Studies by the U.S. Geological Survey in Alaska, Volume 15

Stratigraphy, Paleoflora, and Tectonic Setting of the Paleogene Sheep Creek Volcanic Field, Central Alaska

Professional Paper 1814–G

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of a scene from the Sheep Creek volcanic field in the Alaska Range. Rocks in the foreground expose the unconformable contact between deformed Paleozoic metasedimentary rocks (in the cliff face below) and undeformed rocks of the Sheep Creek volcanic field (in the gentler slope above). The geologist is sitting on the Paleocene–Eocene boundary—one of the two hottest times in the last 100 million years. Photograph by Timothy White.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

Abbreviations

CIA Chemical Index of Alteration

Ma million years before present (abbreviated from mega-annum)

PETM Paleocene–Eocene Thermal Maximum

USGS U.S. Geological Survey

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U.S. Geological Survey Professional Paper 1814–G
[Also see https://pubs.usgs.gov/AK_studies/]

Stratigraphy, Paleoflora, and Tectonic Setting of the Paleogene Sheep Creek Volcanic Field, Central Alaska

By Timothy White,[1] David Sunderlin,[2] and Dwight Bradley[3]

Abstract

In this paper, we provide new information on the stratigraphy and paleoflora of the Sheep Creek volcanic field in the Alaska Range that bolsters our understanding of a key interval in the tectonic, paleoclimate, and paleoenvironmental history of the northern Cordillera. Although the distribution and basic stratigraphy of these rocks have been previously reported, here we document the stratigraphic context of recently dated igneous rocks and paleosols ranging from the Paleocene–Eocene boundary to the early middle Eocene, describe a more complete fossil leaf flora from the succession, and place the Sheep Creek volcanic field in its regional tectonic context of ridge subduction and slab window migration in central Alaska.

Introduction

Upper Cretaceous and Paleogene volcanic rocks are exposed in several post-orogenic outcrop belts across the Talkeetna Mountains and Alaska Range of south-central Alaska (fig. 1). These dominantly volcanic successions, which include interbedded sedimentary rocks, bear on a key time interval in the tectonic, paleoclimate, and paleoenvironmental history of the northern Cordillera. Detailed studies of stratigraphy, geochronology, and (or) geochemistry have been published for some of these rocks, including the Caribou Creek volcanic field (Cole and others, 2006), the Jack River volcanic field (Cole and others, 2007), the Mount Galen Volcanics (Decker and Gilbert, 1978), and volcanic rocks in the Cantwell Formation (Hillhouse and Gromme, 1982; includes the Teklanika Formation of Gilbert and others, 1976). Other volcanic successions have seen little or no research beyond reconnaissance-scale geologic mapping (for example, Csejtey and others, 1992; Winkler, 1992; Bundtzen and others, 1997).

In this paper, we provide new information on the stratigraphy and paleoflora of the Sheep Creek volcanic field, which crops out in an irregular 20-square-kilometer (km^2) area in the western Alaska Range (fig. 2). Bundtzen and others (1982) established the distribution of these rocks during geologic mapping, at a scale of 1:40,000, in the McGrath B2 quadrangle. Bundtzen and others (1982) also worked out the basic stratigraphy and reported the presence of a Paleogene fossil leaf flora. Solie and others (1991) reported K-Ar ages (in million years ago [Ma]) of 49.0±3.4 Ma (whole rock) and 43.6±7.8 Ma (biotite in andesite). More recent, higher resolution U-Pb zircon and $^{40}Ar/^{39}Ar$ hornblende geochronology of tuffs has refined and extended the age range—56.0±1.9 Ma near the base of stratigraphic succession of the Sheep Creek volcanic field and 42.8±0.5 Ma at the top (Bradley and others, 2017). As discussed below in greater depth, these ages link the Sheep Creek volcanic field to an important time interval in the tectonic evolution of south-central Alaska, when subduction of an oceanic spreading center (herein referred to as ridge subduction) is inferred to have triggered the opening of an asthenospheric slab window beneath the region (Bradley and others, 2003). The stratigraphic succession of the Sheep Creek volcanic field also contains paleosols that inform paleoclimate reconstructions, including a 56- to 55-Ma paleosol developed on a volcanic ash that correlates with the approximately (~) 56-Ma Paleocene–Eocene Thermal Maximum (PETM). This paleosol is the most northerly of 10 late Paleocene to early Eocene paleosols that were used by White and others (2017) to construct a North American paleolatitudinal gradient of $d^{18}O$ values of paleosol siderite spherules during one of the warmest intervals in Earth history, when the climate altered the pedogenic landscape through enhanced weathering. The gradient was used as a baseline for interpreting anomalous $d^{18}O$ values from paleosol siderite spherules from the Yakutat terrane (along the Pacific coast just beyond the eastern limit of fig. 1), which are explicable if the terrane originated far to the south (White and others, 2017).

Both of the broadly focused papers cited above (Bradley and others, 2017; White and others, 2017) reported new analytical data for samples from the Sheep Creek volcanic field but did not include much geologic background. The purposes of this paper are to document the stratigraphic context of the dated igneous rocks and the paleosols, to describe a more complete Eocene fossil leaf flora from the succession, and to place the Sheep Creek volcanic field in its regional tectonic context.

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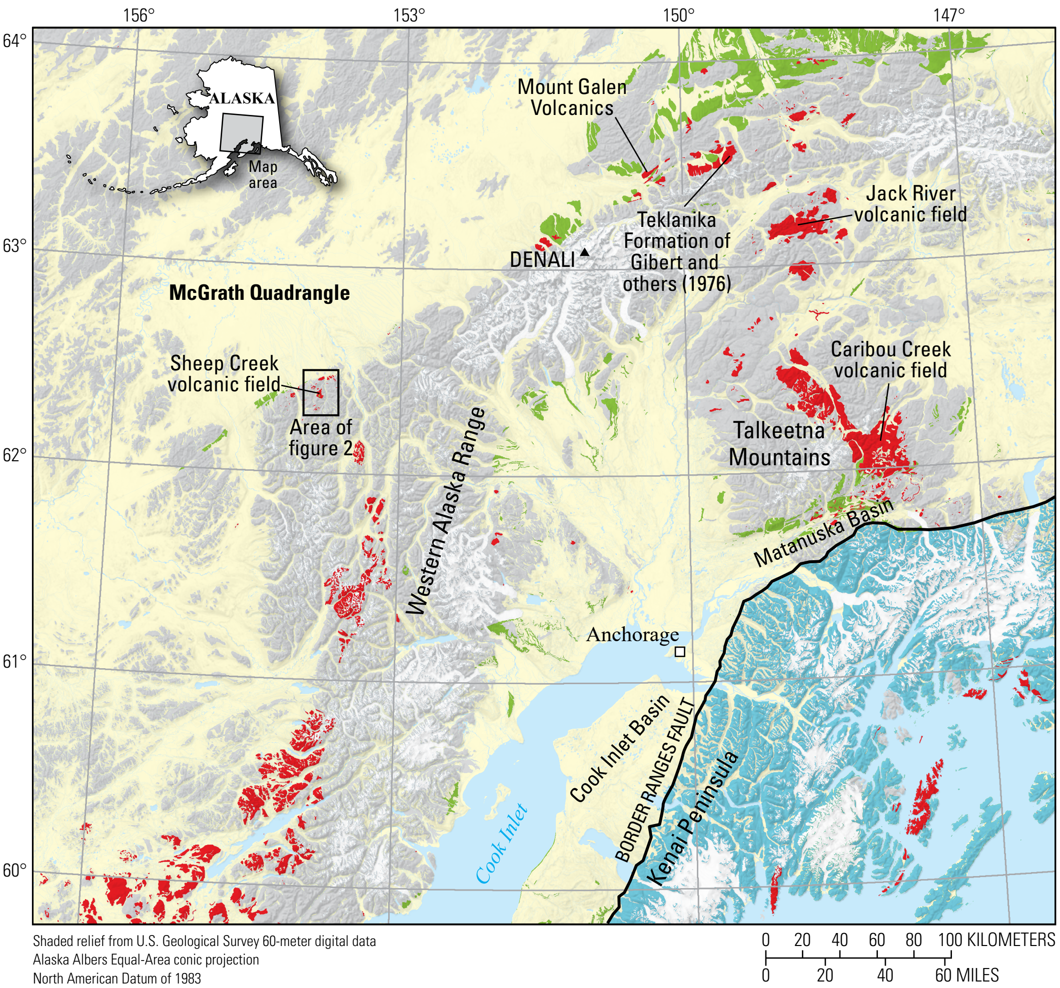


