice may have persisted in mountain valleys for much longer, however (Reger and Pinney 1997; Reger et al. 2007). It is highly likely that a similar chronology of deglaciation applies to Turnagain Arm, as is suggested by the oldest minimum date for deglaciation yet obtained from the area, from the Girdwood bog 1, core 1 (~13 800 cal years BP; Table 2). Pollen data indicate that the earliest known vegetation to colonize upper Turnagain Arm during and immediately following deglaciation was an herb–shrub tundra composed of *Salix*, dwarf *Betula*, Cyperaceae, Poaceae, *Artemisia*, and other herbs and ferns, especially Polypodiaceae types. It is likely that the initial plants to colonize Turnagain Arm spread from nearby refugia in the Kenai lowlands, northwest Kenai Mountains, and southern Chugach Mountains (Karlstrom 1964; Ager 2001; Reger et al. 2007).

A gap in the Girdwood area pollen record between ~13 400 and ~10 900 cal years BP prevents reconstruction of the local vegetation history for that missing interval, except by inference from the pollen record from near Hope (Fig. 1B, site 7), which spans part of the missing interval from Girdwood (Fig. 5). The pollen-record-based vegetation history and radiocarbon ages from the site near Hope suggest that herb–sedge tundra may have persisted in Turnagain Arm until ~11 400 cal years BP (Ager and Carrara 2006). This was followed by shrubby vegetation in which *Alnus*, Polypodiaceae, and Cyperaceae were dominant taxa near Hope; whereas *Betula* (probably *B. nana*), *Salix*, *Alnus*, and Polypodiaceae predominated near Girdwood. In the Girdwood area, *Alnus* and Polypodiaceae were dominant plant species until ~6800 cal years BP when tree birches (*Betula neoalaskana*, *B. kenaica*) began to colonize locally. *Alnus*–*Betula*–Polypodiaceae vegetation persisted in the area until ~3200 cal years BP when *Tsuga mertensiana*, then *Picea sitchensis* arrived and rapidly developed a conifer-dominated coastal forest vegetation.

Summaries of vegetation histories from several sites between the Anchorage Lowland and northwest Prince William Sound place the Girdwood pollen records into a broader regional context (Fig. 5). A pollen record from Golden, in northwestern Prince William Sound (Heusser 1983*a*) shows that *Alnus* populations were small, but already expanding in that area by ~11 500 cal years BP (Figs. 1B, 5). The dates for *Alnus* expansion between Golden and the Anchorage Lowland (Fig. 5) suggest an east-to-west colonization from Prince William Sound for that shrub type.

Populus trees (probably black cottonwood, *P. trichocarpa*) may have colonized floodplain environments in the Girdwood area as early as ~8900 cal years BP. However, the history of cottonwoods (*Populus trichocarpa*) is based on only rare occurrences of *Populus* pollen in the peat cores we have analyzed from this region. *Populus trichocarpa* trees grow in the Girdwood valley lowlands today and have probably been present in Turnagain Arm for most of the Holocene. Pollen of *Populus* is fragile and is often underrepresented in pollen records. The reconstruction of the history of *Populus* in Turnagain Arm is further complicated by scattered occurrences of the boreal forest species balsam poplar (*Populus balsamifera*) near Hope and Portage (Viereck and Little 1975). *Populus balsamifera* and *P. trichocarpa* also hybridize, adding still another complication to understanding the history of these taxa (Viereck and Little 2007). Trembling aspen (*Populus tremuloides*) has been reported near Hope and in the valleys of the northern Kenai Mountains south of Turnagain Arm (Viereck and Little 1975), and its pollen is similar to that of *Populus balsamifera* and *P. trichocarpa*. Therefore, the history of *Populus* species in Turnagain Arm will remain obscure until plant macrofossils can be found, identified, and dated.

The rapid spread of coastal conifer species occurred during an interval of cooler, wetter climates and Neoglacial ice expansion ~3300–2900 cal years BP (Heusser et al. 1985; Barclay et al. 2009). Wind transport of conifer seeds from western Prince William Sound into upper Turnagain Arm may have been favored by greater storm frequency and severity during Neoglacial cold intervals (Heusser 1960, 1983*a*, 1983*b*, 1985). Storms spawned by low pressure systems in the northeast Pacific – Gulf of Alaska region generate high wind speeds that favor wind transport of seeds from east to west along the southern coast, especially in autumn and winter (Heusser 1960; Shulski and Wendler 2007).

