Flank collapse at Mount Wrangell, Alaska, recorded by volcanic mass-flow deposits in the Copper River lowland

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Abstract: An areally extensive volcanic mass-flow deposit of Pleistocene age, known as the Chetaslina volcanic mass-flow deposit, is a prominent and visually striking deposit in the southeastern Copper River lowland of south-central Alaska. The mass-flow deposit consists of a diverse mixture of colorful, variably altered volcanic rocks, lahar deposits, glaciolacustrine diamicton, and till that record a major flank collapse on the southwest flank of Mount Wrangell. The deposit is well exposed near its presumed source, and thick, continuous, stratigraphic exposures have permitted us to study its sedimentary characteristics as a means of better understanding the origin, significance, and evolution of the deposit. Deposits of the Chetaslina volcanic mass flow in the Chetaslina River drainage are primary debris-avalanche deposits and consist of two principal facies types, a near-source block facies and a distal mixed facies. The block facies is composed entirely of block-supported, shattered and fractured blocks with individual blocks up to 40 m in diameter. The mixed facies consists of block-sized particles in a matrix of poorly sorted rock rubble, sand, and silt generated by the comminution of larger blocks. Deposits of the Chetaslina volcanic mass flow exposed along the Copper, Tonsina, and Chitina rivers are debris-flow deposits that evolved from the debris-avalanche component of the flow and from erosion and entrainment of local glacial and glaciolacustrine diamicton in the Copper River lowland. The debris-flow deposits were probably generated through mixing of the distal debris avalanche with the ancestral Copper River, or through breaching of a debris-avalanche dam across the ancestral river. The distribution of facies types and major-element chemistry of clasts in the deposit indicate that its source was an ancestral volcanic edifice, informally known as the Chetaslina vent, on the southwest side of Mount Wrangell. A major sector collapse of the Chetaslina vent initiated the Chetaslina volcanic mass flow forming a debris avalanche of about 4 km^3 that subsequently transformed to a debris flow of unknown volume.

Résumé : Un dépôt de mouvement de masse de roches volcaniques, datant du Pléistocène, couvre une grande superficie; ce dépôt, connu sous le nom de dépôt de mouvement de masse de roches volcaniques de Chetaslina, est proéminent et visiblement frappant dans les basses-terres du sud-est de la rivière Copper, du centre-sud de l’Alaska. Le dépôt de mouvement de masse comprend un mélange varié, haut en couleur, de roches volcaniques à altération variable, de dépôts de lahar, de diamicton glacio-lacustre et de till qui rappellent un important effondrement de flanc sur le flanc sud-ouest du mont Wrangell. Le dépôt est bien exposé à proximité de sa source réputée et des affleurements stratigraphiques, continus et épais, nous ont permis d’étudier ses caractéristiques sédimentaires afin de mieux comprendre l’origine, la signification et l’évolution du dépôt. Les dépôts de mouvement de masse de roches volcaniques de Chetaslina, dans le bassin de drainage de la rivière Chetaslina, sont surtout des dépôts primaires d’avalanches de débris et comprennent deux principaux types de faciès, un faciès de blocs, à proximité de la source, et un faciès distal mixte. Le faciès de blocs est composé entièrement de blocs fracturés et éclatés soutenus par d’autres blocs; certains blocs atteignant 40 m de diamètre. Le faciès mixte comprend des particules de la dimension de blocs dans une matrice mal triée de débris rocheux, de sable et de silt provenant de la comminution de blocs plus gros. Les dépôts de mouvement de masse de roches volcaniques affleurant le long des rivières Copper, Tonsina et Chitina sont des dépôts de mouvement de masse de débris qui ont évolué à partir de la composante d’avalanche de débris du mouvement de masse et à partir également de l’érosion et de l’entraînement de diamictons glaciaux et glacio-lacustres locaux dans les basses-terres de la rivière Copper. Les dépôts de mouvement débris proviennent probablement du mélange d’une avalanche de débris distale et de la rivière ancestrale Copper ou par la rupture d’un barrage formé par une avalanche de débris en travers de la rivière ancestrale. La distribution des types de faciès et la chimie des éléments majeurs des clastes dans le dépôt indiquent que la source était un ancien édifice volcanique connu de façon informelle sous le nom de cheminée de Chetaslina, sur le côté sud-ouest du mont Wrangell. Un effondrement majeur du secteur de la cheminée de Chetaslina a provoqué le

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mouvement de masse des roches volcaniques de Chetaslina, formant une avalanche de débris d'environ 4 km^3 qui s'est par la suite transformée en un écoulement de débris d'un volume inconnu.

[Traduit par la Rédaction]

Introduction

Studies of volcanic deposits are the primary means of investigating the history and characteristics of past episodes of volcanism and the evolution of long-lived volcanic centers. The products of volcanism, be they proximal volcanic deposits (e.g., lava flows, tephra) or far traveled volcanic mass flows, provide important information about volcanic processes and are often a guide to the nature of future volcanic activity. At many volcanoes in Alaska, the geologic record of volcanic events and processes is poorly known. This makes it is difficult to evaluate possible future events and interpret past behavior in terms of present activity and monitoring of unrest. Geologic studies of volcanic deposits are essential for hazard assessment, deciphering eruption frequency, and for establishing the context of unusual or rare events in the long-term evolution of volcanic centers (e.g., Hildreth and Fierstein 2000). Large-volume volcanic mass-flow deposits, such as debris-avalanche and debris-flow (lahar) deposits, are particularly important because such deposits often record key events in the geologic evolution of a volcano. In this paper, we describe a unique sequence of volcanic mass-flow deposits at Mount Wrangell, Alaska. These deposits provide new information about a large, previously unrecognized flank collapse of a large Quaternary shield volcano, record evidence of flow transformation from debris avalanche to debris flow, and confirm numerous observations about the behavior and characteristics of large volcanic mass flows.

Mount Wrangell is a large, ice-covered shield volcano in the western Wrangell – St. Elias Mountains of south-central Alaska (Fig. 1). The volcano is made up of an extensive series of andesitic lava flows of Pleistocene age (Richter et al. 1990) that extend as much as 40 km beyond the volcano summit. The volume of extrusive lava flows on Mount Wrangell is about 1000 km^3 (Richter et al. 1995), making it one of the most voluminous volcanoes in North America. The volcano has been less active during the Holocene and eruptive products of this age are not well documented (D.H. Richter, personal communication, 2000). However, phreatic, ash-producing eruptions from the summit craters are relatively common and, as recently as 1902, the summit was blanketed by ash (Richter et al. 1995).

Effusive, lava-producing eruptions have been the dominant eruptive style of Mount Wrangell and clastic volcanic mass-flow deposits are rare within the voluminous pile of Mount Wrangell lavas (Nye 1983; Richter et al. 1990). However, southwest of the Mount Wrangell massif in the southern Copper River lowland (Fig. 1), postglacial stream incision has exhumed an extensive sequence of debris-avalanche and debris-flow deposits that suggest a more complex history of Mount Wrangell. The debris-avalanche deposit and a related debris-flow deposit, named the Chetaslina volcanic debris flow by Yehle and Nichols (1980), contain large blocks of primary and altered volcanic rock (mainly andesitic lava), primary lahar sediment, reworked glaciolacustrine deposits, till, and occasional scoriaceous pyroclasts. The deposit is well exposed along the upper Chetaslina and East Fork Chetaslina rivers and is discontinuously exposed along the Copper River from the mouth of the Chetaslina River downstream to Chitina (Fig. 2). The deposit also crops out along the lower Chitina River (Fig. 2; Yehle and Nichols 1980) and along the Kuskulana and Tonsina rivers (Fig. 2).

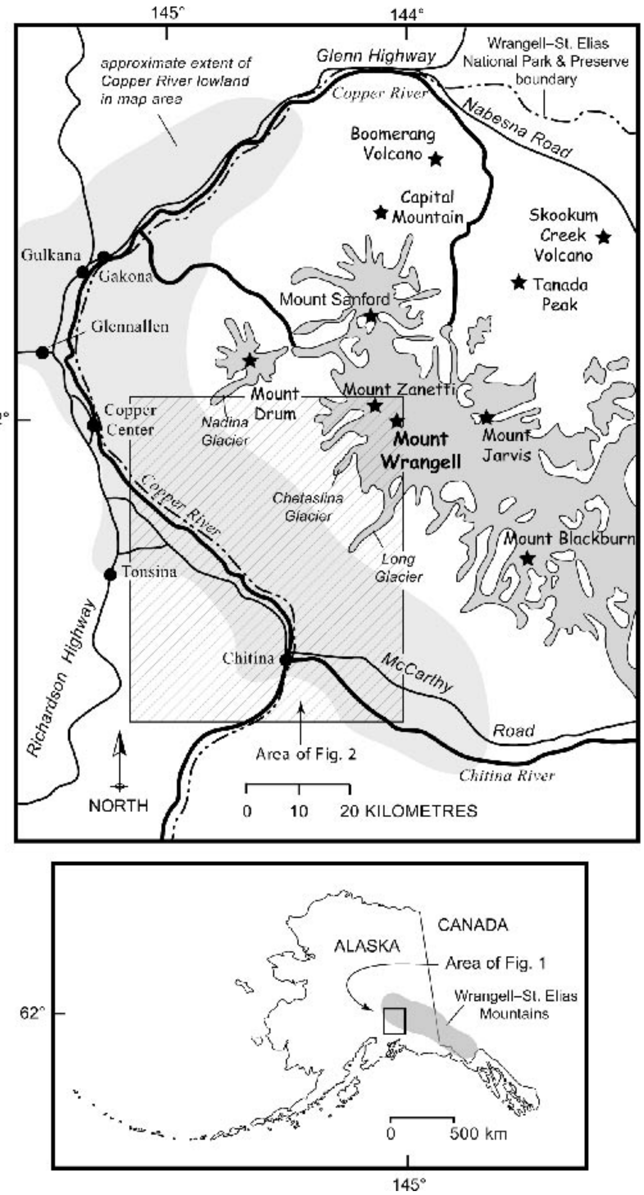
The results of previous work in the area and reconnaissance-level studies of the Chetaslina volcanic debris flow (Richter et al. 1995; Nichols and Yehle 1985; Yehle and Nichols 1980) were inconclusive about the source, timing, and significance of these deposits. Only general observations about the sedimentology, stratigraphic setting, and age of the deposits has been reported, and the evolution and sequence of events associated with emplacement of this volcanic mass-flow deposit were not known. Large-volume (>1 km^3), subaerial debris-avalanche deposits are uncommon at broad, low-profile, continental shield volcanoes like Mount Wrangell. More often, such deposits form at steep-sided, high-relief stratovolcanoes, such as Bezymianny, Bandai, Komagatake, Mount St. Helens, and Shasta (Crandell et al. 1984; Siebert 1984, 1996; Siebert et al. 1987). The excellent exposure, apparently large volume of the Chetaslina volcanic debris-flow deposit (ca. 13 km^3; Yehle and Nichols 1980), unusual association with a continental shield volcano, and concerns about the possibility of a future flank collapse and associated hazards prompted the present study.

Descriptions of volcanic debris-avalanche deposits in Alaska are few even though they have been widely recognized at numerous volcanoes in the Aleutian arc (Miller et al. 1998). Recent evaluations of the mechanical properties of granular mass flows (Major and Iverson 1999; Iverson and Vallance 2001; Iverson and Denlinger 2001) and their attendant hazards (Vallance and Scott 1997) require a reassessment of traditional interpretations of volcanic mass-flow deposits. We will show that the Chetaslina volcanic debris flow, as defined by Yehle and Nichols (1980), consists of three major units: (1) a debris-avalanche deposit with two distinct facies types, (2) a debris-flow deposit, and (3) a hyperconcentrated-flow deposit. We present evidence for the flow regime of the debris avalanche and comment on the flow-transformation process. We also propose the new name Chetaslina volcanic mass-flow deposit as a replacement for the name Chetaslina volcanic debris flow of Yehle and Nichols (1980) to avoid ambiguity about the processes that formed this deposit.

Study area

Mount Wrangell is one of at least 12 volcanic centers of late Cenozoic age in the Wrangell – St. Elias Mountains of southeast Alaska and southwestern Yukon Territory (Fig. 1) and is part of a vast volcanic terrain covering about 10 000 km^2 called the Wrangell volcanic field (Richter et al. 1990). Mount Wrangell is a 4317-m-high shield volcano

Fig. 1. Map of western Wrangell volcanic field and the southeastern Copper River basin showing location of place names mentioned in text. Approximate extent of modern glaciers shown in grey.



with an ice-filled summit caldera that is approximately 4 × 6 km in diameter. More than 90% of the shield is covered by glacier ice (Richter et al. 1995), and the total ice volume on the volcano is at least 100 km^3 (Benson and Follett 1986)

The Wrangell – St. Elias Mountains are the eastern boundary of the Copper River lowland (Fig. 1), a broad, intermontane lowland that was periodically flooded by glacial lakes that formed in response to Pleistocene glaciation of the Talkeetna, Chugach, and Wrangell – St. Elias mountains (Hamilton and Thorson 1983; Ferrians 1989). Glaciolacustrine deposits are present throughout the Copper River lowland and are exposed along most major rivers and streams in the basin (Williams and Galloway 1986; Williams 1989; Ferrians 1989).

The Copper River is the primary drainage in the study area, and it flows in a southerly direction along the west side of the Wrangell – St. Elias Mountains (Fig. 1). Postglacial incision by the Copper River and its tributaries has produced some spectacular exposures of the Quaternary deposits in the Copper River lowland, where river bluff exposures in many areas are more than 100 m thick and many kilometres in length.

Previous studies

Volcanic mass-flow deposits in the Copper River basin have been described by Ferrians et al. (1958), Ferrians and Nichols (1965), Richter et al. (1979), Yehle and Nichols (1980), and Nichols and Yehle (1969, 1985). Earlier studies mention clasts of reddish andesite in gravel deposits exposed along the Copper and Tonsina rivers (Schrader and Spencer 1901; Mendenhall 1905), but these deposits were not specifically attributed to a volcanic source.

The name Chetaslina volcanic debris flow was used by Yehle and Nichols (1980) to describe an unsorted, block-rich, volcanic debris-flow deposit exposed along the Chetaslina, East Fork Chetaslina, Copper, Tonsina, Kotsina, and Chitina rivers (Fig. 2). Yehle and Nichols (1980) categorized the deposit as a volcanic mudflow and suggested that the deposit may have resulted from an explosive eruption of Mount Wrangell.

