Origin of Unconsolidated Quaternary Deposits at Harriet Point near Redoubt Volcano, Alaska

Scientific Investigations Report 2021–5071

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U.S. Geological Survey, Reston, Virginia: 2021

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Volume		
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

Abbreviations

cal. yr B.P.	calibrated years before present
ky	thousand years
Ma	million years before present
yr B.P.	years before present

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Abstract

Unconsolidated boulder-rich diamicton units exposed in sea cliffs at Harriet Point southeast of Redoubt Volcano were evaluated to better understand their provenance relative to the late Quaternary eruptive history of the volcano. A previous study concluded that deposits at Harriet Point were emplaced by a large volcanic landslide originating on the southeast flank of Redoubt Volcano (Begét and Nye, 1994). Field-based analysis of the stratigraphy and sedimentology of the Harriet Point deposits and numerical simulations of the volcanic landslide area of inundation indicate that none of the deposits are volcanogenic. All of the unconsolidated boulder-rich diamicton units at Harriet Point are glacial in origin and can be reconciled using the presently available model for late Quaternary glaciation of Cook Inlet.

Introduction

Unconsolidated deposits on the flanks of volcanoes provide an important record of primary eruptive events and can be useful chronostratigraphic markers when part of nonvolcanic sequences. Such deposits are key to interpreting the eruptive history of a volcano and provide context for assessing volcanic hazards. Ascribing a mode of origin to unconsolidated volcanic deposits can be difficult and fraught with uncertainty because deposits can appear sedimentologically similar despite having vastly different origins.

As part of ongoing studies of Redoubt Volcano by the Alaska Volcano Observatory, we have evaluated the postglacial (upper Pleistocene through Holocene) record of eruptive activity through outcrop-scale studies of unconsolidated deposits preserved on the flanks and in the general vicinity of the volcano. Our focus was on tephra-fall deposits and volcaniclastic mass-flow deposits, including the lahar, pyroclastic-density current, and debris-avalanche deposits common in the main drainages of the volcano. Our goals were to document physical evidence for postglacial eruptive events and integrate the results with existing records of Redoubt Volcano eruptive activity derived from the study by Schiff and others (2010) of tephra deposits in lake cores near the volcano.

After the 1989–90 Redoubt Volcano eruption, various studies were initiated to better understand the effects of the eruption (Miller and Chouet, 1994). An associated study sought to evaluate the eruptive history of Redoubt Volcano on the basis of historical activity and the geologic record of volcaniclastic

deposits preserved on the flanks of the volcano (Begét and Nye, 1994). In that study, Begét and Nye (1994) described "a previously unrecognized debris-avalanche deposit from Redoubt Volcano" exposed in sea cliffs southeast of the volcano at Harriet Point (fig. 1). Begét and Nye (1994) estimated an areal extent of about 40 square kilometers (km^2) for the deposit, which they called the Harriet Point debris-avalanche deposit, and gave an age of emplacement of 13,000 to 10,500 years before present (yr B.P.; uncalibrated). If the deposit had a thickness of 1 to 5 meters (m), a plausible range for debris avalanches (Siebert, 1984), the volume of the volcanic mass flow would have been 0.04 to 0.2 cubic kilometers (km^3)—a small deposit relative to other terrestrial volcanic debris-avalanche deposits on Earth (Siebert, 1984; Shea and van Wyk de Vries, 2008).

Large volcanic debris-avalanche deposits (>1 km^3) are typically associated with a major sector collapse event that leaves behind a tell-tale horseshoe-shaped scar on a truncated edifice (Voight and others, 1983; Capra and others, 2002; Ponomareva and others, 2006). Such scars persist for tens of thousands of years (Siebert, 1984). The modern volume of the Redoubt Volcano edifice is about 30 to 35 km^3, and although the configuration of the volcano when the Harriet Point deposit may have been emplaced is not known, there is no evidence the volcano was notably different around 13,000 years ago except that it supported a more extensive cover of glacier ice (Kaufman and others, 2011). Thus, a debris avalanche that originated on the southeast flank of Redoubt Volcano and extended roughly 30 km to Cook Inlet, forming a 40 km^2 deposit—as suggested by Begét and Nye (1994)—would be expected to have left some kind of failure scar, but no such feature has been observed or documented. This report presents field observations and stratigraphic analysis that support a new interpretation of the unconsolidated deposits exposed at Harriet Point as glacial in origin rather than volcanogenic.