EXPLANATION

- Quaternary sediments
- Tertiary sedimentary rocks
- Tertiary extrusive rocks
- Rocks of the Chugach-Prince William terrane
- Bedrock, undifferentiated
- Snow and ice
- Fault

Figure 1. Map showing location of the study area in relation to other outcrop belts of similar-age volcanic rocks in south-central Alaska. Geology from Wilson and others (2015). The area shown as “Bedrock, undifferentiated” includes the Wrangellia-Peninsular-Alexander composite terrane and the Kahiltna assemblage of Box and others (2019). The name “western Alaska Range” refers to that part of the mountain range located west and southwest of Denali.

EXPLANATION

Stratified rocks

- Qs — Quaternary sediments
- Tcb — Coal-bearing sandstone, shale, and conglomerate (Neogene)
- Tevm — Mafic volcanic rocks (Eocene)
- Tevf — Felsic volcanic rocks (Eocene)

Mystic sequence or subterrane

- JTRtv — Mafic volcanic and intrusive rocks (Early Jurassic to Late Triassic)
- PDs — Sheep Creek formation of Bundtzen and others (1997)—Sandstone, shale, conglomerate (Permian to Late Devonian)
- Dl — Limestone and dolomite (Late Devonian)

Dillinger sequence or subterrane

- DSbr — Barren Ridge Limestone—Calcareous siltstone (Late Devonian to Silurian)
- Stc — Terra Cotta Mountains Sandstone—Turbiditic micaceous sandstone (Silurian)
- SOpr — Post River Formation—Black graptolitic shale and siltstone (late Silurian to Ordovician)

Intrusive rocks

- Teg — Granitic rocks (Eocene)
- Tpg — Granitic rocks (Paleocene)
- Tpm — Mafic plutonic rocks (Paleocene)
- Kucg — Granitic rocks (Late Cretaceous, 65–75 Ma)

Contact

Fault—Dashed where approximately located, dotted where concealed. Bar and ball on downthrown side. Sawteeth on upper plate. Arrows show sense of relative displacement

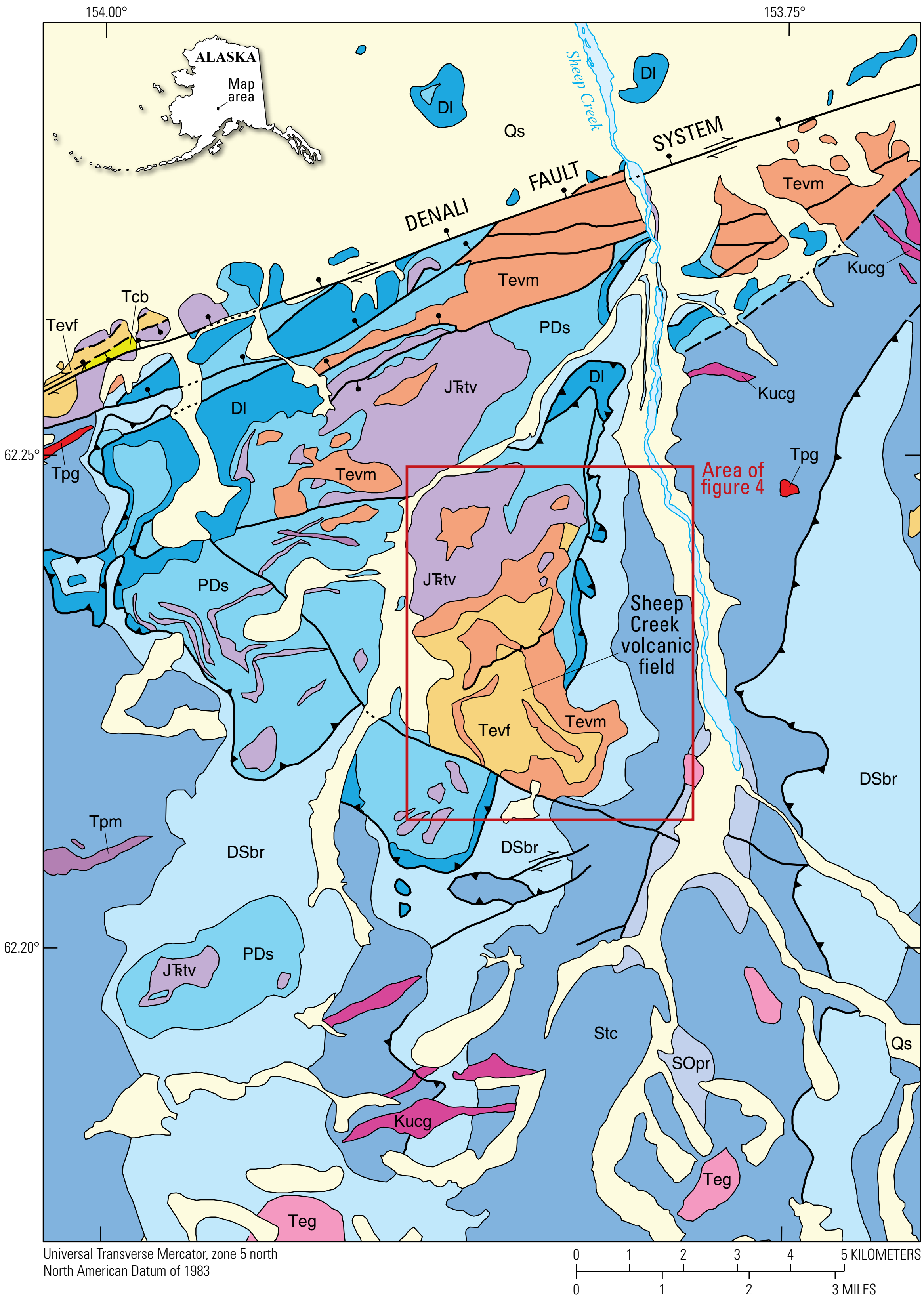


Figure 2 (pages 2–3). Geologic map of the Sheep Creek volcanic field (red box) and surrounding area in south-central Alaska. Modified from Bundtzen and others (1997).

