Postglacial Climate and Vegetation of the Western Alaska Peninsula

James W. Jordan, Department of Environmental Studies,
Antioch New England Graduate School, Keene, NH 03431
Andrea Krumhardt, Geophysical Institute, University of Alaska, Fairbanks, AK 99775

Abstract: Pollen analysis of a sediment core at Cold Bay, Alaska, indicates a sequence of four vegetation zones representative of trends in postglacial climate. The sequence suggests cool, relatively dry conditions from 9000 – 6200 yr B.P. (^{14}C years); warmer, moister conditions from 6200 – 3200 yr B.P.; cool, moist conditions from 3200 – 2100 yr B.P.; and cool, wet conditions from 2100 – 0 yr B.P. Vegetation throughout the record consisted of treeless tundra dominated by shrubs, herbs, and grasses. Regional pollen records are influenced both by climatic factors and volcanism. The lack of visible volcanic ash deposits in the core described here, and its evidence of a regionally documented shift toward sedge-dominated vegetation about 3000 yr B.P., suggest that the site provides a good approximation of regional climate change during the Holocene. The transition to cooler moister conditions after 3200 yr B.P. is also recorded by coastal dune stabilization on the western Alaska Peninsula, and is broadly correlative with Neoglacial indicators in southern and western Alaska. Changes in solar radiation and shifts in the position and intensity of the Aleutian low-pressure and North Pacific high-pressure centers are the dominant mechanisms of postglacial climate change.

Key words: Disturbance, Effective Moisture, Neoglacial Climate

INTRODUCTION

Investigations of paleoclimatic change are important for understanding the mechanisms and consequences of global environmental change. Reconstructions of Holocene environmental conditions in southern Beringia (western Gulf of Alaska through the Aleutian Islands, Figure 1) emphasize the spatial complexity of vegetation change and the variable influences of postglacial climate on regional biogeography (Anderson and Brubaker 1993; Barnosky et al. 1987; Hu et al. 1995). Paleoenvironmental interpretations based on pollen records have stressed both climatic (Ager 1982; Anderson and Brubaker 1993; Hu et al. 1995) and edaphic (Heusser 1983, 1990) controls. Postglacial flooding of the Bering platform and latitudinal shifts in the position of the Aleutian low-pressure and North Pacific high-pressure systems during the Holocene have influenced temperature, cloud cover, and the distribution and intensity of precipitation. But pervasive Holocene volcanic and seismic activity in the eastern Aleutian arc (Begét and Nye 1998; Carson 1998; Coats 1950; Miller and Smith 1987) complicates interpretations of vegetation–climate relationships because this activity influences sedimentation, pedogenesis, and topography.

This paper presents new pollen data from a sediment core in marsh deposits at Cold Bay on the western Alaska Peninsula (Figure 2). The 9000-year pollen record is compared with previous records from the nearest sites in the region – Umnak Island in the eastern Aleutian chain and the Shumagin Islands and adjacent Alaska Peninsula (Heusser 1973, 1983). These paleoclimatic data are important because they fill a geographic gap in the environmental history of eastern Beringia (Hu et al. 1995) and add to our understanding of the relationship between postglacial vegetation and dynamic environmental change in southern Beringia.

SETTING

The study area extends from Unimak Island in the west, and includes the western Alaska Peninsula as far east as Port Moller and the Shumagin Islands in the east, It is centered at about 55° N/163° W. A maritime climate prevails over the region and vegetation consists of treeless tundra. Average annual precipitation ranges from 850 to 1500 mm (increasing to the west) with annual air temperatures averaging 4°C. Annual wind speed from all sectors averages 30 kph with highest velocities exceeding 130 kph in winter. Grasses (Poaceae), sedges (Cyperaceae), crowberry (*Empetrum*) and lichen dominate coastal tundra vegetation, with willow (*Salix*, *sp*.), dwarf birch (*Betula nana*) and alder (*Alnus crispa*)

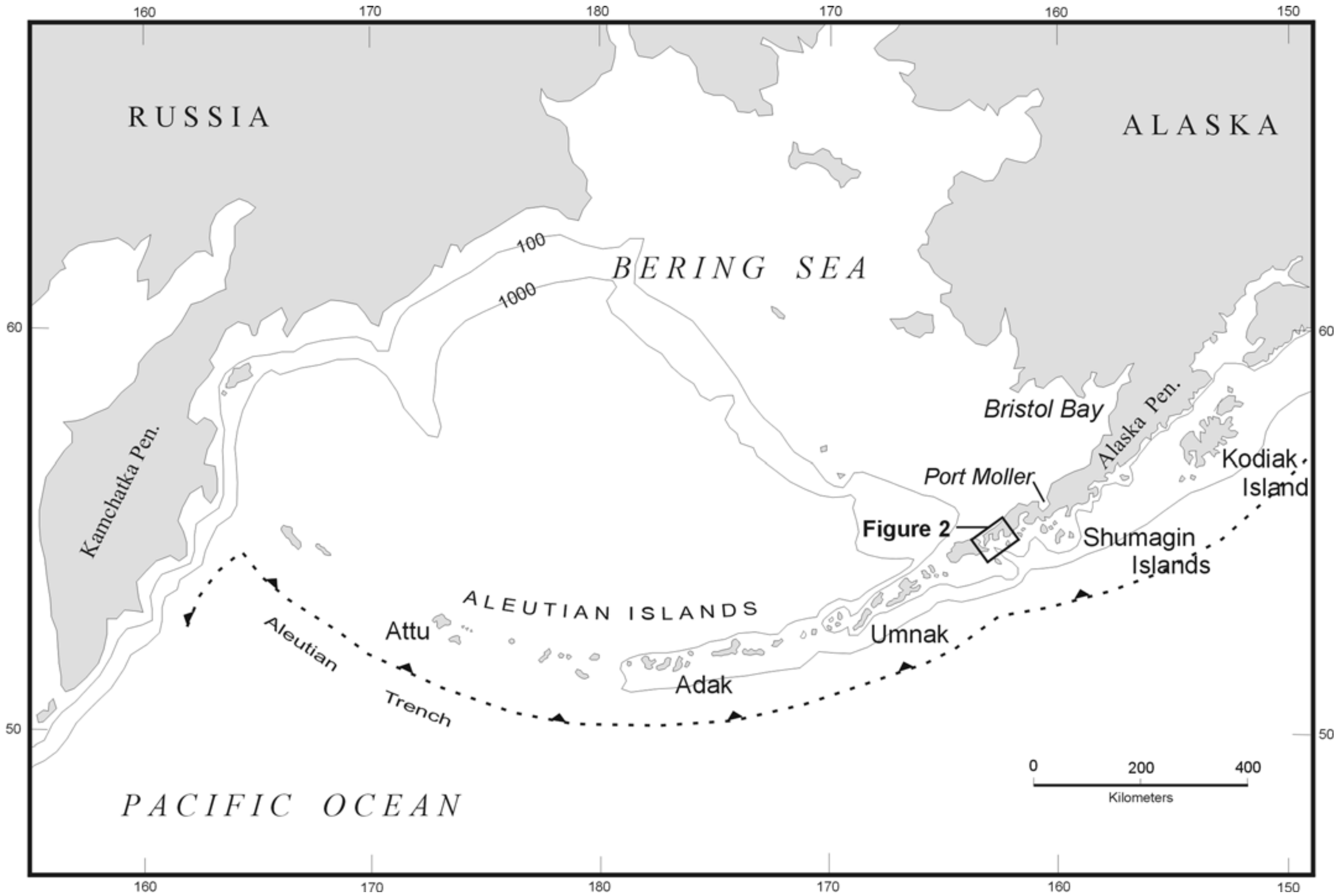


Figure 1. Map of the Aleutian arc showing places mentioned in text. 100 m isobath roughly corresponds to limit of subaerial exposure of the Bering platform during the Last Glacial Maximum.

occurring in more sheltered areas (Viereck et al. 1992). Vegetation cover thins rapidly with elevation because of exposure to persistent wind. Bluff edges and moraine crests higher than about 30 m above sea level (asl) are typically drier and deflated, and support only limited soil cover and restricted patches of *Empetrum* or dwarf willow.