Deposits at Harriet Point

Harriet Point (lat 60°23'43.85" N., long 152°14'11.26" W.) is a triangular-shaped promontory along the west side of Cook Inlet about 21 kilometers (km) south of the mouth of Drift River, 26 km northeast of the mouth of Crescent River, and 10 km west of Kalgin Island, a prominent island in the middle part of Cook Inlet (fig. 1). Unconsolidated surficial deposits are exposed discontinuously for about 6 km along the promontory in sea cliffs that are as tall as 25 m (fig. 2). Deposits exposed in the bluff at
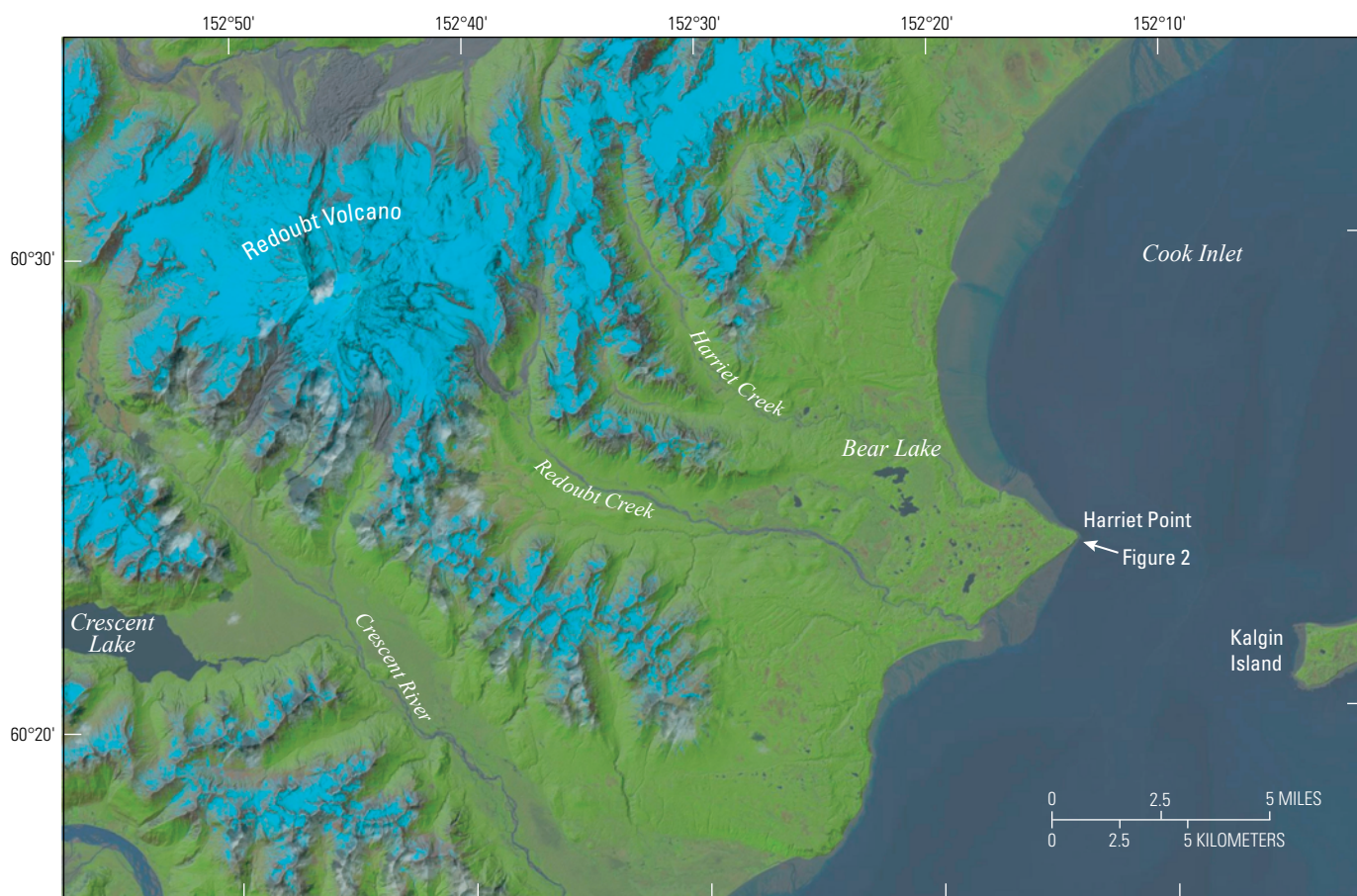
Base from National Elevation Dataset (NED) 60m resolution and Landsat 8 satellite image overlay
Alaska Albers Equal-Area Conic projection, North American Datum of 1983
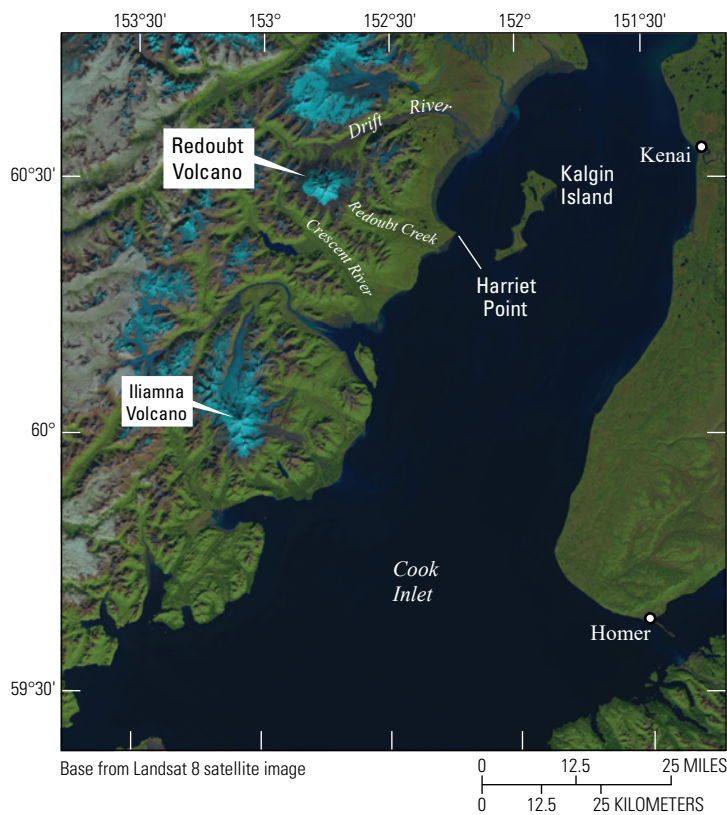
Base from Landsat 8 satellite image

Figure 1.   Maps showing the location of Harriet Point and Redoubt Volcano in the Cook Inlet region of south-central Alaska.
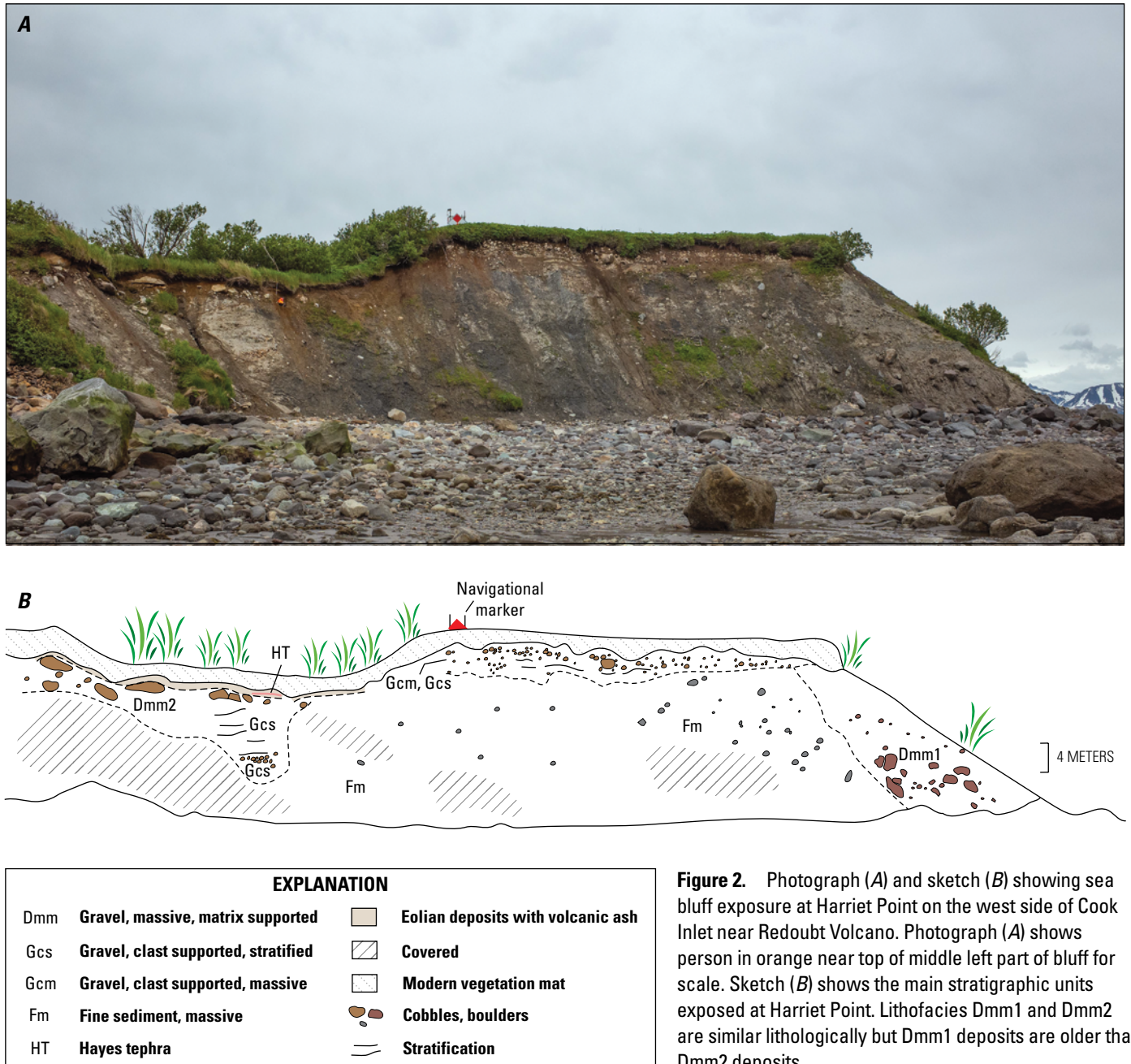
Figure 2. Photograph (*A*) and sketch (*B*) showing sea bluff exposure at Harriet Point on the west side of Cook Inlet near Redoubt Volcano. Photograph (*A*) shows person in orange near top of middle left part of bluff for scale. Sketch (*B*) shows the main stratigraphic units exposed at Harriet Point. Lithofacies Dmm1 and Dmm2 are similar lithologically but Dmm1 deposits are older than Dmm2 deposits.