Regional Geologic Framework

The western Alaska Range is the site of a wide, Late Cretaceous collisional suture zone of deformed Jurassic and Cretaceous turbidites, which are known as the Kahiltna assemblage (Box and others, 2019). The collision involved the Wrangellia-Peninsular-Alexander composite terrane to the south and the Farewell and Yukon-Tanana terranes to the north, which by the Late Cretaceous had been accreted to the North American margin (Box and others, 2019). The Sheep Creek volcanic field unconformably overlies recumbently folded turbidites that were involved in this collision. The turbidites were mapped as the informally named Sheep Creek formation by Bundtzen and others (1997), which is a late Paleozoic part of the Mystic subterrane of the Farewell terrane (Dumoulin and others, 2018). Note that the stratigraphic succession of the Paleogene Sheep Creek volcanic field and the informally named Devonian to Permian Sheep Creek formation (both of Bundtzen and others, 1997) (fig. 2) are entirely different and unrelated rock units.

The Late Cretaceous collision established the broad regional convergent-margin tectonic framework that still exists today. By about 70 Ma, four belts can be recognized: an accretionary prism (Chugach terrane), a forearc basin (Matanuska and Cook Inlet basins), a magmatic arc (in the western Alaska Range and southern Talkeetna Mountains), and a retroarc foreland basin (lower part of the Cantwell Formation) (Bradley and others, 2017). During the Paleogene, an oceanic spreading center is believed to have been subducted along the convergent margin of southern Alaska (fig. 3; Bradley and others, 2003; Haeussler and others, 2003). A chain of near-trench plutons is interpreted to show that the trench-ridge-trench triple junction (McKenzie and Morgan, 1969), where ridge subduction occurred, migrated about 2,000 km from west to east along the continental margin between ~61 and ~50 Ma. Two

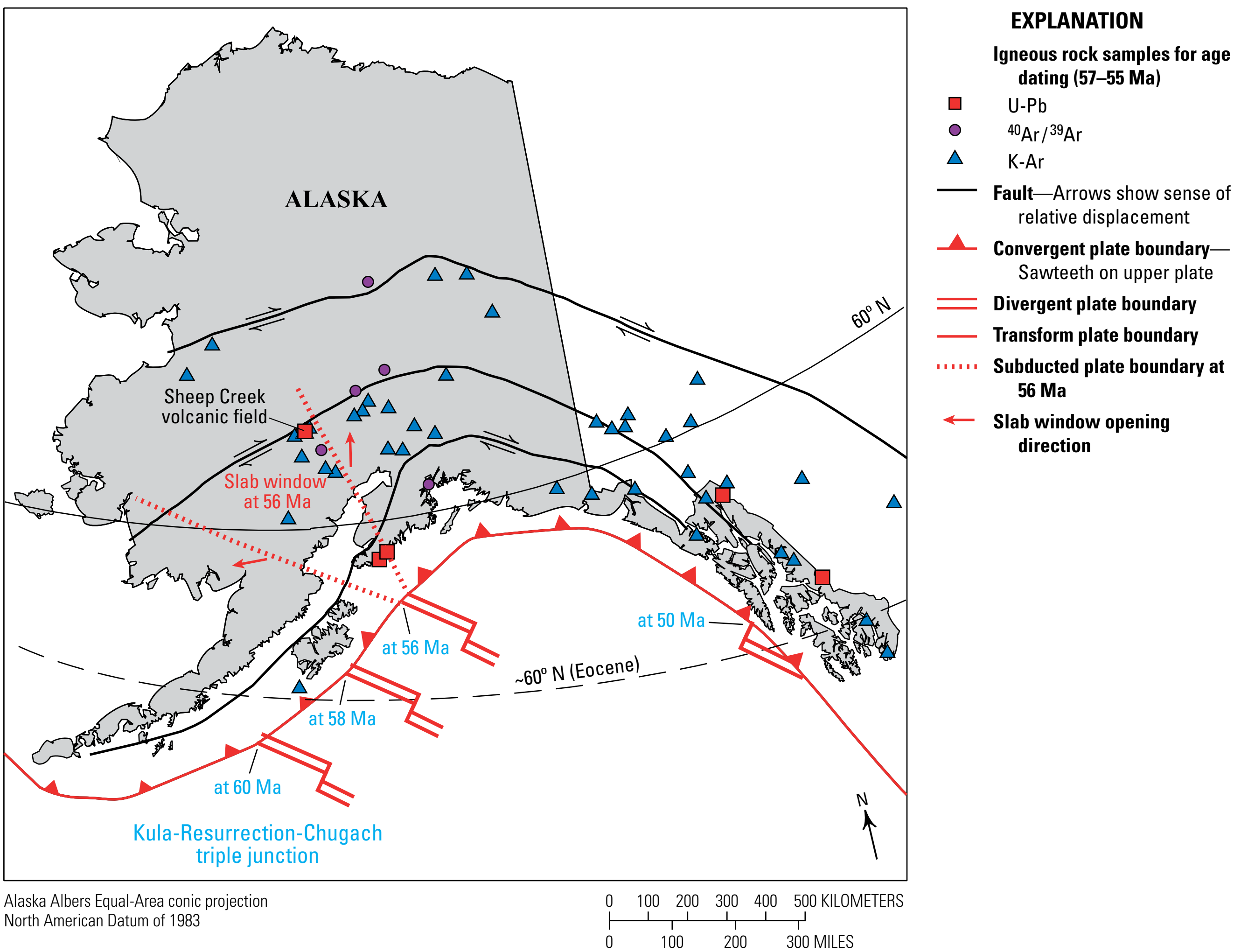


Figure 3. Map of Alaska showing location of the Paleogene subduction zone and migration of the Kula-Resurrection-Chugach triple junction from 60 to 50 million years ago (Ma). Also shown are the generalized outline of the slab window at 56 Ma and the locations of dated igneous rocks that bear on the location of the slab window at that time. Red arrows show the schematic subsurface trajectories of the subducted Resurrection and Kula Plates during opening of the slab window. Red dotted lines schematically show the reconstructed limits of the slab window at 56 Ma. Red solid ines show schematic, sequential positions of a ridge-transform system that marked the boundary between the Resurrection and Kula Plates at 60, 58, 56, and 50 Ma. Modified from Bradley and others (2003, 2017).

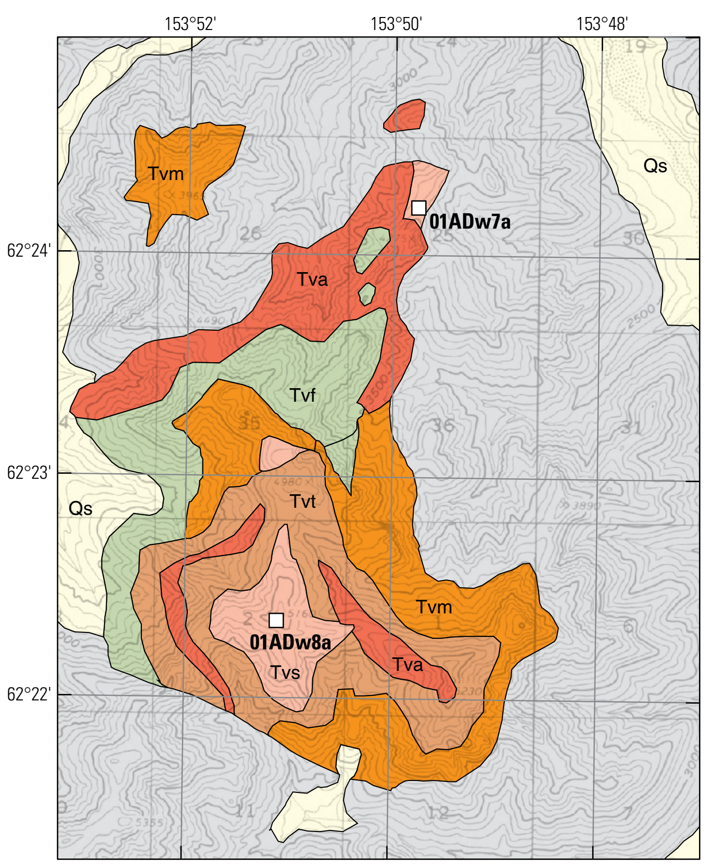
oceanic plates were successively subducted beneath a sector of the margin that lay outboard of the Sheep Creek volcanic field—the Resurrection Plate from before 70 Ma to 56 Ma and the Kula Plate from 56 to 42 Ma (Bradley and others, 2003; Haeussler and others, 2003).

