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Mid-Holocene Sector Collapse at Mount Spurr Volcano, South-Central Alaska

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Abstract

Radiocarbon-dated volcanic mass-flow deposits on the southeast flank of Mount Spurr in south-central Alaska provide strong evidence for the timing of large-scale destruction of the south flank of the volcano by sector collapse at 4,769–4,610 yr B.P. The sector collapse created an avalanche caldera and produced an ~1-km^3-volume clay-rich debris avalanche that flowed into the glacially scoured Chakachatna River valley, where it transformed into a lahar that extended an unknown distance beyond the debris avalanche. Hydrothermal alteration, an unbuttressed south flank of the volcano, and local structure have been identified as plausible factors contributing to the instability of the edifice. The sector collapse at Mount Spurr is one of the later known large-volume (>1 km^3) flank failures recognized in the Aleutian Arc and one of the few known Alaskan examples of transformation of a debris avalanche into a lahar.

Introduction

The catastrophic eruption of Mount St. Helens in 1980 served to catalyze volcanologists to study and understand the various mechanisms by which volcanoes collapse, and the hazards posed by this process. Large-scale volcanic flank collapse now is widely recognized as a significant process at many volcanic centers (Siebert, 1984; McGuire, 1996; Voight and Elsworth, 1997) and is regarded as one of the more catastrophic processes in the evolution of an individual volcano. In the Aleutian Arc of Alaska, sector collapse has been recognized at several volcanoes (Siebert and others, 1995; Waythomas and Wallace, 2002; Waythomas and others, 2002, 2003a), but few studies have focused exclusively on this phenomenon, and so the mechanisms of collapse and the types of ensuing deposits are poorly known.

Recent thermal and seismic unrest at Mount Spurr in the eastern Aleutian Arc (fig. 1; Power, 2004; De Angelis and McNutt, 2005) has prompted additional study of the volcano by the Alaska Volcano Observatory and a reevaluation of its Holocene geologic history in an attempt to better understand potential hazards, especially those associated with a summit eruption. One aspect of this work has been field-based study of an ~1-km^3-volume debris-avalanche deposit that spilled from an avalanche caldera in the ancestral edifice of Mount Spurr (fig. 2). Previously, little was known about the sector collapse and its associated debris-avalanche deposit. Although studies are still in progress, the purpose of this chapter is to report new information about the age and origin of the Mount Spurr sector collapse and debris avalanche and to comment on the implications of this information as it pertains to the geologic history of the Mount Spurr volcanic center.

Geologic Setting

Mount Spurr (fig. 2) is an ice- and snow-covered, multiple-vent volcanic center in the Cook Inlet region of south-central Alaska (fig. 1). The volume of the edifice is ~20 to 40 km^3, and the base of the volcanic pile is ~700 m above sea level along the south flank of the volcano in the Chakachatna River valley and ~3,000 m above sea level to the north, where Mount Spurr lavas overlie granodiorite basement rocks of Tertiary age (Nye and Turner, 1990). The volcano consists of an ancestral edifice composed of andesite lava flows and pyroclastic rocks that is breached by an avalanche caldera. A small stratocone at the summit includes an open, east-facing snow-filled somma that contains a small snow-filled crater. Historically, periods of elevated heat flux to the summit area have resulted in the formation of a conspicuous melt pit within the snow-filled crater (Coombs and others, 2006). Mount Spurr also includes Crater Peak, an andesitic, historically active satellite cone on the south flank of the volcano that last erupted in 1992 (Keith, 1995). According to regional tephrostratigraphic studies, the latest eruption of the summit vent may have been at 6–5 ka (Riehle, 1985). The summit cone and Crater Peak both formed sometime after ancestral Mount Spurr underwent a major sector collapse that created an avalanche caldera and produced an ~1-km^3-volume debris-avalanche deposit. Previous workers inferred that the sector collapse and debris avalanche occurred during an eruption in late Quaternary to early Holocene time (Nye and Turner, 1990).

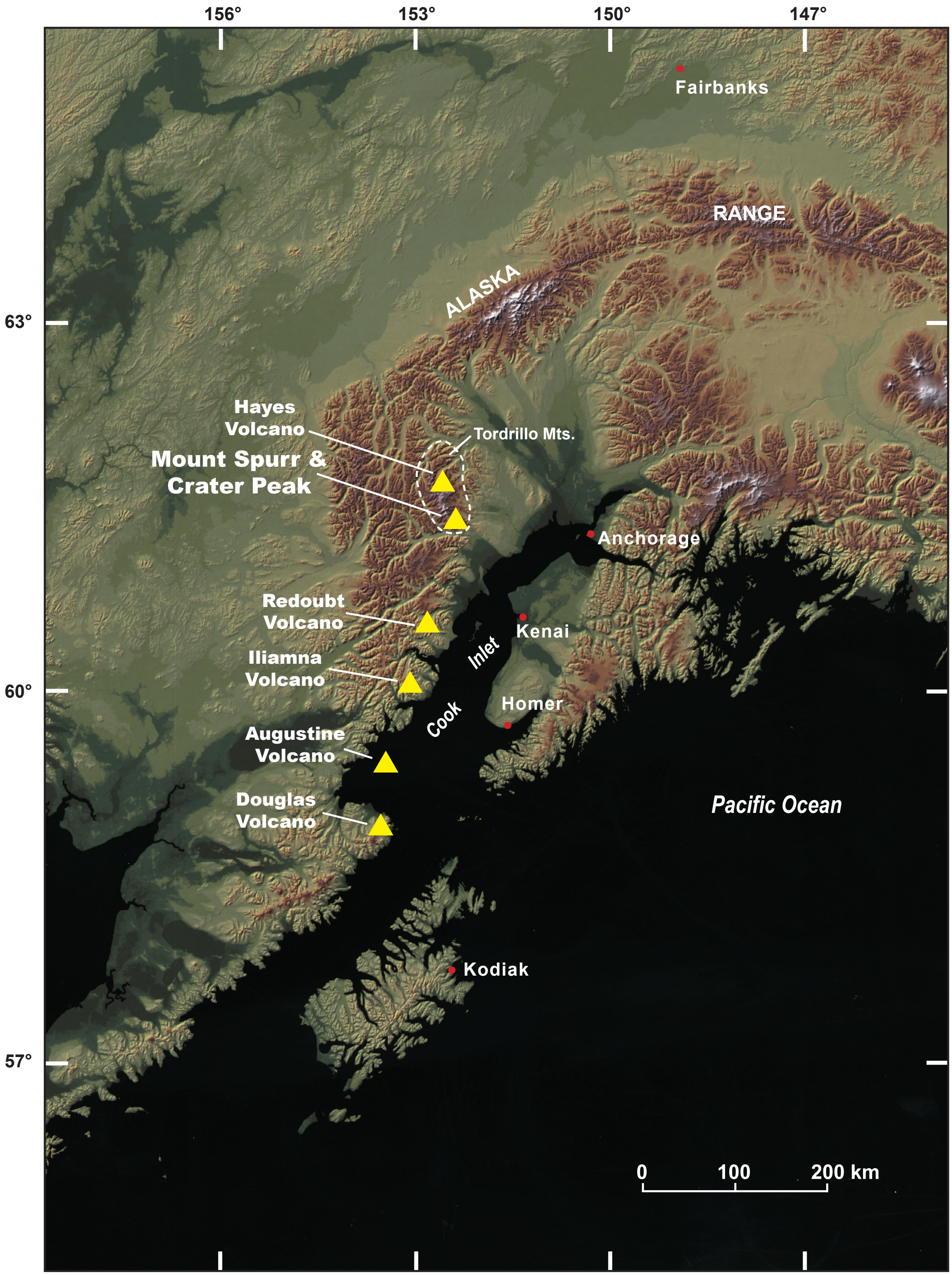

Figure 1. Cook Inlet region, south-central Alaska, showing locations of Mount Spurr and other volcanoes mentioned in text.