Harriet Point consist of several glacigenic lithofacies that are described below.

Unconsolidated deposits at Harriet Point contain cobbles and boulders derived from Redoubt Volcano and exposed bedrock in the upland terrain of the Redoubt Creek drainage (fig. 1). The main rock types at Harriet Point form a prominent boulder lag deposit at the base of the sea bluff (fig. 3). The primary lithologies are medium to dark gray-green and gray-maroon andesite and lesser amounts of dioritic rocks. These rocks were likely derived from Redoubt Volcano, the Early Jurassic Talkeetna Formation, and

Jurassic plutonic rocks (units Qv, Jtk, and Jqd, respectively, on fig. 4; Wilson and others, 2012).

The sequence of unconsolidated deposits exposed at Harriet Point consists of several distinct lithofacies types. To facilitate field-based description of the deposits, a mnemonic lithofacies code modified from Eyles and others (1983) was used (table 1). The first letter of each code is capitalized and denotes the lithofacies. Fine-grained deposits that consist of some combination of silt, sand, and clay—but are mostly mud (silt and clay)—are denoted with the letter "F." Deposits that are poorly sorted

Figure 3. Photograph showing unconsolidated deposits exposed at Harriet Point. The base of the outcrop contains an assemblage of lag boulders derived from wave erosion of the unconsolidated deposits exposed here. The largest boulders are 2 to 3 meters in length and consist primarily of gray-green to gray-maroon andesite.

Table 1. Explanation of lithofacies code, modified from Eyles and others (1983).

Lithofacies code	Lithofacies	Sedimentary structures
Fl	Fine grained—mostly silt and clay (mud)	Laminated
Fm	Fine grained—mostly silt and clay (mud)	Massive
Dmm	Diamict—poorly sorted mixture of sand, silt, clay, cobbles, and boulders	Matrix supported, massive
Gcm	Gravel—pebbles, cobbles, boulders	Clast supported, massive
Gcs	Gravel—pebbles, cobbles, boulders	Clast supported, stratified

mixtures of clasts, sand, and mud are denoted with the letter "D" in reference to the term diamict—a poorly sorted unconsolidated deposit consisting of cobbles, boulders, sand, and mud that can be either clast or matrix supported. Predominantly gravel deposits at Harriet Point are denoted by the letter "G." Additional, uncapitalized letters are used to indicate sedimentary structure(s) characteristic of each lithofacies (for instance, the "m" in the Fm lithofacies code refers to the massive nature of that lithofacies).

Fm and Fl Lithofacies

The Fm lithofacies at Harriet Point consists of medium to dark gray, fissile, generally massive silt and clay (mud) with sporadic faint lamination and occasional matrix-supported cobbles, pebbles, and small boulders (figs. 2, 5). Deposits are designated Fl where they exhibit lamination (fig. 5). Some of the cobbles and small boulders are associated with downward sags in the mud-rich matrix, indicating that these clasts fell into fine-grained, deformable sediment. At Harriet Point, the Fm and Fl lithofacies constitute about 80 percent of the sea bluff exposure (fig. 2). The Fm lithofacies is also exposed in sea cliffs west and southwest of Harriet Point and can be traced inland along Redoubt Creek for several kilometers.

Dmm1 Lithofacies

The Dmm1 lithofacies consists of medium brown, poorly sorted, massive, matrix-supported diamicton with angular to subangular cobbles and boulders of andesite and scattered dioritic rocks (figs. 2, 6). Many of the cobbles and boulders are faceted, and surface striations are present on some clasts. Overall, this lithofacies is hard, compact, and difficult to excavate with a shovel. The matrix of the deposit is a mixture of silt, sand, and fine gravel that is mostly comminuted rock debris. The Dmm1 lithofacies has an abrupt, erosional contact with the Fm lithofacies and is younger than the Fm lithofacies.

Dmm2 Lithofacies

The Dmm2 lithofacies consists of orange brown, slightly oxidized, poorly sorted, mostly massive, matrix-supported gravel with angular to subangular cobbles and boulders of andesite and scattered dioritic rocks (figs. 2, 7). These deposits have a slightly greater content of sand and gravel than the Dmm1 lithofacies and are in gradational contact with associated Gcs and Gcm lithofacies deposits (fig. 7).
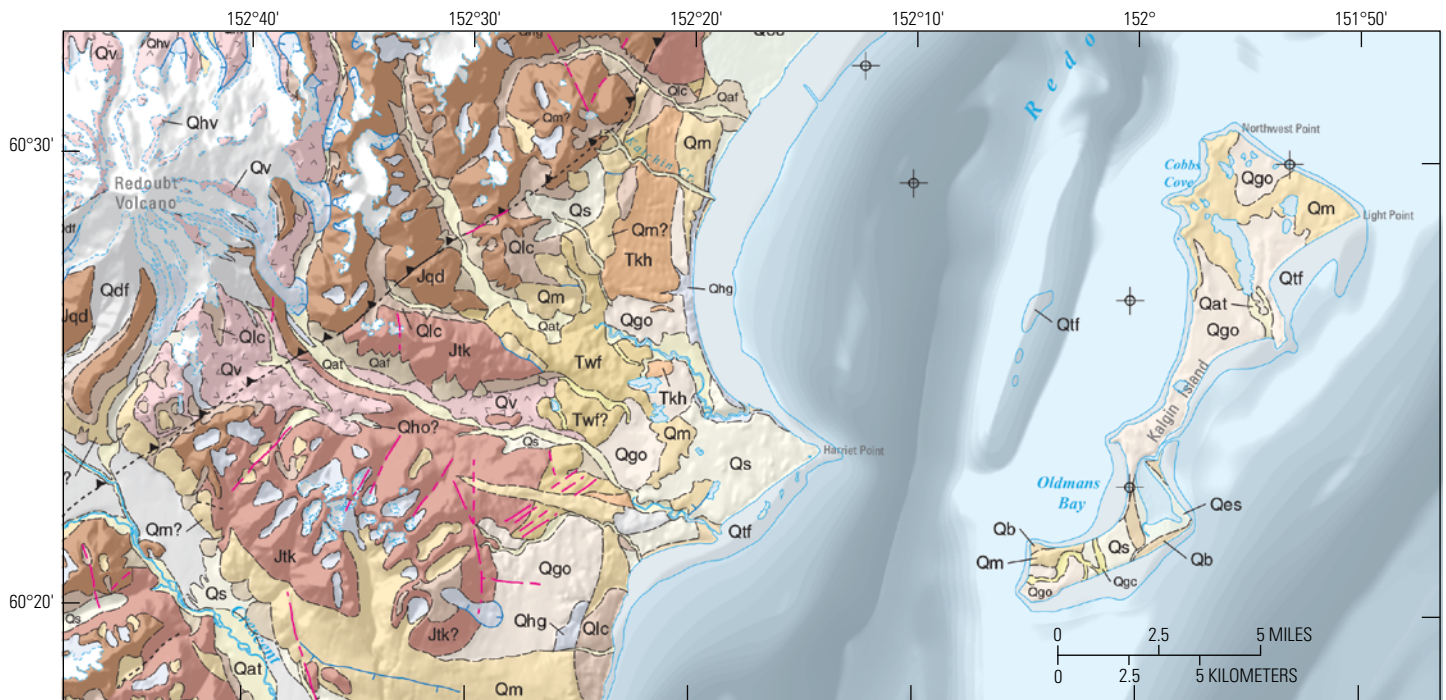
Shaded relief base from National Elevation Dataset (NED), 60 m resolution

