

Geologic Studies in Alaska by the U.S. Geological Survey, 1999

Edited by Larry P. Gough *and* Frederic H. Wilson

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Introduction

By Larry P. Gough and Frederic H. Wilson

The collection of nine papers that follow continue the series¹ of U.S. Geological Survey (USGS) investigative reports in Alaska under the broad umbrella of the geologic sciences. The series presents new and sometimes preliminary findings that are of interest to earth scientists in academia, government, and industry; to land and resource managers; and to the general public. Reports presented in *Geologic Studies in Alaska* cover a broad spectrum of topics from various parts of the State (fig. 1), serving to emphasize the diversity of USGS efforts to meet the Nation's needs for earth-science information in Alaska.

The papers in this volume are organized under the topics: Hazards, Geologic Framework, Environment and Climate, and Resources. This organization is intended to reflect the scope and objectives of USGS geologic programs currently active in Alaska. The two Hazards studies discuss volcano-related topics in the seismically active south-central Alaska region. The first paper revisits the eruptive events of Redoubt Volcano that occurred more than a decade ago and the subsequent development of the Alaska Volcano Observatory (AVO). This treatise documents the historic impact of this eruption and briefly summarizes the state of our knowledge of the other Cook Inlet, Alaska Peninsula, and Aleutian Island volcanoes. Finally, it discusses the recent role that AVO has had in seismic station installation and hazard assessment at volcanically active sites throughout the world. The second paper discusses the eruptive history of Snowy Mountain in the upper Alaska Peninsula. Because subsets of its 25–30 lava flows erupted as packages in short episodes, calculation of the volcano's lifetime average volumetric eruption rate is problematic. A portion of the cone was hydrothermally weakened and collapsed in the late Holocene producing a 22-km² debris avalanche.

Geologic Framework studies provide background information that is the scientific basis for present and future earth science investigations. The first paper compares and contrasts the Insular-Intermontane suture zone (IISZ) of southeast Alaska with the Adria-Europe suture zone (AESZ) of Switzerland and Hungary. The study develops the hypothesis that the zones have distinct differences as well as similarities and neither is a simple lithotectonic terrane boundary. The second paper discusses the relation among volcanic, glacial, and tectonic activity in the Cold Bay and False Pass 1:250,000-scale quadrangles on the Alaska Peninsula. During Pleistocene time, continental-shelf glaciations and two massive volcanic centers were the dominant controls over landscape development. The third paper gives detailed geologic information for Paleozoic rocks within the Taylor Mountains D-1 quadrangle portion of the Holitna

¹ From 1975 through 1988, *Geologic Studies in Alaska* was published as a series of USGS Circulars, which were titled "The United States Geological Survey in Alaska: Accomplishments during 19xx." From 1989 to 1994, the series was published as the more formal USGS Bulletins. As a result of a reorganization in 1995 of USGS publications, the series has been published as USGS Professional Papers.

Lowland of southwestern Alaska. Because of the excellent preservation of megafossils, these Silurian and Ordovician strata lend themselves to detailed stratigraphic investigations. Further, low thermal alteration indices of this area have made them a potential target of petroleum exploration. The final report in this section discusses the development of a new spectral enhancement approach for interpreting Multispectral Scanner (MSS) and Thematic Mapper (TM) satellite images. This technique enhances the use of remote sensing data in identifying geologic units in areas that have been poorly investigated. This study used this technique to better define the distribution of a JMTu (mafic, ultramafic, and sedimentary) unit and a PzZrqs (pelitic and quartzitic schist) unit.

Environment and climate studies are the emphasis of two papers. One presents the first radiocarbon-dated postglacial vegetation history of the Kenai Mountains of south-central Alaska. This reconstruction is the result of the analysis of pollen assemblages and peat from sediments collected in Tern Lake and presents a minimum age for deglaciation of these interior valleys at $9,310 \pm 200$ yr B.P. Current vegetation, however, developed within the past ca. 2,500 years. A second study discusses the cycling of arsenic and cadmium in sub-arctic boreal forest ecosystems typical of interior Alaska and defines the importance of various natural (geogenic) sources. The transport and uptake into vegetation of these elements from soils developed from loess as well as soils developed from the major rock units is presented. The bioaccumulation of cadmium in willow (*Salix* sp.) and its potential consequence to the health of browsing animals is discussed.

