Stratigraphic and geochemical evolution of an oceanic arc upper crustal section: The Jurassic Talkeetna Volcanic Formation, south-central Alaska

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ABSTRACT

The Early Jurassic Talkeetna Volcanic Formation forms the upper stratigraphic level of an oceanic volcanic arc complex within the Peninsular Terrane of south-central Alaska. The section comprises a series of lavas, tuffs, and volcaniclastic debris-flow and turbidite deposits, showing significant lateral facies variability. There is a general trend toward more volcaniclastic sediment at the top of the section and more lavas and tuff breccias toward the base. Evidence for dominant submarine, mostly mid-bathyal or deeper (>500 m) emplacement is seen throughout the section, which totals ~7 km in thickness, similar to modern western Pacific arcs, and far more than any other known exposed section. Subaerial sedimentation was rare but occurred over short intervals in the middle of the section. The Talkeetna Volcanic Formation is dominantly calc-alkaline and shows no clear trend to increasing SiO_2 up-section. An oceanic subduction petrogenesis is shown by trace element and Nd isotope data. Rocks at the base of the section show no relative enrichment of light rare earth elements (LREEs) versus heavy rare earth elements (REEs) or in melt-incompatible versus compatible high field strength elements (HFSEs). Relative enrichment of LREEs and HFSEs increases slightly up-section. The Talkeetna Volcanic Formation is typically more REE depleted than average continental crust, although small volumes of light REE-enriched and heavy REE-depleted mafic lavas are recognized low in the stratigraphy. The Talkeetna Volcanic Formation was formed in an intraoceanic arc above a north-dipping subduction zone and contains no preserved record of its subsequent collisions with Wrangellia or North America.

Keywords: sedimentology, arc volcanism, subduction, geochemistry, isotope geology.

INTRODUCTION

Magmatism at convergent plate margins represents the second-largest source of new crust to the Earth's surface after the midocean ridge system, but unlike the oceanic lithosphere, which is almost completely recycled back into the upper mantle, arc rocks may be incorporated into the continental crust and preserved. As a result, some have argued that it is in such settings that the continental crust was generated (Taylor and McLennan, 1985; Ellam and Hawkesworth, 1988; Rudnick, 1995). Controversy over this hypothesis continues because island-arc crust is currently understood to be too low in SiO_2 and not sufficiently light rare earth element (LREE) enriched to form continental crust by itself (Taylor and McLennan, 1985; Rudnick and Fountain, 1995). As a solution to this problem, it has been argued that arc crust is transformed into continental crust during final collision with continental margins (e.g., Petterson et al., 1993; Draut and Clift, 2001; Draut et al., 2002). Others propose that some arcs are andesitic rather than basaltic and that the proportion of andesitic arcs may have been greater in the past (e.g., Taylor, 1967; Martin, 1986; Kelemen et al., 1993, 2003). Finally, others emphasize that continental crust may be created by intracrustal differentiation of a basaltic bulk composition, followed by recycling of a refractory mafic component into the mantle (e.g., Herzberg et al., 1983; Kay and Kay, 1991, 1993; Rudnick, 1995; Jull and Kelemen, 2001; Greene et al., 2005). A major problem in assessing the suitability of any of these models is that the composition of original arc crust is not well known. The upper crust is more variable and also evolved in composition than the rest of the crust, but has been less well studied. An accurate assessment of arc upper-crust composition could significantly improve our understanding of general bulk crustal composition. This study was intended to provide constraints on this topic through study of the upper part of an accreted arc section in south-central Alaska.

Sampling of modern arc upper crust has been restricted to a small number of widely spaced, shallow-penetrating boreholes [e.g., Ocean Drilling Program (ODP) Sites 782, 786, 788, and 792 in the Izu Arc (Fryer et al., 1990; Taylor et al., 1990) and ODP Sites 840 and 841 in the Tonga Arc (Parson et al., 1992)]. Island arc crust is relatively poorly known because only a small number of crustal sections are exposed, although a 5-km-thick section has been described in

