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Quaternary Geology, Cold Bay and False Pass Quadrangles, Alaska Peninsula

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Abstract

Recent mapping and interpretation of Quaternary geologic features has improved our understanding of the interaction between volcanic, glacial, and tectonic activity in the Cold Bay and False Pass 1:250,000-scale quadrangles on the Alaska Peninsula. The glacial and volcanic record of the map area strongly suggests that continental-shelf glaciations and two massive volcanic centers were the dominant controls over landscape development during Pleistocene time. Ancestral Morzhovoi and Emmons Volcanoes were major impediments to flow of shelf glaciers during much of the Pleistocene. Our mapping suggests that the area around Emmons Volcano may have also been an important source area for glaciers during this period. Our data further indicate that Frosty Volcano developed late in the Pleistocene, having had no apparent impact on early Brooks Lake glacial advances but serving as a source area for later glacial advances during late Brooks Lake time. We also believe that major Holocene eruptions of Frosty Volcano have yielded multiple debris and ash flows resulting in the construction of a new south summit cone that filled an earlier crater. Frosty Volcano was the source area for multiple Holocene glacial advances, and its flanks preserve the best record of Neoglacial activity in the map area.

Introduction

Recent mapping and interpretation of Quaternary geologic features has improved our understanding of the interaction between volcanic, glacial, and to a lesser extent, tectonic activity in the Cold Bay and False Pass 1:250,000-scale quadrangles on the Alaska Peninsula. This mapping (Wilson and others, 1997) was compiled with earlier mapping conducted as part of the USGS Alaska Mineral Resource Assessment Program (AMRAP) and the Geothermal Energy Program. Previous geologic mapping in the region, which constituted an invaluable database for our studies, was conducted by Kennedy and Waldron (1955), Waldron (1961), Burk (1965), Funk (1973), McLean and others (1978), and DuBois and others (1989). Field studies by the authors were conducted over an extended span of years, including 1983, 1988, 1990–91, and 1996 by Wilson and 1996 by Weber. Our interpretation of Quaternary units and events is mostly based on air photo interpretation and correlation with similar units in quadrangles to the north and east.

It is important here to note our near total lack of success in acquiring rigorous age control on the events we can document through our fieldwork and air photo interpretations. There are, of course, multiple reasons for this—the most important were our very limited time in the field and that material suitable for age determination (essentially radiocarbon dates) is rare and often found in nondiagnostic localities. Clearly, the lack of radiocarbon-datable material associated with glacial deposits or tephra (only the Fisher or Funk ash is well controlled), the youth of the events, and the low potassium content of the rocks (preventing reliable K-Ar dates) confounds our attempts to apply ages. Much of the history described postdates the development of Emmons Caldera, itself not tightly dated (140 ka±25–50 ka?). However, the lack of age control on Quaternary events is not restricted to the Cold Bay region and is a problem along the entire Alaska Peninsula.

With respect to the Holocene, the one radiocarbon date that we believe helps to define an age is on a Neoglacial moraine derived from Frosty Peak. Yielding a maximum age for the advance of about 1,060 yr B.P., one could surmise that this is not a Little Ice Age advance. Given that the particular glacier advanced 5 km down valley, whereas other Neoglacial moraines recognized in the area are not more that 1 km beyond existing glaciers or cirques, this is an unusual circumstance.

Quaternary Glacial Units

A Quaternary glacial sequence (table 1) was originally defined for the Cold Bay vicinity by Funk (1973). Later, Detterman (1986) slightly refined this sequence and incorporated it into an Alaska Peninsula stratigraphy, showing correlations of Quaternary units the length of the Peninsula. The Brooks Lake drift (see table 1), formerly called the Brooks Lake Glaciation, is generally accepted as the late Wisconsin or last glacial maximum (LGM) on the Alaska Peninsula. Although recent work at the northern end of the Alaska Peninsula (Riehle and Detterman, 1993; Mann and Peteet, 1994; Stilwell and Kaufman, 1996) has questioned the assignment of some deposits to particular glacial episodes or advances in that region, the general stratigraphy, nonetheless, seems to hold up rather well. Using largely air photo interpretation and limited time on the ground we have attempted to apply this regional stratigraphy to the geology of the Cold Bay and False Pass region. Ground "truth" that would allow detailed description and assignment of units is limited due to restrictions on time in the field imposed by weather and funding. It is clear that a universal application of the general stratigraphic framework established for the Alaska Peninsula can be locally unworkable due to local climatic, topographic, and volcanic conditions. These local conditions, particularly growth and degradation of volcanic edifices, may have resulted in non-synchronous glacial advances. In addition, tectonic instability resulted in the incomplete preservation of deposits of some episodes (Winslow and Johnson, 1989a). In spite of these factors, we believe that we have developed a reasonable scenario for the geologic history of the region; this scenario is a hypothesis for which we encourage further testing.

Late Quaternary History of the Cold Bay Region

We have reconstructed the sequence of glacial and volcanic events during part of the Pleistocene and Holocene in the Cold Bay region (fig. 1). We have divided the discussion of that history into regional sections because, although there are similarities across the areas, each part of the region has a distinct character. From northeast to southwest, the regional sections include (1) the Emrnons buttress region, the area between Pavlof Bay and Cold Bay, (which includes Emmons Caldera and Mt. Dutton), (2) the area between Cold and Morzhovoi Bays, discussed as the Morzhovoi Volcano buttress region, and (3) the Ikatan Peninsula and Unimak Island area. Each of these discussions reports our data and describes a possible scenario for the section or area.

Quaternary Glacial-Volcanic Interactions

In the Cold Bay–False Pass region, the interactions of glaciers and active volcanoes have had a strong influence on the type and morphology of Quaternary deposits. Elsewhere on the Alaska Peninsula (for example, Detterman and others, 1981; Detterman, 1986), Quaternary glacial and volcanic deposits can be mapped and interpreted almost independently. In our map area, however, the active volcanoes of Unimak Island (Shishaldin, Isanotski Peaks, and Roundtop), Frosty Peak, Morzhovoi Volcano, Mount Dutton, and the Emmons Caldera–Pavlof group of volcanoes have exerted control on the glaciers of the region. On Unimak Island, deposits of presumed Brooks Lake age indicate that Shishaldin Volcano in the adjacent Unimak 1:250,000-scale quadrangle may be a largely Holocene feature. Fournelle (1988) mapped parts of Shishaldin Volcano, particularly its northwest flank and he did not report

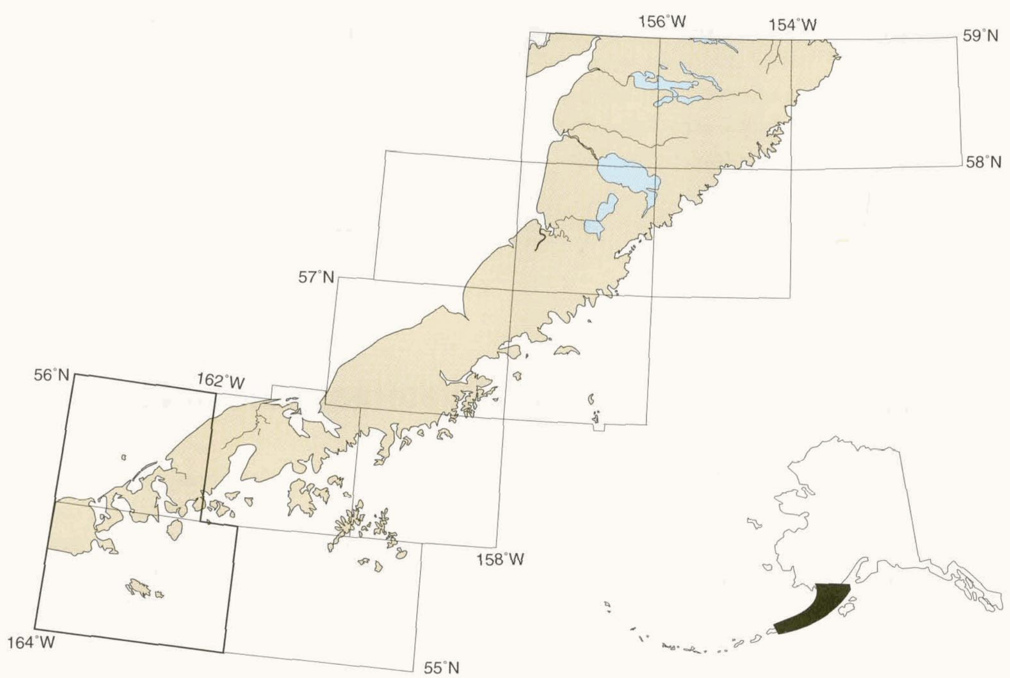


Figure 1. Map showing the location of the Cold Bay and False Pass region.

Table 1. Correlation of Alaska Peninsula glacial sequences.

Time division	Cold Bay area (Funk, 1973)	Alaska Peninsula (Detterman, 1986)		Northern Alaska Peninsula (Stilwell and Kaufman, 1996)		This report (based on the Cold Bay region)	
Holocene	Frosty drift	Neoglaciation		--		Neoglaciation	
Late Wisconsin				Ukak			
	Russell Creek drift Cold Bay unit	Brooks Lake Glaciation	Iliuk advance Newhalen advance	Brooks Lake drift	Iliuk Newhalen	Brooks Lake drift	Iliuk advance Newhalen advance
			Iliamna advance Kvichak advance		Undivided Iliamna and Kvichak		
Early Wisconsin	Morzhovoi Bay unit	Mak Hill drift sheet		Mak Hill			Iliamna advance Kvichak advance
Pre-Wisconsin	Not present	Johnston Hill drift sheet				Mak Hill drift sheet Johnston Hill drift sheet	
	Not present	Oldest drift		Oldest drift(?)		Oldest drift	

any glacially derived deposits, except for those associated with modern glaciers. During our examination of air photos covering Unimak Island, no glacial deposits of Brooks Lake age derived from Shishaldin Volcano were identified and glacial deposits derived from elsewhere or deflected around the other volcanoes of the island do not show any apparent influence from Shishaldin Volcano. By implication, Shishaldin Volcano is largely a post-Wisconsin feature.