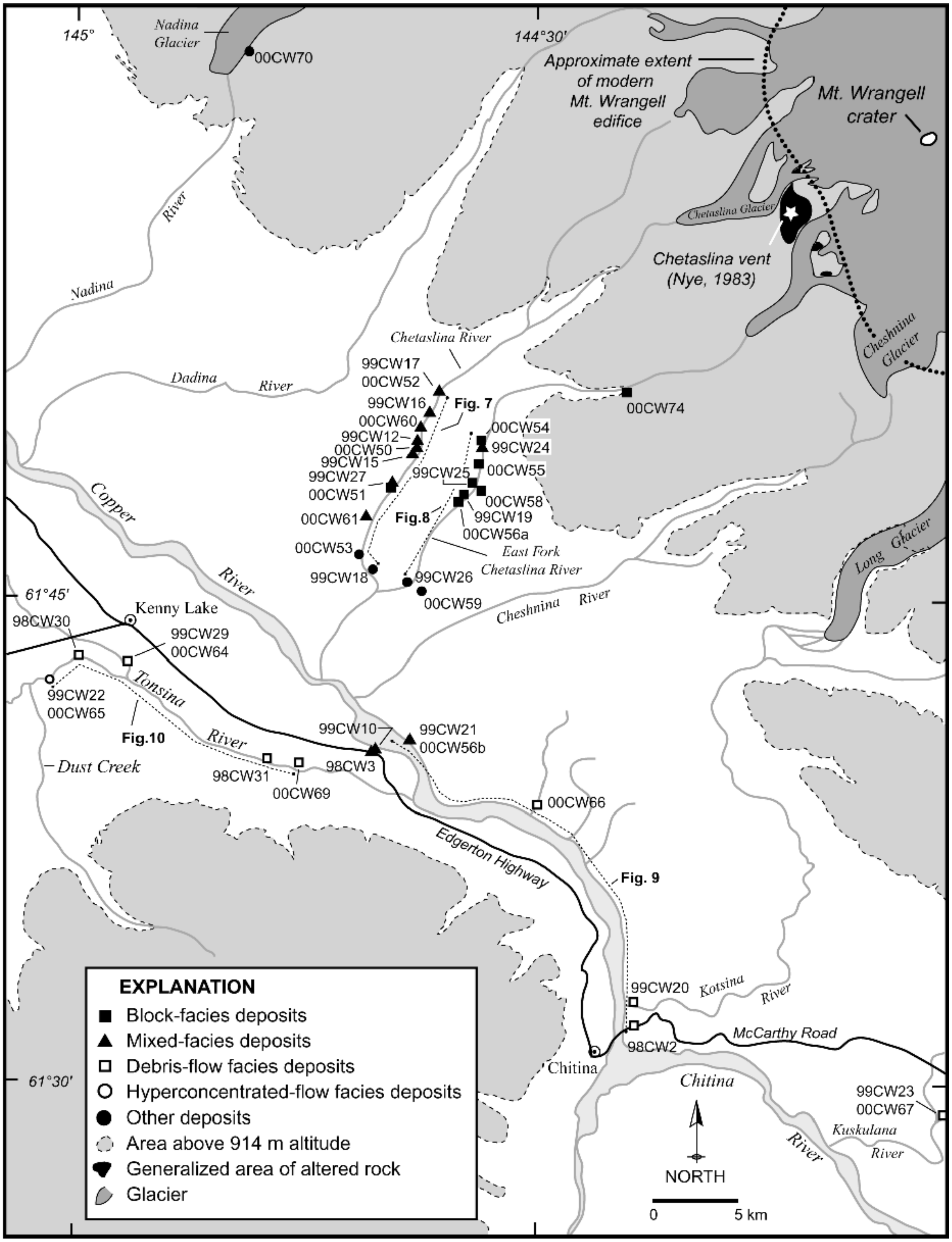
Geologic studies of Mount Drum, a volcano located northwest of Mount Wrangell (Fig. 1; Richter et al. 1979; 1990), led to a hypothesis that an explosive eruption and flank collapse of Mount Drum initiated the Chetaslina volcanic debris flow (Richter et al. 1995). According to Richter et al. (1995), the source of all known deposits of the Chetaslina volcanic debris flow, including the debris-avalanche deposits along the Nadina Glacier (Richter et al. 1979), is Mount Drum.

Sedimentologic nomenclature

We propose the name Chetaslina volcanic mass-flow deposit as a replacement for Chetaslina volcanic debris flow as defined by Yehle and Nichols (1980) to avoid confusion about the genesis of this unique deposit related to the inadvertent use of the process term debris flow (Table 1). The more general name, Chetaslina volcanic mass-flow deposit, includes all known deposits of the Chetaslina volcanic debris flow described in previous work (Yehle and Nichols 1980; Nichols and Yehle 1985; Richter et al. 1995). The Chetaslina volcanic mass-flow deposit is exposed only in the southern part of the Copper River lowland (Fig. 2), and it consists of debris-avalanche, debris-flow, and hyperconcentrated-flow deposits and includes a number of associated facies (Table 1).

Our terminology for describing the gross sedimentologic characteristics of the Chetaslina volcanic mass-flow deposit is described as follows. In general, we follow the nomenclature of Crandell et al. (1984), Ui et al. (1986), Glicken (1991, 1996), Palmer et al. (1991), Schneider and Fisher (1998), and Ui et al. (2000), who have developed a practical and easily applied set of descriptive terms for debris-avalanche deposits on the basis of their studies of debris-avalanche deposits at various volcanoes around the world. We have employed the facies concept (Pettijohn 1975) to illustrate the overall sedimentary architecture of the deposits and use the terms block facies, mixed facies, debris-flow facies, and hyperconcentrated-flow facies to describe the features of the

Fig. 2. Outcrops of the Chetaslina volcanic mass-flow deposit and other relevant deposits. Facies types indicated by symbols and numbers adjacent to symbols identify stations where stratigraphic data were collected. Light-toned fill indicates areas above 914 m altitude.



Base from U.S. Geological Survey Valdez & Gulkana Quadrangles, 1:250,000 scale

Chetaslina volcanic mass-flow deposit observable at the outcrop scale. These facies types developed as the volcanic mass-flow moved away from its source and evolved from a block-rich debris avalanche to a debris flow and relate to the overall sedimentology of the deposit. The spatial distribution of the various facies types, so far as is known, is indicated on

Table 1. Sedimentologic nomenclature and terminology.

Previous name	New name	Components
Chetaslina volcanic debris flow	Chetaslina volcanic mass-flow deposit	- Debris-avalanche deposits - Debris-flow deposits - Hyperconcentrated-flow deposits

Deposit	Facies types and *characteristics*	Process
Landslide blocks	Block facies *Block supported, no matrix*	Sector collapse
Debris-avalanche deposit	Block facies *Block-against-block architecture, some matrix* Mixed facies *Some particles matrix supported*	Concentrated granular mass flow
Debris-flow deposit	Debris-flow facies *All particles matrix supported; includes nonvolcanic particles*	More dilute granular mass-flow
Hyperconcentrated-flow deposit	Hyperconcentrated-flow facies *Clast and matrix supported; better sorted than other facies types; occasional large particles of volcanic rock*	Dilute granular mass flow

Descriptive terms	Definition
Particle	A general term for the coarse components of a sedimentary mixture. A particle can range in size from a few centimetres to many tens of metres.
Debris-avalanche block	A piece of the volcanic edifice displaced by sector collapse, or fragments of the substrate entrained by the mass flow. Size range is metres to tens of metres
Clast	An intact rock of any size. Many clasts may be debris-avalanche blocks.
Matrix	Unconsolidated sediment ranging in size from clay to boulders and typically surrounding particles
Fracturing	Impact-generated cracks within debris-avalanche blocks or particles. Intensely fractured clasts may be referred to as shattered.
Rubble schlieren	Intact but smeared and deformed debris-avalanche blocks.

Fig. 2. Terms used to describe the constituents and features of the Chetaslina volcanic mass-flow deposit are modified from Glicken (1991) and are briefly defined in Table 1.

Investigators of volcanic mass-flow deposits have sought to characterize the particle-size composition of the < 4 mm size fraction using standard particle-size analysis (Glicken 1986; Ui et al. 1986; Siebert et al. 1989, 1995). During our study of the Chetaslina volcanic mass-flow deposit, we found it difficult to select what we believed were representative samples of the deposit matrix. In most locations the deposit was poorly mixed, and in many instances, the sediment making up the deposit matrix was derived from an adjacent partially intact block. Given the variety of block types present in the deposit, it was not possible to select a representative matrix sample from a given outcrop; therefore, we sought to characterize the Chetaslina volcanic mass-flow deposit on the basis of its overall sedimentary architecture (Glicken 1991). We raise this issue because particle-size data reported by Yehle and Nichols (1980) indicate that the Chetaslina volcanic mass-flow deposit has a clay-rich matrix. We did not find this to be universally true of the entire deposit; rather, the particle size of the matrix is related to the state of disaggregation of the large blocks. The particle-size data reported by Yehle and Nichols (1980) are not representative of the matrix texture of the Chetaslina volcanic mass-flow deposit, and their data apply only to limited parts of the debris-flow facies.

Block facies

Block-facies deposits are thick accumulations (>10 m) of debris-avalanche blocks with minimal or no interblock matrix of any size fraction (Fig. 3A). Typically, debris-avalanche blocks that make up the block facies are in contact producing a block-against-block macrotexture (Fig. 3A). It was difficult to determine the actual dimensions of the blocks in this facies and the size of individual blocks was estimated as their apparent intermediate diameter in outcrop. Blocks in the block facies range in size from a few metres to more than 30 m in diameter, and one block along the Copper River measured about 40 × 60 m. The contacts between blocks often exhibit sheared textures and contain zones of rock flour and unsorted angular rock debris that was likely produced by strong block interactions during transport. Debris-avalanche blocks are either fractured or shattered (Fig. 3B) and many of the block interiors exhibit “jigsaw” fractures and cracks (Shreve 1968; Glicken 1991). Even though most of the blocks

Fig. 3. Block-facies deposits. (A) Block-facies deposit, exposure 00CW54, East Fork Chetaslina River. Note fractured internal texture of individual blocks (outlined) and contact relations indicating flow-induced deformation. (B) Internal texture of fractured blocks at exposures 00CW58. Locations of exposures shown on Fig. 2.

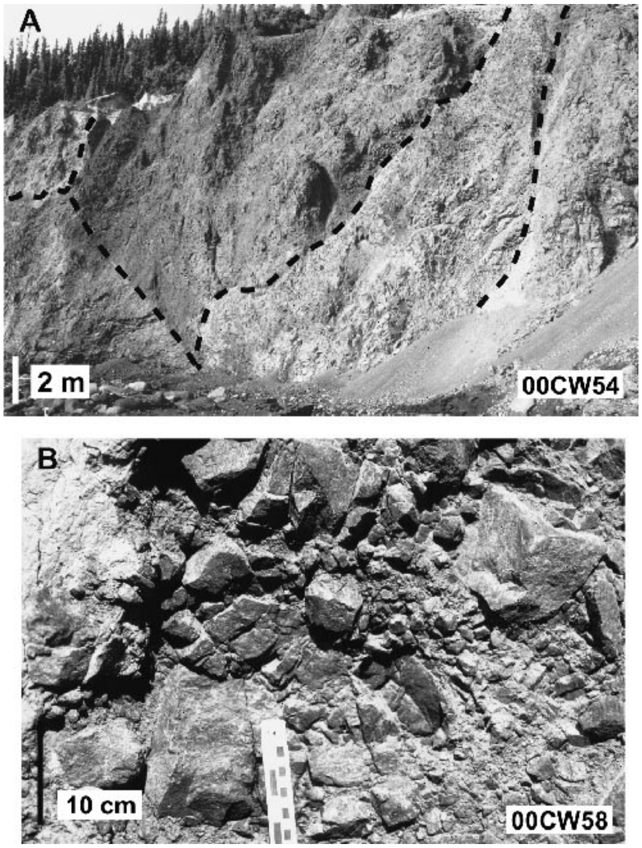
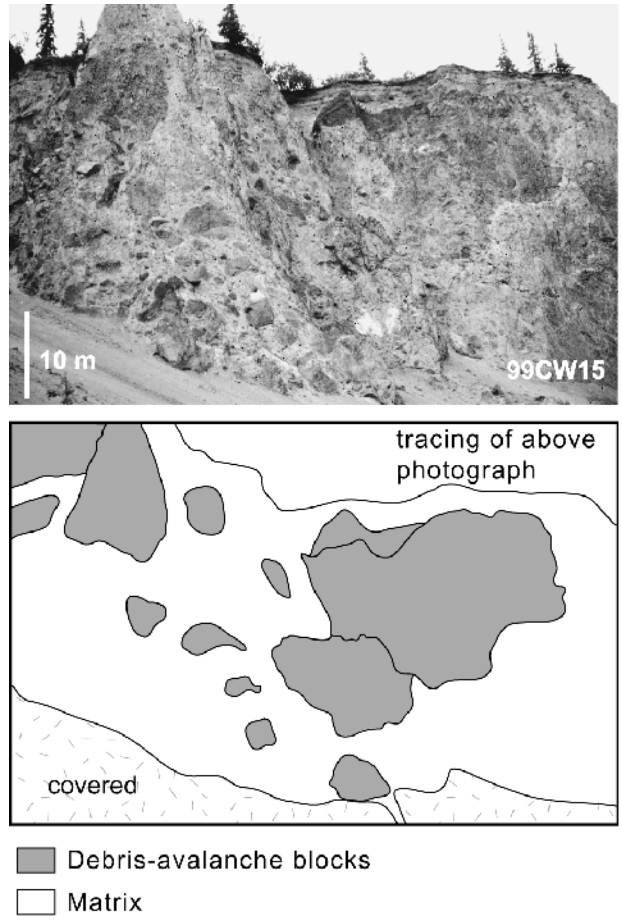


Fig. 4. Mixed-facies deposit, exposure 99CW15, Chetaslina River. Location of section shown on Fig. 2.



in the block-facies are fractured or shattered, they retain a recognizable geometry and original bedding and layering are often discernible.