Papers related to resource issues comprise the topic of the final report. This paper presents a brief statistical summary of the geochemistry of rock samples collected in the east-central portion of the Eagle 1:250,000-scale quadrangle. This study helps define the rock unit source of both resource- and environmental-based chemical elements of interest in the Fortymile mining district.

Two bibliographies at the end of the volume list reports covering Alaska earth science topics in USGS publications during 1999 and reports about Alaska by USGS authors in non-USGS publications during the same period.

Figure 1. Index map of Alaska showing 1:250,000-scale quadrangles and locations of study areas discussed in this Professional Paper.

Figure 1. Location of historically active volcanoes in Alaska (Miller and others, 1998).

Figure 2. North Pacific (NOPAC) air routes and the 100 active volcanoes in Alaska, Kamchatka, and the Kurile Islands; windrose diagrams show that most of these air routes are downwind or cross the belt of active volcanoes. In 1998, more than 20,000 passengers and millions of pounds of cargo were being transported daily over these routes, including more than 90 percent of the all-cargo flights between Asia and North America. From Miller and Casadevall (2000).

Figure 3. *A*, Seismically monitored volcanoes in Alaska as of 1989. *B*, Seismically monitored volcanoes in Alaska as of 1999. The Katmai group network monitors seven closely spaced young volcanic centers: Griggs, Katmai, Novarupta, Trident, Mageik, Martin, and Snowy.

Figure 4. Map showing AVO satellite coverage used to monitor volcanic activity. Box A shows Geostationary Meteorologic Satellite coverage, 8-km resolution, 24 images/day. Box B shows Geostationary Orbiting Environmental Satellite (GOES) coverage, 8-km resolution, 48 images/day. Box C shows GOES, daytime only, 2-km resolution, 48 images/day in summer and 10 images/day in winter; polar orbiting Advanced Very High Resolution Radiometer satellite coverage is 1 km resolution, 4 images/day of the western Pacific (Kamchatka), and 10 images/day of the eastern Pacific (Alaska).

(Ecuador), and several restless volcanoes in Nicaragua. At this writing, AVO has about 17 full-time scientists and technicians and 27 part-time staff divided between offices in Anchorage and Fairbanks.

Ten years after the last eruption at Redoubt, snow and ice

accumulation have refilled the upper Drift Glacier canyon on the north flank and nearly buried the lava dome emplaced in the summit crater by the last eruption (figs. 5A, 5B). A new glacial tongue extends down from the canyon and has merged with, and overridden, the beheaded piedmont lobe of Drift Glacier (figs. 5B). Vegetation has reclaimed the lower flanks, tributary valleys, and Drift River valley walls, mostly covering the proximal tephra accumulations (figs. 5C), which were as deep as 25 cm. Rust Slough, which once threatened oil storage tanks at DROT when the Drift River changed course during one of the early eruption-induced mud flows, is now sediment filled and readjusted to a seasonal braided flow regime. As surface vegetation gains a foothold, only the dozens of acres of dead spruce trees—trunks buried as deep as 2 m—remain as a testament to the muddy flood waters that once inundated the area. Reinforced dikes now guard the storage tanks and an

Text continues on page 12

Figures 5A. Redoubt Volcano, north flank. Snow and ice accumulation in the summit crater and upper canyon of Drift Glacier. Photo on top taken April 11, 1990; photo on bottom taken September 28, 1999.

Figures 5B. Upper canyon of Drift Glacier. Photo on top taken on April 25, 1990 (Steve Brantley); photo on bottom taken September 28, 1999. Inset box shows approximate area shown in top photo. Note the advancing glacial tongue (immediately below box) that merges with, and laps onto, the piedmont lobe of Drift Glacier.