At many localities in the Cold Bay vicinity, a distinctive volcanic ash deposit has been mapped (see Funk, 1973). Later workers referred to this as the "Funk" ash and used it in correlations throughout the area. According to T.P. Miller (oral commun., 1997), this ash is derived from the eruption at 9,100 yr B.P. of Fisher Caldera on Unimak Island west of the map area (Miller, 1990). The presence of the Funk ash overlying many of the glacial sequences in the region provides one of the strongest means we have of controlling ages of these sequences and separating definitely Neoglacial and probable late Wisconsin deposits.

Emmons Buttress Region

A group of high mountains centered around present-day Mt. Emmons, Mt. Dutton, and the Aghileen Pinnacles at one time formed an island and acted as a buttress to deflect massive northward-flowing glaciers from the continental shelf to the south. The end moraines of several of these vast ice bodies were deposited to form the heads of Pavlof Bay, Cold Bay, and other bays, connecting several former islands to form the presently continuous landmass of the Alaska Peninsula. In addition to the Emmons buttress, ancestral Morzhovoi Volcano and the range of mountains between the west side of present-day Morzhovoi Bay and False Pass also served as buttresses to deflect ice flow from the shelf glaciers.

The Emmons buttress includes the oldest bedrock in the map area. Sandstone of the Indecision Creek Sandstone and Snug Harbor Siltstone Members of the Naknek Formation of Late Jurassic age crop out in the vicinity of Black Hill (fig. 2). The Amoco Production Company Cathedral River #1 exploratory well (Detterman, 1990), drilled to 14,301 ft (4,360 m) in 1973–74 on the Cathedral River, started in the Snug Harbor Siltstone Member of the Naknek Formation (see Detterman and others, 1996). It penetrated a thick Mesozoic section, including most of the Naknek Formation, the Shelikof, Kialagvik, and Talkeetna Formations, and bottomed in the Kamishak Formation of Late Triassic age. The Emmons buttress contains the most distal exposures of Mesozoic rocks on the Alaska Peninsula; farther west, bedrock is entirely of Tertiary or Quaternary age.

Although the Emmons buttress deflected the shelf glaciers, it was also, at the same time, high enough to support its own mountain glaciers, not only during the period of deposition of the extensive Wisconsin-age moraines at the heads of Cold Bay and Pavlof Bay but during earlier glaciations as well. Fortunately, the deposits of some these earlier episodes were protected on the northwest (lee) side of the Emmons buttress from scouring by shelf glaciers. Classic U-shaped valleys on ancestral Morzhovoi Volcano indicate it also supported a number of mountain glaciers; however, older glacial deposits that may have been derived from this volcano have been covered by the construction of Frosty Volcano on the north or removed by the shelf glaciers on its other flanks.

The northwest side of Emmons buttress is relatively inaccessible and little of the glacial story has been studied on the ground, but there are available excellent aerial photos taken during topographic mapping. In addition, the eruptive history of the volcanoes in the buttress group is being studied as a

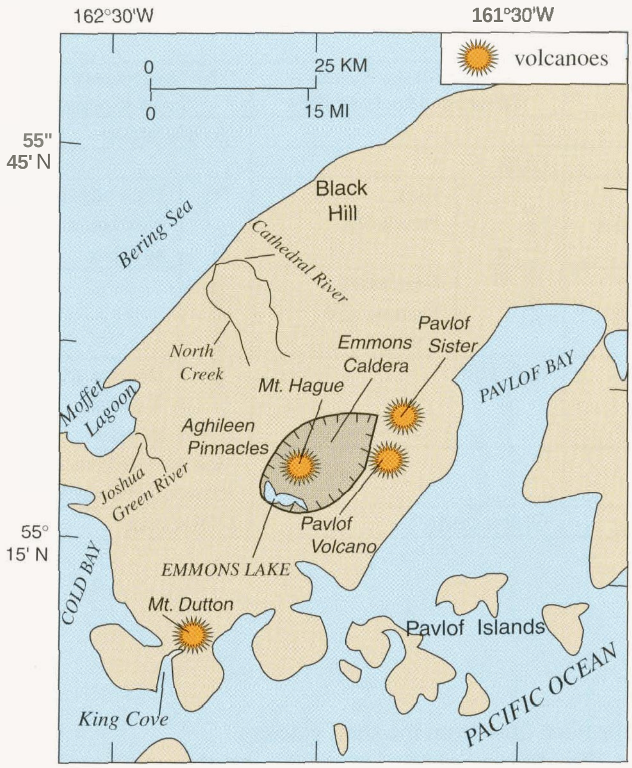


Figure 2. Index map showing location of the Emmons buttress region.

part of the work of the Alaska Volcano Observatory. Largely through study of the 1:40,000-scale black and white and color-infrared aerial photographs, we are able to suggest the following sequence (from oldest to youngest) of events impacting the Emmons buttress (see table 2).

The oldest evidence of glaciation on the Emmons buttress is bedrock scouring in the vicinity of Black Hill (fig. 2); see also Wilson and others (1997). The bedrock of Black Hill and the surrounding country is composed of sandstone of the Naknek Formation. The morphology of the mountains indicate that they have been glacially overridden. In addition, Detterman's 1983 field notes report his observation of cobbles that he thought were of probable glacial origin at an elevation of about 750 ft (about 225 m). These cobbles provide evidence for glaciation corresponding to the "oldest drift" of Detterman (1986).

The oldest generally visible deposits of mountain (and possibly shelf) glaciation occupy the lowest parts of the Cathedral River valley in the Cold Bay quadrangle. These moraines are dark toned on the air photos, and, from ground observation in the adjoining Port Moller quadrangle, we believe they are probably covered by a substantial thickness (1 m?) of humus, dark soil, and ash layers. The normal irregular topography of these moraines has been extensively subdued by deposition of volcanic air-fall deposits, probable marine transgression, and weathering; reliable distinction between ground and end or lateral moraines and the exact locations of glacial limits cannot be made with certainty. However, we believe from the evidence available that the outermost extent of the deposits is presently under the Bering Sea. We also believe that these deposits may correlate with the Johnston Hill drift of Detterman (1986) based on their position and morphological character. Recent work by Kaufman and others (1995, p. 57) on the northern Alaska Peninsula near King Salmon strongly suggests that the Johnston Hill and Mak Hill moraines of Detterman (1986) may "...represent local ice thrusting related to glacier-bed dynamics during a single glacial phase, rather than regionally and climatically significant ice-marginal positions." Kaufman and others (1995) also suggest correlation of the Johnston Hill and Mak Hill moraines with the Halfmoon Bay drift of (Muller, 1953), which they suggest has an early marine oxygen-isotope stage-5 age (ca. 110 ka). Given this interpretation, deposits we have interpreted as associated with the Johnston Hill and Mak Hill moraines may represent multiple episodes in a single glacial phase. Alternatively, the so-called Johnston Hill drift we recognize may be equivalent to the oldest drift of Detterman (1986) and the scouring and cobbles preserved at Black Hill may provide evidence for an even earlier event not apparent in the King Salmon area.

The arms of a better preserved older morainal arc, which we correlate with the Mak Hill glaciation of Detterman (1986), can be seen farther up the slope enclosing the valley of North Creek to the west of Cathedral River. The Mak Hill moraine, like the Johnston Hill moraine, is also dark toned and probably has soil/ash cover similar to the Johnston Hill deposits. Subdued knob-and-kettle topography is preserved at many places on this arcuate ridge, but very significantly, the outward edge of this moraine shows evidence of modification by the wash of water on a strandline. Instead of a normal end-morainal humpy push-profile, the leading edge of the moraine has a smooth, gently outward-facing slope. The strandline apparently stood slightly below the crest of the moraine at a present-day altitude of between 75 and 90 m (see table 2). On North Creek, a moraine that may be a lesser second advance of the Mak Hill glaciation was deposited at an elevation above the strandline and does not show effects of a higher sea level.

In the northeast part of the Cold Bay quadrangle, on the north side of Black Hill, there is a moraine having similar modified hob-and-kettle characteristics as the oldest of the Mak Hill moraines described above. This feature appears to emerge from a ridge overlain by one of the Pavlof Bay head moraines of Wisconsin age and descends off the hill toward the ocean after crossing a narrow coastal plain. At the foot of the hill, the typical humpy morainal topography has been smoothed by marine erosion below the elevation of 75 to 90 m, reconfirming the sea level determined on the North Creek Mak Hill moraine.

The next younger event seen on aerial photos is displayed in an unusual, relatively light-toned series of low ridges on the slopes north of the Joshua Green River (fig. 3). These ridges seem to drape across the slopes, extending downhill toward the Bering Sea. Informally termed "the snake" during mapping because of their form, they form a continuous band as they wind across the upper part of North Creek and smaller drainages.

Table 2. Provisional Quaternary history of the Emmons buttress region.