The western third of the peninsula and eastern Aleutian Islands are relatively isolated from the Alaskan mainland and separate the relatively warm waters of the north Pacific Ocean from the colder shelf waters of the eastern Bering Sea. The position of the eastern Aleutian arc between seas with such differing physiographic and climatologic characteristics means that frequent and often violent cyclonic storms are generated along its axis. The Aleutian low-pressure anomaly is centered over the archipelago, and is responsible for much of the cyclogenesis over northwest North America (Hare and Hay 1974; Terada and Hanzawa 1994).

Lowland physiography is inherited from late Wisconsin glaciation of the Alaska Peninsula, when a nearly continuous ice cap was centered on the Pacific side of the Alaska Peninsula and on the eastern Aleutian Islands. Alpine and continental ice of the Alaska Peninsula Glacier complex (Mann and Peteet 1994) flowed north across the peninsula, depositing moraine complexes and outwash on the Bering Sea shelf (Funk 1973; Waldron 1961). Ice-rafted glacial erratics on the narrow Pacific shelf (Kent et al. 1971) indicate that glaciers terminated at tidewater south of the peninsula. Ice retreated rapidly between 14,000 and 11,000 radiocarbon yr B.P. (Black 1976; Detterman 1986; Dochat 1997; Mann and Peteet 1994). Rapid deglaciation is attributed to warming of the North Pacific Ocean following an increase in global temperature between 14,000 and 12,000 yr B.P., with the subsequent rise in eustatic sea level accelerating the disintegration of tidewater glaciers. Peaks above about 1500 m carry alpine glaciers today, many showing evidence of advance and retreat during the Holocene (Black 1979). Glacial sediments form the heads of bays on the Pacific coast, and are reworked locally into spits and beach ridge complexes. Ground moraine is extensive and connects former volcanic islands at Pavlof, Cold, and Morzhovoi bays (Wilson et al. 1992). Lag deposits of glacial cobbles and boulders occur in many intertidal settings and reflect marine erosion of moraine and outwash deposits.

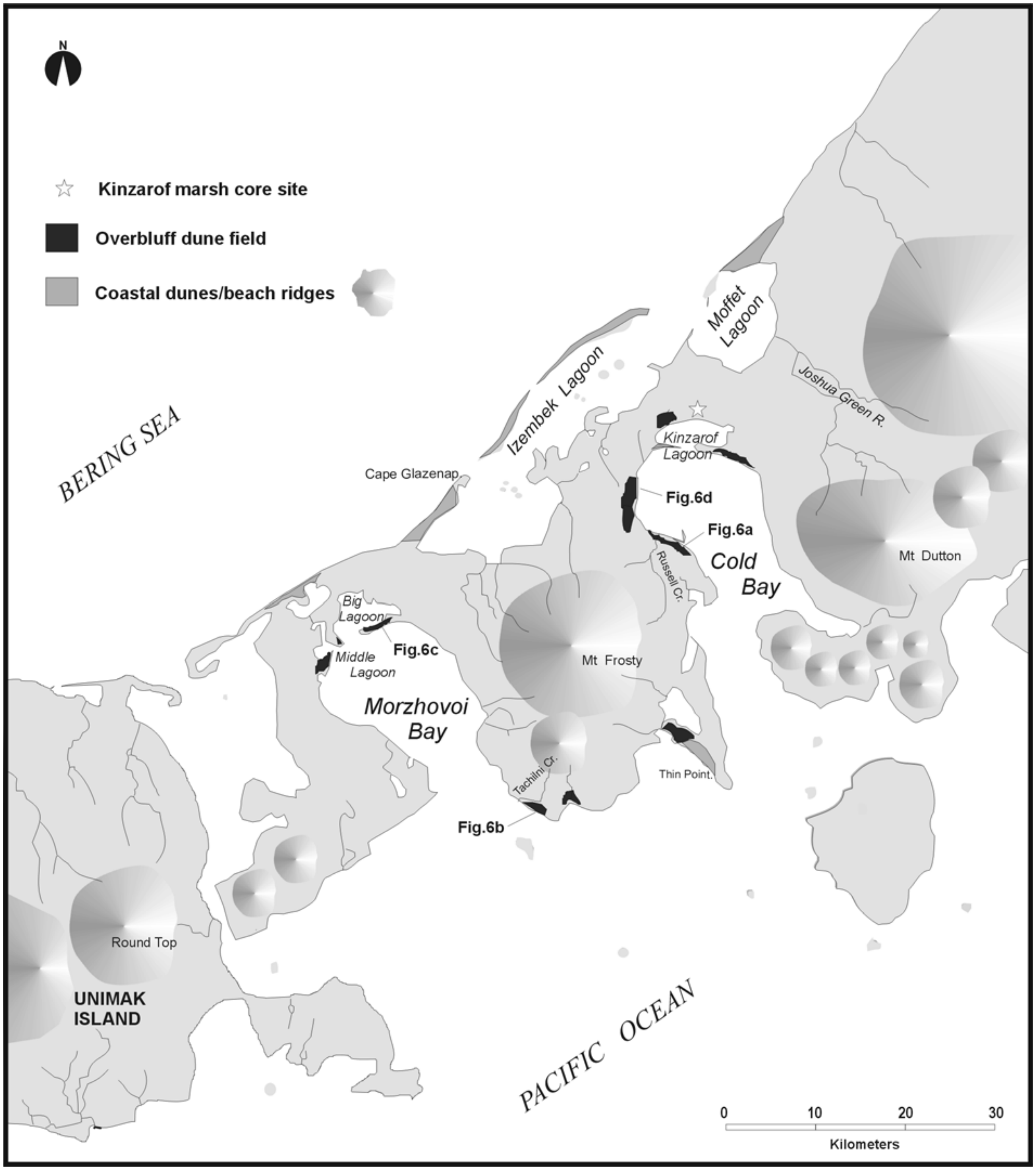


Figure 2. Map of the western Alaska Peninsula showing locations of the Kinzarof marsh core site and major eolian deposits.

Unconsolidated surficial deposits consist of primary airfall tephras and wind-blown glacial, volcanic, and littoral sediments. Lahar or ash flow deposits are locally important parent materials (Miller and Smith 1977; Ping et al. 1988). Tephra deposits vary in thickness because of proximity to source, prevailing winds, and eruption intensity. Only one tephra, associated with the eruption and formation of Fisher caldera on Unimak Island, can be correlated visually across the western Alaska Peninsula (Carson 1998). Radiocarbon ages on the Fisher ash cluster around 9100 yr B.P. (Carson 1998; Dochat 1997; Funk 1973; Jordan 2001) and provide an important early Holocene chronostratigraphic marker.