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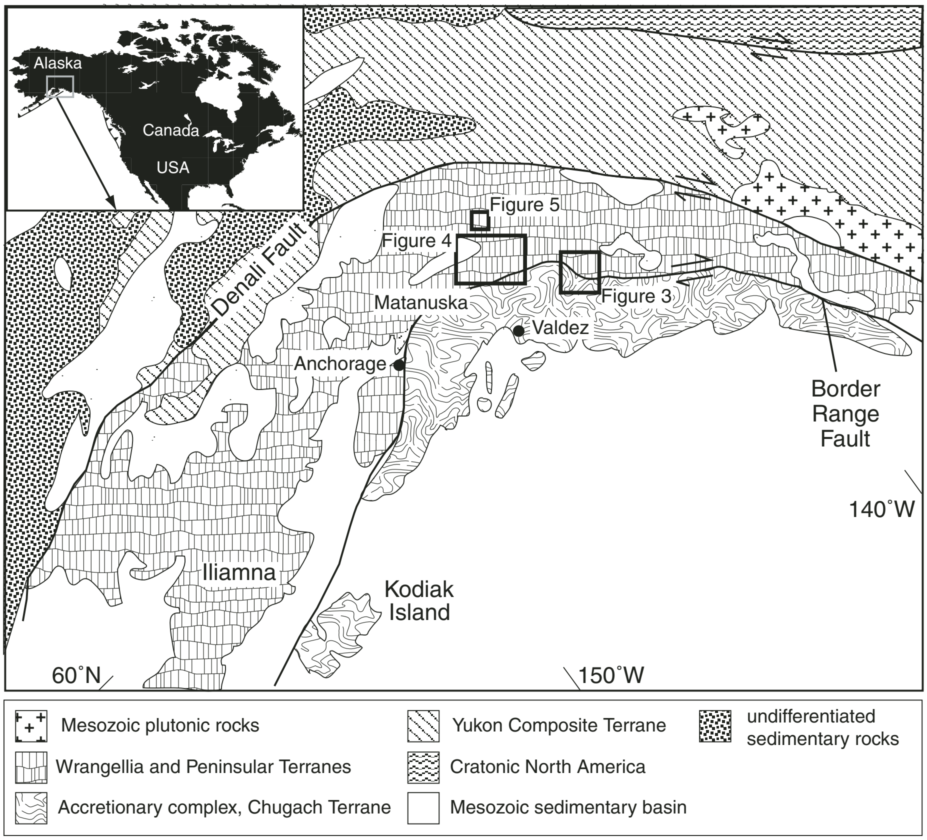


Figure 1. Tectonic map of Alaska and NW Canada showing the major exotic terranes accreted to cratonic North America. The study region is located within the Peninsular Terrane of south-central Alaska, sandwiched between Wrangellia to the north and the Cretaceous accretionary complexes exposed within the Chugach Terrane to the south (modified after Beikman, 1992). Terrane boundaries are all faulted.

Baja California (Fackler-Adams and Busby, 1998). The best-known sequence is exposed in Kohistan and Ladakh (western Himalaya) where a series of oceanic arc lavas, volcaniclastic sedimentary rocks, and associated lower crustal and mantle rocks have been studied. Study of this Dras-Kohistan lower crust and upper mantle has yielded important insight into the petrogenesis of these parts of an oceanic arc (e.g., Honegger et al., 1982; Dietrich et al., 1983; Khan et al., 1989, 1997; Petterson et al., 1991; Miller and Christensen, 1994; Treloar et al., 1996; Yamamoto and Yoshino, 1998). However, deformation and metamorphism during arc accretion has rendered that upper crustal section more difficult to reconstruct and interpret (Clift et al., 2000). Clift et al. (2000) estimated a preserved thickness of only ~2.5 km in the Kohistan-Dras Arc, much less than the 5–7 km measured in the western Pacific (e.g., Tappin, 1994; Suyehiro et al., 1996). As a result, there has previously been no available description of a complete arc upper crustal sequence from any modern or ancient arc.

In this contribution we document the most complete, least deformed, arc upper crustal sequence yet known: the Jurassic Talkeetna Volcanic Formation, a coherent series of arc volcanic and volcaniclastic rocks from an accreted oceanic island arc section exposed in south-central Alaska. Using sedimentary, structural, and geochemical data collected from 2000 to 2003, we interpret the depositional environment and petrogenesis of the Talkeetna Volcanic Formation and assess its implications for the temporal evolution of arc magmatism in the Mesozoic Pacific as well as for the more general role of arc crust in continental genesis.