[See text for explanation; see Wilson and others (1997) for radiocarbon data]

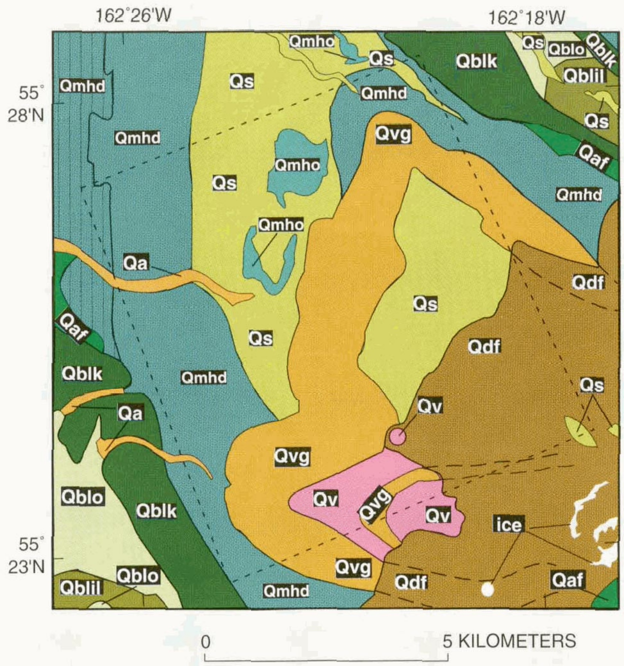
Event	Suggested age	Calibrated radiocarbon age (yr.B.P.)
Historic eruptions	Holocene	
Neoglacial deposits missing		
Tephra beds ("Funk [Fisher] ash") in Cold Bay area lying stratigraphically above Cold Bay moraine correlated with the Newhalen advance (Wilson and others, 1997)	post-Pleistocene 9 ka	Min. 8,650±160 TDS-96-02E (Beta-96825) Max. 10,040±140 TDS-96-02D (Beta 96824)
Evidence for eruptive intervals in buttress area	late Pleistocene (Wisconsin)	
Highstand of the sea, roughly 16 m above MSL (Jordan, 1997)	late Wisconsin or early Holocene	
Brooks Lake drift Iliuk advance missing on Emmons buttress	late Wisconsin	
Brooks Lake drift Newhalen advance missing on Emmons buttress	late Wisconsin	
Brooks Lake drift Iliamna advance, well developed alpine and shelf glacier moraines on west side of buttress	Wisconsin	
Brooks Lake drift Kvichak advance, well developed alpine and shelf glacier moraines on west side of buttress	Wisconsin	
Deposit of volcanoglacial or debris flow northwest of Mt. Emmons and regionally extensive debris apron	Timing relative to highstand of sea unknown	
Highstand of the sea, shoreline developed on Mak Hill drift at elevation of 75–90 m	pre-Wisconsin interstadial	
Mak Hill glacial episode	pre-Wisconsin (110 ka?)	
Johnston Hill glacial episode, extremely subdued moraines and outwash	pre-Wisconsin	
Oldest glaciation of Detterman (1986), inferred from bedrock scouring and probable glacial erratic cobbles	pre-Wisconsin	

They seem to conform to valley configuration and form "V" shapes pointing downstream at their lowest extents in the drainage valleys. In one small drainage, the ridges trend down into a preexisting gully. These ridges probably represent a mixed volcano-glacial event related to the caldera-forming eruption of ancestral Mt. Emmons. This deposit is composed primarily of large angular volcanic rocks and minimal fine sediment and appears to be no more than a few (< 10) meters thick. Because of the lack of fine material, we are reluctant to call this deposit a lahar or volcanic mudflow. We have considered the possibility that this deposit may be the result of a jokulhlaup (Björnsson, 1975), however, descriptions of jokulhlaups emphasize the large proportion of water (80 percent or more). The character of the "snake" and deposits downslope do not indicate the passage of large volumes of fluid. Jònsson (1982) describes a series of "volcanoglacial debris flows" from Katla Volcano in Iceland. In gross aspect these could be similar to the "snake," although they are dominantly (60–70 percent) fine-grained material, largely pumice, having a grain size between 0.5 and 4 mm. However, a later paper on the same deposits (Tòmasson, 1996) suggests that these were truly the deposits of a water-dominant (greater than 80 percent) jokulhlaup and not a volcanoglacial debris flow. Because the Katla eruption that produced these deposits in 1918 was actually observed and still such a fundamental controversy over their mechanism of formation exists, it is clear that it will be difficult to resolve the nature of the "snake." We believe that it represents some type of volcanoglacial debris flow.

An extensive debris deposit covers many of the higher northwestern slopes of the Emmons buttress region (fig. 2) and overlaps the "snake" and the Mak Hill moraine. This deposit consists of dark-colored, poorly sorted volcanic material ranging from large meter-sized angular blocks to mud that blankets older deposits to varying depths. The debris deposits are present as much as 20 km northwest of Mt. Emmons. We believe that, because this debris has such a wide distribution, it was associated with a major volcanic eruption. However, we have no data to indicate if it was hot or contained juvenile material at the time of emplacement. T.P. Miller (oral commun., 1999)

Figure 3A. Aerial photograph showing the southern portion of "the snake," volcanoglacial debris-flow deposits. Photograph is oriented with north diagonal across the picture to the upper left corner. On the left edge of the photograph, moraine of the Mak Hill drift is visible, showing the strandline at 75- to 90-m elevation discussed in the text. The "snake" meanders across the center of the photograph, overlying the moraine in the lower left corner (note — the appearance of the snake has been enhanced by outlining on the reproduced image). Visible in the lower right corner of the photograph are the volcanic debris-flow deposits, which overlie the snake. Photograph is number 1112 of Mission 150, flown June 18, 1962, by the U.S. Air Force. Scale as shown here is about 1:80,000.

does not believe that this deposit was associated with an eruption, particularly the caldera-forming eruptions of the Emmons system. In some areas where he has mapped a similar deposit north of Mt. Dutton, he reports (oral commun., 1998) that it is interbedded with glacial deposits. In our view, the occurrence of these debris deposits at high elevation in a radial pattern on the north and west quadrants surrounding Emmons caldera on slopes truncated by later glacial erosion strongly suggest



EXPLANATION

Qs Undivided surficial deposits

Qa Alluvial deposits

Qaf Alluvial fan deposits

**Brooks Lake Glaciation
Glacial deposits**

Qblo Outwash, undivided

Qblil Iliamna advance end moraine

Qblk Kvichak advance end moraine

Mak Hill Glaciation

Qmho Outwash

Qmhd Drift

Volcanic Units

Qv Volcanic rocks, undivided

Qdf Volcanic debris-flow deposit

Qvg Volcanoglacial debris-flow deposit

- - - - - Dotted line outline is area of figure *3A*

——— _ Contact, dashed where concealed

Figure 3*B*. Section of geologic map southwest of North Creek (Wilson and others, 1997) showing geologic interpretation of the area of the photograph. Approximate area of photograph is dotted outline on map. Scale of map is about 1:125,000.

a genetic association with ancestral Emmons Volcano. Wadge and others (1995) describe debris avalanche deposits in Chile on the flank of Socompa Volcano that may be a partial analog for these deposits on the Emmons buttress.

Ancestral Mt. Emmons may have been the source of the Old Crow tephra (Miller and Smith, 1987), well known as a stratigraphic marker in much of southwestern and Interior Alaska and the Yukon (Hamilton and Brigham-Grette, 1992). Tentative dating of the earliest of the Emmons eruptions, by correlation with the Old Crow tephra, indicates an age of about 140 ka (T.P. Miller, oral commun., 1996). Map patterns indicate that these debris deposits postdate the Mak Hill glacial deposits mentioned earlier which are possibly correlated with the Halfmoon Bay drift by Kaufman and others (1995) having a suggested age of less than 110 ka. Hence, it appears that these debris deposits could be younger than 110 ka. Therefore the extensive debris deposit would not be related to the postulated Emmons eruption that produced the Old Crow tephra; alternatively, Emmons may not be the source of the Old Crow tephra and our Mak Hill really might not correlate with Half Moon Bay in any case.

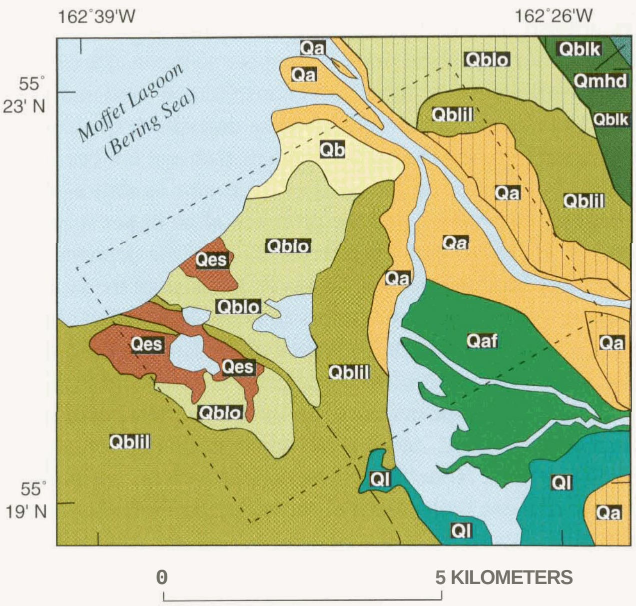
A major glacial episode included in Funk's (1973) Cold Bay unit, which Detterman (1986) correlated with the Kvichak advance of the Brooks Lake glaciation, followed the deposit of the debris mentioned above. Mountain glaciers enlarged the upper valleys of the Joshua Green River, North Creek, and Cathedral River into deep canyons that cut through the volcanic debris-flow and lahar deposits and well into the underlying bedrock. Well-defined, classic end moraines having relatively fresh looking knob-and-kettle topography were deposited in each of these valleys. They are light toned on air photos, probably because soil and vegetation are sparingly developed on the gravelly ridges. Part of the end moraine of this glacial advance on Joshua Green River is currently under Moffet Lagoon. However, there is no evidence to indicate that other moraines of this glacial advance, located below 75 to 90 m on land, were ever affected by the early highstand of the sea. Hence, we believe this stage clearly postdates the 75- to 90-m sea-level stand. On the southern part of the Emmons buttress, we believe that high-level morainal deposits of the shelf glaciers indicate the ice masses of the shelf and mountain areas were continuous.