Soils in the Cold Bay area formed in volcanic parent material that is basic relative to islands farther east (cf. Everett 1971; Ping et al. 1988), and a high proportion of colored volcanic glass indicates the intermediate to mafic composition of source materials (Shoji et al. 1993). Permafrost is absent in coastal plain soils, which have cryic temperature and udic moisture regimes (Rieger et al. 1979).

SITE DESCRIPTION

The establishment of vegetation on deglaciated terrain throughout the eastern Aleutian arc is time-transgressive, occurring earlier with proximity to the mainland. A minimum age estimate for initial vegetation of parts of the upper Alaska Peninsula and Kodiak Island following deglaciation is 14,000 yr B.P. (Detterman 1986; Peteet and Mann 1994). Radiocarbon ages on basal peat deposits overlying glacial till on the western Alaska Peninsula and the Shumagin Islands cluster around 10,500 yr B.P. (Funk 1973; Heusser 1983; Jordan 2001; Jordan and Maschner 2000; Winslow and Johnson 1989). A date of 11,530±100 yr B.P (BETA-96829) on plant macrofossils that overlie till at Cold Bay (Dochat 1997; Jordan 2001) provides the earliest local evidence that shrub tundra was colonizing lowlands shortly after 12,000 yr B.P. None of the radiocarbon ages that have bearing on the timing of widespread deglaciation of the western Alaska Peninsula exceed the 11,500 yr B.P. age from Cold Bay, but evidence from adjacent areas of southern Alaska suggests that coastal areas were ice-free several thousands of years earlier (Mann and Peteet 1994; D.H. Mann, pers. comm. 1999).

As relative sea level rapidly fell during the early Holocene in response to isostatic adjustment to ice sheet disintegration, two prominent shorelines were cut in till and outwash at 25 m and 16 m asl on the western peninsula (Jordan 1997, 2001). Kinzarof marsh (informal name) occupies a basin 16 m asl, landward of the 5 km long marine terrace that rises 25 m above the inner margin of Kinzarof Lagoon at the head of Cold Bay (see Figure 2). The Kinzarof terrace (informal name) is mantled with wave-sorted pebbles and gravel and represents the local postglacial marine limit. It lies at a consistent elevation of 25 m asl, except where it is crosscut by presently underfit stream valleys. The lobate, landward edge of the terrace slopes steeply down into a narrow basin that backs most of the length of the feature. Kinzarof marsh has infilled this basin, which probably formed as a backbarrier lagoon that was impounded behind the emergent barrier bar during the early Holocene. Diatoms identified from organic sandy silt at the base of a 1.35 m core on the margin of the basin immediately landward of the terrace are dominated by *Fragilaria construens spp., F. pinnata, F. cf nitzschiodes, F. capucina v,* and *Fragilaria virescens v exigua* (M. Winkler, pers. comm.), suggesting that the lagoon was freshwater.

METHODS

Sediment cores were recovered from several marshes in the Cold Bay area with a Russian peat sampler (Jowsey 1966). Core lithology was noted in the field and logged in detail prior to subsampling in the laboratory for pollen, diatom, and radiocarbon analyses. Twenty-seven samples were taken at 5 cm intervals from the 135 cm-long core obtained at Kinzarof marsh (Figure 3). Subsamples of 1 cm^3 were prepared for pollen analysis following standard methods (Faegri and Iverson 1992; Shane 1992). *Lycopodium* tablets (Stockmarr 1972) were added to each sample prior to counting in order to calculate influx. Sample counting and pollen identification were conducted at the University of Alaska Fairbanks. All samples produced abundant pollen and spores. Samples were examined under 400x and 1000x (oil immersion) magnification until at least 300 terrestrial pollen grains were counted. The delineation of pollen zones was based on visual inspection of diagrams of pollen percentages and pollen accumulation rates (PAR).

Two samples from the core were submitted for radiocarbon dating. Ages are reported in 14C yr B.P. to facilitate comparison with radiocarbon ages reported from other pollen sections in the region. The lowest sample (130-133 cm) was taken from a lens of peaty fine sand and provided a ^{14}C age of 8620+60 yr B.P. (CAMS-41437). A horizon of sandy peat in the upper part of the core (41-43 cm) yielded a ^{14}C age of 3650+40 yr B.P. (CAMS-41438). Pollen accumulation and sedimentation rates (Figure 4) are based on linear interpolation between these dates. Maximum ages on peat stringers that overlie till in Cold and Morzhovoi bays predate the basal age of the Kinzarof marsh core by 1500 to 2000 years, but synchronous changes in pollen spectra that occur in other cores from the region (Heusser 1973, 1983, 1990; Hu et al. 1995) suggest that pollen stratigraphy is in general chronological agreement with regional palynological data.

VEGETATION AND CLIMATE HISTORY

Early postglacial vegetation assemblages in southern Alaska were dominated by herbaceous taxa (Ager 1982; Anderson and Brubaker 1993; Heusser 1985, 1990; Peteet and Mann 1994). On the Alaska Peninsula and eastern Aleutian Islands, pioneer taxa are indicative of local mesic and hydric habitats and included Cyperaceae, *Artemisia* and other members of the Tubuliflorae, prostrate shrubs such as *Empetrum*, as well as ferns, and *Equisetum*, with *Salix* and Poaceae as important secondary components (Heusser 1983; Peteet and Mann 1994). While most of these taxa are represented in basal