REGIONAL SETTING

The Talkeetna crustal section is located in south-central Alaska and forms part of the Peninsular Terrane (Plafker and Berg, 1994), one of a series of allochthonous tectonic units accreted to the active margin of North America during the Mesozoic and Cenozoic eras (Coney et al., 1980; Gehrels and Berg, 1994; Nokleberg et al., 1994). The Peninsular Terrane is believed to have amalgamated with two other oceanic fragments, the Alexander and Wrangellia Terranes, prior to their accretion to North America during the Latest Jurassic–Early Cretaceous. This composite terrane is known as Wrangellia (Plafker et al., 1989; Nokleberg et al., 1994; Trop et al., 2002; Fig. 1). Subsequent northward subduction under modern Alaska has juxtaposed a large clastic subduction accretionary wedge along the southern edge of the Peninsular Terrane, comprising the Chugach Terrane in the study region (Fig. 1). The Chugach Terrane is a series of metasedimentary units separated from the Talkeetna Arc by the Border Ranges Fault (Little and Naeser, 1989; Figs. 1 and 2), a major right-lateral strike-

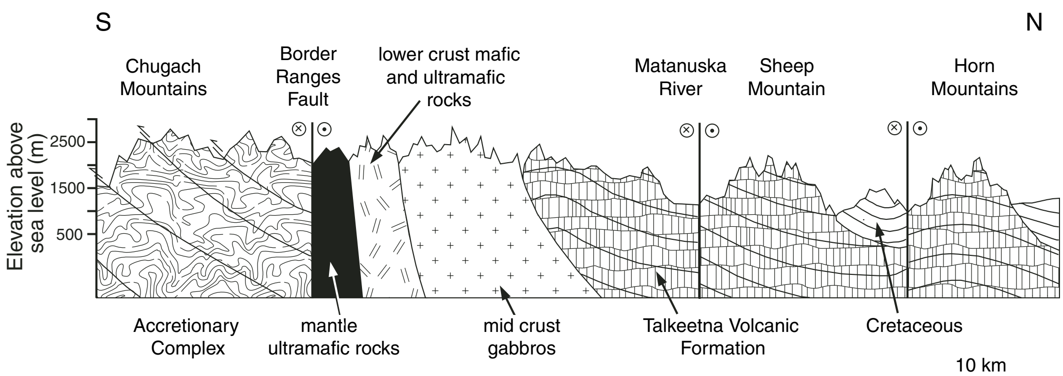


Figure 2. Schematic cross section through the Talkeetna Arc, showing the general northward dip of the arc, dissected by a series of major E-W strike-slip faults.