The two historical eruptions of the Mount Spurr volcanic center have been from the Crater Peak vent in 1953 and 1992. These eruptions were brief but explosive events that produced subplinian and vulcanian ash columns that rose ~20 km above sea level and deposited several millimeters of ash on populated areas of south-central Alaska (Wilcox, 1959; Neal and others, 1995). Although the summit vent has not erupted historically, it is geothermally active; and fumaroles, areas of warm rock, and an occasional melt pit have been observed since at least the 1950s (Turner and Wescott, 1986; Coombs and others, 2006).

Mount Spurr is situated in the Tordrillo Mountains (fig. 1), a rugged, glaciated massif composed primarily of Tertiary and older granitic, sedimentary, and minor volcanic rocks (Barnes, 1966; Reed and Lanphere, 1973; Magoon and others, 1976). Lavas and pyroclastic deposits from ancestral Mount Spurr were erupted onto basement rocks of the Tordrillo Mountains during the middle to late Pleistocene (Nye and Turner, 1990; Nye and others, in press). A steeply dipping, east-northeast-trending reverse fault brings granitic rocks of Tertiary and Cretaceous age into contact with nonmarine clastic rocks southeast of Mount Spurr (fig. 3). This fault, which projects westward beneath the volcano a few kilometers south of Crater Peak (Nye and others, in press), may have influenced edifice stability and sector collapse.

Avalanche Caldera

One of the most striking features of the Mount Spurr volcanic center is the horseshoe-shaped caldera scarp within the ancestral edifice (fig. 2). The rim of the caldera truncates andesitic lava flows of ancestral Mount Spurr and forms a prominent ridgeline above a 30-km^2-area ice and snow field

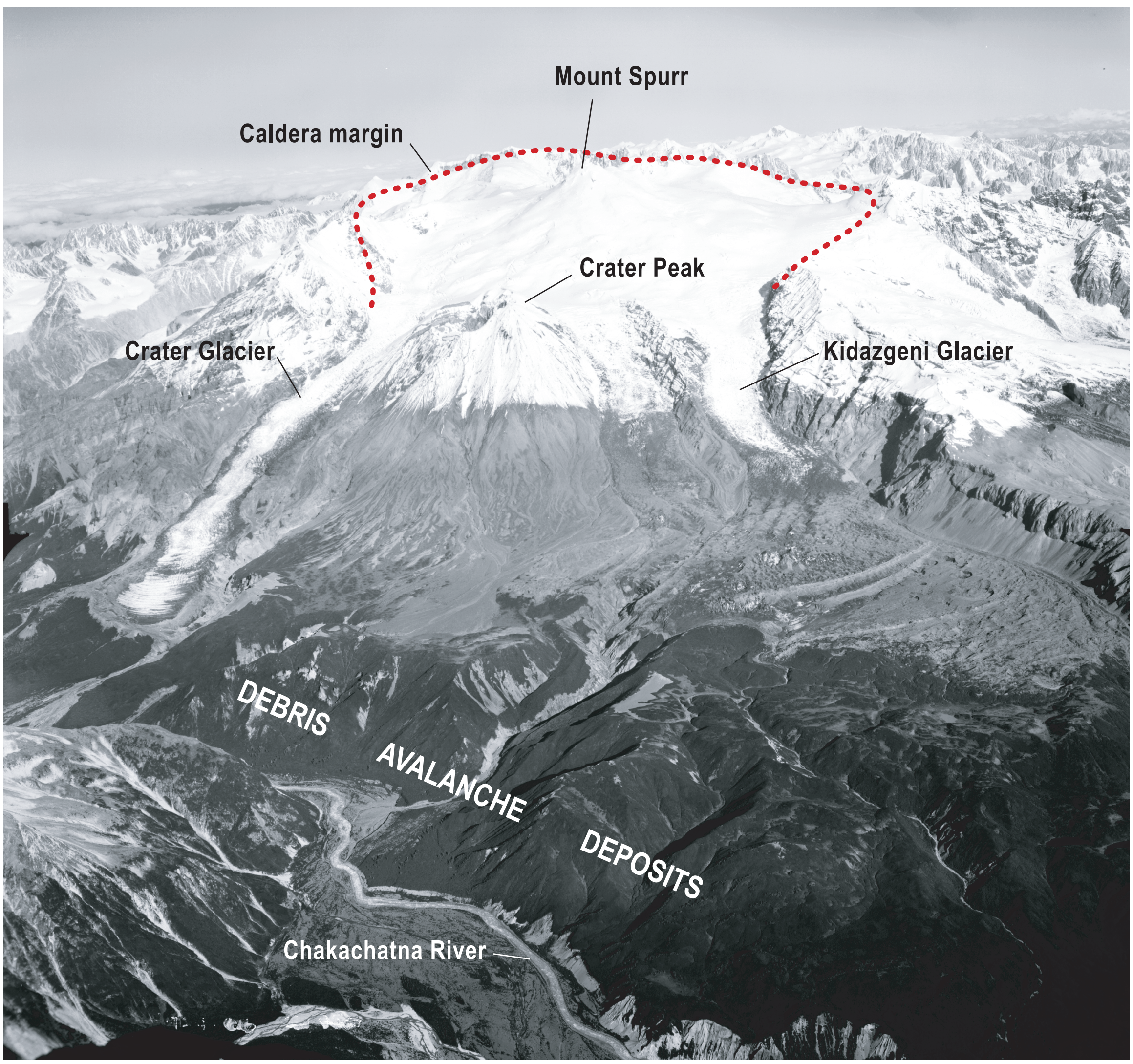

Figure 2. Mount Spurr, showing locations of Crater Peak, avalanche caldera, and debris-avalanche deposit in the Chakachatna River valley (fig. 1). View northward.