EXPLANATION

Surficial deposits

Qs	Surficial deposits, undivided (Quaternary)
Qat	Alluvium along major rivers and in terraces (Holocene)
Qtf	Modern tidal flat and estuarine deposits (Holocene)
Qes	Estuarine deposits (Holocene)
Qaf	Alluvial fan deposits (Holocene and upper Pleistocene)
Qdf	Debris-flow deposits (Holocene)
Qlc	Landslide and colluvial deposits (Holocene and upper Pleistocene)
Qb	Beach deposits (Holocene)
Qhg	Young moraine deposits (Holocene)
Qho	Younger outwash deposits (Holocene)
Qm	Major moraine and kame deposits (upper Pleistocene)
Qgc	Glacioalluvium (upper Pleistocene)
Qgo	Outwash in plains, valley trains, and fans (upper Pleistocene)

Sedimentary rocks

Tkh	Hemlock Conglomerate, undivided (Oligocene)
Twf	West Foreland Formation (Eocene and Paleocene)
Jtk	Talkeetna Formation, undivided (Lower Jurassic)

Igneous rocks

Qv	Volcanic rocks, undivided (Quaternary)
Qhv	Volcanic rocks, undivided (Holocene)
Jqd	Quartz diorite, tonalite, and diorite (Jurassic)

Dike—Dashed where inferred

Bruin Bay Fault—Solid where accurately located; dashed where inferred. Teeth on upthrown block.

Plugged and abandoned well

Figure 4. Geologic map of the Redoubt Volcano-Harriet Point-Kalgin Island area of south-central Alaska from Wilson and others (2012).

Figure 5.   Photographs showing unconsolidated deposits exposed in the lower part of sea bluffs at Harriet Point. *A*, Photograph of base of bluff section at Harriet Point. *B*, Close-up view of Fm lithofacies that consists of clayey silt (pebbly mud) with dispersed subrounded to subangular pebbles (dropstones). Explanation of letters: D, dropstone; Fm, fine sediment (mainly silt and clay), massive; Fl, fine sediment (mainly silt and clay), laminated; Gcs, fine gravel, clast supported, faintly stratified. Shovel in photograph is about 1.5 meters in length.

Figure 6.   Photograph showing unconsolidated deposits of lithofacies Dmm1 at Harriet Point. See figure 2 for distribution of this lithofacies in the sea bluff at Harriet Point. Most of the clasts in the deposit consist of andesitic rocks (likely sourced from Redoubt Volcano and Talkeetna Formation bedrock) with a subordinate amount of dioritic rocks. Length of shovel in photograph is about 1.5 meters.

Gcm Lithofacies

The Gcm lithofacies consists of clast-supported, massive, poorly sorted gravel deposits with slightly sandier textures than the Dmm lithofacies deposits described above (fig. 2). The Gcm lithofacies contains angular to subangular cobbles and boulders of andesite and subordinate amounts of dioritic rocks.

Gcs Lithofacies

The Gcs lithofacies consists of clast-supported, faintly stratified accumulations of sandy gravel with subangular to subrounded cobbles and small boulders of andesite and dioritic rocks (figs. 2, 7). Gcs lithofacies deposits are gradational with associated Gcm and Dmm2 lithofacies deposits but have an erosional basal contact with underlying Fm lithofacies deposits (figs. 2, 7).
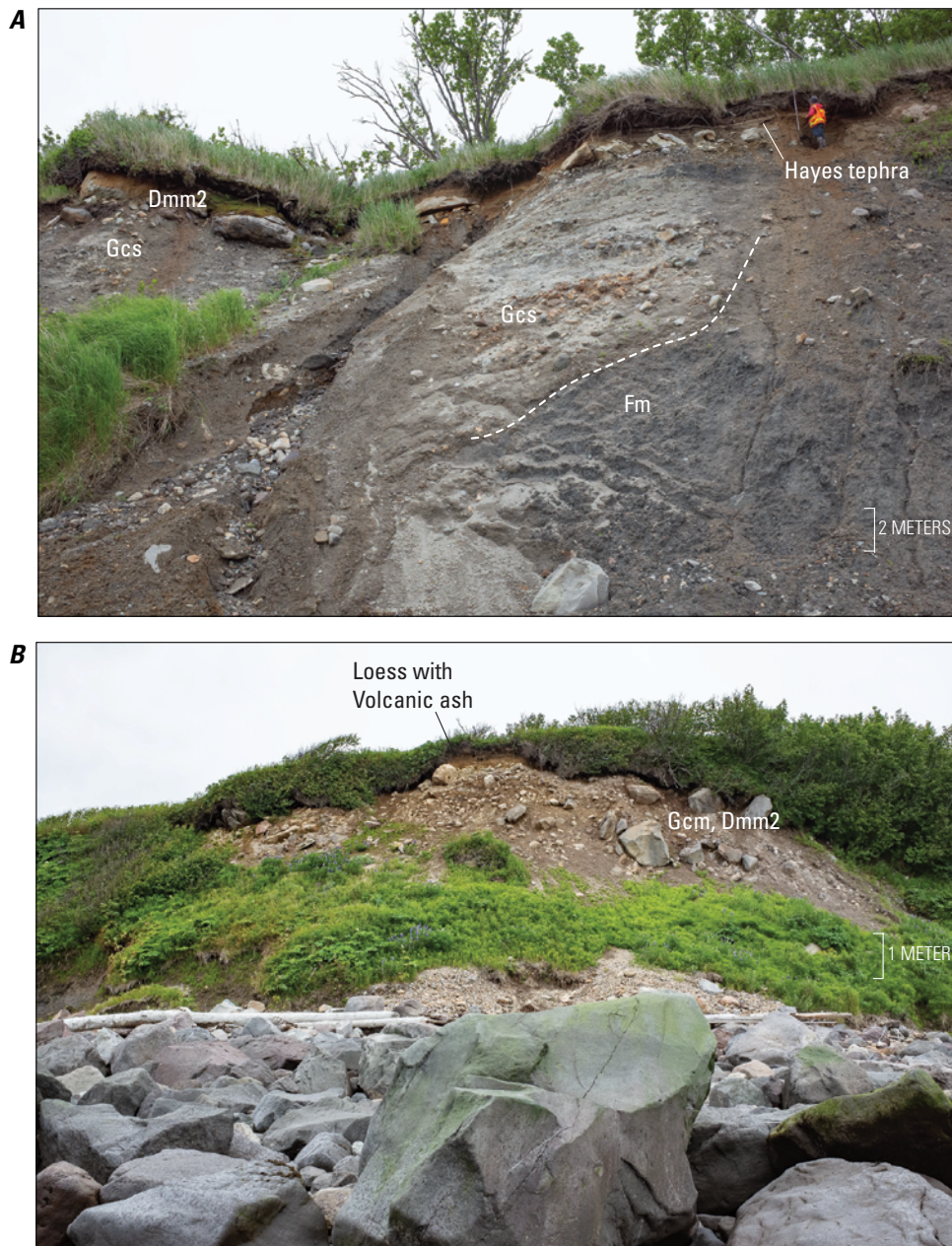
Figure 7. Photographs showing unconsolidated deposits exposed in the southern part of Harriet Point bluff. *A*, Upper part of bluff exposure showing Fm lithofacies deposits at base, unconformably overlain by Gcs lithofacies deposits. Gcs lithofacies deposits grade upward into Dmm2 lithofacies deposits. Note person at top of exposure for scale. *B*, Southernmost end of bluff exposure at Harriet Point, showing Gcm and Dmm2 lithofacies deposits overlain by oxidized loess deposits. Boulders in foreground are mostly gray andesite winnowed from the Harriet Point bluff by wave action.