Figures 5C. Lower north flank and piedmont glacier. Photo on top, taken May 30, 1990, shows damage to vegetation from 25 cm of tephra accumulation. Photo on bottom, taken September 28, 1999, shows revegetation. Inset box shows area portrayed in top photo.

elevated “safe” house has been constructed at DROT to protect personnel from high water. The lower Drift River has reestablished its main channel to Cook Inlet and the upper and middle sections of Drift River continue to adjust and redistribute the massive amount of sediment and debris delivered during the eruption.

The seven-station seismic network at Redoubt continues to record normal background seismicity (approximately one to two magnitude-0.5 and higher volcanic earthquakes per week, a level sustained since 1991—S. McNutt, oral commun., 2000). Fumaroles on and around the dome still emit steam, which occasionally forms a wispy cloud over the summit. These steam clouds can be seen from Anchorage and the Kenai Peninsula during favorable weather conditions and often prompt calls to AVO from concerned citizens.

Due largely to the efforts of AVO during the past 10 years, aircraft traversing Alaskan skies are far less likely to plunge into a gritty ash cloud. As for Redoubt, the volcano presently sleeps under the watchful eyes of AVO. With three eruptions during the past 100 years, Redoubt will likely wake from its slumber sometime during the new century and once again put AVO to the test.

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Figure 2A. Simplified geologic map of Snowy Mountain volcanic center. Exposed lavas of Southwest Snowy volcano in red, of Northeast Snowy volcano in blue. Vent complex of former indicated by "*." Holocene lava dome occupying amphitheater (hachured) of latter is darker blue. Most of both cones covered by glacial ice (white). Basement rocks undivided are beige; they are largely Jurassic sedimentary rocks north of the volcanoes and largely Tertiary volcanic rocks to the south, although Tertiary intrusive rocks are also common in both sectors. Active alluvium (al) is pale yellow; debris avalanche deposit (d.av) is bright yellow. Glacial till is stippled. Stippled part of debris avalanche deposit was superficially remobilized when overrun by Neoglacial advance (and subsequent retreat) of Serpent Tongue Glaciers. Terminal positions of glacier snouts are dotted for 1951, entire for 1984–87. Contour interval 200 ft; selected elevations are given in feet (1 m = 3.28 ft).

Figure 2B. Place names mentioned in text and locations of samples listed in tables 2 and 3. There being no ambiguity, only the last two digits of the sample numbers given in the tables are shown on the map. Same base as panel A. Topography simplified from USGS 1:63,360 quadrangles Mt. Katmai A2, A3, B2, and B3. In northern part of map, sites of two radiocarbon-dated samples atop Rainbow River debris avalanche are indicated by ×440 and ×930, as discussed in text.

Figure 4. Two views of Southwest Snowy edifice, July 1998. *A*, East side of intrusive vent complex (swayback knob 6600+) and, at right, north-dipping stack of lava flows that make up Peak 6770. Vertical exposures visible are, respectively, 225 m and 175 m. View toward WSW. *B*, Southwest face of intrusive complex (knob 6600+), with lava stack of Peak 6770 in background clouds. View toward NNE. Foreground face, about 200 m high, consists below of steeply jointed intrusive andesite, overlain by rim cliff of chaotic vent breccia, which is densely agglutinated and cut by dikes. These rocks are in turn overlain by remnants of three lava flows, each 10 to 15 m thick, that cap knob 6600+.

Figure 5. Three andesite lava flows forming the glacially carved, sinuous, WNW. ridge of Southwest Snowy volcano, July 1999. At right, mesa 5300+ is scoured atop the middle flow, which is only 10–15 m thick at the left but thickens distally to 100 m at its eroded terminus. Ramping over this flow from the left, the top flow (rich in black glassy zones) maintains a 60-m-thick remnant that forms Crag 5720. Base of the lowest flow is ice covered; flow is 60 m thick in foreground and as thick as 150 m distally (below the promontory at far right). Its upper part is brecciated and oxidized, and locally (as at the lower left) the flow appears to be compound. View westward to nameless mountains of pre-Quaternary basement rocks on the Ikagluik-Rainbow divide. Pale-gray veneer on mesa (and on many distant slopes) is pumice-fall deposit of 1912 from Novarupta, which lies 23 km WSW.