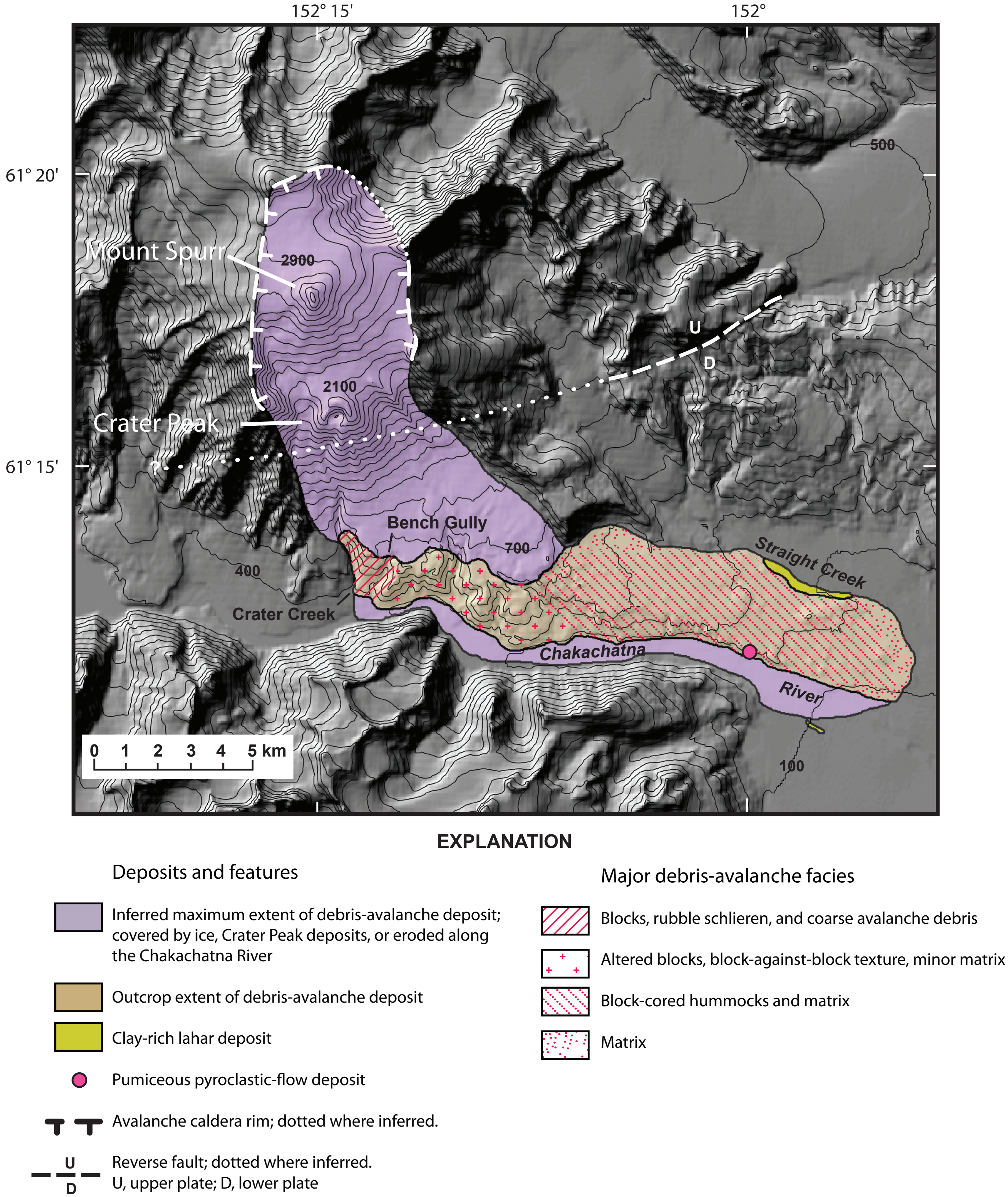

Figure 3. Shaded-relief contour map of Mount Spurr area (fig. 1), showing locations of debris-avalanche deposit and clay-rich lahar deposits along Straight Creek and the Chakachatna River. Contour interval, 100 m.

that fills the caldera. The northeastern part of the scarp has been eroded by glacial ice, and the southern part of the caldera is covered by lava flows and pyroclastic deposits that make up the Crater Peak cone (fig. 2). The caldera, which opens to the southeast, is ~5 km wide by 8 km long; its depth is unknown because of extensive ice and snow cover, although radar measurements in the eastern part of the caldera ice field indicated an ice thickness of ~450 m (March and others, 1997).

Debris-Avalanche and Lahar Deposits

Sector collapse of the Mount Spurr edifice produced a debris avalanche that filled the Chakachatna River valley south of Crater Peak (fig. 3). The debris-avalanche deposit extends from the distal south flank of Crater Peak ~20 km downvalley to the mountain front at the entrance to the Chakachatna-McArthur River lowland (fig. 3). Emplacement of the debris avalanche temporarily dammed the Chakachatna River and forced the river to reestablish its course along the steep south wall of the Chakachatna River valley (Waythomas, 2001). Incision and erosion of the debris-avalanche deposit by the Chakachatna River has formed some spectacular exposures of the deposit along the north side of the river, examples of which are shown in figure 4.

At least four main facies types are identified within the debris-avalanche deposit (fig. 3): (1) blocks, rubble schlieren, and coarse, angular avalanche debris (figs. 5, 6); (2) altered blocks with little intervening matrix and outcrop-scale block-against-block texture (fig. 4*A*); (3) block-cored hummocks surrounded by granular matrix sediment (figs. 4*B*–4*D*); and (4) a matrix facies consisting of poorly sorted, granular, matrix-supported volcanic debris, sand, silt, and clay. The matrix facies grades into a clay-rich lahar facies that is exposed in several outcrops along Straight Creek and in at least one outcrop on the south bank of the Chakachatna River (fig. 3).

The debris-avalanche deposit contains numerous block-size clasts of altered andesitic lava from ancestral Mount Spurr (fig. 4*C*), some of which are tens to several hundreds of meters in diameter (fig. 4). Hydrothermally altered rock and rock debris makes up 60 to 80 volume percent of the deposit and includes various materials, from slightly altered and oxidized andesitic lava to clay. Although geochemical characterization of the debris-avalanche deposit was not an aspect of this study, Nye and Turner (1990) indicated that the blocks and boulders within the deposit are geochemically similar to the lavas of ancestral Mount Spurr (fig. 7). The debris-avalanche deposit also contains clasts of andesitic lava similar to the lavas on Crater Peak (fig. 7).