Another glacial advance followed, correlated on the basis of position and surface characteristics with the Iliamna advance of the Brooks Lake glaciation by Detterman (1986), leaving similar morainal deposits in each of these valleys but upstream of the Kvichak shelf and alpine moraines. In Joshua Green valley, a moraine of this advance forms a complete arc cut only by the river close to modern sea level. This moraine provides the key to date the mountain glacial sequence. The left arm of the Joshua Green River morainal ridge merges with one of the shelf glacier moraines that delineate the head of Cold Bay (fig. 4). Based on the character of the deposits, both from aerial photos and ground observation, we believe these moraines are essentially coeval.

In the immediate area of Cold Bay, two even younger advances from the shelf icecap are provisionally correlated with the Newhalen and Iliuk advances of the Brooks Lake

Figure 4A. Aerial photograph showing merging of moraines from the Joshua Green River valley and Cold Bay. Smaller morainal ridge in center of photograph is moraine of alpine(?) glacier flowing down Joshua Green River valley. It merges with moraine of the Iliamna advance derived from the shelf and flowing into and through Cold Bay. The form of the moraine of the alpine glacier indicates that the glacier was deflected northward at time of deposition. This image is not as clear as the original photograph; the original shows no indication that the moraines were any different in age. A thin ridge of moraine is just visible between the lakes in front of the shelf glacier moraine; this ridge appears overrun by the alpine glacier. Upper left corner of photograph is the Bering Sea. Photograph is oriented with north diagonal across the picture, pointing toward the upper left corner (note—the appearance of the snake has been enhanced by outlining on the reproduced image). Photograph 1193 of Mission 150, flown June 19, 1962, by the U.S. Air Force. Scale as shown here is about 1:80,000.

drift. However, with few exceptions, the remnants of no younger moraines can be identified in the canyon valleys of the Emmons buttress. The exceptions occur in the Cathedral Valley, where a deposit we suggest might be a small moraine is located at the junction between its east and west forks. This deposit occurs as a set of three ridges that form a remnant arc partially across the east fork valley. Across the valley, a deposit shown on the map of Wilson and others (1997) as a moraine of the Iliamna advance, has a morphology that suggests the arcuate ridge from across the valley may have originally joined



EXPLANATION

Qa Alluvial deposits

Qaf Alluvial fan deposits

Qb Beach deposits

Qes Estuarine deposits

Ql Lacustrine deposits

Glacial deposits
Brooks Lake Glaciation

Qmhd Drift

Qblo Outwash, undivided

Qblil Iliamna advance end moraine

Qblk Kvichak advance end moraine

Vertical lines indicate areas of marine inudation

Water

- - - - Dotted line outline is area of figure 4A

—— — Contact, dashed for internal contacts.

Figure 4*B*. Section of geologic map at mouth of Joshua Green River (Wilson and others, 1997) showing geologic interpretation of the area of the photograph. Approximate area of photograph is dotted outline on map. Scale of map is about 1:125,000.

this moraine. This could indicate that the ridge is either a recessional moraine of the Iliamna advance or less likely a moraine of the Newhalen advance. At Cold Bay, the morphology of the Iliamna moraine suggests a multi-stage event and the Newhalen moraines show a distinctively less weathered form than the Iliamna moraines. In the Cathedral Valley, we do not have the information to resolve which glacial event, if any, these arcuate ridges might be associated with; on the basis of their apparent character on air photos, we suggest that they are most likely associated with the Iliamna advance. Whatever its age, the deposit at the valley junction has been eroded by large quantities of water flowing down the main valley. This should be no surprise because the head of the main valley has post-glacial lava flows of at least two ages. These might have catastrophically melted any ice or snow accumulated, producing jökulhlaups. To the west of this moraine arc in the valley of the west fork of Cathedral Valley, which originates under the Aghileen Pinnacles (see fig. 2), is a deposit that is strongly suggestive of a moraine or debris flow. It served at one point as a dam, backing up an ephemeral large lake in the west fork valley. In the east fork of Cathedral Valley, upstream of this deposit, are young, Holocene lava flows from Little Pavlof Volcano in the adjacent Port Moller 1:250,000-scale quadrangle. If this deposit in the west fork valley is a moraine, it is most likely derived from a tributary glacier during the Iliamna advance.

Many parts of the Cold Bay region record evidence of a highstand of the sea about 15 m above present sea level. Particularly well preserved are shorelines in Joshua Green River valley. Evidence of this highstand can be found as terraces in much of the coastal area, where deposits older than Newhalen advance glacial deposits are affected. Similar terraces are well known northward along the Alaska Peninsula. In the vicinity of Cold Bay, these terraces are present at roughly the same elevation on both the Pacific and Bering Sea coasts; to the north on the Alaska Peninsula, for example in the Chignik and Wide Bay areas and the Port Moller 1:250,000-scale quadrangle, terrace elevations gradually increase from west to east, indicating differential uplift (Detterman, 1986, p. 156). We believe that there are isostatic, eustatic, and tectonic components to this uplift record.

The lack of evidence for latest Pleistocene (post-Iliamna advance) and Holocene glaciation on the northeast side of the buttress indicates that additional volcanic event(s) may have taken place. In addition to the lava flows on Cathedral Creek, the head of the Middle Fork of Joshua Green River canyon contains a lava flow and a small debris flow. Morphological evidence suggests that the Joshua Green River valley has had large discharges of water which we attribute in part to volcanic activity melting the glaciers that had existed (and exist today) on the volcanoes at the head of the valley in post-Iliamna time. Pavlof Volcano, Pavlof Sister, Little Pavlof, and Mt. Hague on the northeast side of the buttress all developed since the formation of Emmons caldera and are known to have had many Holocene and historic eruptions; their ash and ash-flow deposits are distributed on the northeast side of the buttress. These volcanic deposits could be covering the late Pleistocene and Holocene glacial deposits, or, more likely in our opinion, the active volcanism may have prevented the development of glaciers in this part of the buttress.

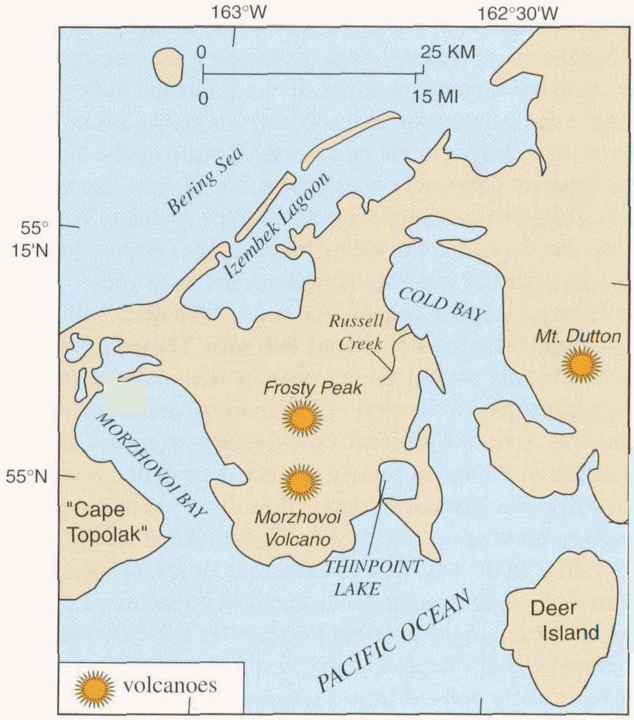


Figure 5. Index map showing location of the Morzhovoi Volcano and Frosty Peak buttress region.

Morzhovoi Volcano and Frosty Peak Buttress Region

The Morzhovoi Volcano and Frosty Peak buttress region (fig. 5) consists in large part of ancestral Morzhovoi Volcano. Located between present-day Cold and Morzhovoi Bays south of Frosty Peak (fig. 1), it has probably been an island volcanic center during much of the Quaternary. Extensive glaciation has removed much of the original volcanic edifice, and only remnant flows from the volcano remain. Waldron (1961) recognized that these remnant flows represented a large volcanic center, which he termed Morzhovoi Volcano.

Underlying the volcanic flows of Morzhovoi Volcano is the type locality and a key reference section of the late Miocene Tachilni Formation (Detterman and others, 1996). Both of these sections are exposed on the south flank of the volcanic pile. The Tachilni Formation consists of marine and nonmarine sandstone, mudstone, and conglomerate having a chiefly volcanic provenance. It is richly fossiliferous and the fossils indicate shallow water deposition (Detterman and others, 1996). Unconformably overlying the Tachilni are volcanic rocks that grade upward into the Morzhovoi volcanic pile.

Northwest of the volcanic center, the Morzhovoi Bay Formation of Funk (1973) is exposed in a sea-cliff exposure along the Bering Sea coast at the head of Morzhovoi Bay. Funk (1973, 1976) also mapped areas of outcrop of the Morzhovoi Bay Formation in the northeast part of the Cold Bay 1:250,000-scale quadrangle. Divided into two units, the lower unit consists of 10 to 12 m of well-compacted, dark grayish-brown till, containing numerous angular boulders having minor oxidation rinds. The upper unit consists of moderately well sorted, stratified, and consolidated sand and gravel or silt and clay. Funk interpreted these deposits in the Cold Bay region to be glaciomarine deposits that had not been subaerially exposed on the basis of the minor oxidation, lack of weathering profiles, and the presence of an upper stratified member. We agree with his interpretation of the deposits at the head of Morzhovoi Bay; however, because of the lack of weathering we suggest that rather than the Mak Hill it should be assigned to the Kvichak advance of the Brooks Lake drift. Only in the area north of the Aghileen Pinnacles did Funk (1973) map any deposits showing surface expression of his Morzhovoi Bay unit, and it is not apparent that he actually visited this area. Nonetheless, we concur with his assignment of some of these rocks north of the Aghileen Pinnacles to an older glacial event, which we correlate with the Mak Hill event as described in the section on the Emmons Buttress above.