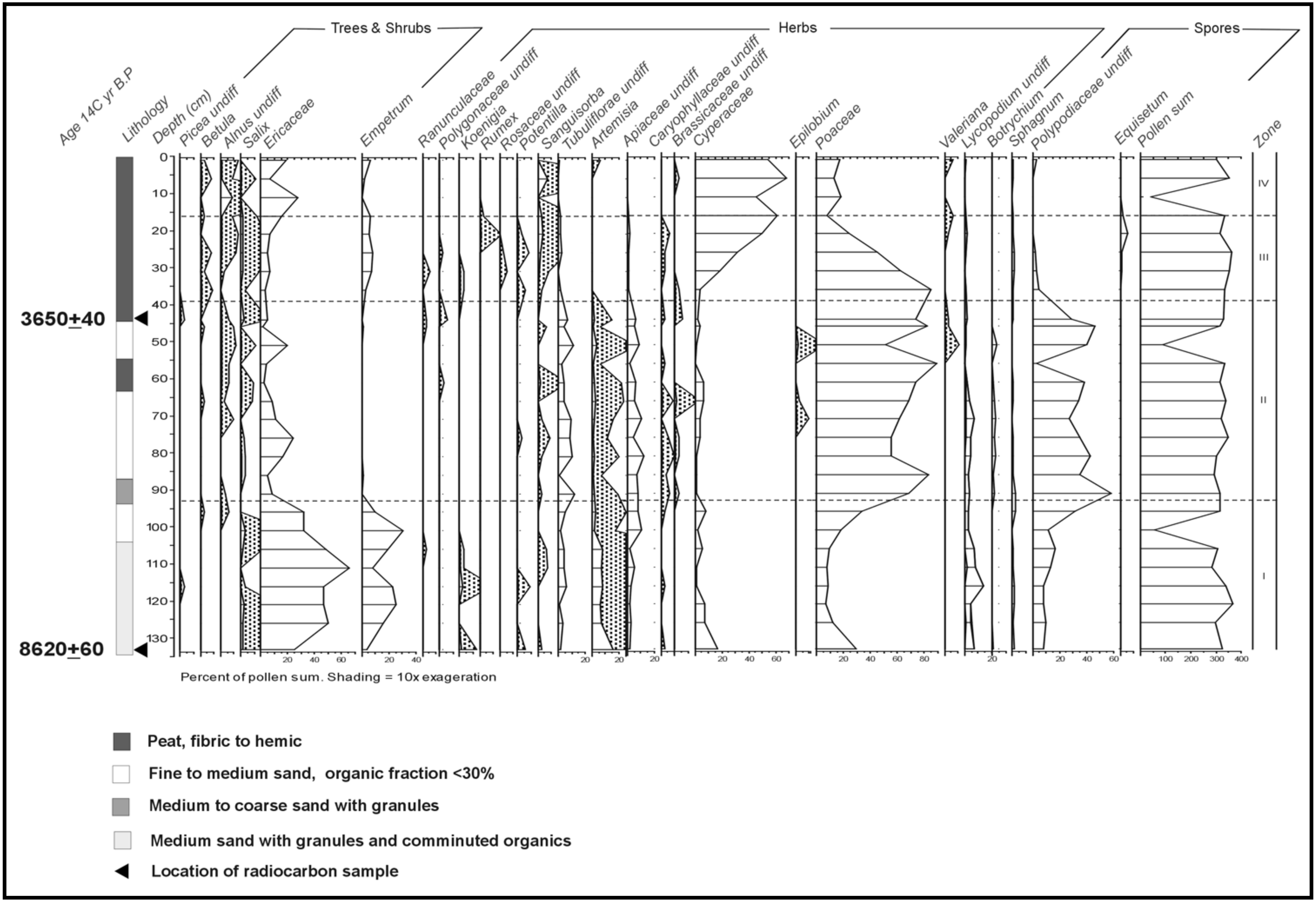


Figure 3. Pollen percentages, core lithology, and radiocarbon ages at Kinzarof marsh.

levels at all sites, differences in their relative abundance indicate strong microclimatic control on vegetation composition (cf. Matthews 1992).

Pollen stratigraphy at Kinzarof marsh records the development of vegetation communities near this site over time. The following zonation provides a framework to interpret vegetation characteristics from pollen abundance throughout the core. Vegetation – climate inferences are made based on the identification of pollen zones and are presented in a separate section.

Zone I (9000 – 6200 yr B.P.) Empetrum shrub tundra

A shrub tundra dominated by *Empetrum* and other Ericales and various forbs and grasses characterized the vegetation cover of the early Holocene landscape. High percentages of Ericales, particularly pollen of *Empetrum*, suggest that a dwarf shrub tundra occupied a variety of sites at mid- and low elevations (100 m to sea level). Poaceae and *Artemisia* are notable elements of the early landscape, and probably occupied more xeric upland sites. Minor amounts of Cyperaceae pollen and fern spores suggest that mesic-tundra communities may have been present locally. *Salix* pollen, while present in relatively low amounts throughout the core, reaches its highest percentages and PAR during this period. This suggests that shrub tundra communities containing significant amounts of willow probably were not common near Kinzarof marsh, but were appearing on the eastern Aleutian arc in the early Holocene (cf. Heusser 1973, 1983).

Zone II (6200 – 3200 yr B.P.) Graminoid-forb and fern tundra

The dramatic increase in pollen of Poaceae and Polypodiaceae (fern spores) indicates the appearance of tundra dominated by grasses and ferns about 6200 yr B.P. Tubuliflorae and Apiaceae reach their highest percentages and PARs during this period, suggesting that a variety of forbs and herbs became important components of tundra communities. Ericales drop in abundance but probably were common in exposed locations based on modern distributions. An increase in fern spores may indicate mesic tundra communities in coastal lowlands (Peteet and Mann 1994). Increased PARs among all of the dominant taxa of this zone suggest that vegetation cover became more continuous during the mid-Holocene than at the end of Zone I. The increase of *Alnus* seen in the PAR diagram in Zone I probably indicates its expansion on the eastern Alaska Peninsula and Shumagin Islands, but because of its capacity for long-distance wind transport it probably did not grow locally (Colinvaux 1981).

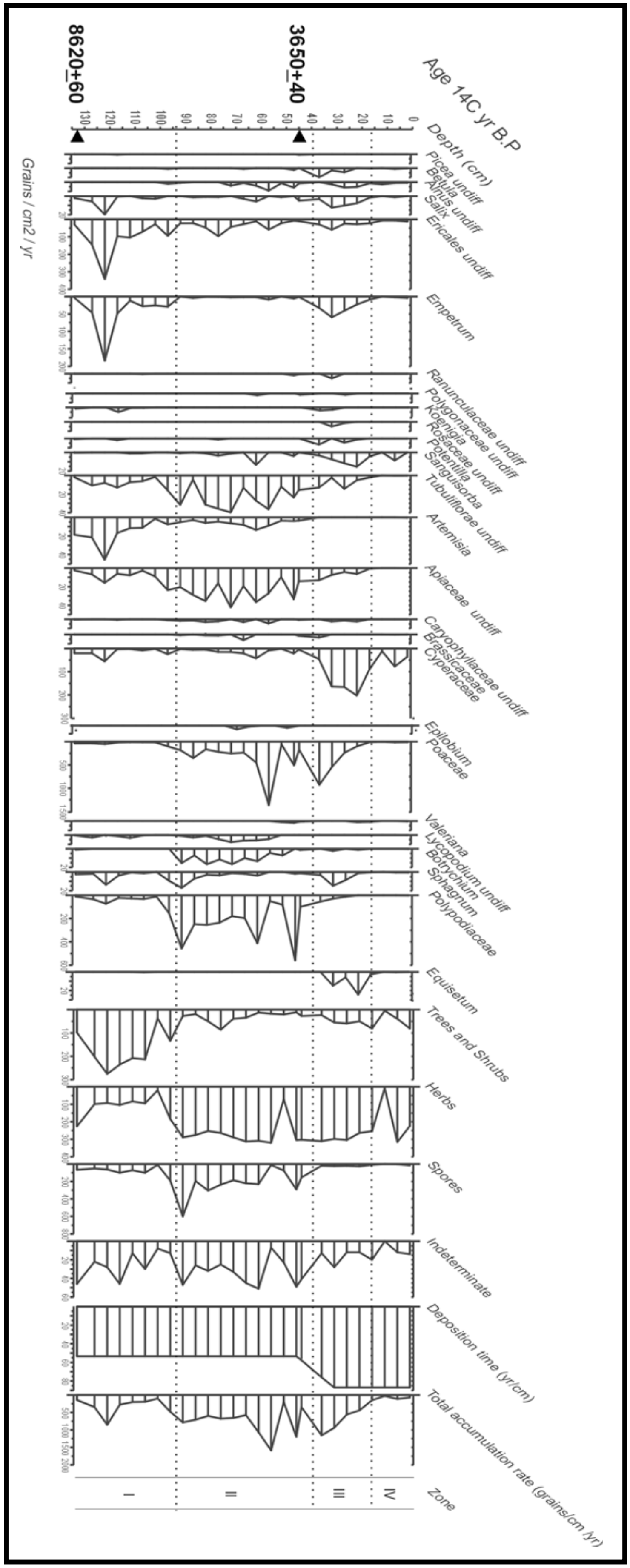


Figure 4. Pollen accumulation rates at Kinzarof marsh.