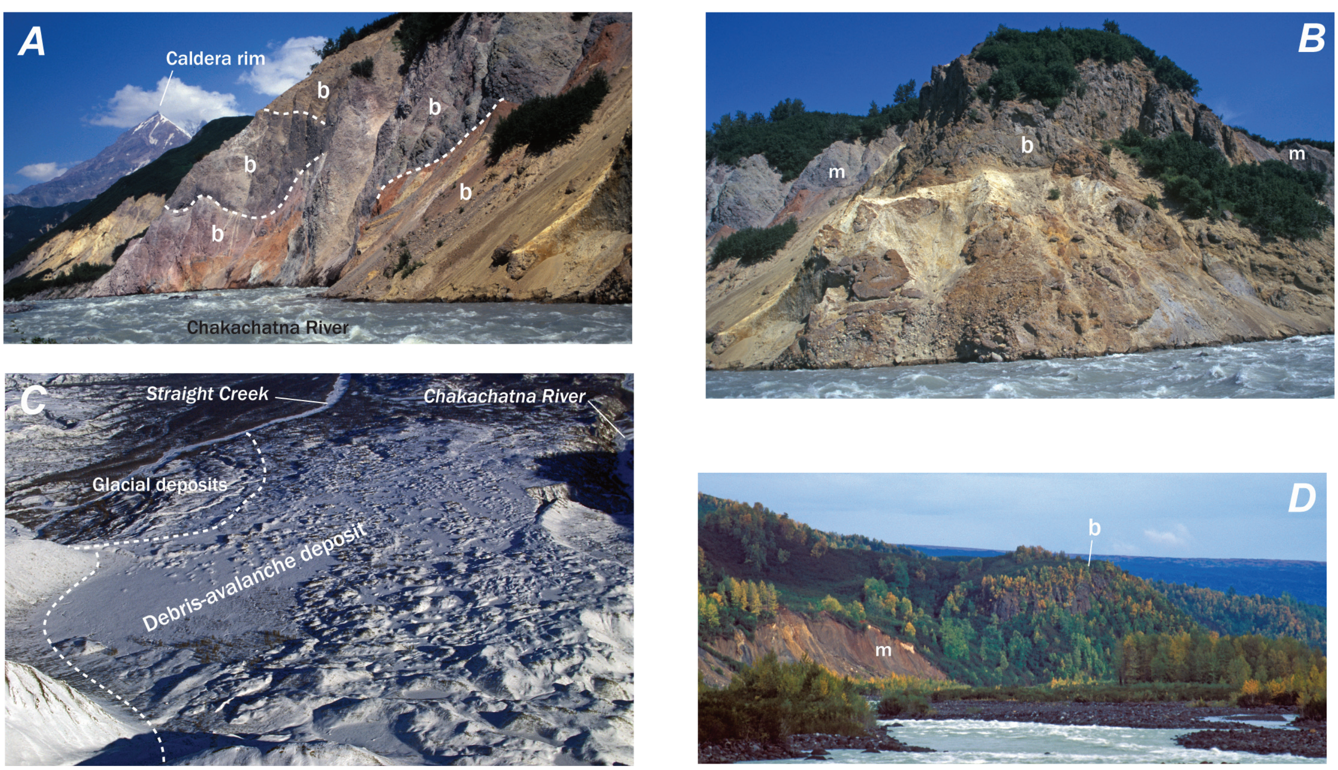

Figure 4. Examples of debris-avalanche deposit in the Chakachatna River valley (figs. 2, 3). *A,* Block-against-block texture. Individual blocks are tens of meters in diameter and have little to no intervening matrix. *B,* Block-cored hummock. Approximate relief above Chakachatna River is 50 m. *C,* Surface of debris-avalanche deposit between Straight Creek and the Chakachatna River, showing hummocky morphology. *D,* Large block exposed along north bank of river. Approximate relief is 80 m.

Previous work at the Mount Spurr volcanic center by Nye and Turner (1990) identified an area of clast-supported block-and-ash-flow deposits exposed in the lower part of Bench Gully and along Crater Creek (fig. 3). Field study of these deposits in 2005 indicated that they contain mostly andesitic rubble and jigsaw-fractured clasts with no matrix ash (figs. 5, 6). Distinctive lensoid apophyses of rock rubble called rubble schlieren (Glicken, 1991), which are common in the more proximal part of the debris-avalanche deposit (figs. 5, 6), are a component of one of the main facies types (fig. 3). A 1.4-km-long outcrop along Crater Creek (fig. 5) contains an ~300-m-thick assemblage of andesitic rubble that is overlain by a block of ancestral Mount Spurr lava and shows deposit bedding that dips north, toward the volcano. The andesitic rubble in this outcrop is geochemically and petrographically similar to the lavas of Crater Peak (fig. 7; Nye and Turner, 1990). Bedding, thickness, and stratigraphy are all consistent with a debris-avalanche origin for these deposits.

Debris-avalanche deposits that contain appreciable amounts of clay produced by hydrothermal alteration of volcanic rocks are known as cohesive or clay-rich debris-avalanche deposits (Scott and others, 1995). The Osceola mudflow at Mount Rainier in Washington is a well-known example of such a deposit (Vallance and Scott, 1997). Because hydrothermal clays contain water and typically have high pore-fluid pressure and low shear strength, they contribute to the instability of volcanoes that have undergone significant hydrothermal alteration (López and Williams, 1993; Day, 1996; Reid, 2004). Once collapse occurs, the clays contribute water and reduce the cohesive forces within the failed mass, allowing the clay-rich debris to evolve spatially from an avalanche to a lahar (Carrasco-Nuñez and others, 1993; Vallance and Scott, 1997; Capra and others, 2002).

During fieldwork in 2005, clay-rich lahar deposits were discovered along Straight Creek and the Chakachatna River just beyond the terminus of the debris-avalanche deposit