Rock types present in the block facies include gray, black, red, and maroon andesitic lava and basaltic–andesite lava; vesicular basalt; and massive, basaltic lava. Hydrothermally altered volcanic rocks are common in block-facies deposits. The degree of alteration varies from minor oxidation to clay, and less than 25% of the blocks in the block facies are altered to clay.

Mixed facies

The mixed facies of the Chetaslina volcanic mass-flow deposit is a chaotic assemblage of matrix-supported debris-avalanche blocks of fractured and shattered volcanic rock and laharic debris (Fig. 4). Typical exposures of the mixed facies consist of angular to rounded, multicolored, variably altered and variably fractured blocks of volcanic rock and lahar sediment in a matrix of unsorted disaggregated rock rubble, sand and silt (Fig. 4). Individual blocks in the mixed facies are geometrically distinct and intact and range in size from 1 m to tens of metres in diameter.

The mixed facies is the product of progressive disaggregation of debris-avalanche blocks, where formerly solid blocks derived from the failed edifice have broken apart by intense particle interaction or shearing under high overburden pressure (Davies et al. 1999). Mixing of matrix material during flow contributes to the heterogeneous and unsorted nature of the mixed facies and results in a predominantly matrix-supported deposit.

Debris-flow facies

The debris-flow facies of the Chetaslina volcanic mass-flow deposit consists of massive, poorly sorted, matrix-supported gravel with occasional boulder-size blocks of volcanic rock (Fig. 5). The debris-flow facies contains boulder-size nonvolcanic blocks of glaciolacustrine diamicton, till, and loess, and intact, rounded blocks of primary laharic debris, all of which were eroded from their primary deposits by the flow. Distinctive, black, scoriaceous pyroclasts also are present in debris-flow facies deposits (Fig. 5B). Nonvolcanic blocks and scoriaceous pyroclasts are uncommon in block- and mixed-facies deposits. Most of the nonvolcanic blocks, even though they are unconsolidated, are rounded to subrounded, indicating that they possessed sufficient cohesive strength and remained intact as they were incorporated into and transported by the debris flow. Debris-flow facies deposits range in thickness from 10 to 40 m, and the best examples of this facies type are in the exposures along the Tonsina River (Figs. 2, 5A).

Hyperconcentrated-flow facies

The hyperconcentrated-flow facies consists of matrix- and

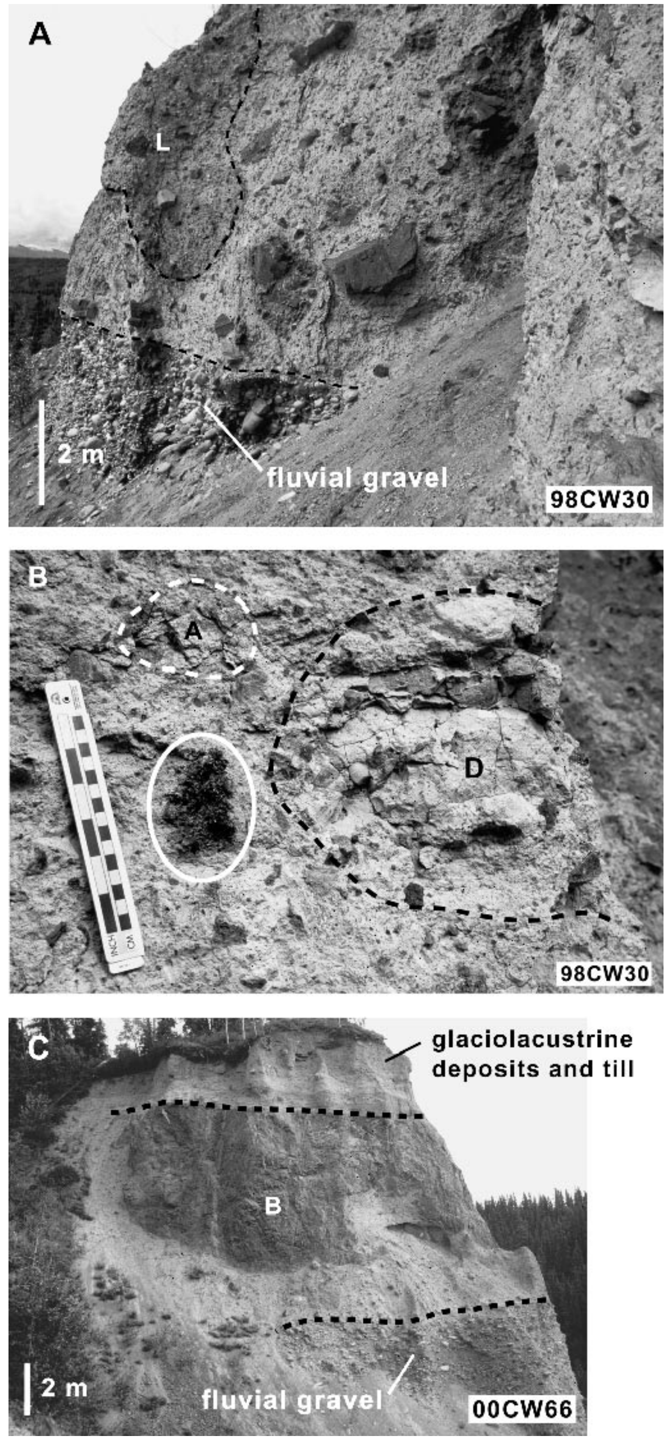


Fig. 5. Debris-flow facies deposits. (A) Typical exposure of the debris-flow facies along the Tonsina River. Particles in this deposit consist of angular to subangular volcanic rock and intact rounded blocks of primary lahar sediment (indicated by L and outlined). The matrix of the deposit is a mixed assemblage of till, glaciolacustrine diamicton, angular volcanic gravel, sand and silt. (B) Typical example of debris-flow facies matrix. Clast of glaciolacustrine diamicton (indicated by letter D) is outlined by black dashed line. Clast of altered volcanic rock is indicated by letter A and circled by white dashed line. The clast near the center of the photograph and circled by a solid white line is a scoriaceous andesite pyroclast eroded from a pyroclastic-flow deposit that crops out on the East Fork Chetaslina River (locations 99CW26 and 00CW59, Fig. 2). (C) Matrix-supported debris-avalanche block of fractured andesite (indicated by letter B and outlined) in debris-flow facies deposit near the Copper River. Top of block was apparently sheared off by glacier ice during a Pleistocene ice advance into the Copper River lowland.

clast-supported, angular to subrounded gravel with occasional boulder-size blocks of volcanic rock similar to those in the block-, mixed-, and debris-flow facies deposits (Fig. 6). Deposits of this facies type are known at only one location along the Tonsina River near the mouth of Dust Creek (Fig. 2). At this location the deposit is 30–40 m thick and massive to faintly stratified (Fig. 6). Sub-units within the deposit, denoted by concave-up scour surfaces, exhibit crude normal grading over vertical distances of several metres. The hyperconcentrated-flow facies contains the least amount of fine sediment (fine sand, silt, and clay) and is the best sorted of all of the facies types in the Chetaslina volcanic mass-flow deposit. This facies represents the downstream runout component of the debris-flow facies and likely was deposited by a flow slightly more dilute than a typical debris flow.

Deposits along the Chetaslina River

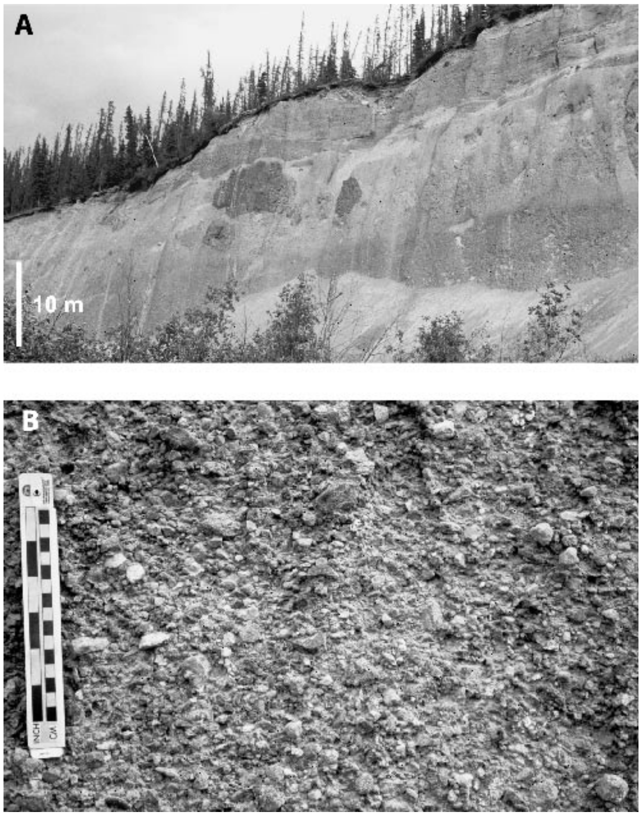
Volcanic mass-flow deposits are discontinuously exposed in high river bluffs along the Chetaslina River in a zone 10–20 km upstream from the mouth of the river (Fig. 2). At most locations, deposits of the Chetaslina volcanic mass flow are more than 25 m thick, make up nearly all of the exposed section, and consist mostly of mixed-facies deposits (Fig. 7). In some outcrops, mass-flow deposits are found at various stratigraphic positions within thick sequences of unconsolidated Quaternary glacial and glaciolacustrine diamicton (Figs. 7F, 7G, 7I). These deposits warrant discussion, because they were previously interpreted as separate primary volcanic debris-flow deposits (Yehle and Nichols 1980; Nichols and Yehle 1985).

At sites 99CW27 and 00CW51 (Fig. 2), three mass-flow deposits are present in a 75- to 100-m-thick sequence of unconsolidated Quaternary sediment (Figs. 7F, 7G). The stratigraphically oldest of the three deposits is a block-facies debris-avalanche deposit composed of yellow-orange, hydrothermally altered debris-avalanche blocks of andesite each several tens of metres in diameter. This deposit is exposed at river level and cannot be found farther downstream along the Chetaslina River.

A second mass-flow deposit at sites 99CW27 and 00CW51 rests on fluvial gravel (probably outwash) and is stratigraphically above the basal block-facies deposit (Fig. 7G). The second deposit is 5–7 m thick and is discontinuously exposed across the outcrop. This deposit is matrix supported, exhibits faint stratification, and contains boulder- size blocks of hydrothermally altered volcanic rock, glaciolacustrine diamicton, and primary lahar sediment. Its relation to the underlying debris-avalanche deposit is not known, but it must represent either a primary volcanic debris flow from a source in the upper Chetaslina River basin or a secondary debris flow derived from the debris-avalanche deposit upstream from this location.

A third mass-flow deposit at sites 99CW27 and 00CW51,

Fig. 6. Hyperconcentrated-flow facies deposits along the Tonsina River. (A) Exposures 00CW65 and 99CW22. Note large blocks of volcanic rock within deposit. (B) Gravelly texture of hyperconcentrated-flow facies. Note range of clast shapes and relatively well-sorted nature of deposit. Scale is 15 cm in length.



is present midway up the bluff at the farthest downstream part of the exposure (Fig. 7F). This deposit is 3–5 m thick, matrix supported, massive, and contains rounded to subrounded blocks of glacial and glaciolacustrine diamicton, hydrothermally altered volcanic rock, cobble and small boulder-size fractured blocks of volcanic rock, and blocks of unconsolidated lahar sediment. More than 50% of the blocks in the deposit are nonvolcanic. The mass-flow deposit is laterally discontinuous and thins and pinches out in an upstream direction. The basal contact of the deposit is sharp and abrupt, underlying fluvial gravel deposits are scoured and abraded, and some clasts are beveled flat, indicating erosion by a high-energy flow.

Sites 99CW27 and 00CW51 are the only locations where we observed more than one mass-flow deposit in a vertical stratigraphic section. The oldest deposit at the base of the section (deposit 1, Fig. 7G) is texturally and compositionally similar to the debris-avalanche deposits exposed farther upstream and is probably correlative with these deposits. The overlying mass-flow deposits (deposits 2 and 3, Figs. 7F, 7G) could be secondary debris-flow deposits derived from high-relief mounds or hummocks in the debris-avalanche deposit. Although the primary surface morphology of the debris avalanche has been destroyed by erosion, it is likely that debris-avalanche hummocks were present in the primary deposit. Erosion of the hummocks, or other parts of the debris-avalanche deposit, could have formed secondary debris flows that produced deposits 2 and 3 at sites 99CW27 and 00CW51 (Figs. 7F, 7G). We found no evidence for lahar-producing eruptions at Mount Wrangell that occurred subsequent to the formation of the debris avalanche and suggest that deposits 2 and 3 in this section are debris-flow deposits not directly related to volcanic activity.

One additional mass-flow deposit, similar to the secondary debris-flow deposits at sections 99CW27 and 00CW51, is present at site 00CW53 (Fig. 2 and 7I). This deposit is laterally discontinuous, matrix supported, wavy bedded, and contains several rounded blocks of hydrothermally altered volcanic rock 1–2 m in diameter, and a few subrounded blocks of laharic debris, but mostly reworked glaciolacustrine diamicton. Blocks similar to those in the debris avalanche deposit account for only about 25% of this deposit. The mass-flow deposit at site 00CW53 is also a secondary debris-flow deposit that probably formed by erosion of the debris-avalanche and other unconsolidated deposits.

The downstream-most exposure of the Chetaslina volcanic mass-flow deposit along the Chetaslina River is a mixed-facies deposit at site 00CW61 located in a steep, narrow tributary valley entering the Chetaslina River from the west (Figs. 2 and 7H). The deposit is matrix supported, massive, and contains rounded to subrounded blocks of hydrothermally altered volcanic rock, rubble schlieren, glaciolacustrine diamicton, laharic debris, and fractured debris-avalanche blocks. The basal contact of the Chetaslina volcanic mass-flow deposit at site 00CW61 is sharp and abrupt, and the underlying deposits at the contact are striated, abraded, and beveled flat. This indicates that the substrate was eroded by a fast-moving debris flow, or was glaciated sometime prior to deposition of the debris-flow deposits.