Waldron (1961) suggested an early to middle Quaternary history for Morzhovoi Volcano, leading to caldera formation (see table 3). A poorly reproducible and therefore unpublished preliminary K-Ar age determination on a flow high in the section (Nora Shew and F.H. Wilson, unpub. data) suggests an age of less than 1 Ma, which is consistent with the timing Waldron suggested. In spite of the extensive glaciation of the volcanic center, glacial deposits of any age are uncommon in the immediate vicinity of this volcano. Lacustrine or marine deposits are present in three of the south-facing, glacially carved valleys of the remnant Morzhovoi Volcano behind or landward of beach dune deposits. We believe that water bodies were impounded in these lower valleys by shelf ice during one or more advances of the Brooks Lake glaciation. By inference then, Morzhovoi Volcano must have been glaciated early during the Brooks Lake glaciation or before. Small moraines are located in two of the south-facing valleys of Morzhovoi Volcano, one of which also has evidence of flooding. These moraines are probably correlative with one of the younger Brooks Lake advances and the Russell Creek alpine advances and are not Neoglacial moraines because they extend to much lower elevation (less than 30 m and 75 m) than Neoglacial moraines. The latter typically do not extend much below 300 m in elevation.

The north crater of Frosty Peak Volcano (fig. 6) is ice filled and has a glacier draining it to the west. Previous mapping (Waldron, 1961; Funk, 1973, 1976; Brophy, 1984) had shown extensive glacial deposits extending radially from Frosty Volcano. In the valley draining the north crater of Frosty Volcano, these glacial deposits were mapped as extending virtually to the coast of Morzhovoi Bay. However, we found that this valley below the glacier and its Neoglacial moraine had been largely filled by a clast-rich, hydrothemally altered, volcanic debris flow derived from the north crater of Frosty Volcano that may extend to within 1 km of the coast of Morzhovoi Bay. Late Wisconsin glacial deposits are lacking or at least buried by volcanic debris-flow deposits in much of this valley. We were unable to determine if the debris-flow deposits from the North Crater overlie drift of Funk's (1973) mapped Russell Creek (Iliuk) age in the valley or are overlain by drift. Air photo interpretation suggests that Russell Creek morainal deposits are located at the distal end of the debris-flow deposits, constraining the age of the eruption to younger than the drift. A radiocarbon date on peat of 6,700 yr B.P. (GX2788, Wilson and others, 1997; table 1), reported as coming from either lacustrine deposits (Funk, 1973) or outwash (Funk, 1976), is interpreted as a minimum age associated with these glacial deposits. Funk (1973) did not describe the section in which this radiocarbon sample was collected nor locate it precisely because only crude topographic maps were available in the area in the early 1970's. Therefore, it is not possible to determine if the dated peat deposits overlie the debris-flow deposits or if the debris-flow deposits extend as far as the site of the sample. Funk (written commun., 1997) was not able to clarify the nature of the deposits from which the sample was collected and therefore this radiocarbon date is not useful in constraining the age of the debris flow. Funk's (1973) Frosty drift is derived from the present glacier in the North Crater, and he suggests it is of Neoglacial age. The Neoglacial moraine extends less than 1 km down valley from the present glacier as shown on the published 1:63,360-scale topographic map that was compiled from 1987 aerial photography. By 1996, the glacier had receded farther up-valley. The age of the Russell Creek drift has been considered latest Pleistocene or earliest Holocene (Detterman, 1986), and, if this unit really is present at the distal end of the valley, it constrains the age of the crater-forming eruption to the early Holocene or later.

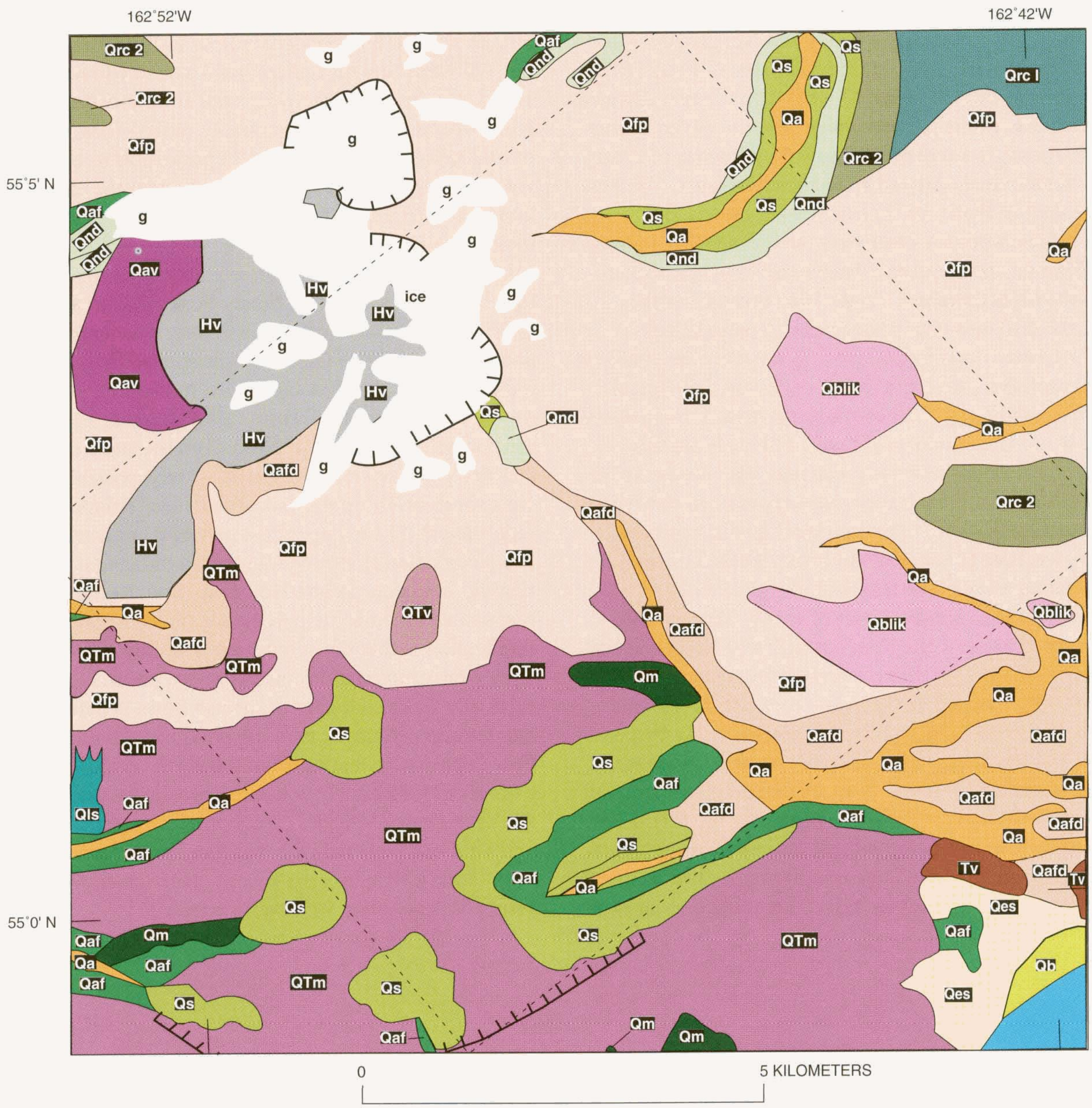
We believe that Frosty Volcano is largely a latest Wisconsin and Holocene constructive feature (see figures 7 and 8 and Wilson and others, 1997) based on the pattern of Brooks Lake glacial moraines near Frosty Volcano. This is in contrast to Waldron's (1961) interpretation that the caldera-forming eruption of the north caldera of Frosty Volcano was of Pleistocene age. Our mapping indicates that the timing of the caldera-

Table 3. Provisional Quaternary history of the Morzhovoi Volcano and Frosty Peak buttress region

[See text for explanation]

Event	Suggested age	Calibrated radiocarbon age
Morainal deposits at Frosty Peak, both north and south craters	Neoglacial	1,060 yr. B.P. TDS-96-09A (Beta-96827)
Emplacement of summit cone-building volcanic rocks of south peak	Holocene(?)	
Eruption of ash flow from Frosty Peak (south crater). Flow ponded behind earlier lava flow		
Development of North Crater and emplacement of volcanic debris flow deposits west of Frosty Volcano	early Holocene(?)	
Tephra beds ("Funk [Fisher] ash") in Cold Bay area lying stratigraphically above moraines identified as Newhalen and Russell Creek	post-Pleistocene 9 ka	Min. 8,650±160 TDS-96-02E (Beta-96825) Max. 10,040±140 TDS-96-02D (Beta 96824)
Highstand of the sea, roughly 16 m above MSL (Jordan, 1997)	late Wisconsin or early Holocene age	
Eruption of massive lava flow from Frosty Peak; flow may have erupted in an icefield	late(?) Wisconsin	
Russell Creek alpine drift and Brooks Lake drift, Iliuk advance. Iliuk advance deposits may form a submerged ridge at mouth of Cold Bay (see Wilson and others (1997)	late Wisconsin	
Brooks Lake drift, Newhalen advance glacial deposits found on west shore of Cold Bay	late Wisconsin age	
Brooks Lake drift, Iliamna advance; forms bulk of glacial deposits north of Morzhovoi Bay and Cold Bay	Wisconsin age	
Brooks Lake drift, Kvichak advance; outer rim of glacial deposits north of Morzhovoi Bay and Cold Bay	Wisconsin age	
Glaciomarine(?) deposits north of Morzhovoi Bay	Wisconsin or earlier age	
Eruption of ancestral Morzhovoi Volcano	about 1 Ma	

Figure *6A.* Aerial photograph showing the southern flank of Frosty Volcano. North is diagonal across the picture, pointing to the upper left. In the upper center of the photograph, the south peak of Frosty Volcano is visible, composed of the "volcanic rocks of the summit cone" as mapped by Waldron (1961). The rocks fill an older crater, whose rim is visible surrounding the summit cone. In the upper left corner, the thick ponded flow discussed in the text is visible. Just below (southeast) of this flow are ash-flow deposits ponded behind it. The same ash flow came down the linear valley running down the right center of the photograph. In this valley, the ash flow continued to the right off the photograph, reaching the coast. Unfortunately, thin cloud cover obscures some of the image as does the poor resolution of the reproduction; however, just visible at the head of the linear valley is Neoglacial moraine extending about 1 km from the crater. Photograph 11-5, taken July 26,1987, for the U.S. Geological Survey.