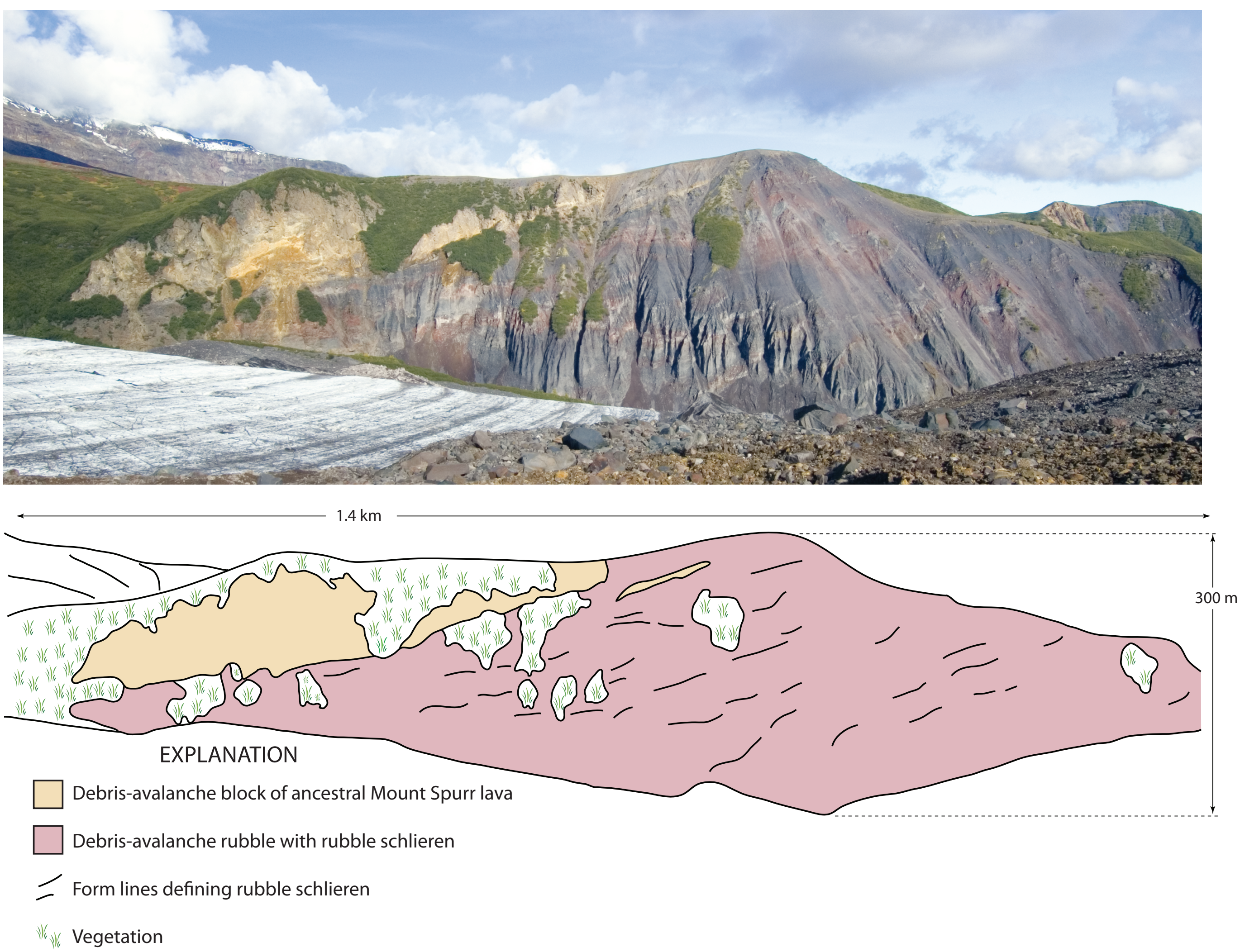

Figure 5. Large outcrop of debris-avalanche deposits along east side of Crater Creek (fig. 3). Thickness, bedding, features, and distribution of rock types in outcrop indicate origin by debris avalanche. Photograph taken September 2005.

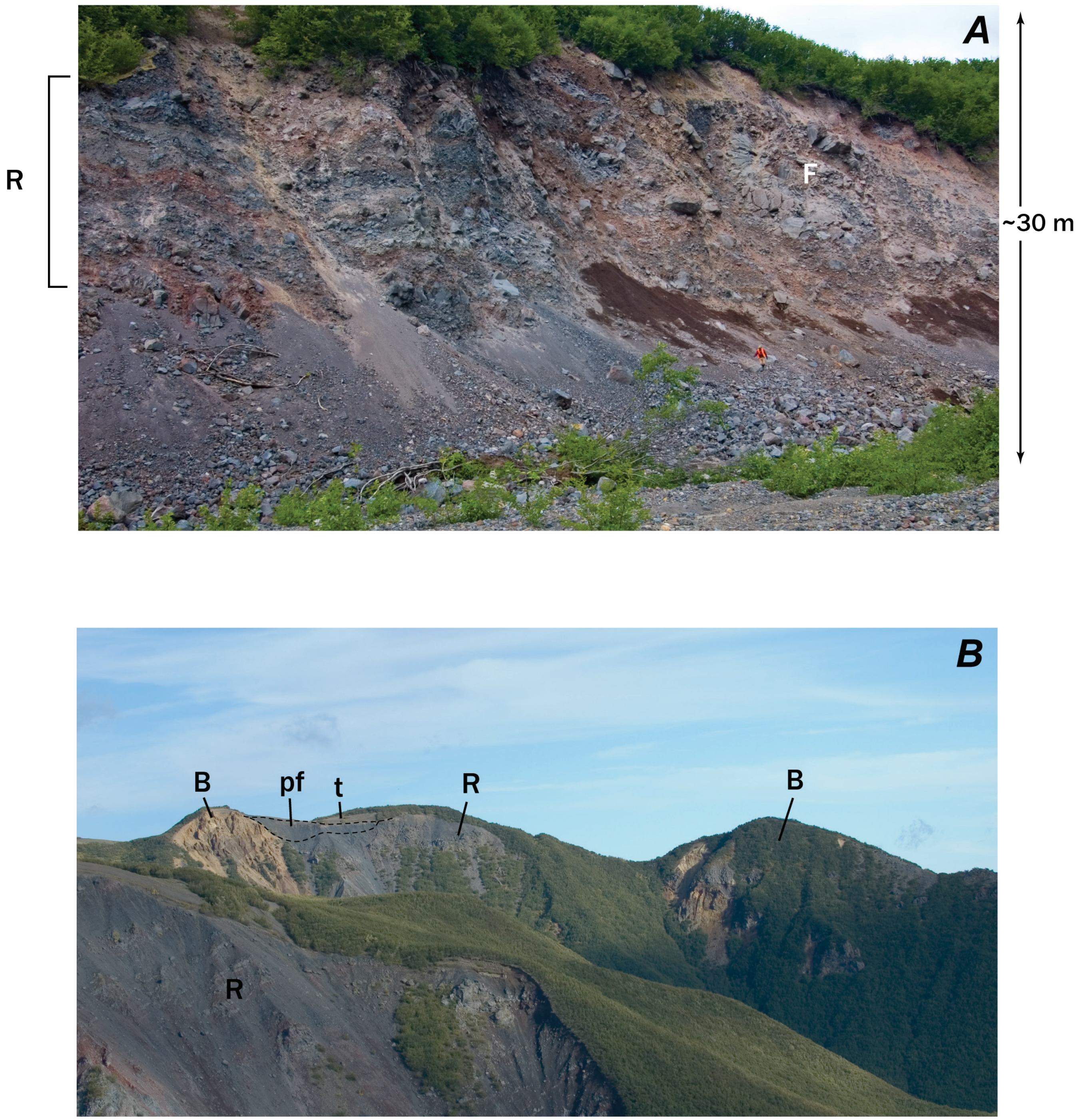

Figure 6. Debris-avalanche deposits along Bench Gully (fig. 3). *A,* Exposure of andesitic rubble, rubble schlieren, and internally fractured boulders (F). Matrix consists of angular cobbles and finer sediment produced by comminution of larger particles. *B,* East bank of gully, showing debris-avalanche deposits consisting of angular rock debris in rubble schlieren (R), blocks of altered ancestral Mount Spurr lavas (B), and young drape of pyroclastic fall (t) and flow (pf) deposits erupted from Crater Peak.

(fig. 3). The lahar deposits contain pods and lenses of hydrothermal clay and altered rock debris, clasts of andesite from Mount Spurr, and a few subrounded, cobble- to pebble-size clasts of light-gray, slightly vesicular pumiceous material with an overall massive, matrix-supported texture (fig. 8). It is unknown whether the pumiceous material is juvenile and may be a syncollapse product, or older material eroded by the debris avalanche and lahar. Decollemont structures and the podlike lenses of hydrothermally altered material indicate that the lahar deposit originated by flowage as it evolved contemporaneously from the debris-avalanche deposit. As the lahar evolved from the debris avalanche, it flowed into the Chakachatna River valley, where it overran a vegetated lowland and incorporated logs, twigs, and branches of alder, willow, and spruce (fig. 9).

Age of the Debris-Avalanche Deposit

The timing of the Mount Spurr flank collapse and debris-avalanche deposit previously was generally known only from stratigraphic relations with other unconsolidated deposits in the study area (fig. 1; Nye and Turner, 1990). The fresh-appearing, hummocky morphology of the debris-avalanche deposit (fig. 4*C*) and the absence of overlying glacial deposits indicate that the deposit was emplaced after late Pleistocene glaciation of the Chakachatna River valley. Although the absolute timing of ice retreat in this area has not yet been determined, it is reasonable to assume that it was broadly synchronous with late Pleistocene ice retreat elsewhere in southern Alaska (Hamilton, 1994), and so, by about the beginning of the Holocene (~10 ka), the upper Chakachatna River valley should have been largely ice free. Thus, the absence of clear evidence for glaciation of the debris-avalanche deposit indicates that the deposit formed after late Pleistocene glaciers had retreated completely or at least partly from the area, most likely sometime between 14 and 9 ka (Hamilton, 1994).