Exposures along the Chetaslina River downstream from site 00CW53, such as site 99CW18 (Fig. 7J), do not contain mass-flow deposits of any kind. Mass-flow deposits next appear about 15 km downstream from site 00CW53, along the Copper River near the mouth of the Tonsina River (Fig. 2).

Deposits along the East Fork of the Chetaslina River

Deposits of the Chetaslina volcanic mass-flow deposit also are well exposed in a 5- to 7-km-long reach of the East Fork Chetaslina River about 10 km upstream from the confluence with the Chetaslina River (Fig. 2; Yehle and Nichols 1980). Nearly all of the deposits exposed along the East Fork of the Chetaslina River are block-facies deposits (Fig. 8). These deposits do not extend as far downstream as do the deposits on the Chetaslina River (Fig. 2). Fractured and shattered debris-avalanche blocks, rubble schlieren, blocks of hydrothermally altered lava, and laharic debris are common in the debris-avalanche deposits along the East Fork Chetaslina River (Fig. 8).

A pyroclastic-flow deposit exposed along the East Fork Chetaslina River, just upstream from the confluence with the Chetaslina River, is the only other volcanic mass-flow deposit known in the East Fork Chetaslina River drainage. This deposit is significant because pumice and scoria from the pyroclastic-flow deposit are found in debris-flow-facies deposits in the Tonsina River drainage to the southwest (Fig. 2). This indicates that the pyroclastic-flow deposit was eroded by the debris avalanche and, therefore, predates it.

Analysis of a single pumice pyroclast in the pyroclastic-flow deposit (Fig. 8) gave a K–Ar age of 342 ± 16 ka (D.H. Richter, personal communication, 2000 and unpublished data), and we consider this a maximum-limiting age for the debris avalanche. In the upper Chetaslina River drainage, debris-avalanche deposits are overlain by a lava flow that yielded a K–Ar age of 270 ± 40 ka (Nye 1983). Thus, the debris avalanche probably formed between about 340 and 270 ka.

Deposits along the Copper River

Debris-avalanche deposits also are recognized along the Copper River between the mouths of the Chetaslina and Kotsina rivers (Fig. 2). In this area, deposits of the mixed and debris-flow facies are exposed at river level within high bluffs overlain by metres to tens of metres of glacial and glaciolacustrine diamicton (Fig. 9). At sites 98CW3, 99CW10, 99CW21, and 00CW56b (Fig. 2), the debris-avalanche deposit contains fractured blocks of red andesite and slightly smaller blocks of yellow hydrothermally altered volcanic rock. None of the blocks are in direct contact but are suspended in a matrix of rock rubble, till, and laharic debris. These deposits are characteristic of the mixed facies.

Farther downstream at sites 00CW66, 99CW20, and 98CW2 (Fig. 2), deposits of the Chetaslina volcanic mass-flow deposit are finer grained, matrix supported, contain fewer large blocks, and have a higher percentage of matrix relative to large particles. Nonvolcanic blocks are more common and include till, glaciolacustrine diamicton, and fluvial sediment.

Collectively, the deposits along the Copper River record the transformation of debris avalanche to debris flow, but we are uncertain if the transformation was contemporaneous with the debris avalanche. The presence of nonvolcanic blocks in the deposit indicates that the mass flow was able to erode the bed and banks of the ancestral Copper River and local tributaries and must have increased its volume. The increase in flow volume required water, and a plausible source of water was most likely the ancestral Copper River. Other sources of water could have been lakes, glacier ice, permafrost, or possibly groundwater.

Deposits along the Tonsina River

Deposits of the Chetaslina volcanic mass-flow deposit exposed along the Tonsina River (Fig. 2) consist of debris-flow and hyperconcentrated-flow facies deposits (Fig. 10). These deposits are well exposed near the top of 20–50-m-high river bluffs, mostly on the north side of the Tonsina River (Fig. 11). The deposits contain boulder-size blocks of fractured hydrothermally altered volcanic rock, boulder-size blocks of primary laharic debris, and glaciolacustrine diamicton (Fig. 5). Deposits of the Chetaslina volcanic mass-flow deposit along the Tonsina River are generally about 10 m thick, although hyperconcentrated-flow deposits exposed near the mouth of Dust Creek at section 99CW22 (Figs. 2, 6) are about 30–40 m thick. Dark-colored scoriacious pyroclasts, identical to those in the pyroclastic-flow deposit in the East Fork Chetaslina drainage (Fig. 8) are common in the Tonsina River deposits (Fig. 5B).

The debris-flow deposits along the Tonsina River overlie thick deposits of well-sorted, clast-supported cobble gravel (Gcp, Fig. 10). The gravel deposits contain clasts of volcanic rock derived from Mount Wrangell and record aggradation of the Tonsina River valley by high-energy braided streams that flowed generally to the southwest. Rounded cobbles, similar to those in the underlying gravel, are common in the lower part of all debris-flow deposits along the Tonsina River and are evidence for flow bulking (Scott 1988).

The debris-flow deposits are slightly thicker (about 12 m) at section 00CW69 relative to section 98CW30, where the deposits are about 6–8 m thick. In general, the thickness of the deposits exposed along the Tonsina River decreases with increasing distance from Mount Wrangell. The thick hyperconcentrated-flow deposits at section 99CW22 probably record substantial downstream volume increase of the debris flow, as it mixed with the ancestral Tonsina River or localized ponding of the flow upstream of channel constrictions.

Deposits along the Kuskulana River

Deposits of the Chetaslina volcanic mass-flow deposit farthest from Mount Wrangell that we examined are exposed along the Kuskulana River, a northern tributary to the Chitina River in the southeast part of the study area (Fig. 2). The Kuskulana River deposits of the Chetaslina volcanic mass-flow deposit are debris-flow facies deposits (Fig. 12). About 80% of the deposit is matrix and these deposits are the most matrix-rich deposits we observed. The deposits consist of a poorly sorted assemblage of sand, silt, and angular gravel, and partially disaggregated blocks of glaciolacustrine diamicton, loess, till, and laharic debris with isolated boulder-size blocks of fractured, multicolored, altered volcanic rock in complete matrix support (Fig. 12).

Other deposits

Other mass-flow deposits not part of the Chetaslina volcanic mass-flow deposit, are present in the Copper River basin and have been described by previous researchers (Nichols and Yehle 1985; Richter et al. 1979, 1987). Because some of these deposits are thought to be part of the Chetaslina debris flow as originally defined (Yehle and Nichols 1980), we briefly review these deposits and give revised interpretations.

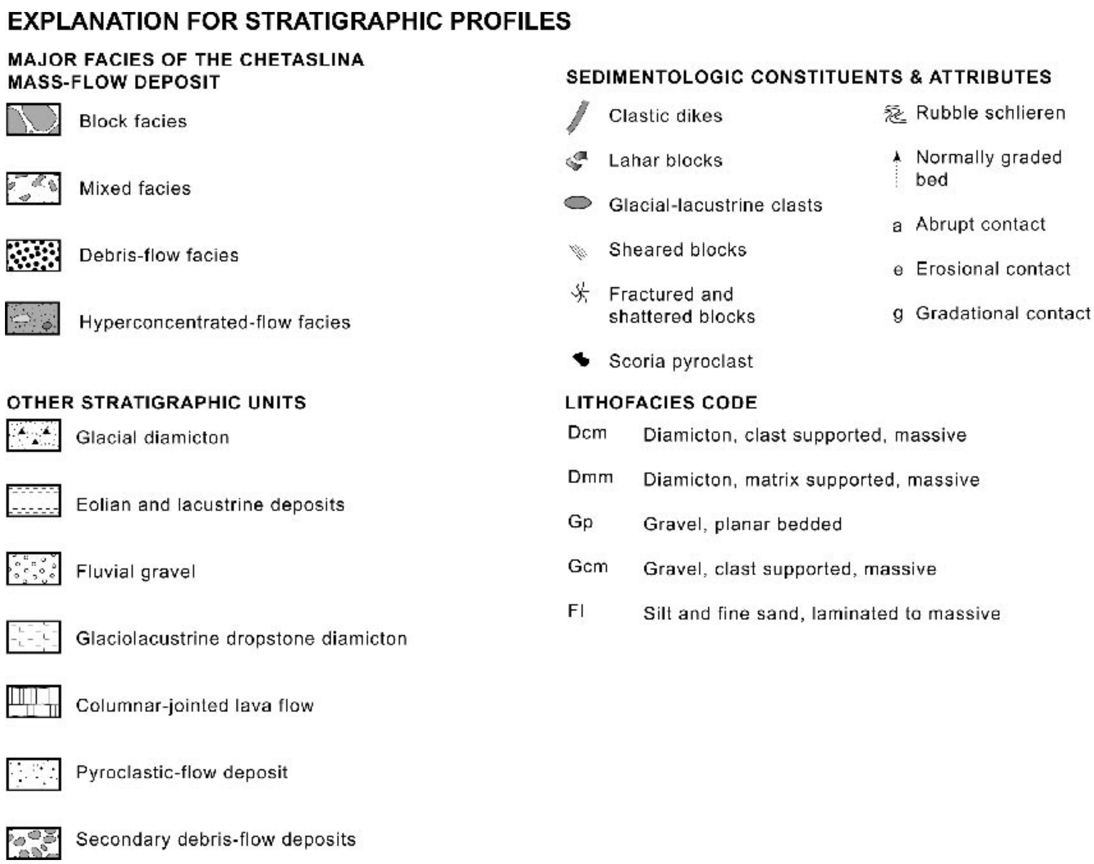
Nadina Glacier debris-avalanche deposits

During geologic mapping studies of Mount Drum volcano, Richter et al. (1979) discovered a thick (>350 m) volcanic debris-avalanche deposit along the margin of the Nadina Glacier (Fig. 13) on the south flank of Mount Drum (location 00CW70, Fig. 2). Debris-avalanche deposits in this area consist of grey to orange-brown weathering, poorly sorted, clast-supported, angular dacite rubble with small amounts of hornblende-bearing, dense pumice. Blocks of hydrothermally altered rock, similar to those found in the Chetaslina volcanic mass-flow deposit, are absent from the deposit. Exotic blocks of laharic debris and glacial and glaciolacustrine diamicton also are absent from the deposit, and fractured debris-avalanche blocks, so common in the Chetaslina volcanic mass-flow deposit, are rare.

The field characteristics and gross sedimentology of the

Fig. 7. Stratigraphic profiles and photographs of the Chetaslina volcanic mass-flow deposit along the Chetaslina River. See Fig. 2 for location of sections. The base of each section is river level. (A) Mixed-facies deposits, sites 99CW17 and 00CW52. (B) Andesite lava flow overlying mixed-facies deposits of the Chetaslina volcanic mass-flow deposit. A K-Ar age on the lava flow of 270 ± 40 ka (Nye 1983) gives a minimum-limiting age for the debris avalanche. (C) Mixed-facies deposits, site 00CW60. (D) Mixed-facies deposits, site 99CW12. Note rounded block of lahar sediment (letter L) in upper left corner of exposure show in photograph. (E) Mixed-facies deposits, site 99CW15. (F) and (G) Multiple mass-flow deposits within thick sequence of glaciolacustrine diamicton and outwash. Deposit 1 is a block-facies deposit of the Chetaslina volcanic mass-flow deposit. Deposits 2 and 3 are secondary debris-flow deposits derived from the Chetaslina volcanic mass-flow deposit but are not contemporaneous deposits. (H) Mixed-facies deposits, site 00CW61. Lower contact with underlying glacial diamicton is sharp and abrupt, and clasts in the diamicton in contact with the Chetaslina volcanic mass-flow deposit are striated and beveled flat. (I) Secondary debris-flow deposit, site 00CW53. J. Stratigraphic profile at site 99CW18. Chetaslina volcanic mass-flow deposits absent at this location and not found downstream of site 00CW61.

Fig. 7 (legend).



Nadina Glacier debris-avalanche deposit indicate that it is distinctly different from the Chetaslina volcanic mass-flow deposit. We could find no physical evidence to correlate the Nadina Glacier debris-avalanche deposit with the Chetaslina volcanic mass-flow deposit. We agree with Richter et al. (1979) that the source of the Nadina Glacier debris-avalanche deposit is Mount Drum and that it records a major sector collapse of that volcano.

Deposits along the Nadina River

Volcanic mass-flow deposits along the Nadina River downstream from Nadina Glacier (Fig. 2) have been described by Nichols and Yehle (1985, p. 368). Initially, we thought that these deposits could be lahar deposits formed by reworking of the Nadina Glacier debris-avalanche deposit. However, we failed to locate any volcanic mass-flow deposits along the Nadina River during helicopter traverses up and down the river during our fieldwork in 1999 and 2000.

Deposits along the Kotsina River

Volcanic mass-flow deposits were identified along the Kotsina River (Fig. 2) by Yehle and Nichols (1980). We attempted to visit these deposits but were unable to locate them. After several low-altitude helicopter traverses along the Kotsina River, we concluded that deposits of the Chetaslina volcanic mass-flow deposit are not present along the Kotsina River, except at the mouth of the river near its confluence with the Copper River (Fig. 2).