EXPLANATION

- g — glacier ice
- Qs — Undivided surficial deposits
- Qa — Alluvial deposits
- Qaf — Alluvial fan deposits
- Qb — Beach deposits
- Estuarine deposits
- Qls — Landslide deposits

Glacial deposits

- Qm — Moraine, undivided
- Qnd — Neoglacial moraine deposits
- Qrc 2 — Russell Creek glaciation II
- Qrc I — Russell Creek glaciation I
- Qblik — Drift of Brooks Lake Glaciation - Iliuk stade

Volcanic deposits

- Hv — Lava flow, Holocene
- Qav — Volcanic avalanche deposits
- Qfp — Frosty Peak volcanic rocks
- Qafd — Ash-flow deposits
- QTv — Volcanic rocks, undivided
- QTm — Morzhovoi Volcanics
- Tv — Volcanic rocks (Miocene?)
- Water
- Dotted line outline is area of figure 6A
- Crater rim

Figure 6*B*. Section of geologic map (Wilson and others, 1997) showing geologic interpretation of the area of the photograph. Approximate area of photograph is dotted outline on map. Scale of map is about 1:125,000.

forming eruption is latest Pleistocene or Holocene, most likely between the last Wisconsin glaciation and Neoglaciation for the following reasons. The Cold Bay moraine of Funk (1973) includes deposits largely of the Kvichak and Iliamna advances and to much less extent the Newhalen advance of the Brooks Lake drift; these glacial deposits show no influence of Frosty Volcano. Yet moraines derived from Frosty Volcano (the Russell Creek drift of Funk, 1973) extend over these older morainal ridges, whereas, elsewhere, glacial advances younger than the Iliamna and Kvichak advances are much less extensive than the older moraines. As the Iliuk advance of the Brooks Lake drift was one of the least extensive (Ukak advance? of Pinney and Beget, 1991, is possibly the youngest and least extensive), we found it disconcerting that Russell Creek drift from Frosty Peak overlaps the drift of early Brooks Lake age (Cold Bay moraine of Funk, 1973) . From this relationship, we infer that Frosty Volcano was constructed largely after the Iliamna advance but early enough to become an accumulation zone for later (younger) glacial episodes. Therefore, we have concluded that Frosty Peak (volcano) did not exist during most of the Brooks Lake glaciation.

The uppermost, southern part of Frosty Volcano (the actual Frosty Peak) is a late Wisconsin(?) and Holocene constructive feature, largely filling a preexisting crater. The unit Waldron (1961) mapped as *"volcanic rocks of the summit cone"* nearly fills this crater. Largely covered today by perennial snow and ice, these volcanic rocks show no evidence of extensive glaciation, implying post-glacial emplacement. Off the southwestern flank of the south peak (see fig. 6*B*), a lava flow (labeled "Hv") was erupted that did not flow more than 3 km from its source, yet it is nearly 300 m thick at its distal end. Its form, which is a lobate ridge extending into an existing glaciated valley, indicates that it may have been erupted into an icefield and ponded, similar to the flows derived from the 1983 eruption of Veniaminof Volcano (Yount and others, 1985). On the opposite valley wall from this flow, a similar, more weathered—and presumably older—flow, shown as part of unit QTm, forms a prominent projection from the valley wall, and together these flows nearly dam the initially south draining, glacially carved valley. At some later time (after melting of the ice and, therefore, we believe in Holocene time) an eruption yielding an ash flow came from Frosty Peak (shown as unit Qafd near Frosty Peak, Wilson and others, 1997). To the southwest, this ash flow was largely trapped and dammed behind the above-mentioned lava flows, forming a thick deposit that has since been moderately dissected by fluvial erosion. In the narrow valley draining Frosty Peak to the southeast, pyroclastic flows from the same eruption also traveled down-valley and spread widely, possibly reaching the west shore of Thinpoint Lake (shown as Thinpoint Lagoon on older maps). In the uppermost part of this narrow valley is a Neoglacial(?) moraine, probably indicating that the eruption did not occur in late Holocene time. Because no distinctive source area for the pyroclastic flows is apparent, the implication is that the summit-cone-building flows of Frosty Peak were erupted after this explosive event. However, the relatively fresh character of the ash flows is evidence that they are definitely younger than the previously described debris flow deposits emanating from the north crater. These relatively extensive Holocene(?) volcanic deposits on the south and west flanks of Frosty Volcano (areas previous workers had apparently not reached) indicate that previous inferences by Waldron (1961), Brophy (1984), and others about the history of Frosty Volcano may well be incorrect.

Table 4. Provisional Quaternary history of the Ikatan Peninsula and Unimak Island region.

[See text for explanation]

Event	Suggested age
Development of *tombolo* connecting former Ikatan Island and Unimak Island, creating Otter Cove	post-1850 **A.D.**
Deposition of ash over a wide area in the vicinity of Otter Cove from volcanic eruption of Roundtop and Isanotski Peaks	March 10, 1825
Highstand of the sea, roughly 16 m above MSL (Jordan, 1997)	late Wisconsin or early Holocene
Brooks Lake drift, Iliuk advance, not recognized with certainty	late Wisconsin
Brooks Lake drift, Newhalen advance, forms fragmentary morainal arc north of Roundtop	late Wisconsin
Brooks Lake drift, Iliamna advance, forms large arcuate moraines north of Roundtop and Isanotski Peaks	Wisconsin
Brooks Lake drift, Kvichak advance, glacial deposits north of Roundtop and Isanotski Peaks	Wisconsin
Mak Hill(?) glacial episode, moraines along northeast coast of Unimak Island	pre-Wisconsin

Ikatan Peninsula and Unimak Island Region

Unimak Island (fig. 7) appears to contain many of the basic Quaternary geologic units seen elsewhere in the Cold Bay region. The easternmost of the Aleutian Islands, it is dominated by late Pleistocene(?) and Holocene volcanic centers. No glacial deposits other than a few Neoglacial moraines were observed on the Pacific coast side of the island or on the Ikatan Peninsula. At low elevation in a few areas, marine terraces are apparent near the Pacific coast, indicating some relative uplift. On the north or Bering Sea side of Unimak Island, extensive glacial deposits are present in the lowlands. Deposits from shelf glaciers that overrode the Ikatan Peninsula and adjacent Alaska Peninsula are found on the extreme northeast of the island. Farther west, the glacial deposits were likely derived from the Roundtop and Isanotski Peaks volcanic centers. At the extreme western edge of the map area, no glacial deposits were recognized that were derived from Shishaldin Volcano, supporting the contention of Fournelle (1988, 1990) that it is largely a late Pleistocene and Holocene edifice. Alternatively, extensive volcanic pyroclastic and debris deposits on the north side of Shishaldin Volcano may overlie glacial deposits that might correlate with the Brooks Lake drift.

Deposits of Holocene volcanic eruptions are apparent on Unimak Island near each of the three volcanoes that are wholly or partly in the map area of Wilson and others (1997). A large expanse of nonvegetated volcanic ash covers valley floors west of Otter Cove on the southeast part of the island. These deposits are extensive enough that we were unable to distinguish their source other than it must have been in the vicinity of Roundtop and Isanotski Peaks. Veniaminov (1840, p. 18) reports a volcanic eruption on March 10,1825, that is probably the source of this ash. He says, "... the northeast range of Unimak exploded in five or more places and over a large area ..." and goes on to say the ash covered the end of the Alaska Peninsula to a depth of several inches. In part because of the extensive distribution of the deposits, and in part because of Veniaminov's (1840) report, we believe that these deposits may represent eruptions from both the Roundtop and Isanotski Peaks volcanic centers. In contrast to the deposits on their south flanks, recent volcanic debris is not as apparent on the north flanks of these volcanoes, where older glacial deposits of Brooks Lake age are preserved.

Russian maps dating from the mid-1800's show a passage between Ikatan Bay and Otter Cove (fig. 7, or see Veniaminov, 1840, p. 107). Chuck Martinson (oral commun., 1990), a local resident, has reported speaking in the 1950's with False Pass village elders who remembered paddling through this passage during their youth. The two parts of the island were connected by the present tombolo sometime in the late 1800's or early in the 1900's. Fournelle (1988, p. 29–30) also reports similar evidence from Finch (1934) about the historically recent joining of the Ikatan Peninsula to Unimak Island and attributes the joining to uplift on the order of 3 m in 200 yr (or about 150 m in Holocene time). Another suggestion is that this change could have been the result of a reworking of deposits from the 1825 volcanic eruption. However, there is little confirming information.