Zone III (3200 – 2100 yr B.P.) Sedge-Graminoid-Empetrum shrub tundra

This period marks a transition in tundra communities that spanned a thousand-year interval between the middle and late Holocene. It is represented by a major shift in the ratio of grasses to sedges and by a decline in ferns. Cyperaceae rose abruptly as Poaceae became a secondary component, suggesting local, comparatively wet edaphic conditions (Heusser 1989). Ericaceae and *Empetrum* pollen became more abundant, as did taxa common in mesic to hydric environments such as *Sanguisorba*, *Equisetum*, and *Sphagnum*. *Betula*, *Alnus* and *Salix* shrubs probably underwent regional expansion at this time based on their accumulation rates.

Zone IV (2100 – 0 yr B.P.) Sedge-Empetrum tundra

By about 2100 yr B.P. a tundra characterized by sedges and Ericales had replaced the grass and forb-dominated vegetation of the middle Holocene. Increased moisture availability is also suggested by an increase in pollen of *Sanguisorba*. Ericaceae and *Empetrum* became more abundant on the landscape and a relatively high percentage of *Alnus* pollen probably indicates the arrival of this shrub in the region.

In summary, pollen spectra at Kinzarof marsh indicate a vegetation succession that begins in the early Holocene with the dominance of Ericaceae and lesser amounts of Poaceae and Artemisia, followed by an abrupt rise of Poaceae and ferns from 6200-3200 yr B.P. A pronounced transition to vegetation dominated by sedges occurs after 3200 yr B.P., with the modern sedge and shrub tundra being established after about 2100 yr B.P.

DISCUSSION

Disturbance mechanisms

Substantial variability in the pattern of change among species assemblages in coastal tundra communities led Heusser (1990) to identify volcanism as a disturbance mechanism that can overshadow climate as the primary control on succession. The effect of volcanism on vegetation varies widely among sites in the region. Geochemical composition, frequency, magnitude and season of eruption, mean annual precipitation, and postdepositional reworking are all factors that can influence site conditions and complicate interpretations of vegetation history. Topography, exposure, and substrate also will influence the response of vegetation to burial by tephra. Pollen sections of Holocene age on the central Aleutian islands of Adak and Atka, for example, record 24 and 17 tephra horizons, respectively (Heusser 1990). Vegetation assemblages at these sites have experienced frequent and continuous successional disturbance. By contrast, 11 sites distributed between Umnak Island, the Shumagin Islands and adjacent Alaska Peninsula record between one and five tephras deposited during the Holocene (Heusser 1983, 1990). Because eruptions can produce thin tephra deposits that may not be visible in outcrop, these numbers should be considered as minimums.

In instances where tephra deposition is infrequent or light, the effect of inputs of volcanic material are transitory and are not differentiated from vegetation change due to climatic variations (Heusser 1985). Pollen sites that appear to be least affected by volcanism occur on the Shumagin Islands and portions of the Alaska Peninsula adjacent to them. The stratigraphy of the Kinzarof marsh core lacks visible horizons of volcanic ash (see Figure 3) and the basal age of 8600 yr B.P. postdates the major caldera-forming eruption of Fisher volcano by several centuries. Disturbance due to volcanism is probably not a significant factor influencing the sequence of vegetation changes at Kinzarof marsh. To better understand the significance and mechanisms of postglacial climate change recorded at Kinzarof marsh, it is therefore useful to compare it with paleoclimatic proxy data from the region.

Climatic reconstruction at Kinzarof marsh

Shrubs represented by the Ericales and *Salix* and *Betula* dominated or formed a significant part of early Holocene vegetation communities in the Aleutian Island region, reflecting a widespread warming trend following deglaciation of the North Pacific coast (Heusser et al. 1980). Basal pollen samples from Kinzarof marsh record a vegetation assemblage that is consistent with this pattern. The dominance of Ericales and relatively high percentage of *Artemisia* pollen in Zone I suggest that well drained substrates and relatively cool, dry climatic conditions prevailed in the region, especially in upland areas. Their occurrence is broadly indicative of heath communities adapted to persistent wind and variable amounts of precipitation (Heusser 1990; Hultén 1968). The presence of *Sphagnum*, Cyperaceae and Polypodiaceae are indicative of lowland meadows today and suggest that moist meadows were also present in the shrub tundra.

The dramatic increase of grass and fern pollen during Zone II suggests climatic amelioration and mesic conditions at Kinzarof marsh. Hu et al. (1995) note that modern meadow communities dominated by Apiaceae and ferns in the Bristol Bay area are indicative of relatively warm summer temperatures and abundant winter precipitation. Heusser (1973) infers that climatic or edaphic drying accompanied the appearance of tundra dominated by grass and willow on Unmak Island between 8500 and 3500 yr B.P., while noting that earlier sedge tundra communities containing abundant pollen of Apiaceae were wet and poorly drained. Given the lack of taxa indicative of hydric conditions (e.g., Cyperaceae, *Sphagnum* and *Equisetum*), the dominance of grass and ferns with mesic forbs and herbs as secondary components suggests that climate was relatively warmer and perhaps moister than the preceding period.

The increase in sedges during Zone III coincides with the dominance of Cyperaceae in pollen records from the Shumagin Islands and central Alaska Peninsula after 4000 yr B.P. (Heusser 1983). This shift is indicative of wet, cool climatic conditions that prevailed for extended periods of time (Heusser 1983). *Empetrum* was an important secondary element of the tundra at this time, indicating the spread of heath communities in exposed and windy areas.

The shift in the ratio of Cyperaceae to Poaceae, the relative abundance of Ericaceae and *Empetrum*, and the appearance of *Alnus* in Zone IV marks the establishment of modern vegetation, and presumably climate, on the western Alaska Peninsula. This sedge-heath tundra is characteristic of cool, wet edaphic conditions but can occur in both wet and dry sites exposed to strong wind (Heusser 1985). Peat accumulation accompanied these conditions; many coastal bluff exposures of stratified sand, silt and peat stringers are capped by up to 1 m of sedge peat that must have accumulated during the past 2000 years.

COMPARISON OF KINZAROF MARSH WITH CLIMATE PROXIES OF THE NORTH PACIFIC

Regional pollen data

Pollen stratigraphy records the variable influences of climate, volcanism, and seismic activity as they condition the composition and distribution of vegetation in the eastern Aleutian arc, although factors such as island area and proximity to mainland source areas also affect dispersal effectiveness (Hu et al. 1995; Hultén 1968; Woodward 1987). Regional vegetation reconstructions based on pollen data do, however, share several comparable features. Maritime shrub and herb tundra prevailed throughout the Holocene, changing slightly in composition through time (Heusser 1973, 1978). At all sites, deglaciated terrain is typically colonized by pioneer taxa that include a variety of herbs represented by Apiaceae and *Artemisia*, by both sedges and grasses, and by shrubs including *Salix*, *Empetrum*, and *Betula* (Heusser 1990). The assemblage of species that comprise pioneering communities are time-transgressive in the region, making their initial appearance over a 4000 year period of deglaciation that begins on the eastern Alaska Peninsula about 13,000 yr B.P. and ends in the western Aleutians possibly as late as 7000 yr B.P. (Black 1981).