Deposits along the Chitina River

We were unable to directly examine deposits of the Chetaslina volcanic mass-flow deposit exposed along the Chitina River

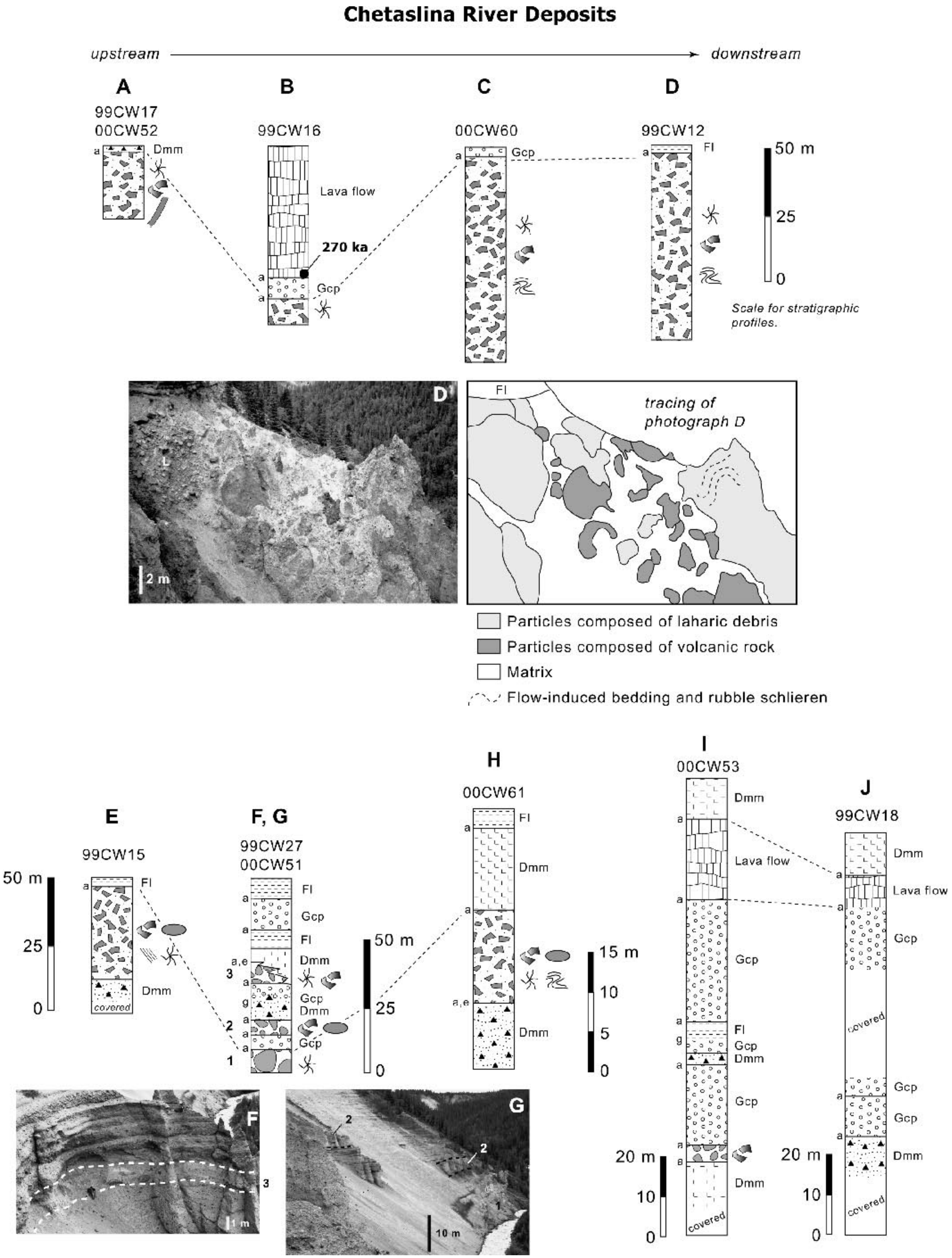

Chetaslina River Deposits
upstream
downstream
A
99CW17
00CW52
Dmm
B
99CW16
Lava flow
270 ka
Gcp
C
00CW60
Gcp
D
99CW12
Fl
50 m
25
0
Scale for stratigraphic profiles.
D
2 m
L
Fl
tracing of photograph D
Particles composed of laharic debris
Particles composed of volcanic rock
Matrix
Flow-induced bedding and rubble schlieren
E
99CW15
Fl
Dmm
covered
F, G
99CW27
00CW51
Fl
Gcp
Fl
Dmm
Gcp
Dmm
Gcp
H
00CW61
Fl
Dmm
Dmm
15 m
10
5
0
I
00CW53
Dmm
Lava flow
Gcp
Fl
Gcp
Dmm
Gcp
Dmm
covered
20 m
10
0
J
99CW18
Dmm
Lava flow
Gcp
covered
Gcp
Gcp
Dmm
covered
F
1 m
G
10 m

Fig. 8. Stratigraphic profiles of the Chetaslina volcanic mass-flow deposit along the East Fork of the Chetaslina River. See Fig. 2 for location of sections and Fig. 7 for explanation of symbols. Sections are arranged from upstream (left) to downstream (right). Pyroclastic-flow deposits thought to be older than the Chetaslina volcanic mass-flow deposit also are shown (sections 99CW26 and 00CW59). Scoriaceous pyroclasts from the pryoclastic-flow deposit are found in Chetaslina volcanic mass-flow deposits exposed along the Tonsina and Copper rivers farther downstream.

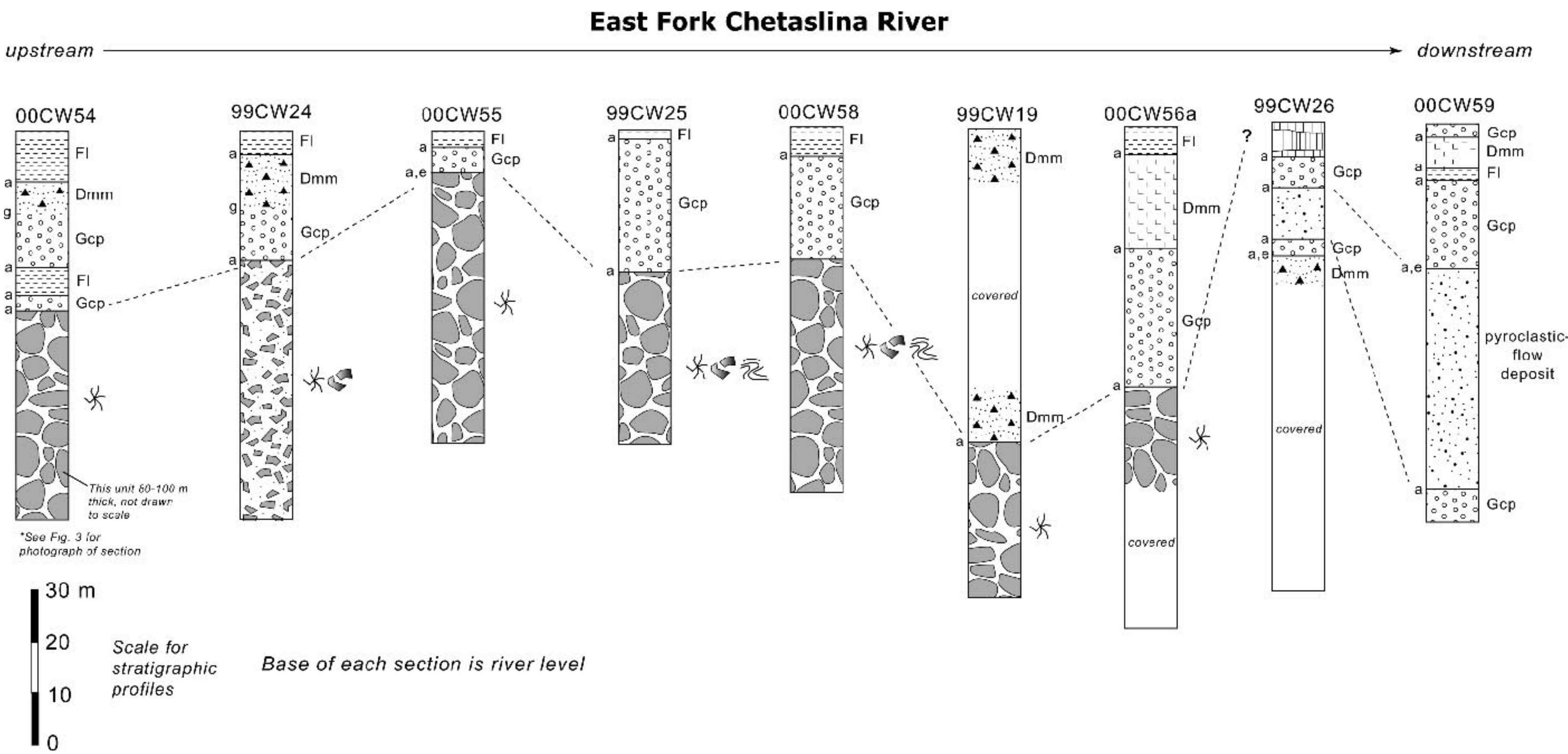


Fig. 9. Stratigraphic profiles and photograph of mixed- and debris-flow facies deposits of the Chetaslina volcanic mass-flow deposit exposed along the Copper River. See Fig. 2 for location of sections and Fig. 7 for explanation of symbols. (A) Site 99CW10, right bank of Copper River just upstream from the confluence with the Tonsina River. Light-colored area in middle of outcrop is a block of soft hydrothermally altered lava. This outcrop is typical of mass-flow deposits exposed along the Copper River.

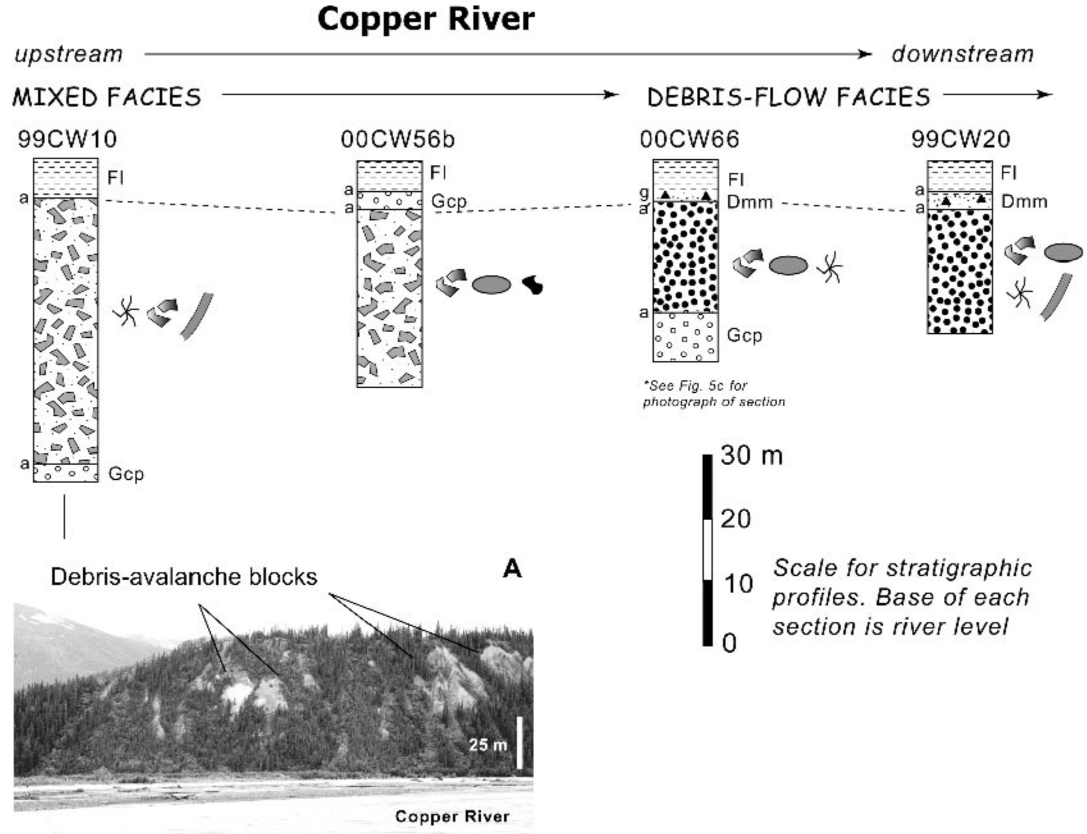


Fig. 10. Stratigraphic profiles of the debris-flow facies of the Chetaslina volcanic mass-flow deposit along the Tonsina River. See Fig. 2 for location of sections and Fig. 7 for explanation of symbols. Note that upstream and downstream refer to the inferred flow direction of the Chetaslina volcanic mass-flow which was opposite to the present flow direction of the Tonsina River.

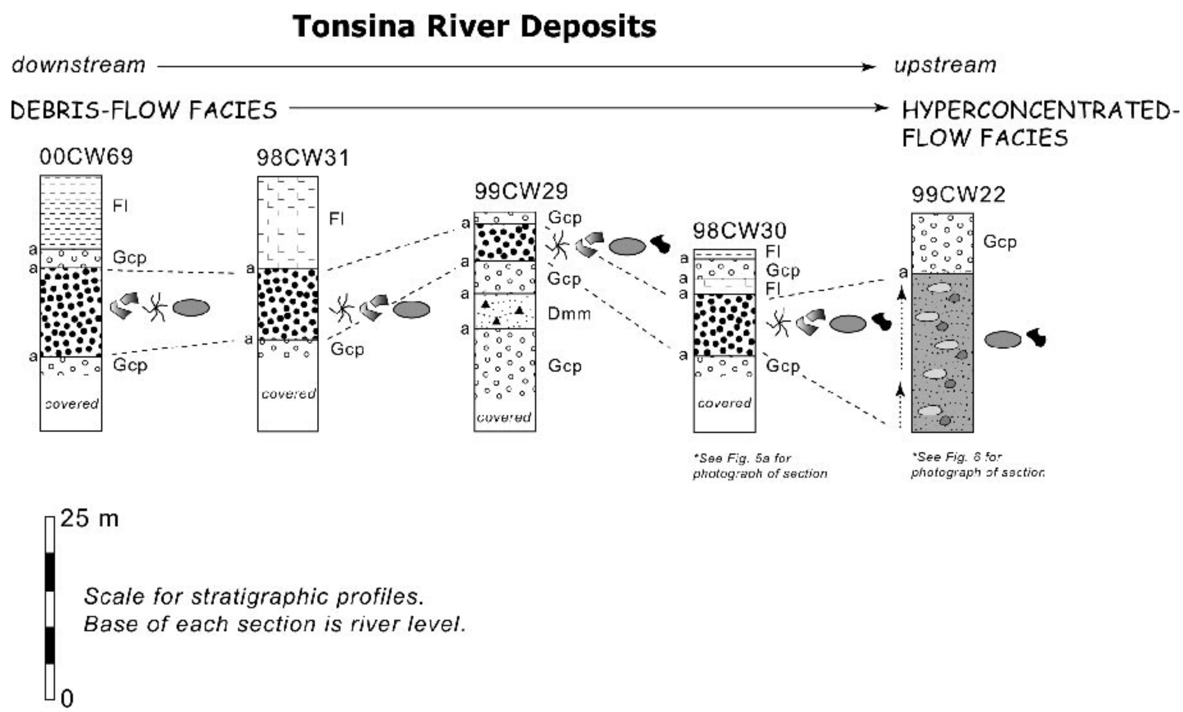


Fig. 11. Stratigraphic setting of debris-flow facies deposits along the Tonsina River.