The debris-avalanche deposit in the Chakachatna River valley is mantled by several Holocene tephra deposits, including a regionally extensive felsic tephra erupted from nearby Hayes Volcano ~3.7 ka (Riehle, 1985, 1994; Riehle and others, 1990; Wallace, 2003). Although the Hayes tephra is some 50 to 100 cm above the top of the debris-avalanche deposit, this tephra provides a minimum limiting age for the debris avalanche and associated sector collapse.

The absence of evidence for glaciation of the debris-avalanche deposit, and its stratigraphic position below the ~3.7 ka Hayes tephra, indicate that the sector collapse and debris avalanche at Mount Spurr occurred sometime in the latest Pleistocene or early to middle Holocene (Nye and Turner, 1990; Waythomas, 2001).

Radiocarbon-dated wood from the clay-rich lahar deposit that evolved from the debris-avalanche deposit now provides direct evidence for the timing of flank collapse at Mount Spurr. Six samples of wood from the lahar deposit that were dated by conventional radiocarbon scintillation-counting tech-

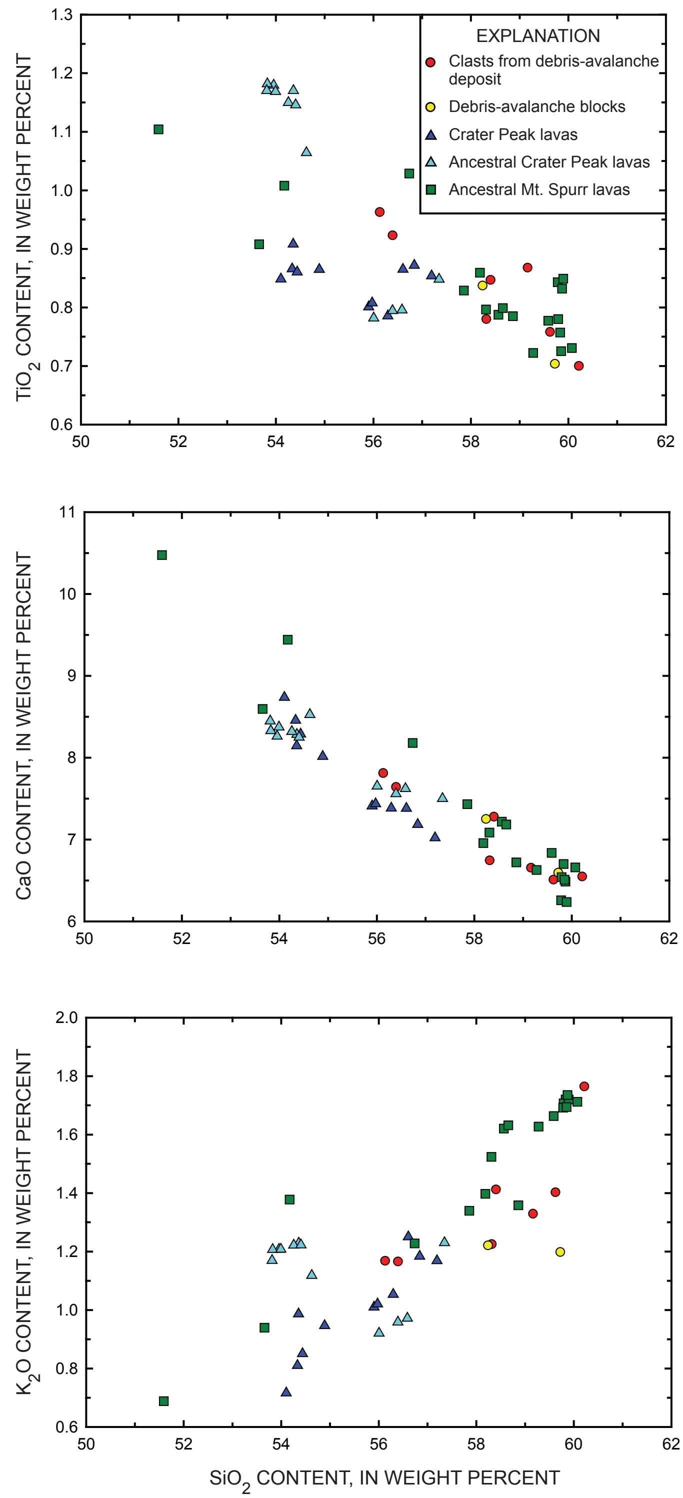

Figure 7. Major-oxide versus SiO_2 contents in various deposits and lithologic units within the Mount Spurr volcanic center (fig. 1; data from Nye and Turner, 1990, and Nye and others, in press). Deposits previously interpreted as block-and-ash-flow deposits by Nye and Turner (1990) are here reinterpreted as part of debris-avalanche sequence. Note geochemical similarity among block-and-ash-flow deposits of Nye and Turner and ancestral Mount Spurr lavas.