A corollary of the ridge subduction hypothesis is the resulting opening of a slab window beneath south-central Alaska. This type of slab window is a gap that opens at depth between two subducting plates that are themselves diverging (Thorkelson, 1996). The new U-Pb and ^{40}Ar/^{39}Ar ages reported by Bradley and others (2017) link the early history of the Sheep Creek volcanic field to the slab window regime. The slab window in figure 3 is positioned with its apex at the site of 56-Ma near-trench intrusive activity in the Chugach terrane; the footprint of the slab window probably would have been approximately triangular, but its shape cannot be precisely reconstructed. To the east of the slab window (fig. 3), igneous rocks with isotopic ages ranging from 57 to 55 Ma are interpreted to represent subduction magmatism.

After ridge subduction, a new subduction zone was established along the Gulf of Alaska margin—a subduction zone that is still active today. The oldest arc rocks that postdate ridge subduction are Eocene in age and correspond to what Wilson (1985) referred to as the Meshik Arc. Wilson and others (2006) reported ^{40}Ar/^{39}Ar ages of 45.1±0.2 Ma and 41.6±0.2 Ma from volcanic rocks in the Dillingham quadrangle that they attributed to the Meshik Arc. Jones and others (2020) reported a U-Pb zircon age of 44.1±0.8 Ma from a granitic dike in the western Alaska Range, which is in the same age range as the Meshik Arc samples of Wilson and others (2006). The U-Pb zircon age of 42.8±0.5 Ma from the tuff near the top of the stratigraphic succession of the Sheep Creek volcanic field (Bradley and others, 2017) is within the same age range and may also represent Meshik Arc, post-slab window activity.

Sheep Creek Volcanic Field

The Sheep Creek volcanic field is in the western Alaska Range (figs. 1 and 2). The main outcrop area lies 5 to 10 km south of the Denali strike-slip fault zone. This fault has a complex history of Cretaceous to Holocene right-lateral displacement (totaling about 134 km) along this segment of the fault (Miller and others, 2002). Bundtzen and others (1997) subdivided the stratigraphic succession in the Sheep Creek volcanic field (fig. 4) into four units: (1) unit Tvm (Bundtzen and others, 1982) consists of columnar-jointed basalt and basaltic andesite flows successively overlain by; (2) unit Tvt, fine- to coarse-grained andesitic air-fall tuffs stacked in a series of fining-upward sequences; (3) unit Tva, andesite flows and lapilli tuffs; and (4) unit Tvs, volcaniclastic sandstone and lacustrine sediments. Bundtzen and others (1997) also recognized a fifth mapping subdivision of the Sheep Creek volcanic field, unit Tvf, which occurs at various stratigraphic levels and consists of felsic tuff and flows. Bundtzen and others (1982)



Base from U.S. Geological Survey, McGrath, 1:63,360, 1958
Universal Transverse Mercator, zone 5 north
North American Datum of 1983

EXPLANATION

Qs	**Quaternary sediments**
	Rocks of the Sheep Creek volcanic field (Paleogene)
Tvs	Volcaniclastic rocks
Tvf	Felsic volcanic rocks
Tva	Andesite
Tvt	Tuffaceous rocks
Tvm	Mafic volcanic rocks
	Bedrock, undifferentiated
	Contact

0 1 2 KILOMETERS
0 0.5 1 MILE

Figure 4. Detailed geologic map of the Sheep Creek volcanic field in south-central Alaska, showing sample locations. Measured stratigraphic section at location 01ADw8a is shown in figure 6. Modified from Bundtzen and others (1997).

did not report thicknesses but a cross section that accompanies the synthesis map by Bundtzen and others (1997) indicates thicknesses of about 215 meters (m) for unit Tvm, 215 m for unit Tvt, 60 m for unit Tva, and 215 m for unit Tvs. The cross section by Bundtzen and others (1997) shows the overall structure of the volcanic field as an open syncline with dips generally less than 10 degrees but locally reaching about 45 degrees.

During our reconnaissance study of the Sheep Creek volcanic field, we were able to visit, measure, and sample two stratigraphic sections (fig. 4). At the first site, station 01ADw7A (fig. 5*A*), we sampled a felsic tuff from rocks that Bundtzen and others (1997) mapped as unit Tvs. The tuff here unconformably overlies cleaved, recumbently and isoclinally folded shale and siltstone of the informally named Sheep Creek formation of Bundtzen and others (1997). The tuff is several meters in thickness and contains carbonized wood; most of the Paleogene section at this site is covered and we were only able to access the basal parts above the more resistant Paleozoic strata. Bradley and others (2017) reported similar $^{40}Ar/^{39}Ar$ and U-Pb ages from the tuff: a U-Pb zircon age of 56.0±1.9 Ma and a $^{40}Ar/^{39}Ar$ hornblende plateau age of 54.7±0.7 Ma. These ages, which overlap within uncertainty, extend the basal range of the Sheep Creek volcanic field strata to within the time interval of the postulated slab window of Bradley and others (2003), and near the boundary between the Paleocene and Eocene. The latter observation is relevant to paleoclimatology and, in particular, to studies of the PETM. Paleopedogenic features were observed within the tuff, including carbonaceous root traces and millimeter-scale siderite spherules. Major oxide analyses of matrix material surrounding the spherules determined a Chemical Index of Alteration (CIA) value of 87.96 indicative of an intensive weathering environment during paleosol formation (Nesbitt and Young, 1982; Fedo and others, 1995).

The second site (station 01ADw8A) (fig. 6) exposes 60 percent of a 280-m-thick succession of welded tuffs interbedded with organic-rich shale and claystone. The bottom third of the succession at this site is dominated by shales and siltstones interbedded with a few welded tuffs. Coal and rooted paleosol horizons (fig. 5*B*) are more abundant within the shale and siltstone intervals in the lower half of the exposed section, compared to higher in the section. Coals and rooted claystone contain abundant permineralized wood, dicot leaves, and conifer foliage. A thin laminated porcellanite in the basal 10 m and other thin tuffs observed through the lower third of the succession are considered to be air-fall deposits (fig. 5*C*). These observations indicate that this portion of the succession corresponds to unit Tvt of Bundtzen and others (1982). The paleosols within the air-fall interval are best characterized as carbonaceous argillisols and histosols, using the classification scheme of Mack and others (1993), or as andisols based on Retallack's (1993) classification. In either usage, the paleosols indicate formation on a volcanic ash parent material under saturated and reducing conditions in which abundant organic matter was preserved.