Stratigraphy and Interpretation of Deposits at Harriet Point

Four main stratigraphic units are preserved at Harriet Point (fig. 2) and are discussed according to their relative ages from oldest to youngest. The oldest unit consists entirely of Fm lithofacies deposits that are about 15 m thick and constitute about 80 percent of the deposits exposed at Harriet Point. The sedimentologic character of the Fm lithofacies indicates that it was the product of either glacioestuarine or glaciomarine deposition; the pebbles and cobbles in the unit are likely ice-rafted detritus (dropstones). It was not possible to make a concerted search for fossils in the unit that might indicate a marine versus freshwater depositional environment. However, the muddy, laminated character of these deposits indicates ice-proximal deposition in water (Smith and Andrews, 2000; Powell and Domack, 2002).

The second main unit consists entirely of Dmm1 lithofacies deposits that are 15 to 20 m thick and found only at the apex of Harriet Point (fig. 2). The hard, compact nature of these deposits and their massive, boulder rich character indicates that they are glacial diamicton deposits (likely basal till or lodgement till).

Both the Fm and Dmm1 deposits are overlain by Gcs, Gcm, and Dmm2 lithofacies deposits, which together make up the third main unit at Harriet Point. The lithofacies assemblage includes basal ice-contact deposits (Dmm2) and ice-stagnation drift (Gcs, Gcm) associated with a downwasting lobe of glacier ice that covered the area. In most places, the lithofacies assemblage of Gcs, Gcm, and Dmm2 are in erosional contact with the underlying Fm and Dmm1 lithofacies deposits indicating that the Gcs deposits may be advance outwash, or possibly glacigenic mass-flow deposits in turn overlain by ice-contact deposits.

The fourth and youngest stratigraphic unit at Harriet Point is a 1- to 2-m-thick sequence of eolian silt deposits (loess) that contain several fine volcanic ash layers—including the "Hayes tephra," a regional stratigraphic marker of middle Holocene age (Riehle and others, 1990; Wallace and others, 2014). These deposits also include several weakly developed buried soils with Bw and (or) Cox horizons. Soil development on the loess parent material has imparted an orange-brown color to the deposits, and this weathered loess and soil, where reworked over the bluff face, gives the appearance of altered material in the upper part of the bluff (figs. 2, 7).

Depositional Model for Harriet Point Deposits

A new interpretation of the main sequence of unconsolidated deposits exposed at Harriet Point is that the deposits and associated lithofacies are all glacigenic in origin. The bluff top eolian deposits may be periglacial deposits but the volcanic ash layers are unrelated to glaciation. As such, the Harriet Point deposits must be reconciled within the established glacial

geologic framework for Cook Inlet (Karlstrom, 1964; Schmoll and Yehle, 1986; Reger and Pinney, 1996; Reger and others, 2007; Kopczynski and others, 2017).

A four-part model of late Quaternary glaciation of the Cook Inlet region was initially proposed by Karlstrom (1964). The basis for his explanation of late Quaternary glaciation are the moraines, outwash deposits, and other glacial features preserved on the Kenai Peninsula, primarily in and around the modern town of Sterling. At the time of his work, Sterling was known as Naptowne, and Karlstrom (1964) named the last major glaciation in the area the Naptowne glaciation. Karlstrom (1964) made a compelling argument that the Naptowne glaciation was broadly correlative with the classical late Wisconsin glaciation of mid-continent North America (Porter and Wright, 1983; Ehlers and others, 2011). According to Karlstrom (1964), the Naptowne glaciation is subdivided into four glacial stades, Moosehorn (oldest), Killey (intermediate), Skilak (younger), and Tanya (youngest). More recent studies have reassessed Karlstrom's model and offered important refinements through improved mapping and geochronology (Schmoll and others, 1972; Schmoll and others, 1984; Reger and Updike, 1983). The most important revision was the recognition of a late Naptowne glacier readvance in the Anchorage area known as the Elmendorf stade which is now accepted as the youngest stade of the Naptowne glaciation and supersedes the Tanya stade (Reger and Pinney, 1996; Schmoll and others, 1999; Kopczynski and others, 2017)

The most current chronology of Cook Inlet glacial events is described by Reger and others (2007) and Kopczynski and others (2017). According to these sources, the Moosehorn stade began about 32,000 to 27,000 calibrated years before present (cal. yr B.P.) and reached a maximum ice extent by about 23,000 cal. yr B.P. During the Moosehorn stade, glacier ice expanded from alpine areas, coalesced, and formed an extensive ice sheet over much of south-central Alaska that was contiguous with the northwestern sector of the Cordilleran ice sheet (Booth and others, 2004; Kaufman and others, 2011; Stroeven and others, 2014). At this time the Harriet Point area was under thick ice cover and the region was isostatically depressed (fig. 8A). During the waning phase of the Moosehorn stade, melting and receding glacier ice led to the development of meltwater lakes, some of which may have evolved to calving bays possibly influenced by tidewater (fig. 8B). Coastal bluff exposures of estuarine deposits along the south shore of Cook Inlet near Kenai, Alaska, contain calcareous barnacle plates that gave a radiocarbon age of 16,480±170 yr B.P. (19,200 cal. yr B.P.) (Reger and others, 1996). The presence of barnacle plates at this location indicates that marine water had reached the Kenai area by 19,200 cal. yr B.P. and that lower Cook Inlet was no longer blocked by glacier ice (Reger and others, 2007).