Discussion

The glaciomarine deposits of the Morzhovoi Bay Formation of Funk (1973) were correlated by Detterman (1986) with Mak Hill drift of early Wisconsin(?) age on the basis of their position, land forms, and weathering characteristics in the northeastern part of the Cold Bay region. We have revised Funk's (1973) mapping in the northeast part of the Cold Bay region, extending the mapping of Quaternary glacial units northeastward toward the adjoining Port Moller region. We examined the sea-cliff exposures reported by Funk on the Bering Sea at the head of Morzhovoi Bay and remain divided over their nature and correlation. These exposures are moderately indurated, locally bedded, marine deposits and do not match the lithologic descriptions of potentially correlative units elsewhere on the Alaska Peninsula. As a unique and geographically isolated exposure, we are not able to establish the position of this particular outcrop sequence in our suggested stratigraphy.

The 75- to 90-m highstand of the sea and the marine erosion that affected the Johnston Hill and lower elevation parts of the Mak Hill moraines as described for the Emmons buttress region makes it difficult to answer the question of whether the Johnston Hill drift represents a separate glacial event or is just an earlier advance of the Mak Hill event. It is not possible with our data to resolve the issue of the distinction of these deposits that was raised by Kaufman and others (1995) on the northern Alaska Peninsula. However, despite the isostatic vagaries of the Alaska Peninsula, we infer from the highstand of the sea that there was a significant warming postdating the Johnston Hill and Mak Hill drifts, more like an interglacial period than an interstadial period. In our experience in the adjacent Port Moller 1:250,000-scale quadrangle and elsewhere on the Alaska Peninsula, there is evidence, particularly in marine terrace levels and uplifted sea caves, that shows the Alaska Peninsula has long been undergoing relative uplift. The uplift has proceeded at a greater rate on the Pacific Ocean side than on the Bering Sea side. Undoubtedly, the sea-level highstands documented here flooded the lower levels of the Johnston Hill and Mak Hill glacial deposits on lower Cathedral River. The significance of the inundation in terms of Quaternary worldwide levels is problematical as the Alaska Peninsula has a complex history of isostatic and tectonic instability (see for example, Winslow and Johnson, 1988, 1989a, 1989b) in part in response to rebound after the melting of the continental shelf glaciers and in part as a response to tectonic adjustments related to the Aleutian Trench and magmatic arc.

We suggest that the earliest two Brooks Lake advances are of early Wisconsin age, rather than the generally accepted late Wisconsin age. Nowhere on the Alaska Peninsula are these glacial advances unequivocally dated. The only reported ages on these older advances are both approximately 26,000 yr B.P. (Stilwell and Kaufman, 1996; Mann and Peteet, 1994) on deposits that have a tenuous relationship to the moraines they purport to date (Kvichak and "Naknek," respectively). In

Figure 7. Ikatan Peninsula and Unimak Island region,

both cases, the dated material came from outwash deposits collected down stream of the moraines. However, that outwash could just as easily be associated with later events and in the case of the Kvichak date, the collected sample was 20 km distant from the moraine it is used to date. There are distinctive weathering and morphological differences between moraines assigned to the Kvichak and Iliamna advances and those of the later Brooks Lake advances. There is also evidence for significant volcanic activity including construction of the Pavlof group, Frosty Peak, and Shishaldin Volcanoes. Together, these lines of evidence suggest a significant time gap between the deposition of the two groups of glacial deposits.

On the Alaska Peninsula, a number of schemes have been proposed to describe the stratigraphy of the Quaternary units. Funk (1973) and Detterman (1986) (table 1) proposed schemes that are applicable to the Cold Bay region, where the youngest Pleistocene (Wisconsin) glacial deposits were assigned to the Brooks Lake drift. Divided by Detterman (1986) into the deposits of four advances, the Russell Creek drift of Funk (1973) was considered equivalent to the Iliuk advance, the youngest of the sequence. Work in the Katmai region (Pinney and Beget, 1991; Pinney, 1993) suggests the existence of a fifth advance, named the Ukak advance. This advance, mapped as part of the Iliuk advance by Riehle and Detterman (1993) may be of early Holocene age. Additional mapping and dating in the Katmai region by Mann and Peteet (1994) and Stilwell and Kaufman (1996) suggest an alternative interpretation for the northern Alaska Peninsula (see table 1). Based on our mapping and interpretations, we suggest yet another modification of the proposed stratigraphy as shown in table 1.

In the Cold Bay region, we do not have sufficient evidence to determine whether deposits of the Ukak advance of Pinney and Beget (1991) and Pinney (1993) exist or to distinguish between the Iliuk (Russell Creek drift) and Ukak advances. In the vicinity of Cold Bay, we were able only with uncertainty to resolve the Cold Bay Formation of Funk (1973) into the deposits of the Kvichak, Iliamna, and Newhalen(?) advances of the Brooks Lake drift. However, with distance from Cold Bay, for example in the Cathedral River valley, distinctive units are more apparent. Even so, in the Joshua Green River valley, the three authors (Wilson, Weber, and Dochat) who focused on the Quaternary units of the revised geologic map (Wilson and others, 1997) were not able to agree on the correlation of the glacial deposits. Weber and Wilson interpret the mapped deposits in the Joshua Green Valley as alpine glacial advances that correlate with the Iliamna and Kvichak advances of the Brooks Lake shelf drift in this area. In our vision, ice from the shelf ice-accumulation zone locally overtopped low passes on the Emmons buttress and joined with existing alpine ice masses to produce the large "alpine" glaciers. In the area northwest of Cold Bay where Iliamna moraine deposited by the shelf glacier is adjacent to that of the second alpine moraine, Wilson and Weber interpret the evidence as indicating coeval ice masses where the larger shelf glacier caused a northward deflection of the alpine glacier flow. Dochat, in contrast, interprets the evidence to show that the Joshua Green moraines are purely alpine advances of early to middle Wisconsin age, predating the Brooks Lake advances. In her interpretation, these alpine glaciers had retreated due to loss of source as sea level fell, the Bering Sea floor emerged, and shelf glaciers built and advanced (Dochat, 1997). As the shelf glaciers advanced, they overrode and deformed the much earlier alpine morainal deposits upon contact, yielding an appearance that the alpine glaciers had flowed northward. However, we consider this scenario unlikely because the uniform weathering and surface characteristics of the alpine and shelf-glacier morainal deposits and because the regular and even arcuate form of the Joshua Green moraines do not indicate post-depositional deformation.

Previous workers (Waldron, 1961; Funk, 1973, 1976; Brophy, 1984) considered Frosty Volcano to have been dormant during Holocene time. For Frosty Volcano, Waldron (1961) inferred two episodes of volcanism widely separated in time. The first may have been coeval with some stage of the eruption of Morzhovoi Volcano, from either a parasitic cone or a new vent. Waldron (1961, p. 694) suggested that Frosty Volcano was largely constructed prior to late Wisconsin time because extensive glacial deposits were derived from it and no volcanic products were mapped on top of these glacial deposits. These glacial deposits were later mapped as the Russell Creek drift by Funk (1973, 1976). Based on limited age control, Funk suggested that the Russell Creek moraines were of latest Wisconsin age. Brophy (1984) largely accepted Waldron's and Funk's mapping of Frosty Volcano, essentially reproducing Waldron's map in his report. Detterman (1986) accepted the latest Wisconsin age of Funk (1976) and correlated the Russell Creek drift with the Iliuk advance of the Brooks Lake drift, best known from the northern part of the Alaska Peninsula but mapped as far southwest as the adjacent Port Moller quadrangle (F.R. Weber, R.L. Detterman, and F.H. Wilson, unpub. data, 1988). Our mapping and radiocarbon dating (Wilson and others, 1997), in conjunction with a reinterpretation of the mapping of Funk (1973) indicate a history of multiple Holocene (Neoglacial) glacial advances in the vicinity of Frosty Peak Volcano. In addition, in many other areas of the map we have mapped undated deposits of presumed Neoglacial age, in some cases mapping more than one moraine to a valley. These deposits typically do not extend far (1 km or less) from local cirques, except near Frosty Peak. At Frosty Peak in the Russell Creek valley, a paleosol overlain by till yielded a radiocarbon age of 1,060 yr B.P. (calibrated age, sample TDS-96-09A, Wilson and others, 1997), indicating a Neoglacial glacier had extended as much as 5 km down-valley from the cirque head. We cannot explain the unusually great distance that this particular Neoglacial glacier extended. However, we presume that it must bear some relation to the newly recognized history of multiple Holocene eruptive events at Frosty Peak Volcano.