The vegetation history of Turnagain Arm is of particular interest because of the strong precipitation gradient that exists along the east–west axis of the fjord (Table 1). Present-day vegetation patterns appear to be heavily influenced by this precipitation gradient, with coastal forest vegetation predominating in upper Turnagain Arm where precipitation is high and maritime climates prevail (Figs. 1A, 1B; Table 1). This strong precipitation gradient has apparently been in existence since at least since the late Wisconsin, as suggested by reconstructions of full-glacial ice extent in south-central Alaska (Karlstrom 1964; Molnia 1986; Kaufman and Manley 2004). Those reconstructions show more extensive glaciers on the outer coasts of Kenai Peninsula than in the northwest Kenai Mountains and Kenai Lowland, a likely result of precipitation shadows that persist to the present day.

In contrast to the coastal rainforest vegetation of upper Turnagain Arm, the vegetation of the Anchorage Lowland and northern Kenai Lowland adjacent to the western end of Turnagain Arm (Fig. 1B) is composed predominantly of boreal forest plant species, including *Betula neoalaskana*, *Betula kenaica*, *Populus balsamifera*, *P. tremuloides*, *Picea glauca*, and *P. mariana*. The dominance of boreal forest in those areas is explained by the more continental climate that exists in the precipitation shadows of the Kenai and Chugach mountains. Much of Turnagain Arm east of the Anchorage and northern Kenai lowlands has a transitional climate, but it becomes progressively wetter to the east, where a maritime climate characterizes the upper valley in the vicinity of Girdwood and Portage (Fig. 1B; Table 1). Within this climate transition zone, the vegetation is an interesting admixture of boreal forest and Pacific coastal forest trees, shrubs, and herbs. West of Bird Creek (Fig. 1B), *Picea* is the most common conifer at lower elevations. Most of the *Picea* trees we have examined within that transition zone appear to be hybrids between coastal *Picea sitchensis* and boreal *P. glauca* (Lutz spruce; Viereck and Little 2007).

In summary, shrub–herb tundra developed in the Anchorage Lowland, and sedge–herb and shrub–herb tundra developed in Turnagain Arm by ~13 800 cal years BP during the waning stages of the Elmendorf glacial event. *Alnus* shrubs rapidly colonized the Turnagain Arm – Anchorage Lowland area beginning ~11 000 cal years BP. The Anchorage Lowland and northern Kenai Lowland were colonized by boreal forest vegetation with *Picea*, *Betula*, *Populus*, and *Alnus* by ~8900–8600 cal years BP, probably via the Matanuska Valley (Ager 1983, 2001; Ager and Brubaker 1985; Williams 1986; Ager and Carrara 2006; Anderson et al. 2006; Jones et al. 2009). Pollen data and radiocarbon ages from a bog near Hope suggest that boreal *Picea* vegetation had begun to colonize western Turnagain Arm, at least as far east as the Hope area, by ~6800 cal years BP (Ager and Carrara 2006). In contrast, eastern Turnagain Arm was blanketed mostly by *Alnus* thickets and ferns for thousands of years after boreal forest arrived in the western Turnagain Arm, even though no physical barriers prevented boreal forest vegetation from spreading farther eastward. Except for scattered populations of *Betula* trees and a few small outlier populations of *Picea mariana* and *Populus balsamifera* (Viereck and Little 1975), boreal forest tree species failed to colonize eastern Turnagain Arm. The progressive shift towards a maritime climate east of Hope and Bird Creek (Fig. 1B; Table 1) may be unfavorable for many boreal forest taxa (Thompson et al. 2006). *Alnus* thickets continued to cover most of the landscapes of eastern Turnagain Arm until the maritime climate-adapted coastal conifer tree species *Tsuga mertensiana* and *Picea sitchensis* began to colonize eastern Turnagain Arm during the late Holocene.

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