The Killey stade was a relatively short-lived ice advance 18,500 to 17,500 cal. yr B.P. (Reger and others, 2007) that produced prominent morainal belts that enclose Tustumena and Skilak Lakes and an ice advance that extended across Cook Inlet from north to south over the area north of Kenai (fig. 8B). The Killey stade ice margin in the vicinity of Harriet Point is uncertain but could have been just beyond Kalgin Island (fig. 8B).
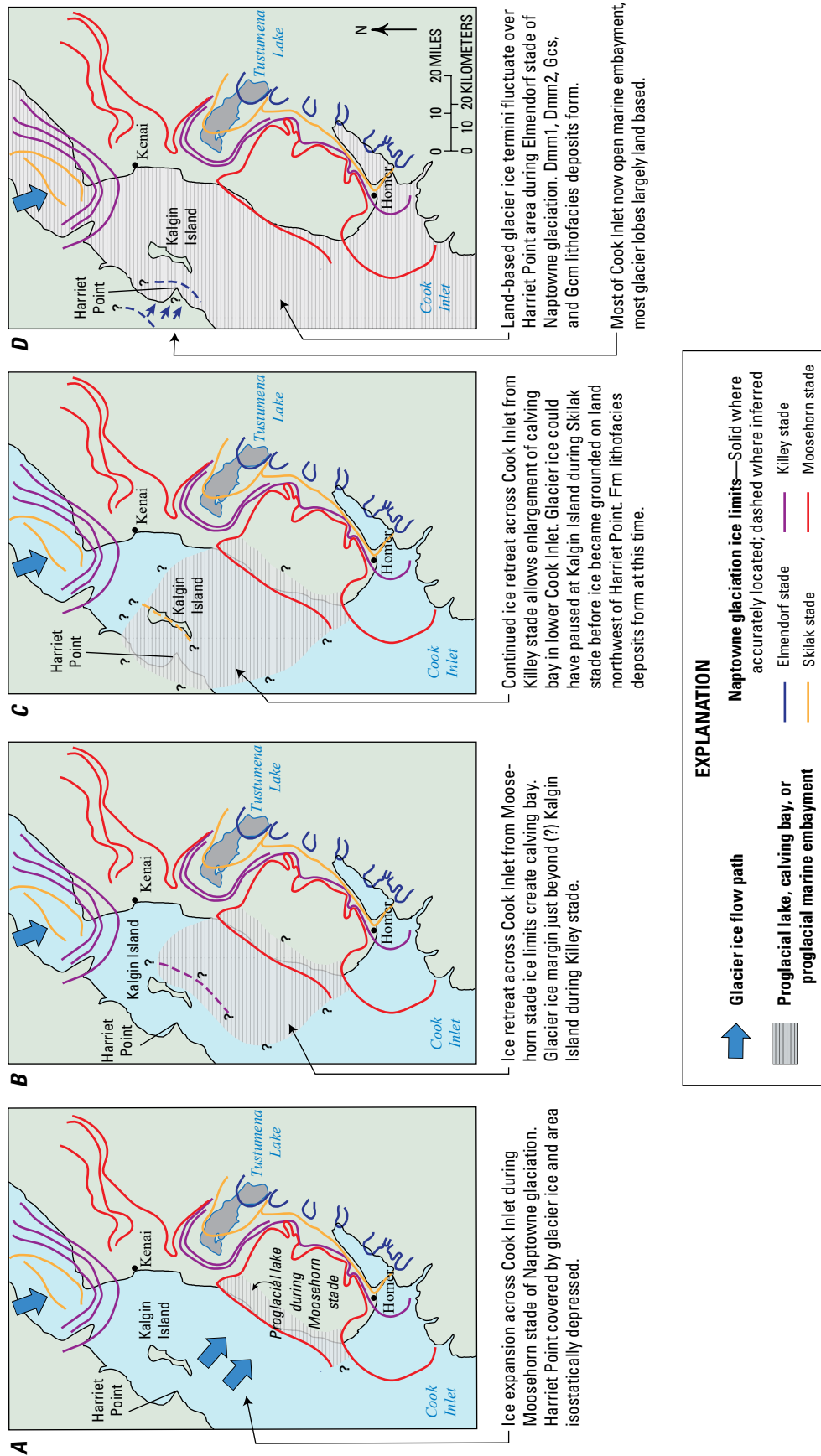
Figure 8.   Schematic diagram showing a depositional model for unconsolidated deposits at Harriet Point (glacier ice limits modified from Reger and others, 2007). *A*, Glacier paleogeography during Moosehorn stade of the Naptowne glaciation. At this time, ice covered the Harriet Point area and flowed across the Cook Inlet trough. *B*, Post-Moosehorn stade paleogeography of the lower Cook Inlet-Harriet Point area. At this time, a calving bay or proglacial glacioestuarine embayment develops in lower Cook Inlet and glacier ice could have paused or advanced slightly at Kalgin Island during the Killey stade. *C*, Continued ice retreat across Cook Inlet allows marine waters to further invade the Cook Inlet trough. At this time, it is plausible that the Harriet Point area remained isostatically depressed, allowing for deposition of Fm and Fl lithofacies deposits in the area. *D*, Cook Inlet is now mostly an open marine embayment and glaciers north of Cook Inlet are now land based. Glacier fluctuations in the Harriet Point area result in the formation of Dmm1, Dmm2, Gcs, and Gcm lithofacies deposits.

During the Skilak stade of the Naptowne glaciation (17,500–16,000 cal. yr B.P), ice lobes no longer blocked Cook Inlet and marine waters extended into the upper part of the Cook Inlet basin (Reger and others, 1995; Reger and others, 2007). Large outlet glaciers reaching Cook Inlet from the north had calving, shallow-marine margins that led to the development of the Bootlegger Cove Formation, a fossil-bearing glacioestuarine unit composed of clay, silt, and sand with abundant dropstones that underlies drift associated with the Elmendorf stade (Reger and others, 1995; Kopczynski and others, 2017). The Fm and Fl lithofacies deposits at Harriet Point possibly developed at this time when the area remained isostatically depressed and at or just beyond the local limits of Skilak stade glacier ice (fig. 8C). Kalgin Island, an arcuate-shaped partly submerged moraimal complex within Cook Inlet, possibly marks the limit of glacier ice during the Skilak stade (fig. 8C).

The final stade of the Naptowne glaciation, the Elmendorf stade, is named for a prominent set of nested moraines just north of Anchorage (Reger and others, 1995; Reger and others, 2007; Kopczynski and others, 2017). During the Elmendorf stade, valley glaciers advanced from the northern Kenai and Chugach Mountains into the adjacent lowlands to form prominent knob-and-kettle terminal moraines and a recessional sequence of ice-disintegration drift (Reger and Updike, 1983; Reger and others, 1995; Kopczynski and others, 2017). According to Reger and others (2007), the age of the Elmendorf stade is about 15,000 to 11,000 cal. yr B.P. A recent reanalysis of the radiocarbon chronology for the Elmendorf stade indicates that the climax of the stadial advance occurred 16,800 to 16,000 cal. yr B.P. (Richard D. Reger, Reger's Geologic Consulting, written commun., 2020). Ice possibly advanced over the Harriet Point area during the Elmendorf stade (fig. 8D) and may have been responsible for generating the Dmm1 lithofacies. Downwasting of Elmendorf stade ice at Harriet Point likely generated ice stagnation drift (Dmm2 and Gcm lithofacies) and outwash (Gcs lithofacies) as well. The arcuate terminal moraines and ice-stagnation drift in lower Redoubt Creek are indicative of late Elmendorf stade ice retreat in the Redoubt Creek drainage (fig. 9). These deposits encompass several kettle lakes, one of which (Bear Lake, fig. 9) was cored several times and found to contain a long Holocene record of lacustrine sediment and volcanic ash accumulation (Schiff and others, 2010). The oldest deposits in Bear Lake (core BL-7) are about 12,000 cal. yr B.P., indicating that ice retreat from the area occurred prior to that time, which is in general agreement with a late Elmendorf stade age for deglaciation of the Harriet Point area.