Figure 6. Ice-topped Holocene lava dome (Peak 6875) on central skyline, partly filling ice-mantled amphitheater on northeast slope of Northeast Snowy edifice, July 1999. True summit (Peak 7090) lies just behind dome to its right. Radial dips surrounding amphitheater define Pleistocene edifice. Smooth skyline slope at right is north-dipping planeze that extends northward into staircase stack of thick coulees (just out of frame to right), illustrated in figure 10. Amphitheater originated by sector collapse and subsequent modification by ice of the acid-altered core of the edifice. Exposed walls of the amphitheater are hydrothermally altered orange-brown, yellow, and white, severely so in permeable breccia zones. Intact remnant of outward-dipping edifice lavas (surrounded by snow) lies at northeast foot of the lava dome. View southwestward across Serpent Tongue Glacier from ridge 3075 (sample site K-2606; 06 in fig. 2), 6 km from the dome.

Figure 7. Southeastward view of Holocene lava dome (Peak 6875) extruded at head of amphitheater seen in figure 6. Icy summit on right skyline is Peak 7090, part of the headwall. Its lavas, like those of the two prows at the left and the 300-m cliff at the right, dip radially away from the dome, serving to define the gutted center of the Northeast Snowy edifice. Relief on the ice-covered north face of the dome exceeds 500 m. Reddish-brown discoloration of glacier surface at right is caused by rockfall and windblown sand and silt from disintegrating cliff of hydrothermally altered andesite at right. Upper part of Serpent Tongue Glacier in foreground. Photo July 1998.

Figure 8. Steep exogenous lava lobe that drapes 250-m-high southeast face of Holocene lava dome (Peak 6875) occupying gutted core of Northeast Snowy edifice, July 1998. Best exposures of ice-mantled but little-eroded blocky lava dome are here on its southeast side. Remnants of stacked lava flows that built the ice-ravaged Pleistocene edifice dip 25° E. at right, 45° WSW. on crag at upper left. Within the lava stacks, permeable breccia zones are hydrothermally altered rusty orange- and yellow-brown; massive zones (flow interiors) are fresh and dark gray. View northwestward.

Figure 9. View northeastward past Crag 6700+ to southwest face of Holocene dome (Peak 6875), which exposes a 25-m-thick stubby lobe of fresh, little-eroded, blocky andesite. Crag at left lies on south rim of cirque-amphitheater and midway between the dome and Peak 7090 (fig. 2); it consists of coarse lava-flow breccia that dips as steeply as 45° WSW., away from the dome. Smoothed and corniced snow surface atop dome is a transient eolian feature that conceals a capping of crevassed ice as thick as 30 m. Foreground snow saddle is about 100 m below top of dome and about 70 m below top of Crag 6700+. Photo July 1998.

Figure 10. Glacially scoured staircase of andesite-dacite lava flows that descends northward from Northeast Snowy volcano and divides the forks of Rainbow River, July 1999. Lowest and second benches are compositionally identical dacite lavas, each 150 m thick. Small mesa right of center (Bench 3685) is a third (andesitic) lava flow 30–50 m thick, apparently banked in against the stack of thicker flows and probably derived from the other (southwest) cone. Still higher bluff (above snow slope at the right margin) is another dacite flow about 200 m thick. Forming the broadest bench, the second flow of the stack yields a K-Ar age of 171 ± 8 ka (table 1). At left in middle distance, smooth-sloping Peak 4665 consists of pre-Quaternary basement rocks, as do most of the skyline peaks and ridges. View is northeastward across head of Rainbow Race Glacier from sample site K-2597 (97 in fig. 2) on WNW. ridge of Southwest Snowy edifice.