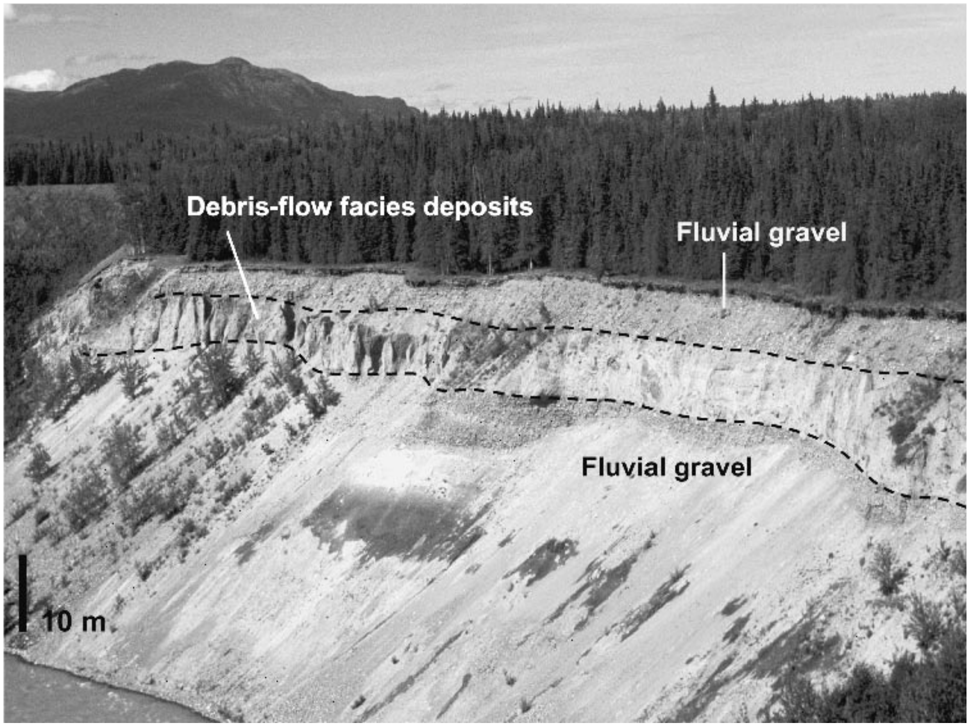
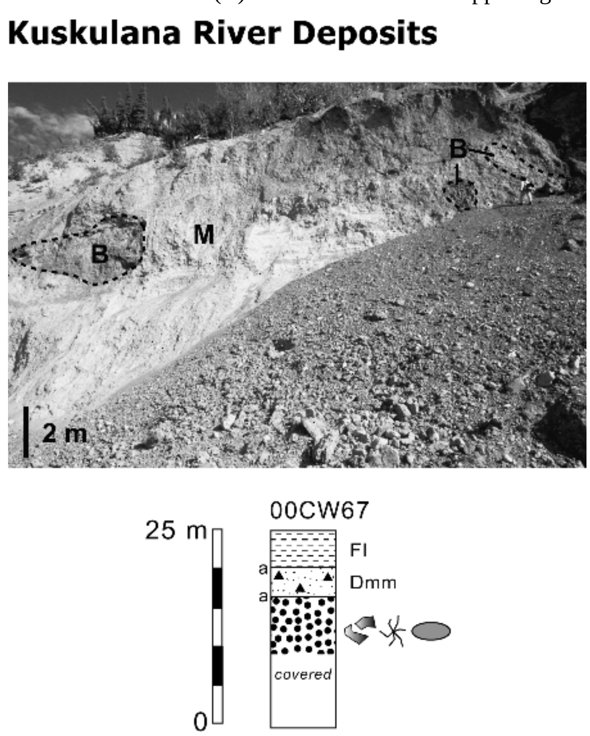


Fig. 12. Debris-flow-facies deposits exposed along the right bank of the Kuskulana River, site 00CW67. See Fig. 2 for location of section and Fig. 7 for explanation of symbols. About 80% of this deposit consists of matrix (M) with isolated boulder-size particles of altered volcanic rock (B). Person for scale in upper right.



that were identified by Yehle and Nichols (1980). During our fieldwork in 1999 and 2000, the Chitina River flowed along the base of the known outcrops of the Chetaslina volcanic mass-flow deposit and prevented access by foot. The deposits in this area resemble the debris-flow facies deposits we examined along the Kuskulana River and are the most distal known deposits of the Chetaslina volcanic mass-flow deposit.

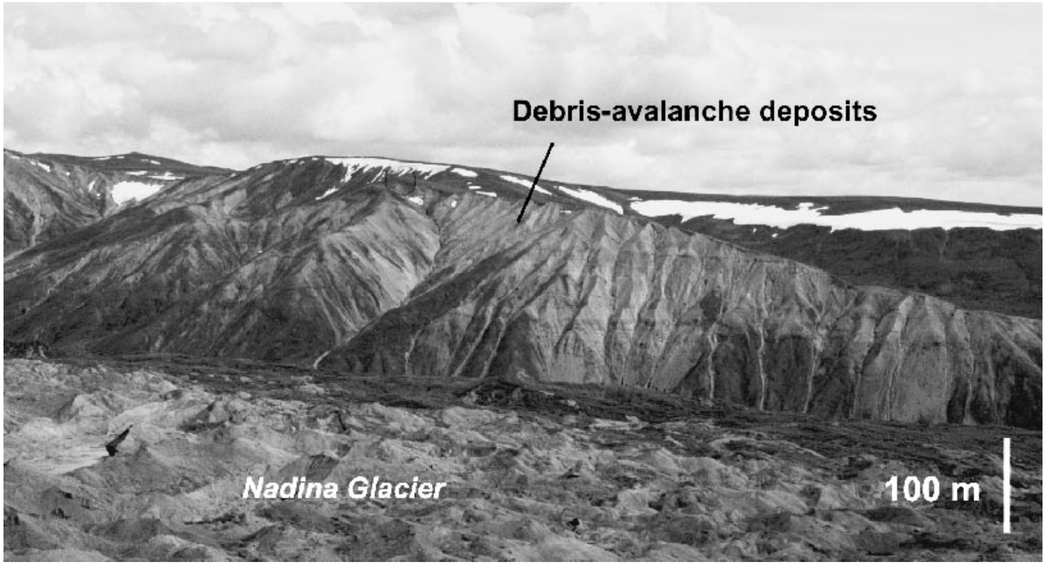
Origin of the Chetaslina volcanic mass-flow deposit

Major-element chemistry

Identification of the source volcano for the Chetaslina volcanic mass-flow deposit was an important objective of this study. We assumed that deposits of the Chetaslina volcanic mass-flow deposit should contain rock types that are geochemically distinct and therefore diagnostic of the source volcano, either Mount Drum or Mount Wrangell. We sought to characterize the Chetaslina volcanic mass-flow deposit geochemically by obtaining major-element data on clasts sampled from debris-avalanche blocks at most of the outcrops we visited (Fig. 2). Cobble-size clasts were collected from fractured debris-avalanche blocks and boulders present in all of the facies types, but primarily from block-facies deposits. The major-element compositions (reported as oxides) of clasts from the Chetaslina volcanic mass-flow deposit and Nadina Glacier debris-avalanche deposit were determined using wavelength-dispersive X-ray fluorescence spectrometry (Arbogast 1996). Analyses were performed by the U.S. Geological Survey, Geologic Division Geochemistry Lab, Denver, Colorado.

Mount Drum and Mount Wrangell are the only possible source volcanoes for the Chetaslina volcanic mass-flow deposit. Therefore, we compared the major-element composition of clasts from the Chetaslina volcanic mass-flow deposit with the major-element composition of lavas from Mount Wrangell (D.H. Richter, unpublished data; Nye 1983), clasts from the

Fig. 13. Debris-avalanche deposits along Nadina Glacier near Mount Drum, site 00CW70. Note the sedimentologic differences between the deposits shown in this photograph with those of the Chetaslina volcanic mass-flow deposit shown in Figs. 7 and 8.



Nadina Glacier debris-avalanche deposit, and lavas from the Chetaslina vent area in the upper Chetaslina River drainage (Nye 1983). Although a detailed analysis of these data is beyond the scope of this paper, we illustrate the differences among the groups of samples using standard alkali–silica plots (Fig. 14) and ternary diagrams of $Na_2O + K_2O–Fe_2O_3–MgO$ (Fig. 15).

The alkali–silica diagram comparing data from the Chetaslina volcanic mass-flow deposit and Nadina Glacier debris-avalanche deposits indicates a slight, but distinct difference between the two groups (Fig. 14A). The group means and standard deviations do not overlap and the slopes of the regression lines through each set of data are different, possibly indicating two separate suites of rocks. The alkali– silica plot comparing data from Mount Wrangell lava flows with the Chetaslina volcanic mass-flow deposit also indicates a slight, but distinct difference (Fig. 14B). The group means and standard deviations overlap slightly and the regression lines are parallel. The lavas from Mount Wrangell erupted from a vent located to the northeast of the Chetaslina vent area and may have been derived from a different magmatic system. Finally, the alkali–silica diagram comparing the Chetaslina volcanic mass-flow deposit with the ancestral Chetaslina vent lavas (Fig. 14C) shows significant overlap of the oxide data, indicating that the samples from these two groups have similar composition.

A ternary diagram that compares $Na_2O + K_2O–Fe_2O_3–MgO$ for samples of the Chetaslina volcanic mass-flow deposit with lavas from Mount Wrangell (Fig. 15A) shows that the two groups are similar and cannot be differentiated with respect to these oxides. However, a similar diagram that compares samples of the Chetaslina volcanic mass-flow deposit with samples of the debris-avalanche deposit along the Nadina Glacier from Mount Drum shows two distinct but overlapping fields (Fig. 15B) and indicates a possible difference among the two groups of samples.

Zones of altered rock and the Chetaslina vent area

An area of highly altered volcanic rock is present on the southwest side of Mount Wrangell about 10 km from the summit crater (Fig. 2). This area includes the remnants of an older, deeply dissected volcano or vent named the Chetaslina vent (Nye 1983). The altered lava flows associated with the Chetaslina vent lie beneath the lavas erupted from Mount Wrangell (Fig. 16) and are therefore older than the bulk of the Mount Wrangell lavas (Nye 1983). The geologic history of the Chetaslina vent is not known, although Nye (1983) suggests that the altered rocks in the vicinity of the vent may be the roots of a larger volcano destroyed by a significant eruption.

The Chetaslina vent area (Figs. 2, 16) is the only known locality of extensively altered lavas on or near Mount Wrangell. Many of the rocks in this area are altered to clay and weather to bright, high-chroma, yellow-brown colors. Similar-appearing altered rocks are present in the Chetaslina volcanic mass-flow deposit. Furthermore, the major-element chemistry of lavas from the Chetaslina vent area is similar to the major-element chemistry of clasts in the Chetaslina volcanic mass-flow deposit (Fig. 14C).

Source of the Chetaslina volcanic mass-flow deposit

Areas of hydrothermally altered rock on volcanoes may be susceptible to failure leading to edifice collapse and debris-avalanche formation (Vallance and Scott 1997; Reid et al. 2001). Hydrothermally altered volcanic rock typically contains significant amounts of low-strength clay with appreciable pore water (Crandell 1971) and was an important causal factor in some large flank collapses (Siebert 1984). In view of the relation between hydrothermal alteration, instability, and edifice collapse, we suggest that the source of the Chetaslina volcanic mass-flow deposit was the Chetaslina vent area on the southwest flank of Mount Wrangell. Hydrothermally altered volcanic rocks are common in the Chetaslina volcanic mass-flow deposit, and we know of no other source for these rocks, except the Chetaslina vent area. Highly altered rocks are conspicuously absent from the debris-avalanche deposits along the Nadina Glacier derived

Fig. 14. Alkali–silica plots for representative samples of the Chetaslina volcanic mass-flow deposit and possible source areas. (A) Comparison of Chetaslina volcanic mass-flow deposit with Nadina Glacier debris-avalanche deposit. (B) Comparison of Chetaslina volcanic mass-flow deposit with Mount Wrangell lava flows. (C) Comparison of Chetaslina volcanic mass-flow deposit with Chetaslina vent lava flows.