Although dating and correlation of moraines and other glacial features in the Harriet Point area (fig. 9) to the established model of Naptowne glaciation elsewhere in the Cook Inlet region awaits further study, the proposed explanation (fig. 8) is a plausible starting point and can be tested with additional fieldwork.

Base from Landsat 8 satellite image; shaded relief base from
National Elevation Dataset (NED), 60 m resolution

EXPLANATION

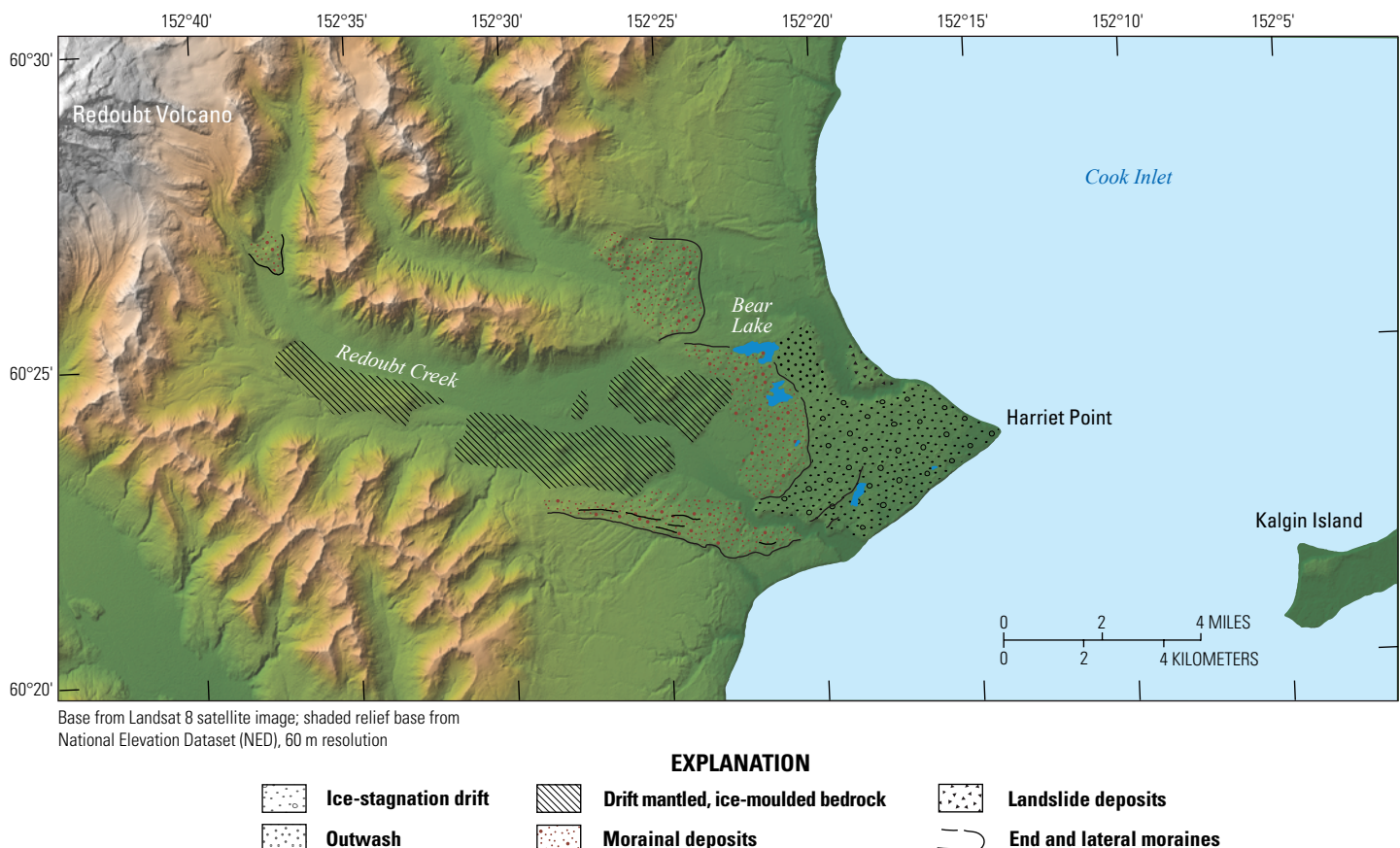|		
Ice-stagnation drift	Drift mantled, ice-moulded bedrock	Landslide deposits
Outwash	Morainal deposits	End and lateral moraines

Figure 9.   Map of glacial deposits and landforms in the Redoubt Creek–Harriet Point area. A lake core from Bear Lake has a basal radiocarbon age of about 12,000 calibrated years before present, indicating that glacier ice had retreated from the area by that time and implying that the glacial deposits in the Harriet Point area are of Elmendorf stade (Naptowne glaciation) age.

Reevaluation of Harriet Point Debris-Avalanche Deposit

As described above, the areal extent and minimum volume (0.04–0.2 km^3) of the Harriet Point debris-avalanche deposit of Begét and Nye (1994) indicates a small but notable flank collapse on the southeast flank of Redoubt Volcano. The resulting debris avalanche would remove as much as 6 percent of the modern edifice, which then regrew to the present-day configuration in about 10,000 years. Removal of 0.2 km^3 of material from the edifice of Redoubt Volcano would require a minimum eruptive rate of 0.02 km^3 per thousand years (km^3/ky) to restore the edifice volume by that amount, assuming that the volcano began rebuilding about 10,000 years ago.

Short-term eruptive rates are not well known for stratovolcanoes in the Aleutian arc. However, Klyuchevskoy Volcano on the Kamchatka Peninsula is similar to many volcanoes in the Aleutian arc, and has an eruptive rate estimated in the range of 22 to 32 km^3/ky (Fedotov and others, 1987). The ice- and snow-clad Klyuchevskoy is one of the most active volcanoes in the world and likely represents an upper bound for the eruptive rates of island-arc stratovolcanoes. In one of the few Alaska studies to address short-term eruptive rates, Jicha and Singer (2006) report that the average eruptive rate across all vents at Seguam volcano[1] over the