Martin, and Alagogshak but much more restricted than those of Novarupta and Mount Katmai (Hildreth, 1987; Hildreth and others, 1999; Hildreth and Fierstein, 2000). Snowy Mountain eruptive products form a typical low-Ti arc suite, containing only 0.57–0.75 percent TiO_2 . Contents of Al_2O_3 are ordinary for arc suites, ranging from 15.7 to 17.4 percent. Relatively primitive material has not erupted at Snowy Mountain, most samples having less than 5.2 percent MgO, but (at 7.1 percent MgO) the olivine-bearing scoria blocks from the vent complex of Southwest Snowy do rank among the most magnesian Quaternary volcanic products yet recognized in the Katmai district.

Figure 11 shows that products of Southwest Snowy (55.5–62.2 percent SiO_2) are generally less silicic than those of Northeast Snowy (61.7–63.7 percent SiO_2) and that they also tend to have slightly higher K_2O at equivalent values of SiO_2 . The Holocene lava dome (at 62.8 SiO_2 , 1.53 K_2O ; fig. 11A) is less silicic than several older lava flows from Northeast Snowy and is, relatively, one of the least potassic.

Three samples of the highly eroded basement volcanic suite directly underlying the Snowy Mountain lavas were studied and analyzed (tables 2, 3). All three are pyroxene dacites, petrographically and chemically rather similar to silicic members of the Snowy Mountain suite, though relatively less potassic and distinctively more hydrated (see LOI, table 3). Thought to be of early Quaternary or late Tertiary age, these rocks are slightly altered remnants of a previous generation of arc volcanoes that apparently lay along or close to the same alignment as that of the modern volcanic chain (figs. 1, 2).

Volume Estimates

Owing to the extensive glacial erosion and the present-day ice blanket, estimates of eruptive volume are not very accurate for these cones. Exposures of Quaternary volcanic rocks today add up to about 6.5 km^2 for Northeast Snowy and only 2.4 km^2 for Southwest Snowy. Extrapolation beneath the ice between outcrops yields minimum areas originally lava-covered of 31 km^2 and 36 km^2 , respectively. Conservative estimates of lost volumes of distal lavas, not counting probable intracanyon lava tongues, could raise total areas to 40 km^2 and 45 km^2 , respectively.

For converting such areas to volume estimates, a cone model is inappropriate because the volcanoes straddle a narrow rangecrest ridge of pre-Quaternary basement rocks and because their bilaterally emplaced lavas draped irregularly rugged topography on both flanks. Along the main drainage divide, Tertiary rocks crop out as high as 5,500 ft only 1 km east of the vent-plugging 6,875-ft dome of Northeast Snowy and as high as 6,000 ft only 1.5 km west of the vent of Southwest Snowy (fig. 2). Although Snowy Mountain lavas are preserved on the north flank down to elevations as low as 2,000 ft, they are flanked there by ridges of basement rocks higher in several places than 4,000 ft. The volume approximation is best treated, therefore, in several parts—two thick near-vent

Figure 11. Whole-rock compositional data for Snowy Mountain samples as identified in inset. Filled circles for Southwest Snowy are magmatic enclaves (tables 2, 3). “Kienle data” (+) are four analyses reported by Kienle and others (1983) for unlocated samples said to have been taken from Snowy Mountain. In addition to Snowy data, fields outlining the compositional ranges determined for our suites of samples from nearby Mount Griggs ($n = 75$), Mount Martin ($n = 13$), and Southwest (New) Trident ($n = 15$) are shown for comparison. *A*, K_2O vs. SiO_2 . *B*, FeO^*/MgO vs. SiO_2 . *C*, CaO (upper array) and total alkalis (lower array) vs. SiO_2 . Data from Hildreth and others (1999, 2000); Hildreth and Fierstein (2000); and table 3 of this report. TH/CA is conventional field boundary between tholeiitic and calcalkaline suites. FeO^* is total iron calculated as FeO. The nomenclatural division between andesite and dacite lies at 63 percent SiO_2 and is simply a conventional tick on a natural continuum in many arc suites.