Conclusions

The glacial and volcanic record of the map area provides evidence strongly suggestive of a region dominated by continental shelf glaciations and three massive volcanic centers during Pleistocene time. Morzhovoi and Emmons Volcanoes were major impediments to flow of shelf glaciers during much of the Pleistocene. Our model suggests that the area around Emmons Volcano may have also been an important source area for glaciers during this period. The map data further indicate that Frosty Volcano developed late in the Pleistocene and had no apparent impact on early Brooks Lake glacial advances. It did, however, serve as a source area for later glacial advances of Brooks Lake age. Early in the Brooks Lake glacial episode, glaciers derived from the continental-shelf ice sheet and from the Emmons Caldera region (fig. 8) flowed northward over the volcanic islands that would today form the core of the Alaska Peninsula. During this period, we believe Morzhovoi Volcano was already extinct, Emmons had already erupted, and the Pavlof group of volcanoes had yet to form. Mount Dutton may have existed as a volcano at this time, although we have little data to confirm this. Roundtop and Isanotski Peaks on Unimak Island probably were active, whereas the glacial record indicates that Shishaldin Volcano had not yet formed. Amak Island may not have formed by this time and is therefore not shown. During the subsequent advances of the Brooks Lake drift (fig. 9), the shelf-ice sheet is again(?) present although glaciers derived from it are less vigorous in crossing the Alaska Peninsula. Earlier in the time frame of fig. 8, alpine moraines derived from the Emmons buttress and a small alpine and shelf(?) glacier tongue passing by Mt. Dutton join in the Joshua Green Valley. Tongues from the shelf-ice sheet enter Cold Bay and partially cross through False Pass; no evidence is available to indicate whether a tongue extended into Morzhovoi Bay. However, the shelf ice must have abutted the remains of Morzhovoi Volcano as evidenced by the lakes dammed in a few of the south-facing valleys. Toward the end of the late Wisconsin, Frosty Volcano formed and became the source of alpine glaciers equivalent in age with the latest Brooks Lake advance (Iliuk). These alpine glaciers actually extended over deposits of a more extensive Brooks Lake advance (Newhalen). At some time after, or in the waning stage of the Brooks Lake drift, an ash flow was erupted from one of the northern Pavlof

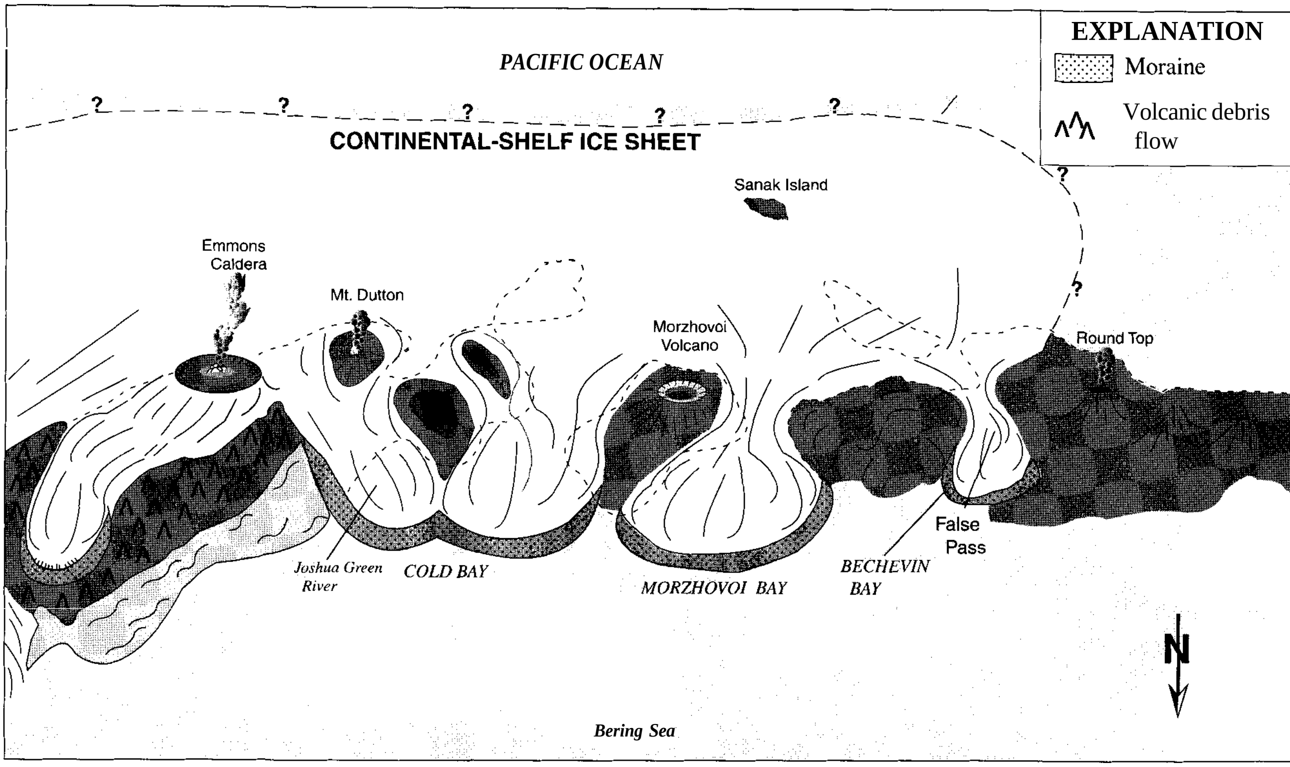


Figure 8. Sketch showing a possible scenario for the environment of the Cold Bay region during the Kvichak or Iliamna advances of the Brooks Lake drift. Inverted "v" pattern indicates debris deposits derived from the eruption of Emmons Volcano; wavy lines indicate area below mapped Pleistocene shoreline. Dotted pattern indicates moraines of active or recently active glaciers.

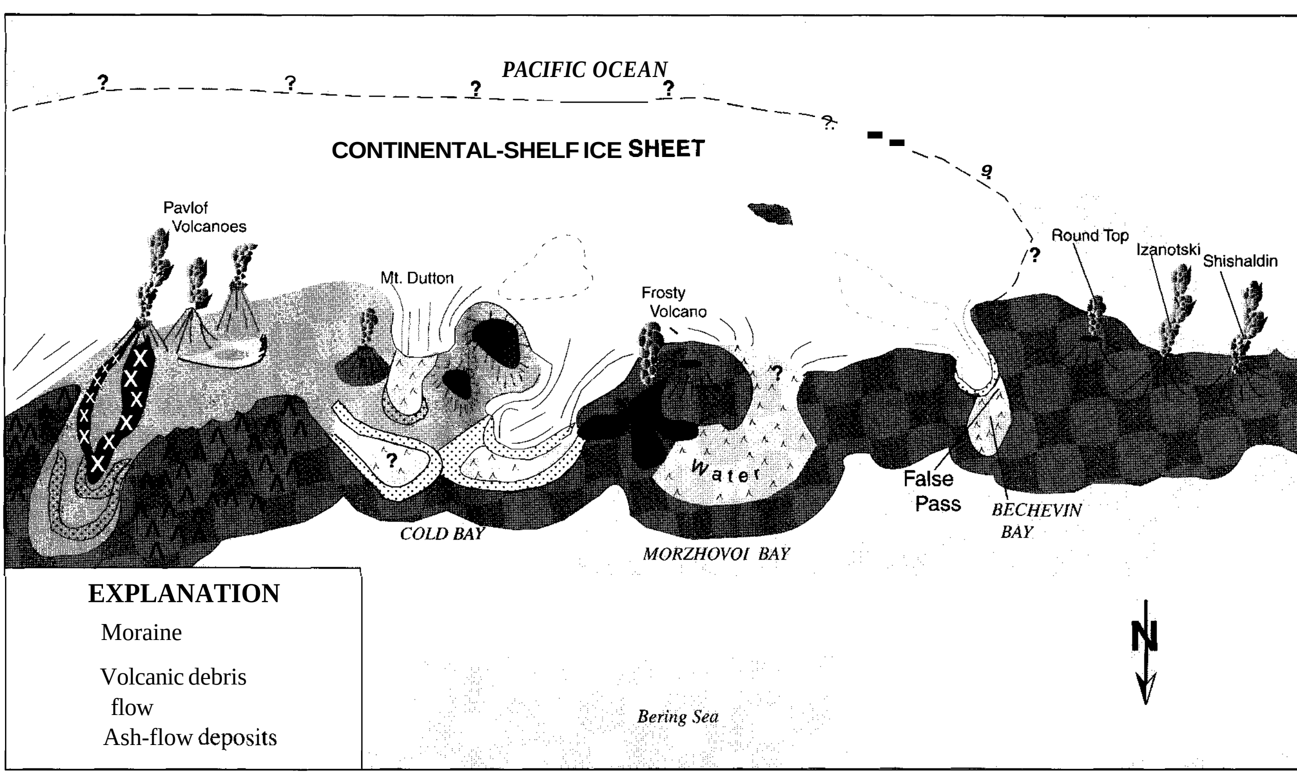


Figure 9. Sketch showing a possible scenario for the environment of the Cold Bay region during the latter advances of the Brooks Lake drift. Inverted "v" pattern indicates debris deposits derived from the eruption of Emmons Volcano; "x" pattern indicates late Pleistocene(?) ash-flow deposits derived from Pavlof group of volcanoes. Dotted pattern indicates moraines of active or recently active glaciers.

group of volcanoes and was dammed behind one of the youngest Brooks Lake moraines in Cathedral Valley. Our map data also show that Frosty Volcano had a number of major Holocene eruptions, yielding multiple debris and ash flows and resulting in the construction of the south summit, filling an earlier crater. Age control on the events we describe is severely limited due to lack of appropriate material for age dates; realistically, most events are only broadly constrained in time. Nevertheless, the events we describe (table 5) fit reasonably well within the generally accepted stratigraphic succession for the Alaska Peninsula, given variations based on the local volcanic and tectonic history.

Table 5. Summary table of the Cold Bay area Quaternary events.

Age	Emmons buttress	Morzhovoi Volcano–Frosty Peak buttress	Ikatan Peninsula and Unimak Island
Holocene	Construction of the Pavlof group of volcanoes; minor eruptions within Emmons caldera	Continued eruption, Frosty Volcano	Construction of Shishaldin Volcano
Holocene		Multiple Neoglacial advances	Minor evidence for Neoglacial advances
late Wisconsin		Iliuk advance Newhalen advance	Iliuk advance Newhalen advance
early Wisconsin	Iliamna advance Kvichak advance	Iliamna advance Kvichak advance	Iliamna advance? Kvichak advance?
pre-Wisconsin	Mak Hill drift sheet		Mak Hill drift sheet
pre-Wisconsin	Johnston Hill drift sheet		
pre-Wisconsin	oldest drift		

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Robert L. (Buck) Detterman's death as the 1992 version of the Cold Bay and False Pass quadrangle geologic map was being compiled left a profound void. His knowledge of and insight into Alaska Peninsula geology was of tremendous value. His friendship, guidance, and contributions to Alaska Peninsula geology will be long remembered.

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