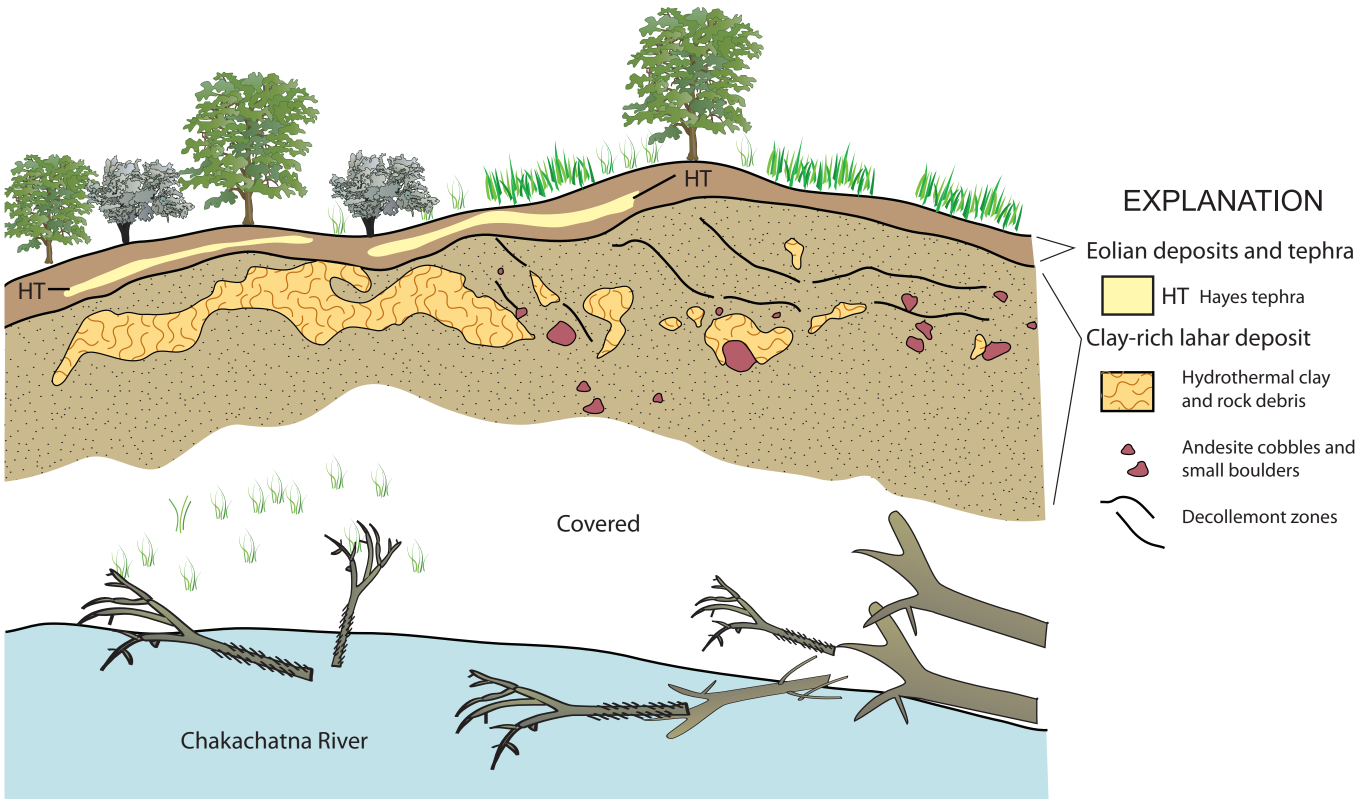

Figure 8. Clay-rich lahar deposit along south bank of the Chakachatna River (fig. 2).

Figure 9. Lahar and tephra deposits exposed along south bank of Straight Creek (fig. 2). *A*, Stratigraphic setting of lahar and younger tephra deposits. *B,* Clay-rich lahar deposit, showing log (w) protruding from outcrop. Samples of alder, spruce, and willow from this outcrop yielded ^{14}C ages listed in table 1.

niques yielded raw ^{14}C ages of 4,040±70, 4,060±60, 4,180±70, 4,210±50, and 4,230±50 yr B.P. (table 1). One sample (05CW311–1b) yielded an anomalous age of 8,390±80 yr B.P., clearly an outlier that indicates possible sample contamination by older organic material. Coal deposits of Tertiary age, present in the vicinity of Straight Creek (Barnes, 1966), could provide local contamination of the sample. Using the radiocarbon calibration program of Stuiver and others (1998), calibrated 2σ age ranges for the wood samples were determined (table 1). If the anomalous age is excluded, the average age of the wood samples is 4,159±26 yr B.P., and the calibrated 2σ age range is 4,610–4,769 yr B.P., which constrains the timing of emplacement of the lahar, the associated debris avalanche, and sector collapse to this interval.

Additional evidence supporting a mid-Holocene age for the lahar deposit comes from an analysis of stratigraphic relations of the lahar deposit and overlying tephra deposits (figs. 8, 9). In all known outcrops of the clay-rich lahar deposit, it is conformably overlain by an ~50-cm-thick assemblage of eolian deposits containing dark scoriaceous granular tephra erupted from Crater Peak (fig. 9; Wallace, 2003). As many as five to seven Crater Peak tephras, several millimeters thick, are present in the unit immediately above the lahar deposit. This unit is, in turn, overlain by a 20- to 30-cm-thick bed of ~3.7-ka

Table 1. Radiocarbon data for wood samples from clay-rich lahar deposits in Straight Creek.

[See figure 2 for location. All ages in 14C years before present (A.D. 1950). GX, Geochron Laboratories, Cambridge, Mass.]

Sample	Laboratory No.	Location (lat N., long W.)	Reported age	$\delta^{13}C$ (permil)	Calibrated 2σ age range
05CW311–2b	GX–32051	Straight Creek 61.21654°, 151.97046°	4,040±70	–25.2	4,377–4,661
04CW105–1	GX–31985	Straight Creek 61.21647°, 151.97061°	4,210±50	–25.9	4,609–4,771
05CW311–1b	GX–31986	Straight Creek 61.21654°, 151.97046°	8,390±80	–26.0	9,246–9,533
06SPCFW001–A	GX–32676	Straight Creek 61.21654°, 151.97046°	4,060±60	–25.5	4,413–4,659
06SPCFW001–B	GX–32675	Straight Creek 61.21654°, 151.97046°	4,180±70	–25.6	4,525–4,854
06SPCFW001–C	GX–32674	Straight Creek 61.21654°, 151.97046°	4,230±50	–26.0	4,612–4,768
Average--			4,159±26	– – –	4,610–4,769

Hayes tephra (Reihle and others, 1990; Wallace, 2003) which is easily recognizable in the field because it contains biotite crystals and is one of the few thick felsic tephras in the Cook Inlet region (fig. 1). Thus, the position of the Hayes tephra, <1 m stratigraphically above the clay-rich lahar deposit, is also consistent with a mid-Holocene age for the lahar deposit.

Origin of the Sector Collapse and Debris Avalanche

Sector collapse is a significant event in the evolution of a volcano that commonly changes the physical characteristics of the edifice for many thousands, if not hundreds of thousands, of years. The main factors promoting edifice instability and sector collapse at Mount Spurr are summarized in table 2. Study of the debris-avalanche deposit indicates that most of it contains hydrothermally altered rock and debris some of which consists of clay (fig. 4). The presence of hydrothermal clay will reduce the effective pore pressure within the edifice (Day, 1996) and contribute water to an evolving mass flow, thus promoting the transformation from a debris avalanche into a lahar (Vallance and Scott, 1997). The fact that ~60–80 percent of the debris-avalanche deposit exposed along the Chakachatna River and its tributaries on Mount Spurr is composed of hydrothermally altered material indicates relatively pervasive alteration of the edifice before sector collapse. No other similar-appearing debris-avalanche deposits are known at Mount Spurr, and so the Chakachatna River debris-avalanche deposit probably resulted from a singular event in the life history of the volcano. Dated lava flows from ancestral Mount Spurr indicate that lava-producing eruptions occurred from ~255±42 to ~59±14 ka (Nye and Turner, 1990; Nye and others, in press), suggesting that hydrothermal alteration has been occurring on time scales of tens of thousands to hundreds of thousands of years.

The south flank of Mount Spurr extends from the Chakachatna River valley to the summit of the volcano without any intervening topography (fig. 2), and the relief between the valley floor and the caldera rim is ~3,100 m. The south flank of the volcano was buttressed by late Pleistocene glacial ice in the Chakachatna River valley that could have been at least several thousand meters thick during the latest glacial maximum (Hamilton and Thorson, 1983; Kaufman and Manley, 2004). Ice levels in the region declined markedly after ~11 ka during the Holocene thermal maximum (Kaufman and others, 2004). Although the extent to which removal of an ice load would have affected the stability of the south flank of the Mount Spurr edifice is uncertain, it is a plausible mechanism to increase the likelihood of sector collapse (Acocella, 2005; Capra, 2006).

Table 2. Factors promoting edifice instability and sector collapse at Mount Spurr.