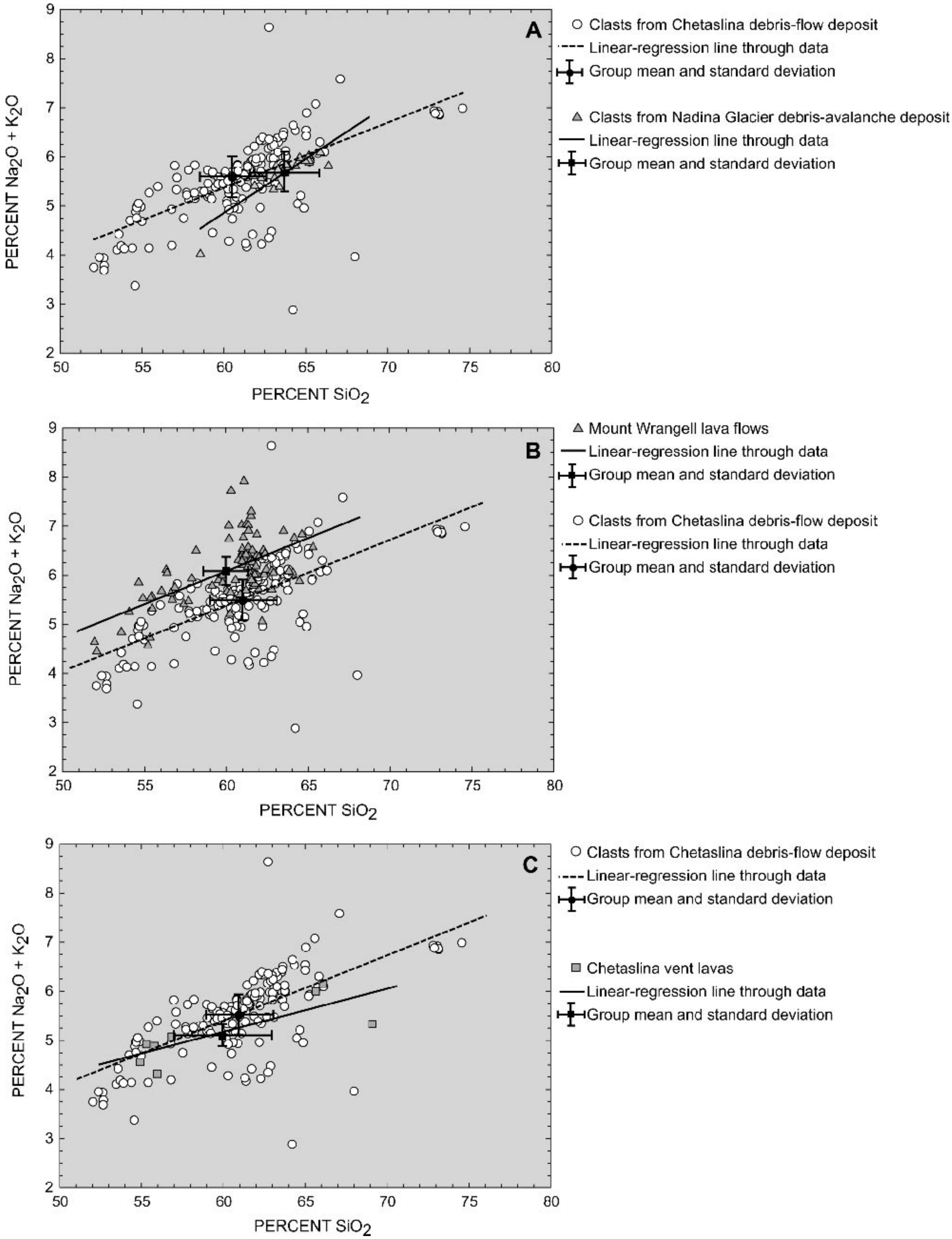


Fig. 15. Ternary diagrams of major-oxide composition of representative samples of the Chetaslina volcanic mass-flow deposit and possible source areas. (A) Comparison of Chetaslina volcanic mass-flow deposit with Mount Wrangell lavas. (B) Comparison of Chetaslina volcanic mass-flow deposit with Nadina Glacier debris-avalanche deposit.

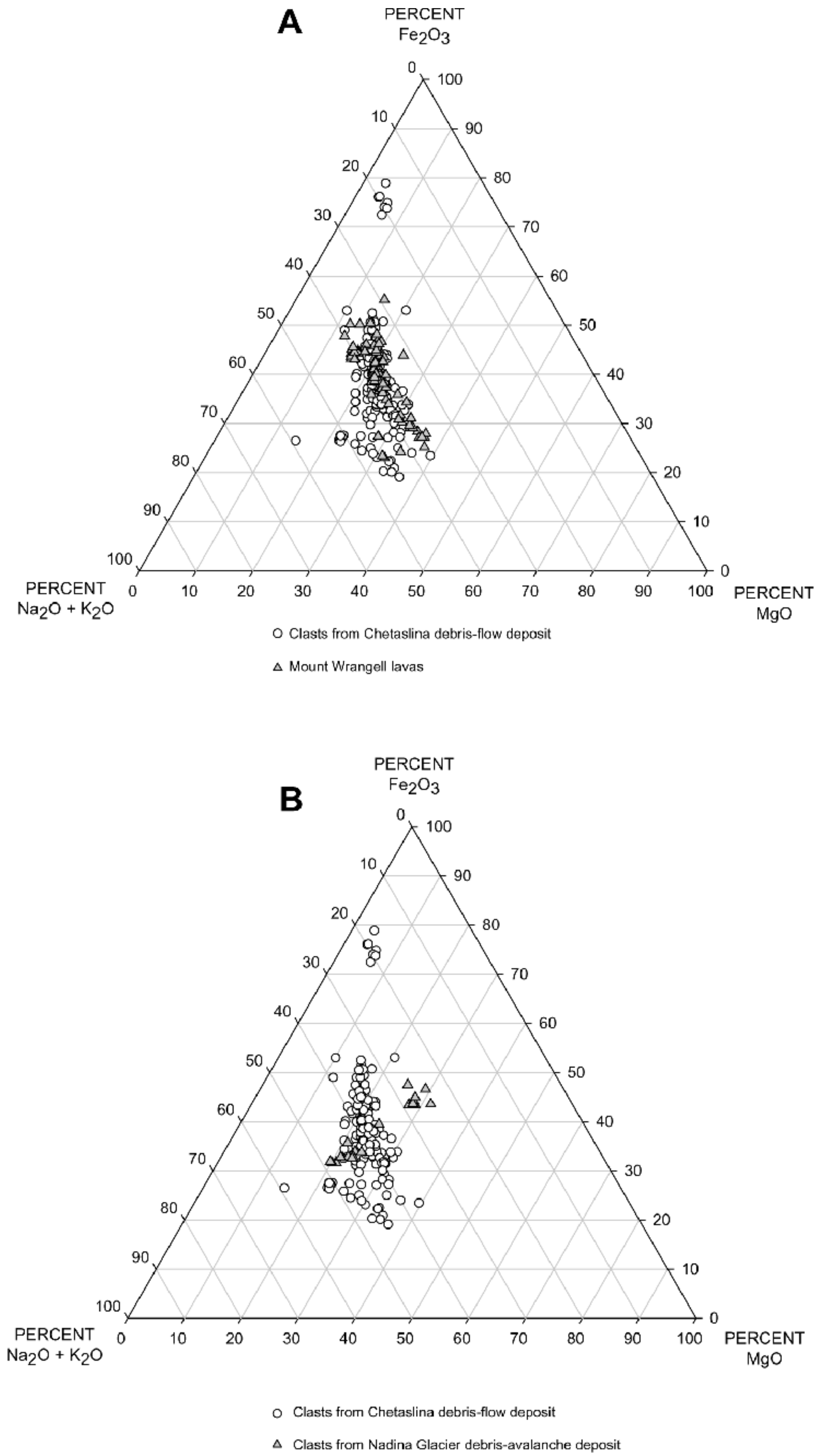
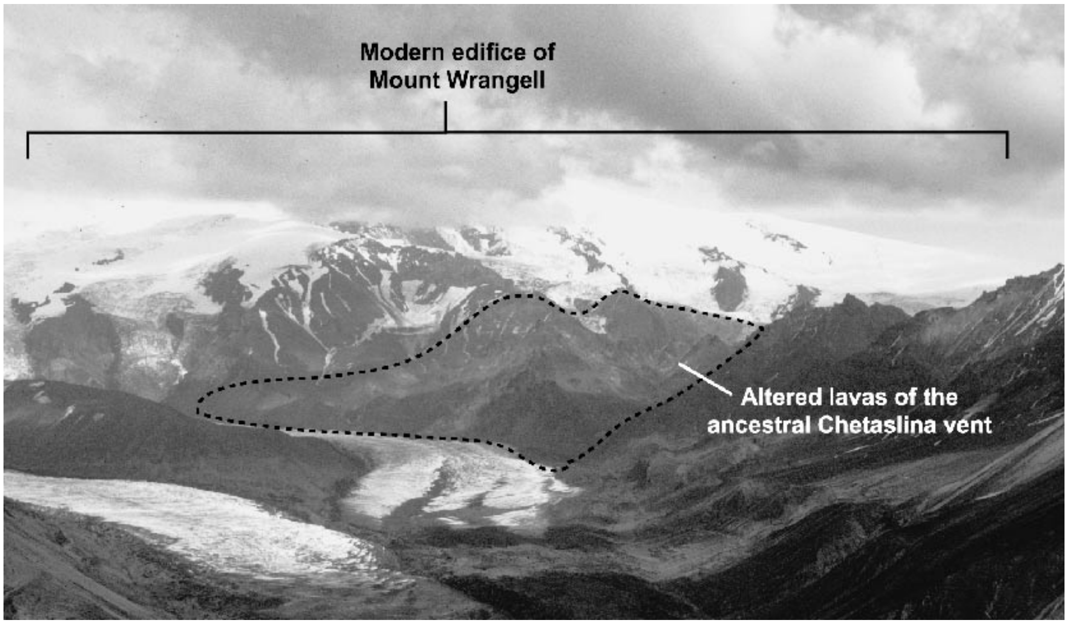


Fig. 16. Southwest flank of Mount Wrangell and the Chetaslina vent area. Hydrothermally altered rocks of the Chetaslina vent area outlined by dashed line. These rocks underlie an extensive sequence of lava flows that form the modern edifice of Mount Wrangell. Chetaslina Glacier in foreground.



from Mount Drum. Therefore, we conclude that the Chetaslina vent area is the most likely source for the Chetaslina volcanic mass-flow deposit.

Evolution of the Chetaslina volcanic mass-flow deposit

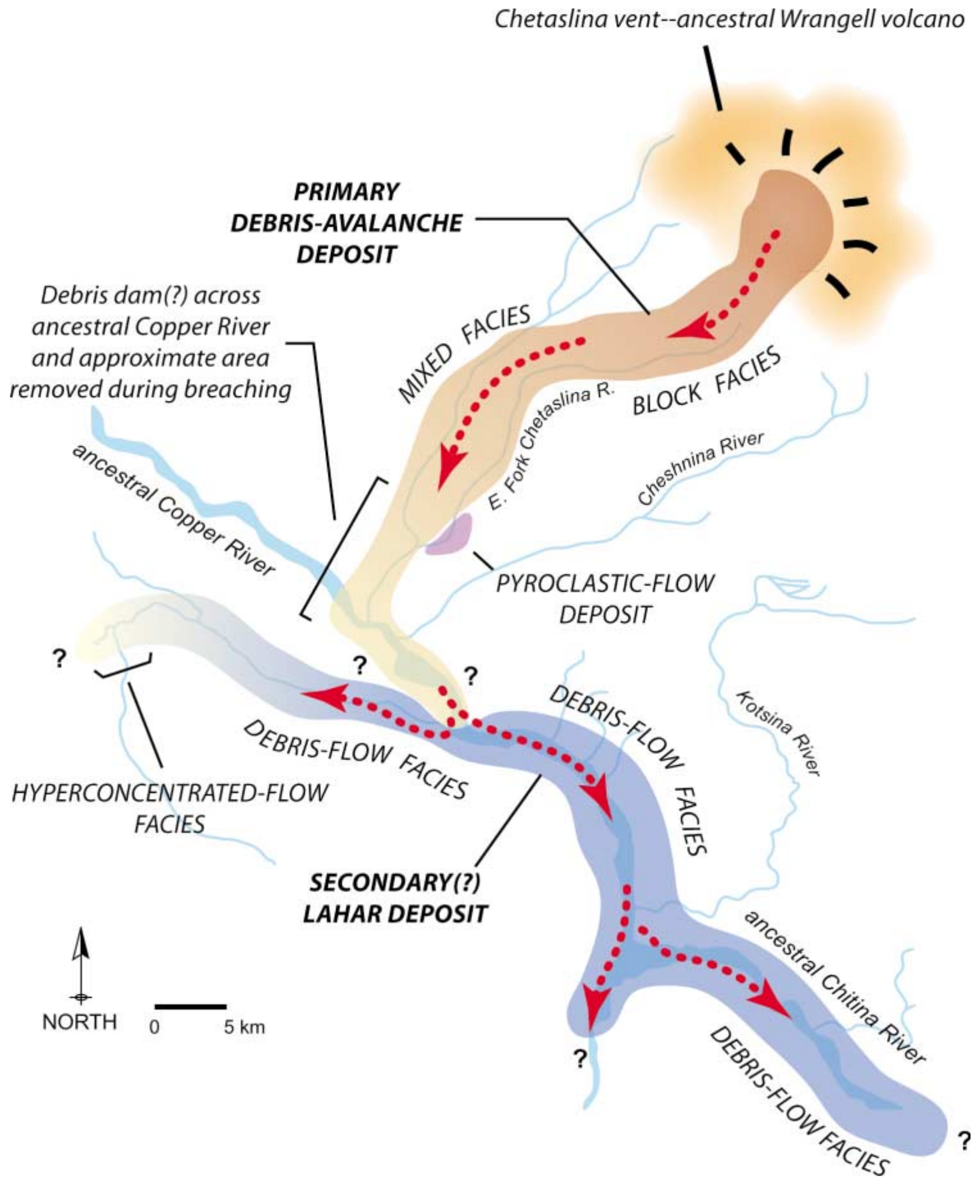
The Chetaslina volcanic mass-flow deposit is genetically related to the destruction of an ancestral volcano by flank collapse on the southwest side of Mount Wrangell (Fig. 2). An area of hydrothermally altered volcanic rock, some lava flows, and dikes in the vicinity of the Chetaslina vent described by Nye (1983) is all that remains of this ancient volcano. The distribution of facies types present in the Chetaslina volcanic mass-flow deposit indicates a general downstream progression from a block rich debris avalanche, to a more matrix rich debris avalanche, to debris flow, and finally, to hyperconcentrated flow (Fig. 17). Because block-facies deposits are most common in the upper East Fork Chetaslina River drainage, we infer that the bulk of the avalanche debris entered the East Fork drainage and then flowed into the Chetaslina drainage (Fig. 17). As the avalanche began to translate downstream, fine, angular debris was generated by intense particle interaction and fragmentation of debris-avalanche blocks that led to the development of the mixed facies. In general, the Chetaslina volcanic mass-flow deposit exhibits a decrease in maximum evident particle size and thickness with increasing distance along the presumed flow path. The avalanche may have partially removed a pumice- and scoria-rich pyroclastic-flow deposit near the present confluence of the East Fork and Chetaslina rivers (Fig. 8) and then came to rest near the mouth of the Tonsina River (Fig. 17).

Transformation of the debris avalanche to a debris flow and hyperconcentrated flow was brought about by the addition of water to the flow. The source of this water could have been the ancestral Copper, Chetaslina, and East Fork Chetaslina rivers, in which case, mixing of the debris avalanche with these rivers could have diluted the flow to produce the debris-flow and hyperconcentrated-flow facies. Other sources of water could have been groundwater, permafrost, or glacier ice. It is possible that the debris avalanche formed a short-lived debris dam across the ancestral Copper River, which would have increased the amount of water available for downstream flow transformation. Breaching and erosion of the debris dam could have led to the formation of the debris-flow and hyperconcentrated-flow facies (Fig. 17) and may explain the lack of Chetaslina volcanic mass-flow deposits along the lower part of the Chetaslina River and in the reach of the Copper River between the mouth of the Chetaslina and Tonsina rivers (Fig. 2).