Previous studies indicate that cool, moist, and windy periods from 10,000 to 8500 yr B.P. and from 3000 yr B.P. to the present favored the development of herb tundra dominated by sedges and grasses (Heusser 1973, 1983). A period of warmth during the mid-Holocene (8500 to 3000 yr B.P.) is regionally recognized and is represented by the development of shrub tundra dominated by *Salix* on Umnak and by *Betula* in the Shumagin Islands (Heusser 1990). Cooler and wetter conditions of the past 3000 years have resulted in a mixed tundra that is dominated by sedges, reflecting generally wet edaphic conditions throughout the region (Heusser 1983).

Pollen data from Kinzarof marsh generally conform to this pattern, with synchronous transitions in assemblages throughout the region occurring at 9000 yr B.P. and at about 3000 yr B.P. (Figure 5). The dominance of grasses and ferns (rather than shrub tundra) indicative of a warming trend between 6200 and 3200 yr B.P. may relate to microclimatic conditions that are evident in modern pollen rain (Peteet and Mann 1994). The abrupt vegetation shifts indicated at Kinzarof marsh at 6200 and 3200 yr B.P. may better reflect regional climate changes than some sites in the region because of the lack of volcanic influence.

Holocene glaciation

Early Holocene glacial deposits near Cold Bay suggest that a period of alpine glaciation occurred on the western peninsula between 11,000 and 6700 years ago, based on a minimum age of 6700+330 yr B.P. (GX-2788) on peat overlying alpine moraines on Mt.Frosty (Funk 1973; Thorson and Hamilton 1986). A climatic mechanism for the “Russell Creek advance” (Funk 1973) is poorly documented as it is out of phase with the Holocene glacial chronology documented for southern Alaska. Its singular occurrence on the western Alaska Peninsula may instead relate to volcanic activity and geothermal warming of summit ice at Frosty volcano during the early Holocene (Thorson and Hamilton 1986).

Neoglacial advances are widely recognized in southern Alaska after 4000 yr B.P. (Calkin 1988; Wiles and Calkin 1994; Wiles et al. 1995). Alpine glacial advances occurred on higher peaks of the Aleutian Islands of Adak and Umnak and on the western Alaska Peninsula after about 3000 yr B.P. (Thorson and Hamilton 1986). Alpine glaciers on Umnak Island apparently reached the coast during the Neoglacial (Black 1976, 1981). Advances of alpine ice during the Little Ice Age (LIA) typically extended less than 2 km beyond modern limits (Detterman 1986; Funk 1973) and occurred only on peaks above 1300 m (Thorson and Hamilton 1986).

The timing of Neoglacial activity at Cold Bay is constrained by a single minimum age of 1190+60 yr B.P. (BETA-96827) on soil organics overlying till in Russell Creek valley (Dochat 1997). Moraines on the flanks of Mt. Frosty indicate that alpine glaciers advanced on several occasions during the late Holocene. While age control on Holocene glacial activity remains equivocal for the Cold Bay area, cooler wetter conditions that initiated Neoglaciation elsewhere in southern Alaska are reflected by the trend toward sedge-dominated tundra apparent in pollen Zone III at Kinzarof marsh around 3200 yr B.P.

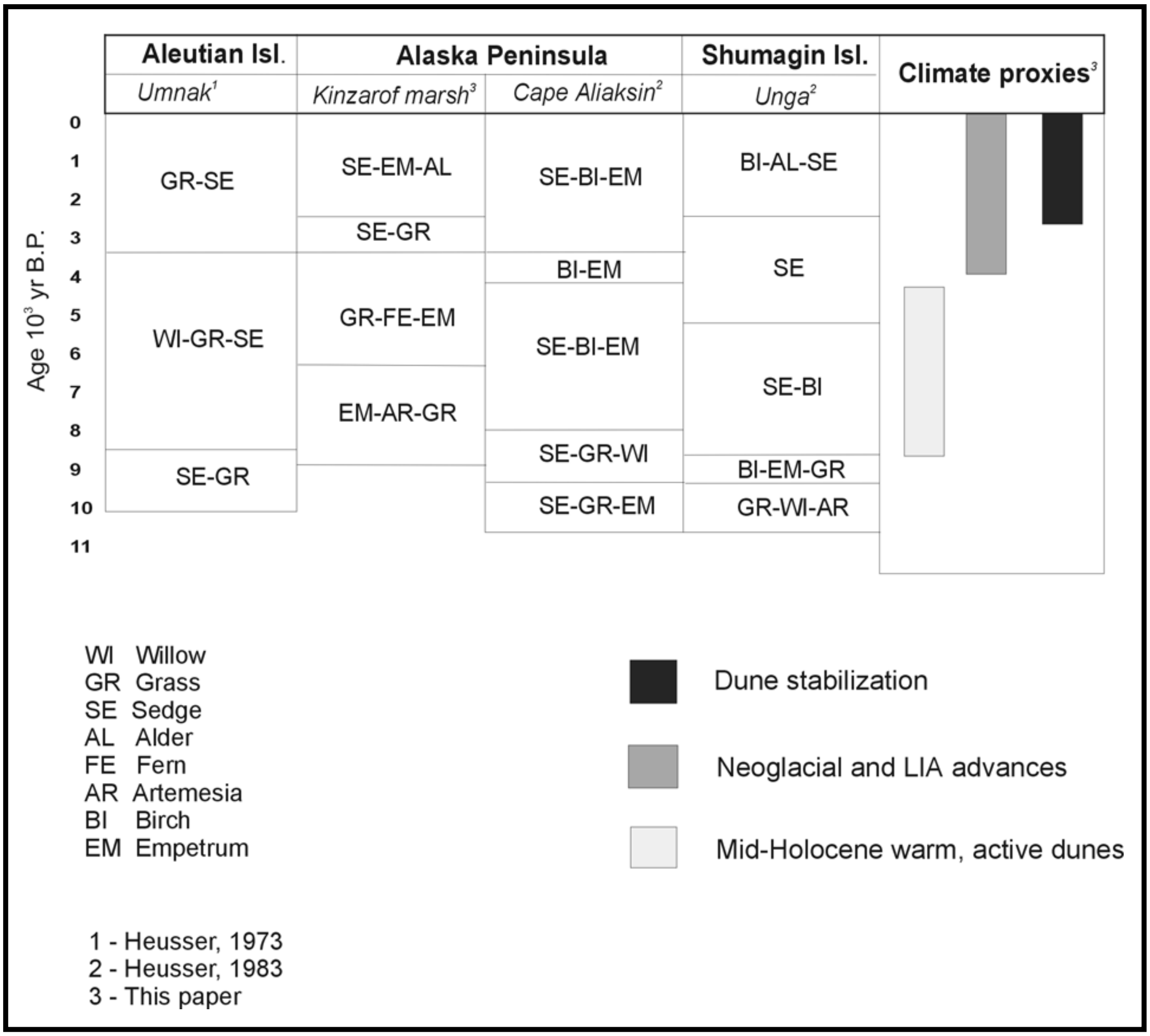
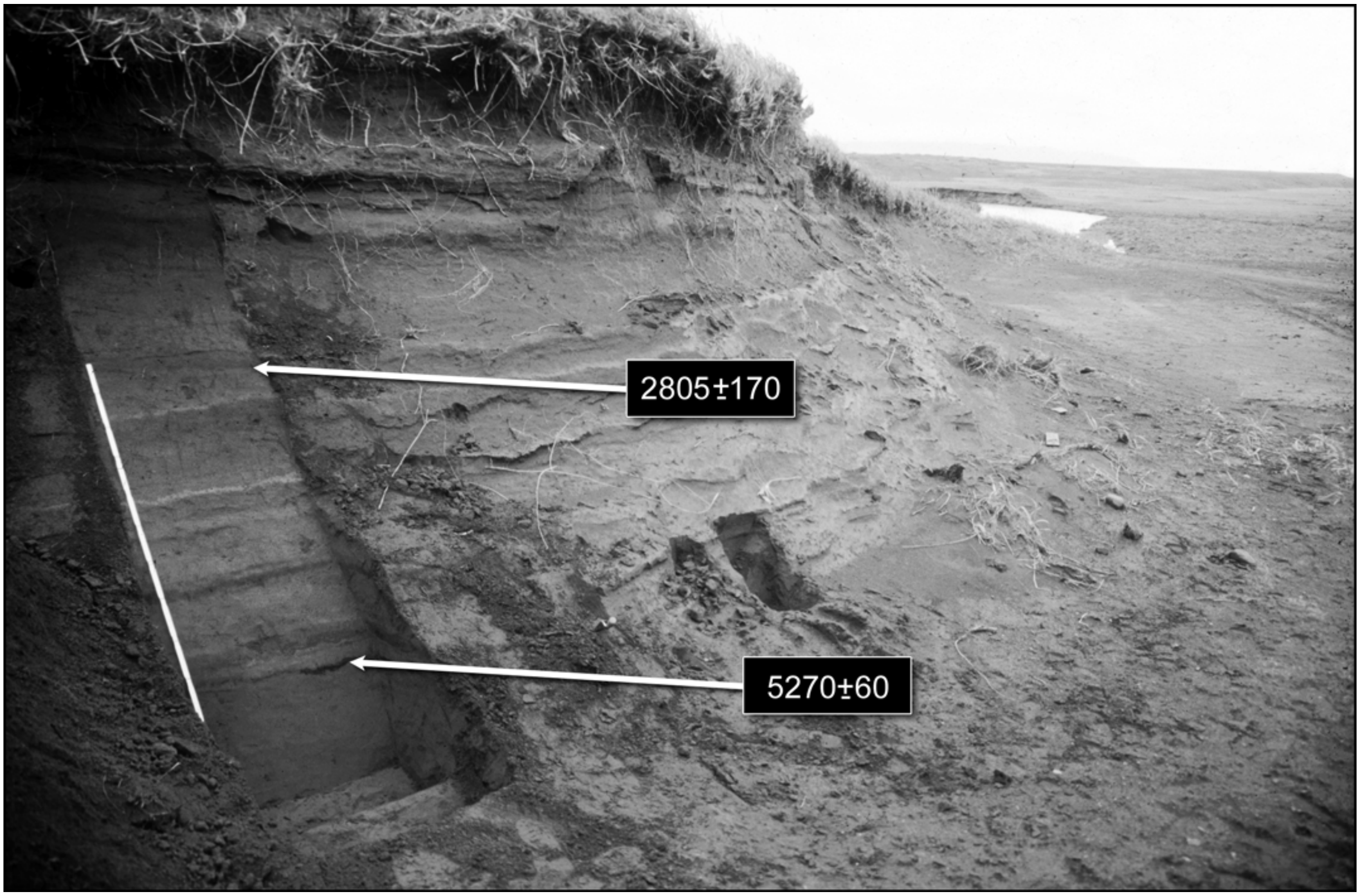