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Figure 5. Diagrammatic sections showing the evolution of the IISZ in southeastern Alaska and adjacent areas; line with “+’s” represents the original Insular-Intermontane superterrane boundary. AX, Alexander terrane; BCSZ, Behm Canal structural zone; CRML, Coast Range megalineament; GR, Gravina overlap assemblage; GTS, Great Tonalite Sill; GTSMZ, Great Tonalite Sill mylonite zone; GTSSZ, Great Tonalite Sill shear zone; NS, Nisling terrane; ST, Stikine terrane; WR, Wrangellia terrane; ?, Oceanic crust(?).

Figure 6. Diagrammatic sections showing the evolution of the Adria-Europe suture zone (AESZ) at its western end where it coincides with the segment of the PAL called the Insubric lineament (modified from Schmid and others, 1989); in all diagrams, the line with "x's" represents the original Adriatic-European superterrane boundary; dashed line in diagrams 5 and 6 is present erosion surface.

five shear zones is the crustal-scale geomorphic and structural component described as the Coast Range megalineament (CRML). The CRML is a 800-km-long, <1-km- to a several-tens-of-kilometers-wide, NNW.-SSE.-trending, essentially straight fault zone whose youngest movement postdates the dominant 50-Ma granitic rocks of the Coast Mountains. It is readily recognizable because of Pleistocene/ Holocene erosion. The CRML and the IISZ as a whole are parallel to the strike of the adjacent rocks and have associated aeromagnetic and gravity gradients. To the west of the IISZ are rocks of the Gravina overlap assemblage and the Alexander and Wrangellia terranes; pieces of those units occur in the zone itself together with rocks of the Nisling and Stikine terranes. East of the zone are crystalline rocks of the Wrangellia, Stikine, and Nisling terranes. The strongly linear nature of the IISZ suggests a strike-slip origin, but no shear-sense indicators or other reliable evidence for lateral movement has been reported for it.

3. The AESZ consists of several separate structural elements that occur in different parts of southern Europe; the youngest and most obvious of these is the crustal-scale geomorphic and structural component called the Periadriatic lineament (PAL). The PAL is the final expression of the series of tectonic, metamorphic, and intrusive events that occurred near and along the contact between the European superterrane to the north and the Adriatic superterrane to the south during the Cenozoic. Those events include both N.- and S.-directed contractional and E.-W. strike-slip faulting. The AESZ is at least 800 km long and varies from a NE.-SW. orientation to the west to E.-W. on the east. The zone in Switzerland, Italy, and Austria consists of several connected and overlapping faults that together result in prominent several-kilometer-wide valleys. The PAL is parallel to the strike of the adjacent rocks, bounds contrasting plutonic and metamorphic belts, and has associated geophysical gradients. In general, crystalline rocks of the Austro-Alpine nappes form the northern part of the AESZ; late Paleozoic, Mesozoic, and Cenozoic rocks of the southern Alps and of the Dolomites are to the south, but many of the rocks on both sides of the PAL are part of the Adriatic superterrane.

Larger Scale Conclusions

1. The conspicuous lineaments associated with both the IISZ and the AESZ are the final and most conspicuous manifestations of the complicated series of superterrane collisional events and are not themselves the boundaries between the superterranes; because of this it is considered likely that other major lineaments are also only a relatively recent component in their collisional histories.
2. Global-scale tectonic suture zones such as these are likely to be at least several kilometers wide and characterized by (a) thrust imbrication of rocks from both sides of the suture, (b) associated elongate geophysical anomalies that approximately parallel the zones, and (c) local mylonite zones.
3. Studies of mesoscopic shear-sense indicators and map-unit relations may not suffice to unravel the strike-slip, transpressional, and contractional movement history of a zone; microfabric studies of the tectonites and mylonites may be required.
4. Suture zones and their lineaments separate magmatic and geophysical belts; this indicates that deep-crustal and perhaps sub-crustal structures exist that are not directly mirrored in the upper-crustal rocks. Similarly, the presence of abundant and commonly elongated tonalitic plutons within the zones may indicate deep-crustal structures.