About one-third of the previously reported extent of the Chetaslina debris flow of Yehle and Nichols (1980) actually consists of primary debris-avalanche deposits. The average thickness of debris-avalanche deposits exposed along the Chetaslina, East Fork Chetaslina, and Copper rivers is about 40 m. This gives a volume estimate of about 4 km^3 for the primary debris-avalanche deposit. If the Chetaslina vent is the source area of the Chetaslina volcanic mass-flow deposit, the runout distance of the primary deposit is about 50 km.

Downstream from the confluence of the Tonsina and Copper rivers, the Chetaslina volcanic mass-flow deposit consists of debris-flow facies deposits that contain a significant amount of nonvolcanic blocks, some as large as 4–6 m in diameter. All of these blocks were derived from preexisting glacial and glaciolacustrine deposits in the Copper River lowland. The nonvolcanic blocks indicate that the flow was capable of entraining large chunks of possibly frozen sediment from the bed and banks of the ancestral Copper River and its tribu-

Fig. 17. Revised extent and facies distribution of the Chetaslina volcanic mass-flow deposit.



taries. Only a highly erosive, channelized flow with a relatively large fluid component could accomplish this task. The geomorphology of the Copper River lowland at the time the Chetaslina volcanic mass-flow deposit was emplaced was probably similar to that of today, except that the area may not have been forested (as it is today), because we find no logs or woody debris in the Chetaslina volcanic mass-flow deposit. Relatively deep canyons and valleys must have existed to channelize the flow and allow for bank undercutting and collapse. Debris-flow facies deposits of the Chetaslina volcanic mass-flow deposit exposed along the Tonsina River rest on fluvial gravel deposits and indicate that the flow in this area inundated a braided, gravel-bed stream.

Flow processes and transformation

The sedimentologic characteristics of the Chetaslina volcanic mass-flow deposit are used to make some general inferences about transport processes. We note, however, that using mass-flow deposits to make inferences about flow processes has important limitations that arise from the inability of a static deposit to fully capture the dynamic nature of the flow. Specific attributes of a mass flow, such as, width, depth, velocity, pore-fluid pressure, degree of mixture agitation (i.e., granular temperature, Campbell 1989), and others may be difficult to estimate from the deposits alone, and such attributes are known to vary considerably throughout the duration of the flow (Iverson 1997).

Recent evaluations of concentrated granular mass flows indicate that rock avalanches and some debris flows move as gravity driven, particle-rich flows that have either friction or collision dominated flow regimes (Iverson and Vallance 2001; Iverson and Denlinger 2001). In such flows, Coulomb friction describes the aggregate stresses associated with particle interactions within the flow and between the flow and its substrate (Savage and Hutter 1989; Iverson and Vallance 2001). The dominant flow regime of a granular mass flow can be estimated by calculating two nondimensional numbers

Table 2. Estimates of key physical and dimensionless parameters for the various facies of the Chetaslina volcanic mass-flow deposit.

Physical and *dimensionless parameters*	Symbol (units)	Block facies	Mixed facies	Debris-flow facies
Solid density	ρ_s (kg·m^{-3})	2400–2700	2400–2700	2400–2700
Fluid density	ρ_f (kg·m^{-3})	2	2	1200
Typical grain diameter	δ (m)	2–10	1–5	0.5–1
Flow shear rate	γ (s^{-1})	5(?)	5–10(?)	3–50
Typical flow thickness	H (m)	10–100	10–20	10–20
Solid volume fraction	ν_s	0.5(?)	0.5(?)	0.6(?)
Fluid viscosity	μ (Pa-s)	2×10^{-5}	2×10^{-5}	0.1
Savage number	N_s	>0.2	>0.1	>0.1
Bagnold number	N_b	$>10^7$	$>10^5$	$>10^5$

Note: Queried values represent uncertain estimates. Values for ρ_s, ρ_f, γ, ν_s, and μ from Iverson and Denlinger 2001.

(N_s, the Savage number, and N_b, the Bagnold number) that relate grain collision stresses, gravitational grain contact stresses, and viscous stresses that arise during granular mass flow. Following Iverson and Denlinger (2001), the dimensionless parameter N_s (Savage 1984), gives an approximate ratio of grain collision to grain contact stresses and provides a physically based means of ascertaining the principal flow regime in steady, free-surface gravity flows of granular media

$$[1] \qquad N_s = \frac{\rho_s \gamma^2 \delta^2}{(\rho_s - \rho_f) g H}$$

where, ρ_s and ρ_f are the solid and fluid densities respectively, γ is the shear rate, δ is a characteristic grain diameter, g is the gravitational constant, and H is flow depth. Representative values for H and δ were determined from field observations, where deposit thickness is used to approximate H and values for all other variables are from Iverson and Denlinger (2001). It is difficult to determine the shear rate γ of an unobserved flow, and therefore, we use values estimated for known geophysical mass flows (Iverson and Vallance 2001, Table 1). We also use a range of values for δ (Table 2), and these correspond to the most abundant size range in each facies type. According to Savage and Hutter (1989), the flow regime of granular mass flows is dominated by grain-collision stresses when $N_s > 0.1$. Application of eq. [1] to the Chetaslina volcanic mass-flow deposit indicates that $N_s > 0.1$ for the block-, mixed-, and debris-flow facies (Table 2) for almost all reasonable combinations of the estimated parameter values. These results indicate that the dominant flow regime of the Chetaslina volcanic mass flow was probably a collision-dominated granular flow, however, estimates of N_s are strongly dependent on γ. For this flow regime to develop, fragmentation of debris-avalanche blocks must have occurred soon after the flow began and this must have generated matrix sediment accompanied by dilation of the flow. If fragmentation occurs early in the flow process, the granular mixture could become dilated and grain collisions would characterize flow behavior. Block facies deposits of the Chetaslina volcanic mass flow exhibit zones of angular rock rubble in the contact space between debris-avalanche blocks, and this indicates that interparticle shear was occurring during flow and implies that there were intervals of frictional contact among blocks. If the flow regime was friction dominated, Savage number estimates would be consistently < 0.1 (Iverson and Denlinger 2001; Iverson and Vallance 2001). Frictional contact among debris-avalanche blocks may have occurred during the deceleration phase or along the margins of the mass flow, as the larger particles became lodged against the bed or each other.

We further evaluate the flow regime of the Chetaslina volcanic mass flow by calculating N_b, the Bagnold number, a dimensionless parameter that estimates the ratio of grain-collision stresses to viscous shear stresses (Iverson and Vallance 2001; Iverson and Denlinger 2001)

$$[2] \qquad N_b = \left[\frac{\nu_s^{1/3}}{\nu_*^{1/3} - \nu_s^{1/3}}\right]^{1/2} \frac{\rho_s \gamma \delta^2}{\mu}$$

where ν_s is the solid volume fraction, ν_* the maximum solid volume fraction ($\nu_* = 0.7$), and μ is the fluid viscosity; other terms as defined earlier in the text for eq. [1]. Using representative values estimated from the Chetaslina volcanic mass-flow deposit (Table 2), N_b exceeds about 10^7 for the block and mixed facies and about 10^5 for the debris-flow facies. Values of $N_b > 450$ indicate a collision-dominated flow regime (Bagnold 1954; Savage and Sayed 1984; Iverson and Denlinger 2001).

Fragmentation of debris-avalanche blocks is a mechanism that could generate interparticle matrix and this could lower the interparticle stresses, resulting in $N_s > 0.1$. Development of a mechanically fluidized basal layer (Campbell 1989) would facilitate continued motion of the debris avalanche, but the base of the Chetaslina volcanic mass-flow deposit was rarely exposed, and we were not able to confirm this effect with field evidence.

Estimates of N_s and N_b are strongly dependent on the values selected for grain diameter and shear rate. Although we can determine grain diameter with field measurements, it is difficult to know if the chosen grain diameter appropriately characterizes the flow, especially for a flow that has a great diversity of grain sizes. Observations of shearing granular mass flows allow calculation of shear rate as the flow speed divided by flow depth and typical values are given by Iverson and Vallance (2001). Assuming that the flow speed of the Chetaslina volcanic mass flow was similar to large observed flows (generally 40–80 m·s^{-1}; Siebert 1996), the range of values we use for γ seems reasonable. Our characterization of the flow regime in this manner is consistent with the sedimentary architecture of the deposit and suggests that the deposit texture at the outcrop scale is largely the result of a collision-dominated mass flow.

Rounded blocks of unconsolidated nonvolcanic sediment are common in some mixed facies deposits. This indicates that the mass flow was able to erode its bed and round particles several metres in diameter suggesting that the flow associated with the mixed facies was at least partially turbulent. The role of pore fluids in the development of the mixed facies is uncertain, but the massive, unsorted, somewhat blended nature of the mixed facies is suggestive of viscous fluid-like flow. Nonvolcanic blocks in the mixed facies likely were derived from the banks of channels incised in Quaternary glacial and glaciolacustrine deposits indicating that the debris avalanche was channelized and probably flowed into an ancestral drainage system. The addition of water and sediment to the flow initiated transformation of the debris avalanche to a debris flow and the debris flow inundated an area downstream at least twice as large as the area covered by the primary debris avalanche. If the debris avalanche had not been confined to a channel, it would have behaved like an unconfined, radially spreading granular flow, formed a fan-shaped deposit (e.g., Palmer et al. 1991) and likely would not have reached the ancestral Copper River.

Conclusions

The Chetaslina volcanic mass-flow deposit is a complex deposit of Pleistocene age that represents a major event in the evolution of the Wrangell volcanic field. The Chetaslina volcanic mass-flow deposit consists of two distinct parts, a debris-avalanche component and a debris-flow component (Fig. 17). The deposit records the collapse of a preexisting volcano southwest of Mount Wrangell previously identified by Nye (1983) and called the Chetaslina vent. The sedimentary architecture of the Chetaslina volcanic mass-flow deposit and its geochemical characteristics are consistent with a source in the Chetaslina vent area. The debris avalanche includes two facies types, the block and mixed facies, and they indicate that the debris avalanche transformed from a block supported debris avalanche to a block-bearing but matrix-rich flow. Further transformation of the debris avalanche to debris flow must have involved the addition of water to the flow, either by mixing with the ancestral Copper River and its tributaries or as a result of breaching of a debris dam formed by the avalanche across the Copper River. Water liberated from hydrothermal clays in the avalanche debris, melting of glacier ice, lakes, permafrost, and groundwater also may have contributed water to the flow. Because debris-avalanche deposits are exposed only along the Chetaslina and East Fork Chetaslina rivers, we are uncertain of the lateral extent of the debris avalanche in the Chetaslina River drainage basin. We did not find deposits of the Chetaslina volcanic mass-flow deposit in the Cheshnina drainage to the south or in the Dadina drainage to the north and suggest that the flow was confined to a channel or valley incised in Quaternary glacial and glaciolacustrine deposits. Thus, the extent of the debris-avalanche deposits shown in Fig. 17 is probably a reasonable approximation and yields a volume of about 4 km^3. Yehle and Nichols (1980) reported a volume of 12.6 km^3 for the Chetaslina debris flow, and Richter et al. (1995 Fig. 17) show an area inundated by the debris flow that is at least five times our estimate. These estimates of the size of the Chetaslina volcanic mass-flow deposit include all possible volcanic mass-flow deposits in the southeastern Copper River lowland and require a correspondingly large source crater. The only obvious candidate is the southwest flank of Drum Volcano (Richter et al. 1995). The sedimentological characteristics of the debris-avalanche deposit just beyond Drum Volcano along the Nadina Glacier (Fig. 13) are clearly different from those we have presented for the Chetaslina volcanic mass-flow deposit and indicate that Mount Drum is not a likely source volcano for the latter. If Mount Wrangell itself was the source of the Chetaslina volcanic mass-flow deposit, as suggested by Yehle and Nichols (1980), a large, conspicuous, amphitheater-shaped collapse scar should be present somewhere on the southwest flank of the volcano. We know of no such feature and suggest that a much smaller collapse occurred and that it removed a preexisting edifice in the Chetaslina vent area to form the debris-avalanche component of the Chetaslina volcanic mass-flow deposit.

During our field studies of the Chetaslina volcanic mass-flow deposit, we found only one location (site 99CW27, Fig. 2) where more than one mass-flow deposit could be identified in stratigraphic succession (Figs. 7F, 7G). Only one of the deposits at this location is part of the Chetaslina volcanic mass-flow deposit; we interpret the other two as local debris-flow deposits possibly derived from the erosion of the debris-avalanche deposit. Previous studies of the Chetaslina volcanic mass-flow deposit by Nichols and Yehle (1985) described three different mass-flow deposits. We could find no evidence to substantiate three distinct volcanic-flowage events in the southeastern Copper River lowland, nor were we certain of any easily applied field criteria that would be useful for distinguishing deposits of different age. The simplest explanation for the origin of the Chetaslina volcanic mass-flow deposit is that it represents a single event brought about by a Bandai-type collapse (Siebert et al. 1987) of an ice-clad, highly altered volcanic edifice in the Chetaslina vent area from 340 to 270 ka.

The Chetaslina volcanic mass flow was a channelized, collision-dominated granular mass flow that rapidly transformed from a volcanic landslide to debris avalanche by fragmentation of the failed edifice. Numerical estimates of the Savage (N_s) and Bagnold (N_b) numbers indicate that grain collisions likely were the dominant influence on the flow regime although we regard our estimates of these dimensionless parameters as crude at best.

The extent to which hydrothermally altered volcanic rock associated with the Chetaslina vent extends beneath Mount Wrangell is not known; therefore, it is difficult to assess the stability of the present edifice. Volcanic activity at Mount Wrangell appears to be on the wane and no eruptions of note have occurred historically. However, the heat flux through the volcano is sufficient to perturb the summit ice cap (Benson and Follett 1986) and may indicate that acid-sulfate weathering of a portion of the edifice may be occurring. Surface deformation of the volcano has not been observed although, if present, it could be concealed by the massive cover of snow and ice. A future collapse of Mount Wrangell is not likely, but for now, the best guide to the nature of a future event are the characteristics of the Chetaslina volcanic mass-flow deposit.

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