Figure 5. Correlation diagram of pollen assemblage zones from sites on Umnak and Unga islands and the Alaska Peninsula.

Eolian stratigraphy

Eolian deposits occur in a variety of settings on the western Alaska Peninsula (see Figure 2). Coastal dunes cap beach ridges at Big Lagoon on Morzhovoi Bay, Thin Point, Cape Glazenap, and Moffet Point. Isolated dune fields occur in bluff head settings up to altitudes of about 40 m at Cold Bay, at the head of Kinzarof Lagoon, and at the mouths of rivers that drain the south face of Frosty Peak. Fine to medium sand derived from coastal erosion and inputs of volcanic material to the littoral zone provide source materials for dune building along the present coast. The Fisher ash underlies thick deposits of wind-blown sand at Cold Bay, indicating the persistence of eolian processes throughout the Holocene. A maximum age estimate for the beginning of deposition of sandy loess that



Figures 6a through 6d. Eolian stratigraphy at selected sites on the western Alaska Peninsula. Figure 6a above is the Russell Creek dunes showing stratigraphy and 14C ages, scale = 2 m. Refer to Figure 2 for location of Figures 6a through 6d.

mantles till at the head of Morzhovoi Bay is 10,830+60 yr B.P. (CAMS-41410), the date obtained on peat overlying till in the same exposure (Jordan 2001).

Stratigraphic evidence of dune stabilization occurs in all units mapped as overbluff deposits on the western Alaska Peninsula. Buried A horizons or weakly-developed paleosols are exposed in two blowouts along the eastern margin of Cold Bay, at Tachilni Creek, and on the spit that embays Big Lagoon at the head of Morzhovoi Bay (Figure 6a-d). Three Ab horizons occur in a 3-m deep dune exposure above the mouth of Russell Creek (Figure 6a). One of these underlies a 2-cm thick tephra, to which it is probably related pedogenically (cf. Ping et al. 1988, 1989). The other two are not associated with tephra deposits and probably reflect changes in moisture regime that fostered vegetation growth, stabilization of the dune surface, and trapping and deposition of fine sand and silt. A bulk soil sample from an Ab horizon 1.7 m below the surface (Figure 6a) provided a conventional 14C age of 2805±170 yr B.P. (A-9337). Radiocarbon analysis of the basal Ab horizon from the overbluff dune field at Tachilni Creek (Figure 6b) provided an AMS age of 2735+50 (AA-31981). The initiation of dune stabilization at Cold and Morzhovoi bays (Figure 6c-d) is not dated, but is provisionally correlated with records at Russell and Tachilni creeks based on stratigraphic evidence.

The timing of dune stabilization and development of paleosols at Russell Creek and Tachilni Creek correlates with increasingly cool and moist conditions suggested by pollen Zone III from Kinzarof marsh. The only additional age control on eolian deposits is an AMS radiocarbon age of 5270±60 yr B.P. (AA-22422) obtained on a widespread charcoal horizon 3.5 m below the surface at Russell Creek. This horizon is not associated with volcanic activity or archaeological materials and may have resulted from a natural grass fire under conditions of relatively warmer and drier conditions during Zone II.

Eolian deposits are common in coastal lowlands throughout the Aleutian Islands (Black 1981) and many show similar stratigraphic evidence of episodic stabilization. A 15 m section of eolian sand on Adak Island preserves evidence of three buried soils that represent periods of increased moisture and dune stabilization (Judson 1946) and may correlate with the record of increased late Holocene moisture at Cold Bay.