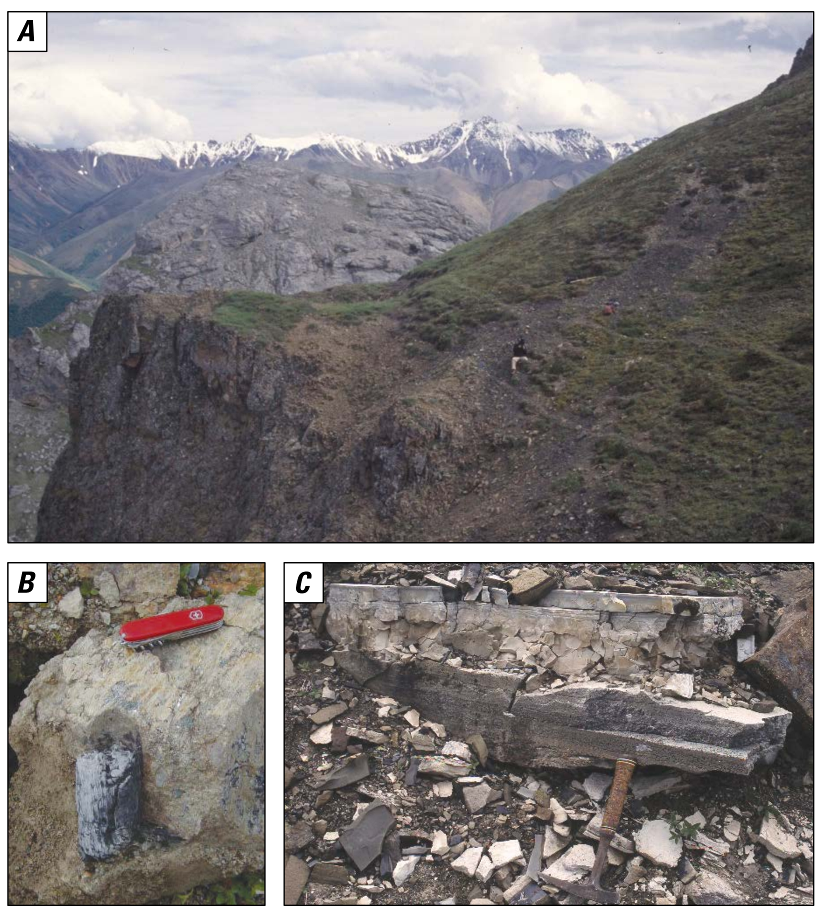


Figure 5. Photographs of the Sheep Creek volcanic field in south-central Alaska. *A*, In the foreground, strata exposed in the prominent cliff face at the first study site, station 01ADw7A, are assigned to the informally defined Paleozoic Sheep Creek formation of Bundtzen and others (1997). The gentler slope on the right is underlain by Paleogene strata of the Sheep Creek volcanic field. Light, yellowish zone beneath the geologist is a tuff and paleosol developed on the tuff that are inferred to correspond to the Paleocene–Eocene boundary, as described in the "Sheep Creek Volcanic Field" section. *B*, An upright, in situ, carbonized stump encased in air-fall tuff. *C*, Air-fall tuff displaying coarsening upward stratigraphy culminating in laminations at top. Photographs *B* and *C* are from the second study site, station 01ADw8A. Photographs by Timothy White.

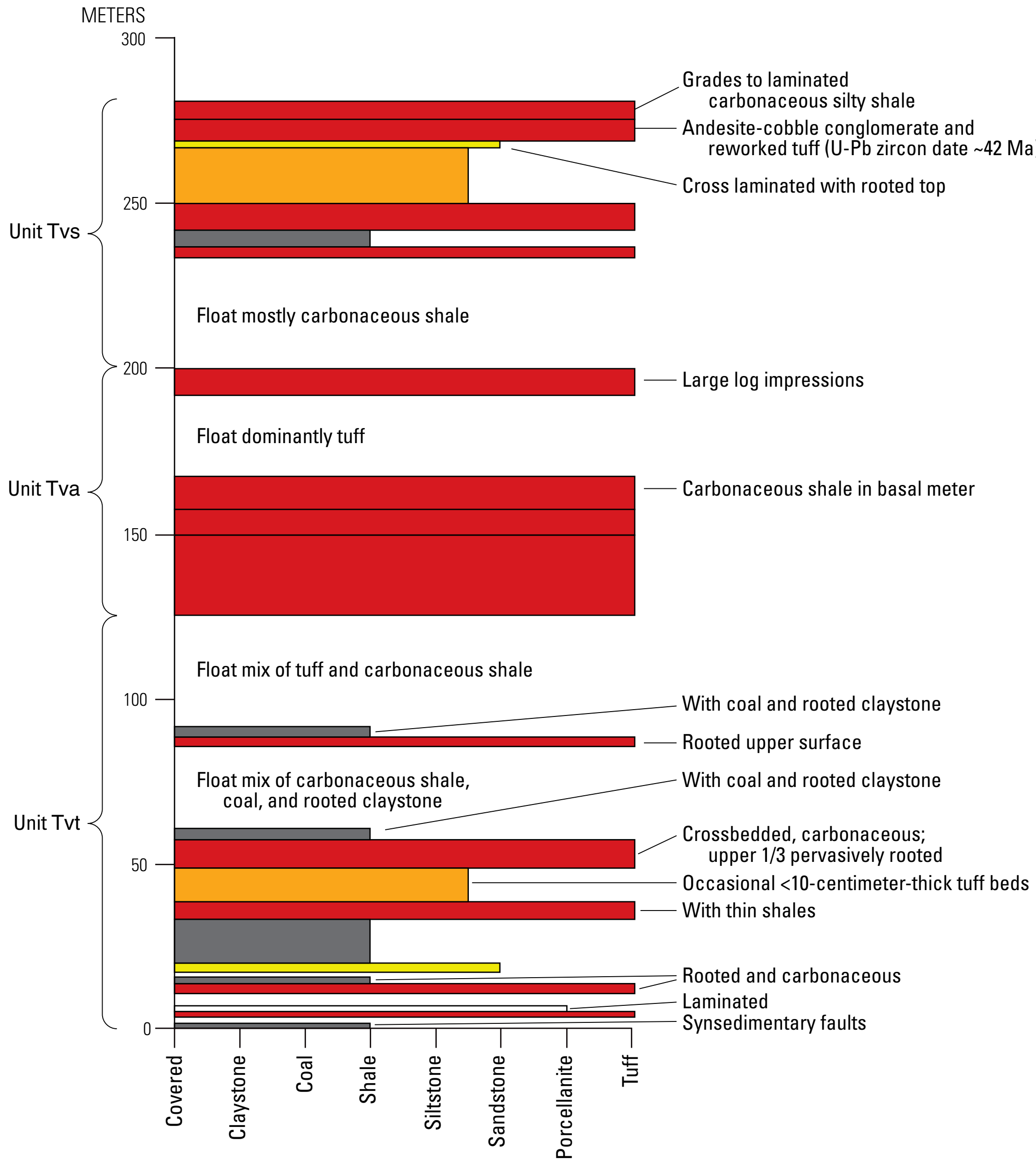


Figure 6. Measured section at station 01ADw8A showing the uppermost 300 meters of the Sheep Creek volcanic field, south-central Alaska. Individual coal and claystone beds are too thin to be shown as rock types at this scale, but their presence is noted where observed. Tuffs in the upper 40 meters of unit Tvs are thin to medium bedded and amalgamated. Labels for units Tvt, Tva, and Tvs show how strata in this measured section best equate to the mapped subdivisions of the Sheep Creek volcanic field of Bundtzen and others (1997). Ages in million years ago (Ma), where given.