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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

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

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.

Figure 6B. 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.

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 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.

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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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Geologic Units

A tabular list of geologic units exposed in the study area follows, proceeding from youngest to oldest. The areal distribution of these units is shown in figure 2. Table 1 gives a list of identified taxa from all known fossil localities within the study area.

- Qs Surficial deposits, undifferentiated (Quaternary)**—Unconsolidated silt, sand, and gravel of fluvial, glacial, colluvial, and other origins
- Kk Kuskokwim Group, undivided (Late Cretaceous and late Early Cretaceous)**—Sandstone, siltstone, shale, and conglomerate. Includes fine- to coarse-grained, greenish-gray to gray, thinly cross bedded sandstone and quartz-chert pebble conglomerate having poorly exposed interbeds of dark shale and siltstone. Unit is widely distributed in southwestern Alaska (see Decker and others, 1994)
- Sab Algal boundstone (Late Silurian)**—Thick- to massive-bedded, light-gray algal boundstone, locally dolomitized; composed primarily of spongiostromate algal heads (including abundant oncoid forms). Sponges and minor accessory brachiopods indicate Late Silurian (Ludlovian-Pridolian) age in the study area. Equivalent to the S1 unit of Gilbert (1981) in the McGrath quadrangles. This unit is time transgressive elsewhere and includes rocks as young as early Early Devonian (Lochkovian) age in the Lime Hills area to the northeast (Clough and Blodgett, 1985, 1988, and 1992; Blodgett and Gilbert, 1992)
- Sls Platy limestone (Early to early Late Silurian)**—Thin- to medium-bedded, laminated, dark-gray to dark-brown, platy lime mudstone having a strong petroliferous odor. Three-dimensional monograptid graptolites are moderately common in rocks of this unit. Coarse-grained limestone debris flows containing clasts of algal boundstone reef material common in uppermost part of unit, immediately below contact with overlying, prograding Sab unit. Contains graptolites and conodonts indicative of early Late Silurian (Wenlockian) age. Lowermost transitional beds with underlying Olss unit contain conodonts of late Early Silurian (late Llandoveryan) age. Equivalent to the uOll unit of Gilbert (1981) in the McGrath quadrangle and the Paradise Fork Formation of Dutro and Patton (1982) in the Medfra quadrangle
- Olss *Tcherskidium*-bearing limestone (Ashgillian, Late Ordovician)**—Brown, medium- to thick-bedded skeletal lime packstone to wackestone containing locally abundant pentameroid brachiopods [*Tcherskidium*, smooth new genus aff. *Tcherskidium*, and *Proconchidium* (or *Eoconchidium*)] indicative of Late Ordovician (Ashgillian) age
- Os Shale (Ordovician, undifferentiated)**—Poorly exposed unit (mostly in frost boils) composed of brown and gray “chippy” shale, silty shale, and silicified limestone. No age definitive fossils known from this unit
- Oab Dark-gray algal limestone (Early Ordovician)**—Medium- to thick-bedded, dark-gray to brown, algal thrombolites (boundstone) interbedded with light-gray-weathering thin- to medium-bedded lime mudstone. Boundstone of this unit is comprised of spongiostromate algal buildups that are typically darker in color, thinner bedded, and have a different suite of accessory algal and biotic components than the algal boundstone of the overlying Sab unit. Contains trilobites indicative of an Early Ordovician age
- Ols Burrow-mottled limestone (Early Ordovician)**—Thin- to medium-bedded, yellow-gray-weathering, dark-gray fresh, burrow-mottled lime mudstone. Peloidal mudstone locally common. Contains gastropods and conodonts indicative of an Early Ordovician age