MECHANISMS OF HOLOCENE CLIMATE CHANGE

Local and regional proxy data support the contention that vegetation changes evident at Kinzarof marsh result from shifts in the location and intensity of dominant pressure systems over the North Pacific Ocean and southern Bering Sea. The present climate of the Alaska Peninsula is dominated by atmospheric and oceanic circulation between these basins. The Aleutian low-pressure system is centered over the Aleutian arc and is strongest in winter. Cyclonic circulation commonly develops over the northeast Pacific during winter, steering storm systems toward southern Alaska and northwest North America because of increased zonal circulation and interaction of the Aleutian low with the Arctic front. In summer the North Pacific high-pressure system dominates increased meridional atmospheric circulation in southern Alaska and storm systems associated with a weaker Aleutian low occur farther north. Decadal scale weather patterns in the North Pacific show strong teleconnection effects on the atmospheric, oceanic, and sea ice environments of the Bering Sea, with the dominant forcing coming from the atmosphere and the winter position of the Aleutian low-pressure system (Hare and Francis 1995; Niebauer and Day 1989). At longer time scales, the latitudinal position of the Aleutian low may be reflected in the geographic distribution of precipitation, long-term trends in mean annual air and sea surface temperatures (SST), and coastal storminess (Mason and Jordan 1993; Mock et al. 1998; Sabin and Pisias 1996).

During the last glacial maximum, the presence, thickness, and geographic extent of Laurentide ice strongly influenced the location, strength, and motion of pressure centers over the North Pacific and Bering Sea. Atmospheric circulation was zonal, with the North Pacific high displaced south of its present position and a strong winter Aleutian low associated with heavy precipitation and glacier expansion in southern Alaska and the western United States (Barnosky et al. 1987; Thompson et al. 1993). Following deglaciation, global circulation models stress the role of seasonal radiative heating of the ocean surface in controlling the position and latitudinal migration of cyclonic and anticyclonic centers (COHMAP Members 1988; Kutzbach et al. 1993). During the early Holocene, peak summer insolation and rising SST resulted in a weakening of the Aleutian low and strengthening and northward migration of the subtropical North Pacific high. July temperatures were warmer and precipitation was lower than

Figure 6b. Tachilni Creek dunes showing basal 14C age and lateral extent of paleosol complex.

Figure 6c. Paleosol complex at Morzhovoi spit dunes, person = ca. 2 m.

present conditions in southern Alaska (Heusser et al. 1985).

The vegetation and climate record at Kinzarof marsh is in agreement with climate models that suggest a general weakening of the Aleutian low between 9000 and 6000 yr B.P. (Kutzbach et al. 1993). This would have resulted in relatively drier and warmer conditions in the Aleutians and Gulf of Alaska during the early to mid-Holocene, which correlates well with pollen data from the region (Heusser 1985; Peteet and Mann 1994). Storm tracks generated by the Aleutian low were also more zonal during the early to mid-Holocene because the remnant Laurentide Ice Sheet in north central Canada continued to steer atmospheric circulation primarily around its southern margin (Kutzbach et al. 1993). A shift in the distribution of radiolarian assemblages after 4000 yr BP indicates a drop in sea surface temperatures which coincides with the southward migration of the North Pacific high and intensification of the Aleutian low-pressure system over the northeast Pacific Ocean (Sabin and Pisias 1996). The Aleutian low has intensified during the late Holocene, resulting in cooler and wetter conditions that are widely represented in pollen records around the North Pacific (Heusser et al. 1985) and an increase in the intensity of coastal storms in the Bering and Chukchi Seas (Jordan and Mason 1999; Mason and Jordan 1993). Precipitation maxima are also indicated by lowered snow lines and Neoglacial ice advances in the Gulf of Alaska (Wiles and Calkin 1990, 1994) and dune stabilization on the western Alaska Peninsula.

KINZAROF MARSH IN THE CONTEXT OF BERINGIAN AND NORTH AMERICAN RECORDS

The size and climatic variability of Beringia results in great spatial and temporal variability of late Quaternary vegetation patterns (Hu et al. 1999). Linkages between vegetation and climate can also be problematic because of the broad ecological tolerances of major taxa (Lozhkin et al. 1993). But the timing of postglacial vegetation change apparent at Kinzarof marsh is broadly synchronous with trends observed in continental settings of Siberia and especially central and northwest Alaska (Anderson 1988; Lamb and Edwards 1988; Lozhkin et al. 1993). The magnitude of vegetation change suggested by percentage changes in taxa at zone boundaries suggests that shifts in effective moisture and/or temperature were relatively abrupt and, furthermore, that they were associated with broader shifts in oceanic conditions that dominate the climate of the Aleutian arc.

Pollen stratigraphy at Kinzarof marsh records Holocene climate fluctuations that are also recognized over a much broader region than Beringia and thus may provide reliable evidence of the interaction of Pacific and Arctic airmasses that affect short and long term climate over northern North America. Geomorphic and biotic evidence of changes in Holocene climate that are linked to shifts in the position of these airmasses have long been recognized in eastern Beringia and western Canada (Bryson et al. 1965; Bryson and Wendland 1967). Changes in these large-scale atmospheric circulation systems are known to produce responses in the latitudinal position of treeline and in alluvial systems on a continental-scale (Bryson 1966; Bryson et al. 1965; Knox 1983; Sorenson et al. 1971). The abruptness of change between pollen zones and the temporal correlation with distant sites suggests that locales similar to Kinzarof marsh may record fluctuations of marine climate that are significant at regional to subcontinental scales. Clearly the potential for pollen-based climate records from the western Alaska Peninsula to represent broader trends in Beringia depends on corroborating data from additional sites in the region.

CONCLUSIONS

The complex patterns of vegetation succession suggested by pollen stratigraphy on the Alaska Peninsula and eastern Aleutian Islands reflect the variable influences of atmospheric, oceanic and geological processes on vegetation. While some Aleutian sites record a history of vegetation disturbance related to tephra deposition, the pollen record from Kinzarof marsh on the western Alaska Peninsula has been relatively unaffected by volcanic activity and represents a reasonable approximation of postglacial climate change. The region's maritime setting has damped the amplitude of changes in climate and vegetation assemblages throughout the Holocene. But because regional climate is largely controlled by the interaction of the North Pacific high-pressure and Aleutian low-pressure centers, changes in their long-term position and strength have had recognizable affects on vegetation and landscape development.

The peak in early Holocene warmth seen elsewhere in Alaska (Anderson and Brubaker 1993; Anderson et al. 1994; Bartlein et al. 1991) was moderated in coastal areas of southwest Alaska because of postglacial flooding of the Bering platform (Lozhkin et al. 1993). Sea surface temperature maxima in the North Pacific also lagged maximum summer insolation during the early Holocene (Sabin and Pisias 1996), keeping mean annual air temperatures low relative to continental areas.

In areas of the Aleutian arc where ash falls had a relatively minor impact on plant communities, postglacial temperature and precipitation varied sufficiently to force broad shifts in vegetation assemblages within the coastal tundra biome. Initial vegetation communities at such sites show an abundance of shrubs (*Empetrum*, *Salix*, or *Betula*), grasses and herbs that represent relatively long growing seasons and well-drained substrates (Heusser 1983, 1990). Conspicuous changes in pollen stratigraphy that occur at Kinzarof marsh between 6200 and 3200 yr B.P. reflect warm and moist conditions also seen at sites on Umnak Island, the Shumagin Islands and central Alaska Peninsula (Heusser 1985). Localized dunes were active at this time based on the lack of stable surfaces in regional eolian deposits. After 3200 yr B.P. vegetation changes at Kinzarof marsh indicate the onset of cooler wetter conditions that initiated Neoglacial advances and the stabilization of dunes. These conditions have persisted through the late Holocene, reflecting the region's maritime climate and marking the development of modern coastal tundra communities of the eastern Aleutian arc.

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Figure 6d. Cold Bay dunes showing stratigraphy of partially exhumed basal paleosol, person = ca. 2 m.

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