An approximately 75-m-thick dominantly welded tuff interval was observed above the succession of air-fall tuffs and paleosols described in the preceding paragraph. We assign these strata to unit Tva—andesite and lapilli tuffs—of Bundtzen and others (1982). Thus, the stratigraphic relationships at this measured section differ from those reported by Bundtzen and others (1997) because here, unit Tva overlies unit Tvt. This dominantly welded tuff interval includes leaf and axis impressions within the tuffs and in some instances, poorly preserved logs, suggesting that lahars swept down across a vegetated and forested landscape. The uppermost third of the outcrop reveals a return to interbedded shales, siltstones, and welded tuffs, albeit with far fewer observed rooted horizons and no observed coals. We equate this part of the section to Bundtzen and others' (1982, 1997) unit Tvs—volcaniclastic sandstone and lacustrine silt—from which we sampled a relatively thin reworked felsic tuff with fossil leaves that is interbedded with an andesite-cobble conglomerate, probably another lahar deposit. Zircons from this sample yielded a $^{238}U/^{206}Pb$ age of 42.8±0.5 Ma (Bradley and others, 2017). A prominent 15-m-thick sandy siltstone interval was observed beneath the dated tuff, which probably corresponds to a fossil leaf-bearing unit of similar thickness that was observed by Bundtzen and others (1982, 1997).

Paleobotany

A small suite of plant macrofossils was collected from the study section during field reconnaissance and represents a preliminary list of taxa in the unit. The collection from the present study includes dicot leaves within the families Trochodendraceae (*Zizyphoides* sp.), Betulaceae (*Alnus* sp.), Juglandaceae (*Hicoria antiquora*), Cercidiphyllaceae (*Trochodendroides* sp.), and Salicaceae (*Populus kenaiana*) as well as the shoots of the cupressaceous conifers *Metasequoia* cf. *occidentalis* and ?*Chamaecyparis* sp. (fig. 7). When combined with fossil plants reported by Bundtzen and others (1982) from USGS plant locality 11126, the list of families expands to include dicot remains in Lauraceae, Vitaceae, and Fagaceae; Arecaceae within the monocots; conifers of Pinaceae and Podocarpaceae; and the sphenophyte *Equisetum*. Dispersed fragmentary plant remains are also common in the sampled strata including carbonized woody debris and one sample containing a poorly preserved, parallel-veined, putative monocotyledonous form. Without sufficient morphotype diversity sampled in this study, no leaf physiognomic approaches to estimating paleoclimate parameters were attempted.

Division Coniferophyta (Heer, 1864)
Order Coniferales (Ettingshausen, 1895)
Family Cupressaceae Gray, 1822
Genus *Metasequoia* Miki, 1941
Metasequoia cf. *occidentalis* Chaney, 1951
Figures 7*A*, 7*B*
Specimens: F2-11C, F3-19.2B

Description.—Short needle conifer foliage with opposite needle arrangement and prominent needle midvein; needles have rounded apices. Needle length and shape varies, likely based on tree positioning with longer needle forms (fig. 7*A*) proximal on the branch with distal, young shoots with shorter needles (fig. 7*B*).

Genus *Chamaecyparis* Spach, 1841
?*Chamaecyparis* sp.
Figure 7*C*
Specimen: F5-37A

Description.—Scale-leaved conifer foliage arranged in spreading dorsi-ventrally flattened splays with acute angle branching. Fossil material described within variation from *Chamaecyparis* and *Fokienia*.

Division Spermatophyta Knowlton, 1919
Class Magnoliopsida Cronquist and others, 1996
Order Trochodendrales Takhtajan, 1981
Family Trochodendraceae Prantl, 1865
Genus *Zizyphoides* Seward and Conway, 1935
Zizyphoides sp.
Figure 7*F*
Specimen: F3-16.1A

Description.—Simple, unlobed, elliptic, symmetrical leaf of notophyll laminar size. Long petiole is marginally attached at an acute base angle and convex base shape. Leaf margin is mostly untoothed; first venation is palmate.

Family Betulaceae Gray, 1822
Genus *Alnus* Miller, 1754
Alnus sp.
Figure 7*H*
Specimen: F3-17B

Description.—Simple, elliptical, symmetrical, unlobed leaves of micro- to mesophyll size. Petiole attachment into an obtuse base angle with rounded base shape. Where preserved, apex angle is obtuse. Leaves are toothed with regular tooth spacing. Primary veins organized pinnately with uniform secondary vein spacing.

Family Juglandaceae Perleb, 1818
Genus *Hicoria* Rafinesque-Schmaltz, 1808
Hicoria antiquora (Newberry, 1868)
Figure 7*D*
Specimen: F6-46

Description.—Simple, obovate, asymmetrical, unlobed leaf of microphyll laminar size. Petiole attachment marginal at an acute base angle. Leaf apex angle acute. Crenate toothed leaf margins with regular tooth spacing at 6.5 teeth per centimeter. Primary venation pinnate with secondary veins arranged alternately and increasing spacing toward base.