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[1] The informal name "Seguam volcano" is used here because the official volcanic name, Pyre Peak, does not coincide with the full geographic or geologic extent of the volcano (Seguam volcano comprises multiple vents—of which Pyre Peak is only one).
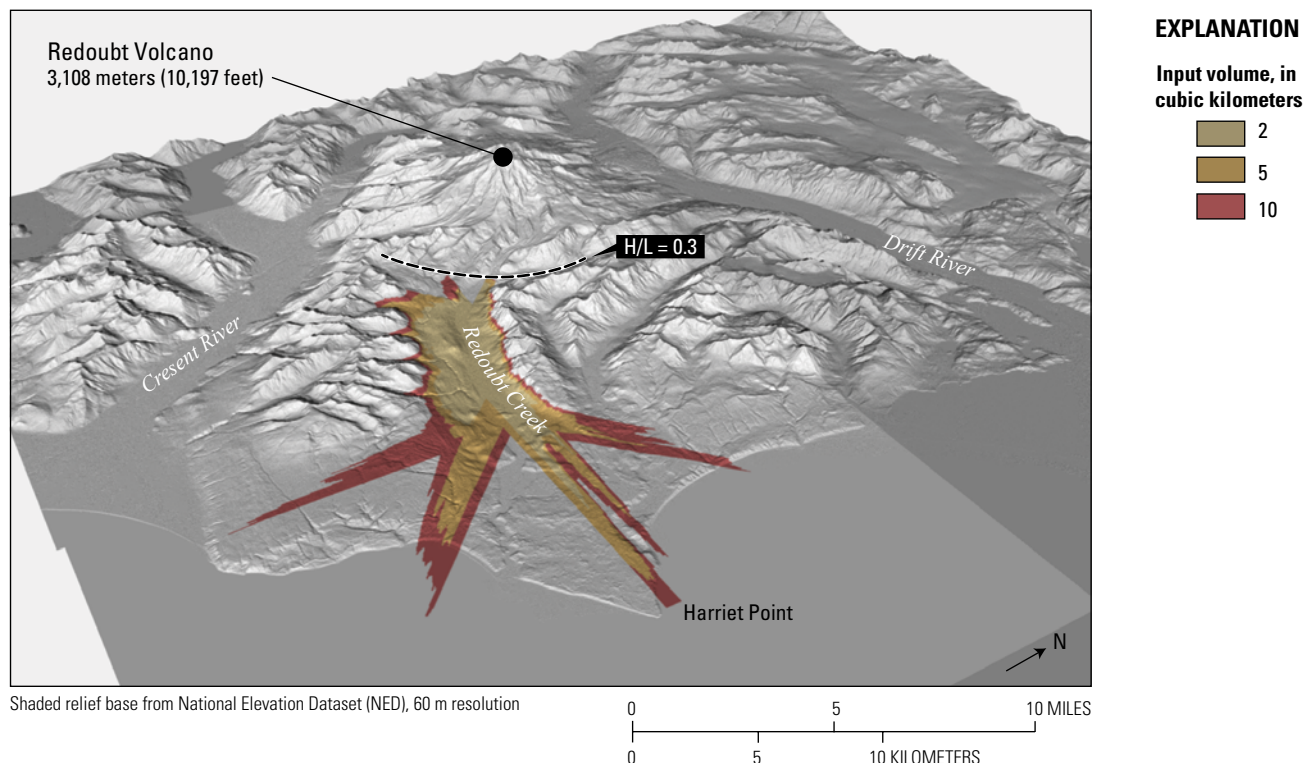
past 9,000 years was 1.2 km^3/ky, but rates as high as 4.7 km^3/ky over a similar period were estimated for one of the main basaltic cones on Seguam Island. At Akutan Island, in the central Aleutian Islands, Holocene eruptive rates are much lower, on the order of 0.3 km^3/ky (Coombs and Jicha, 2021). The average long-term (from 3.5 million years ago [Ma] to the present) eruptive rate for the Aleutian arc has been estimated by Marsh (1982) and Crisp (1984), who gave rates of 1.6 km^3/ky and 2.1 km^3/ky, respectively. In the Cascade Range, Quaternary extrusion rates as high as 2 to 5 km^3/ky were estimated for Mount Adams, and about 2 km^3/ky for Mount St. Helens (Sherrod and Smith, 1990). In the context of these reported values, eruptive rates at Redoubt Volcano on the order of 0.02 km^3/ky are certainly plausible.

The areal extent of the Harriet Point debris-avalanche deposit of Begét and Nye (1994) is reported as covering an area of 40,000,000 square meters (m^2), and if (as described above) the deposit has a thickness of 1 to 5 m, then the corresponding volume would be 0.04 to 0.2 km^3. A functional relation between landslide area of inundation and landslide volume as implemented in the computational model LAHARZ (Schilling, 1998; Griswold and Iverson, 2008) was used to simulate areas on the southeast flank of Redoubt Volcano in the Redoubt Creek drainage that would be inundated by volcanic landslides with volumes in the range of 0.04 to 0.2 km^3. LAHARZ is based on calibrated power-law equations of the form $A = cV^{2/3}$, relating flow volume (V) to planimetric area of inundation (A) for a mass flow as it exits a predefined proximal zone (height/length = 0.3 on fig. 10) and spreads downstream within the drainage of interest

EXPLANATION

Input volume, in cubic kilometers

- 2
- 5
- 10

Shaded relief base from National Elevation Dataset (NED), 60 m resolution

0   5   10 MILES

0   5   10 KILOMETERS

Figure 10.   Image showing inundation of the Redoubt Creek drainage by volcanic landslides estimated with the numerical model LAHARZ (Schilling, 1998; Griswold and Iverson, 2008). The simulation results indicate that a volcanic landslide with a volume greater than 5 cubic kilometers would be required to inundate the Harriet Point area. H/L, height to length.

(Iverson and others, 1998). Best-fit values of the coefficient *c* are determined from logarithmic transformation and linear regression of mass-flow inundation area and volume data. A specific mass-flow volume is used as initial input to the LAHARZ model, and the corresponding area of inundation is portrayed on a digital elevation model of the topography for the region of interest.

LAHARZ simulations of volcanic landslides in the Redoubt Creek drainage (fig. 10) indicate that landslides with volumes in excess of 5 to 10 km^3 would be required to match the extent of the Harriet Point debris-avalanche deposit of Begét and Nye (1994). An avalanche with a volume of 0.04 to 0.2 km^3 would have a very restricted inundation area limited to the upper part of the Redoubt Creek drainage and, at this volume, could not reach Harriet Point.

Summary

Field-based stratigraphic and sedimentologic analysis of deposits exposed at Harriet Point southwest of Redoubt Volcano indicate a sequence of glaciomarine or glacioestuarine deposits overlain by glacial deposits that may be of Elmendorf stade age. The origin of the deposits at Harriet Point have been reinterpreted and there is no compelling evidence that any of the unconsolidated deposits exposed there originated by volcanic mass-flow processes. The "Harriet Point debris-avalanche deposit" of Begét and Nye (1994) is a massive, matrix-supported diamicton that locally has an apparent orange cast. The orange appearance is caused by a thin surface cover of slightly oxidized reworked loess that extends over the bluff face from its bluff top location. Thus, the apparent orange color of the deposit in some locations is unrelated to the presence of altered volcanic material, which was not observed at the Harriet Point outcrop. Simulations of volcanic landslide inundation of the Redoubt Creek drainage using initial landslide volumes of 2, 5, and 10 km^3 do not produce an area of inundation that matched the previously asserted extent of the Harriet Point debris-avalanche deposit, and no physical basis exists for extensive runout of the Harriet Point debris avalanche. Volcanic debris-avalanche deposits greater than 1 km^3 are typically associated with major sector collapse events that characteristically produce prominent and long-lasting horseshoe-shaped scars on the truncated edifice (Voight and others, 1983; Siebert, 1984; Capra and others, 2002; Ponomareva and others, 2006). Thus, a debris avalanche originating on the southeast flank of Redoubt Volcano and capable of reaching Harriet Point would be expected to have left a failure scar, but no such feature has been observed or documented. The sedimentologic character and sequence of deposits exposed at Harriet Point are consistent with the interpretation that these deposits are primarily glacial in origin and can be explained in the context of late Quaternary deglaciation of the Cook Inlet area.

Acknowledgments

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