Factor	Evidence	Comments
Hydrothermal alteration.	Pervasive alteration of rock to clay within debris-avalanche deposit.	~60–80 percent of the debris-avalanche deposit consists of hydrothermally altered material.
Unsupported south-east flank.	Southeast flank of volcano falls away to the Chaka-chatna River valley.	Southeast flank of Mount Spurr is unbuttressed by topography and is the area of greatest relief.
Reverse fault beneath volcanic pile.	Southwestward extension of surface fault beneath south flank of Mount Spurr.	Fault is not well documented but may extend beneath the south flank of Mount Spurr.
Shallow magmatic intrusion.	Formation of Crater Peak and Mount Spurr summit cone.	Formation of these two cones required magmatic input. A shallow magma body may have destabilized Mount Spurr and subsequently fed the two modern cones.

Geologic mapping in the study area (fig. 1) indicated the presence of a northeast-trending reverse fault a few kilometers east of Mount Spurr (fig. 3; Magoon and others, 1976; Nye and Turner, 1990; Nye and others, in press). If the fault trace is extended westward, it projects beneath the edifice, where it is covered by volcanic rocks of ancestral Mount Spurr and lavas erupted from Crater Peak. Although the Mount Spurr and Crater Peak lavas show no obvious offset along the fault, the fault may be associated with a zone of weaker rock at depth that could have been a pathway for hydrothermal fluids originating deep in the subsurface. The presence of a fault beneath Mount Spurr on the same side of the volcano that underwent flank collapse may be coincidental, but it could also have contributed to the likelihood of sector collapse, as described at other volcanoes (van Wyk de Vries and Borgia, 1996; Vidal and Merle, 2000; Lagmay and others, 2000).

Most large sector collapses involving >1 km^3 of material are associated with magmatic activity, and an ensuing explosive eruption would typically produce extensive pyroclastic flow and fall deposits and, possibly, a lateral blast (Belousov and Belousova, 1998; Alvarado and others, 2006). Despite several attempts by various workers to locate pyroclastic deposits that might have been generated during the sector collapse, no such deposits have been observed in the vicinity of Mount Spurr (Riehle, 1985; Nye and Turner, 1990; Wallace, 2003; Nye and others, in press). Pumiceous pyroclastic-flow deposits of dacitic composition (61.7–62.9 weight percent SiO_2) overlie the debris-avalanche deposit along the Chakachatna River (Nye and Turner, 1990) but are not extensive and are known only at this one isolated locality. Removal of a more extensive deposit by erosion is unlikely, and so a temporal relation of the Chakachatna River pyroclastic-flow deposit to the sector collapse, debris avalanche, and lahar is unclear.

Deep-seated failures of mature stratovolcanoes commonly result from extensive hydrothermal alteration (López and Williams, 1993; Day, 1996; van Wyk de Vries and others, 2000), and the altered material in the debris-avalanche and lahar deposits at Mount Spurr clearly indicates extensive alteration of the edifice. The unbuttressed south flank of the volcano and the possible presence of a reverse fault at depth are plausible additional factors increasing the likelihood of sector collapse. Although the mechanism or event that ultimately caused failure of the edifice is unknown, it is reasonable to assume that the sector collapse probably involved magmatic intrusion and associated hydrothermal activity leading to elevated pore-fluid pressures in the edifice (Reid, 2004). An increase in pore-fluid pressure within the edifice would have been likely, given the apparent extent of hydrothermal alteration and related reduction in rock permeability.

Cryptodome intrusion, which is also a plausible mechanism for the sector collapse at Mount Spurr, could have initiated a deep-seated failure of the volcano (Siebert, 1984; Siebert and others, 1987; Donnadieu and others, 2001). At other volcanoes, deep-seated failures associated with cryptodome intrusion commonly have a substantial magmatic component, though apparently not at Mount Spurr because extensive pyroclastic flow and fall deposits associated with this event have not been recognized.

Discussion

Radiocarbon-dated volcanic mass-flow deposits on the southeast flank of Mount Spurr provide strong evidence for the timing of large-scale destruction of the south flank of the volcano by sector collapse 4,769–4,610 yr B.P. The sector collapse created an avalanche caldera and produced an ~1 km^3-volume clay-rich debris avalanche that flowed into the glacially scoured Chakachatna River valley, where it transformed into a lahar that extended an unknown distance beyond the debris avalanche. Although observation of the transformation from a debris avalanche into a lahar is impossible in known outcrops, many similar deposits show this relation (Carrasco-Nuñez and others, 1993; Vallance and Scott, 1997; Capra and others, 2002), and an explanation of the origin of the clay-rich lahar deposit by other mechanisms is difficult. Hydrothermal alteration, an unbuttressed south flank, and local structure have been identified as plausible factors contributing to the instability of the edifice.

The two stratocones that formed within the avalanche caldera, Mount Spurr and Crater Peak, grew to their present configurations during middle to late Holocene time. The estimated volumes of these two cones, 2 km^3 for Crater Peak and 0.48 km^3 for Mount Spurr, were obtained by using the standard formula for the volume of a cone and are probably accurate to ±20 percent. Using the age of sector collapse as the earliest time for the onset of eruptive activity at Mount Spurr and Crater Peak along with these estimated volumes, average eruptive rates for these two cones are 0.42 km^3/ka for Crater Peak and 0.10 km^3/ka for Mount Spurr, comparable to the time-averaged eruptive rates at other volcanoes in the Aleutian Arc (Hildreth and others, 2003b; Jicha and Singer, 2006) and at arc volcanoes worldwide (Jicha and Singer, 2006).

A suitable explanation for the mechanism of sector collapse awaits the completion of additional fieldwork at Mount Spurr. Blast or tephra deposits associated with the event may be located and dated in cores from lakes in the lowlands southeast of Mount Spurr, because these settings offer the greatest potential for preserving such deposits. If pyroclastic deposits more extensive than the single small outcrop of pumiceous pyroclastic debris along the Chakachatna River cannot be located, magmatic involvement in the sector collapse may have been minimal. The Mount Spurr sector collapse may have been a Bandai-like edifice collapse (Sekiya and Kikuchi, 1889; Siebert and others, 1987) that resulted from long-term hydrothermal alteration of the edifice. Numerical modeling of the effects of hydrothermal pressurization within volcanic edifices indicates that the heating associated with magmatic intrusion at depth can increase internal pore-fluid pressures sufficiently to reduce effective stresses that could lead to massive edifice collapse (Reid, 2004; Thomas and others, 2004). Such collapses can occur without magmatic intrusion into the edifice and would not be associated with eruption of juvenile material (Siebert and others, 1987). Because volcanic sector collapses provoked by nonmagmatic processes are much less amenable to monitoring (van Wyk de Vries and others, 2000), such events pose a substantially higher risk.

Although post-collapse volcanism at Crater Peak and Mount Spurr has not rebuilt the edifice to its precollapse size, evidence of a shallow hydrothermal system and historical eruptions of Crater Peak suggest that internal alteration of the volcanic core is continuing (Power and others, 2004; De Angelis and McNutt, 2005). Thus, although an edifice collapse could occur in the future, it is likely only after Crater Peak and Mount Spurr have grown considerably larger than at present.

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