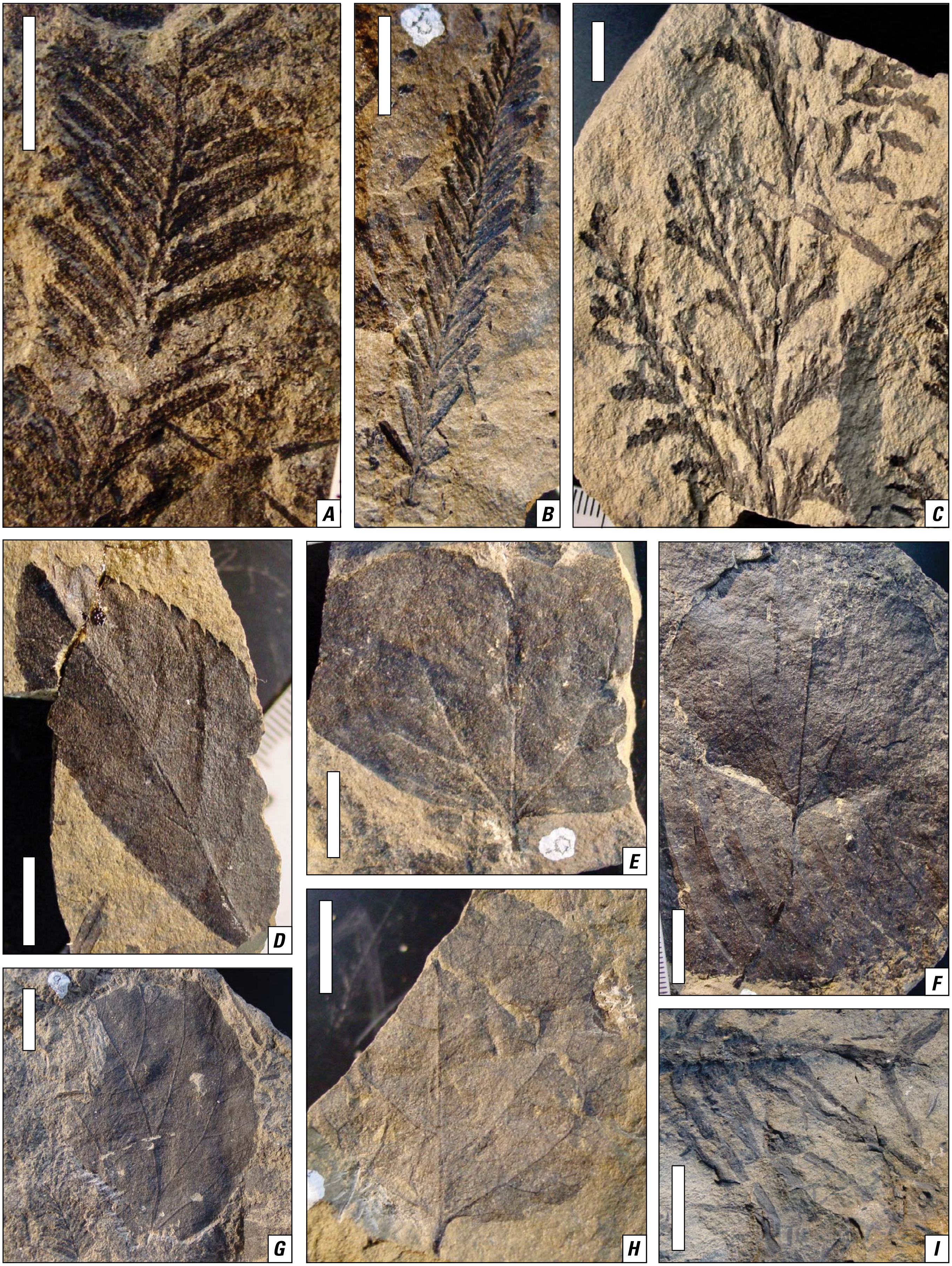
Family Salicaceae Brisseau-Mirbel, 1815
Genus *Populus*
Populus kenaiana Wolfe, 1966
Figure 7*G*
Specimen: F2-11A

Description.—Simple, elliptic, unlobed, and likely symmetrical leaf of notophyll laminar size. Length to width ratio 1.4. Crenate toothed margin with teeth regularly spaced at ~1.1 teeth per centimeter. Primary venation is palmate with secondary vein spacing decreasing toward base.

Family Cercidiphyllaceae Engler, 1907
Genus *Trochodendroides* Berry, 1922
Trochodendroides sp.
Figure 7*E*
Specimen: F3-19.1A

Description.—Simple, obovate, bilobed, symmetrical leaf of notophyll laminar size. Length to width ratio less than 1. Petiole attaches marginally at obtuse base angle. Apex shape obtuse and emarginate in shape. Leaf untoothed with palmate primary vein pattern.

Figure 7 (page 9). Photographs of plant macrofossils, showing selected paleofloral remains from the Sheep Creek volcanic field, south-central Alaska. *A* and *B*, *Metasequoia* cf. *occidentalis* shoots (specimens F2-11C, F3-19.2B). *C*, ?*Chamaecyparis* sp. splay (specimen F5-37A). *D*, Partial leaf of *Hicoria antiquora* (specimen F6-46). *E*, Partial leaf of *Trochodendroides* sp. (specimen F3-19.1A). *F*, *Zizyphoides* sp. (specimen F3-16.1A). *G*, *Populus kenaiana* (specimen F2-11A). *H*, *Alnus* sp. (specimen F3-17B). *I*, Carbonized roots in fine sandstone. All scale bars are 1 centimeter long. Photographs by David Sunderlin.


A
B
C
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I

Discussion—Implications for Tectonics, Regional Geology, Paleoclimate, and Paleobotany

The age and location of the Sheep Creek volcanic field and associated sedimentary rocks link its origin to subduction of the Kula-Resurrection oceanic spreading center along the Gulf of Alaska margin (Bradley and others, 2003). Before discussing connections between the Sheep Creek volcanic field and ridge subduction, we first summarize the plate geometry and geologic corollaries of this unusual process. Subduction of an oceanic spreading center, or "ridge subduction," can also be thought of as the subduction of two adjacent oceanic plates that are themselves diverging (Thorkelson, 1996). Three geometries are possible: (1) the ridge is perpendicular to the subduction zone, (2) the ridge is parallel to the subduction zone, or (3) the ridge intersects the subduction zone at some angle between 0 and 90 degrees, referred to herein as oblique ridge subduction. The third geometry is the general case, and the one that applies to the present instance. In oblique ridge subduction, three plate boundaries, which are marked at the surface by a trench, a ridge, and another trench, meet at a triple junction. Over millions of years, the location of the triple junction necessarily migrates along the convergent margin.

The most compelling evidence for ridge subduction is preserved in rocks of the Chugach-Prince William composite terrane, which, as it does today, occupied the forearc region of south-central Alaska. In the forearc region, geologic effects of ridge subduction, and consequent opening of a slab window, include (1) intrusion of near-trench granitic plutons; (2) anomalous high-temperature, low-pressure, near-trench metamorphism; (3) emplacement of intermediate to felsic dikes, mostly at high angles to the strike of the margin; (4) motion on an intricate network of transverse strike-slip and normal faults; (5) gold mineralization along these dikes and faults; and (6) uplift of the accretionary prism above sea level (Bradley and others, 2003, and references therein). Rocks and structures that have been attributed to the subduction of a spreading center were superimposed on mainly Mesozoic subduction-accretion related rocks in the upper plate of the subduction zone. One or more of these ridge-subduction effects can be seen at a majority of outcrops in the Chugach-Prince William terrane. Near-trench magmatism, metamorphism, deformation, and gold mineralization took place in the accretionary prism above a narrow slab window, where hot asthenosphere welled up into the gap between the two subducted, but still diverging, plates. Faulting took place as the critically tapered accretionary prism adjusted its shape to changes in the bathymetry of the incoming plate, changes in the convergence direction before versus after passage of the triple junction, and changes in the strength of the upper plate as it was heated and then cooled. The triple junction migrated about 2,000 km along strike from west to east between ~61 and ~50 Ma (Bradley and others, 2003).

Although the geologic effects of ridge subduction were strongest in the forearc, they are also recognized hundreds of kilometers inboard from the subduction zone. Continuing the numbered list from the previous paragraph, the geologic effects include (7) widespread igneous activity along the axial zone of the magmatic arc; followed by (8) magmatic quiescence (Bradley and others, 2017; Jones and others, 2020); (9) strike-slip displacements on through-going, margin-parallel faults; (10) basin subsidence (Trop and others, 2003; Cole and others, 2006, 2007); and (11) localized exhumation of metamorphic rocks (Till and others, 2007; Bleick and others, 2012). In the western Alaska Range, the magmatic flareup is evident from a pronounced peak in igneous ages at 60 Ma, followed by a sharp decline, with little magmatic activity from 51 to 44 Ma (Jones and others, 2020). Both the flareup and lull can be viewed as consequences of ridge subduction and the attendant opening of a slab window. The flareup took place a few million years before the inferred triple junction migrated to a position adjacent to the Kenai Peninsula. At that time, extremely young seafloor would have been subducted beneath the western Alaska Range (Bradley and others, 2017). A pervasive swarm of northwest-striking, intermediate to mafic dikes cuts granitic plutons in the western Alaska Range. These dikes range in age from 58 to 51 Ma (Jones and others, 2020). We suggest that the dikes were intruded at the start of a slab window regime, which lasted until arc magmatism resumed at 44 Ma (Jones and others, 2020). The magmatic lull along the arc presumably marks a time interval when hydrated lithosphere was no longer being subducted beneath the former arc axis; instead, the base of the upper plate came into contact with upwelling asthenosphere. The overall strain regime within the upper plate above the slab window would likely have been extensional or transtensional. This is because the diverging, down-going plates would have exerted different tractions on the base of the upper plate (Thorkelson, 1996). The northwest-striking, 58 to 51 Ma dikes confirm that the former arc was extended subparallel to its strike.

The documented migration of the ridge-trench-ridge triple junction implies that the slab window migrated as well (Bradley and others, 2003). The detailed geometry of the slab window is unknown because the magnetic anomaly patterns of the two subducted plates are not preserved, but the centerline of the slab window would have approximately corresponded to the down-dip projection of the subducting ridge. Regional patterns of pluton ages show that magmatism in western Alaska diminished and then stopped entirely about when the triple junction was at the now-adjacent part of the accretionary complex (Bradley and others, 2017). This is consistent with the most relevant modern analog, in the southern Andes of South America, where the slab window is situated beneath a portion of the magmatic arc that lacks active volcanoes (Forsythe and Prior, 1992).

The amount of coast-parallel strike-slip displacement between the Chugach terrane and the Wrangellia-Peninsular-Alexander composite terrane complicates an understanding of the Paleogene evolution of the western Alaska Range. The boundary between these two entities is the Border Ranges

Fault (fig. 1). If displacement is in the range of thousands of kilometers, as Pavlis and Roeske (2007) suggested, the rationale for a Paleogene slab window beneath interior Alaska would be tenuous. Provenance data and field relations, however, indicate that Paleogene strata in the Matanuska forearc basin was derived from both outboard (Little, 1988) and inboard (Kortyna and others, 2014) flanks. Thus, for this part of Alaska's Pacific margin, geologic evidence does not support major displacements since 54 Ma between the Chugach terrane and the Wrangellia-Peninsular-Alexander composite terrane. We therefore conclude that the Sheep Creek volcanic field has not been significantly offset with respect to the Chugach terrane, with its embedded evidence for ridge subduction. Therefore, it is reasonable to consider the Paleogene histories of the two together, an approach that was previously adopted by Bradley and others (2003, 2017) and Kortyna and others (2014).

Figure 3 shows the reconstructed position of the slab window at about 56 Ma, at the onset of volcanism in the Sheep Creek volcanic field. Age determinations from the older of the two dated tuffs (56.0±1.9 Ma by U-Pb zircon and 54.7±0.7 Ma by $^{40}Ar/^{39}Ar$) reveal that the volcanism began at or soon after the onset of the slab window regime. Judging from the existence of a large, northwest-striking dike swarm in the western Alaska Range of this age (Jones and others, 2020), the regional tectonic regime was likely extensional. The younger of the two ages (42.8±0.5 Ma by U-Pb zircon) is from the youngest known rocks in the Sheep Creek volcanic field and is close to the suggested age of onset of Meshik Arc magmatism (~44 Ma; Jones and others, 2020). Accordingly, we suggest that the Sheep Creek volcanic field was active during two successive episodes of magmatism: slab window and then nascent arc.

The limited extent of the Sheep Creek volcanic field outcrop area indicates localized deposition. Profound basal unconformities are characteristic of rifted and pull-apart basins (for example, Olsen, 1997), and coeval Paleogene extensional basins in British Columbia are characterized by a basal unconformity overlain by unmetamorphosed early Eocene sediments and volcanic rocks (for example, Mathews, 1981). We envision a broadly similar setting for the Paleogene sedimentary and volcanic rocks of the Sheep Creek volcanic field, with basin subsidence initiated by the transition from a magmatic arc to an extending slab window at 56 Ma. Although the northern outcrop limit of the Sheep Creek volcanic field is only about 5 km from the Denali strike-slip fault system, evidence bearing on a possible genetic connection between the two has not been recognized. Bundtzen and others (1982) described Paleocene breccia pipes, small plutons, and some concentrically shaped dike swarms that may be the root zones of volcanic centers in the Sheep Creek volcanic field, and further considered coarse clasts in air-fall deposits as indicative of proximity to active volcanic vents.

The pervasively weathered nature of the basal andisol is consistent with intense pedogenesis, likely attributable to a warmer and wetter climate during the late Paleocene to early Eocene (for example, Barron, 1987; Rea and others, 1990), and indicates a period of landscape stability following unconformity development and basin formation. Otherwise, landscape evolution in the basin was characterized by volcanic and volcaniclastic deposition punctuated by relatively brief episodes of landscape stability, at least long enough for woody vegetation to colonize the landscape and for pedogenesis to proceed. The upward transition to dominantly welded tuffs in the middle third of the succession (fig. 6) may signal that either (1) active volcanism migrated closer to the study area; or that (2) volcanoes matured, developing steeper and higher edifices that provided a more effective ramp to initiate lahar runout into the study area. As the slab window migrated to the east and associated volcanism waned, deposition in the Sheep Creek volcanic field gradually transitioned back toward volcanically derived finer grained organic- and plant-fossil-rich strata but with very little evidence of soil development. The 15-meter-thick fossil leaf-bearing unit beneath the 42-Ma tuff was previously interpreted as sediment deposited in a crater lake (Bundtzen and others, 1997), an observation consistent with waning stages of volcanism in the Sheep Creek volcanic field. Foliage fossils in this unit occur as compressions and impressions, and although no cuticle remains on the foliar surfaces, most dicot leaves are preserved well enough to exhibit primary and secondary venation. Conifer foliage is predominant and commonly occurs in complete shoots with needles or scale leaves intact. The condition of many foliar elements indicates minimal fluvial transport before burial. The presence of carbonized compressions of roots (fig. 7*I*) and overlapping leaves of a single morphotype indicates quiet water deposition, consistent with Bundtzen and others' (1997) interpretation of a lacustrine setting.

Although the paleofloral collection from the Sheep Creek volcanic field is small (~45 specimens), it compares with those from other late Paleocene and early Eocene fluvial-lacustrine deposits of the Alaska Peninsula (Parrish and others, 2010) and in the Matanuska Valley of south-central Alaska (Hollick and Smith, 1936; Sunderlin and others, 2011, 2014), extending the coverage of fossil forest records during a warm regional and global climate phase. Like deposits to its south, the stratigraphic succession of the Sheep Creek volcanic field has yielded an abundance of *Metasequoia* shoots as a dominant macrofossil type, and shares members of most of the sampled families with the southern assemblages. The Sheep Creek volcanic field paleoflora exhibits very little paleoecological leaf damage, consistent with the low levels of this type of plant-arthropod association observed in other Paleocene and Eocene floras of Alaska (Sunderlin and others, 2014). The Sheep Creek volcanic field paleoenvironmental conditions described here add to our developing understanding of what were non-analog terrestrial ecosystems across northern high latitudes at the time (for example, Salpin and others, 2019; West and others, 2019, 2020). With warmer than current conditions in a northern high-latitude daylight regime, such studies of greenhouse paleoclimate records have implications for understanding warming climate and changing ecology in the Holocene and into the future (McElwain, 2018).

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