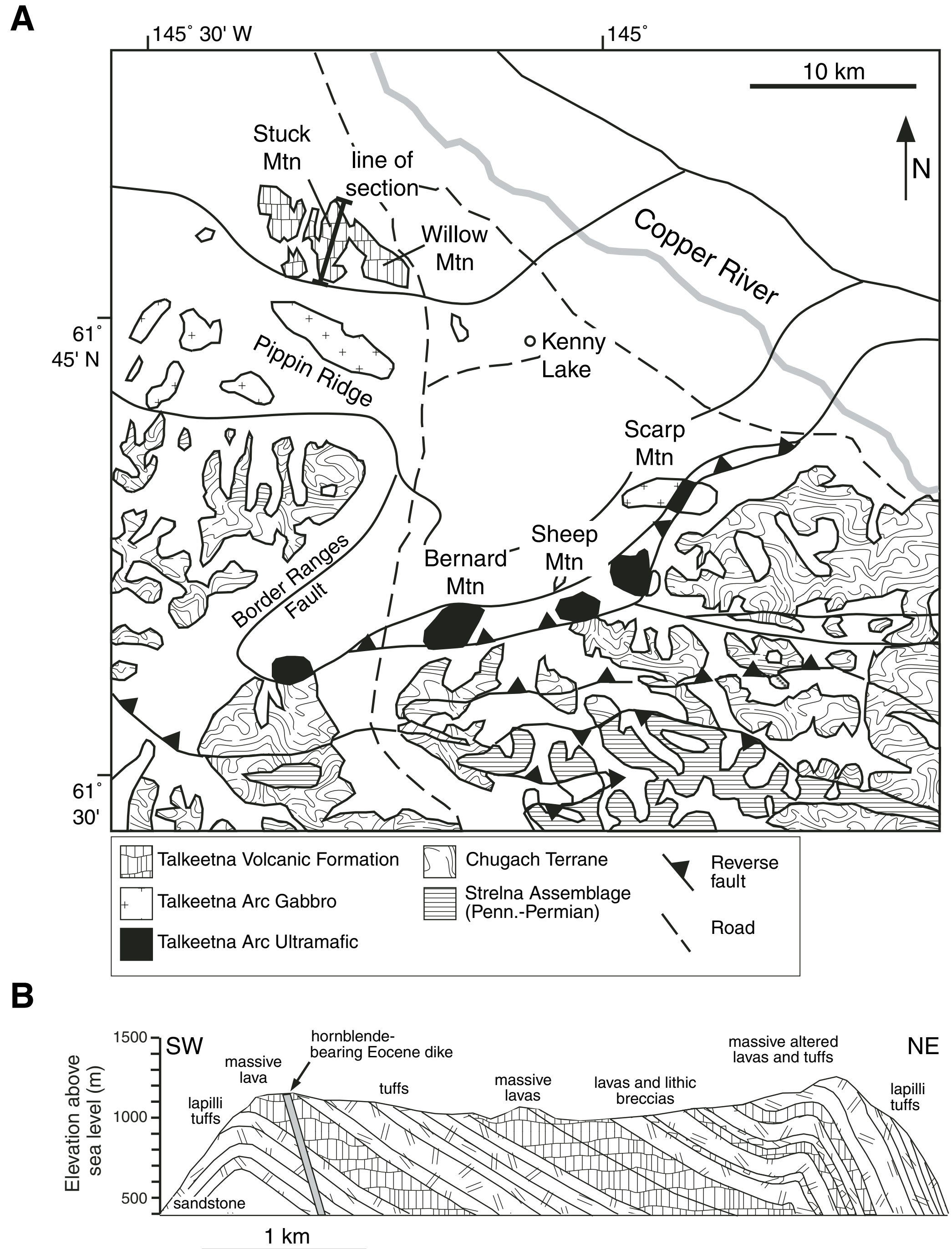


Figure 3. (A) Geological map of the Tonsina area showing the Willow-Stuck Mountain Massif and its juxtaposition to the gabbro of Pippin Ridge modified after Winkler et al. (1981). (B) Cross section through Stuck Mountain. Chemically enriched lavas and Eocene dikes outcrop on south side of the massif. No vertical exaggeration.

slip fault responsible for up to hundreds of km of Cenozoic motion along the western North American margin (Smart et al., 1996).

The Talkeetna arc section (Figs. 1 and 3) was first described by Burns (1983, 1985) and DeBari and Coleman (1989) in the Nelchina-Tonsina region. Early Jurassic plutonic and volcanic rocks extend for >1000 km, stretching from Tonsina in the east to Kodiak Island in the west (Fig. 1). They are bounded on the south by the Border Ranges Fault. Isolated exposures of ultramafic and mafic rocks associated with the arc lie along this southern boundary. Moderate-pressure mafic plutonic rocks comprise a continuous belt >120 km long and up to 10 km wide from Tonsina in the east to at least as far as the Matanuska Glacier in the west (Fig. 1B; Winkler et al., 1981). Intermediate to silicic plutonic rocks (diorites, quartz diorites, tonalites) become more voluminous westward in the midcrustal section (Pavlis, 1983; Plafker et al., 1989). These more silicic plutonic rocks are commonly exposed north of the mafic rocks and intrude mafic plutonic rocks of the arc as well as the Talkeetna Volcanic Formation, which constitutes the arc upper crust (e.g., Newberry et al., 1986). Plafker et al. (1989) suggested that the Talkeetna subduction zone included a north-dipping slab (in present-day coordinates) based on a contemporaneous accretionary complex to the south of the Border Ranges Fault. In contrast, Reed et al. (1983) proposed that the slab dipped south, based on K_2O and SiO_2 trends across the Alaska–Aleutian Range Batholith.

Age control on the Talkeetna Arc is presently sparse. $^{40}Ar/^{39}Ar$ ages of 177–181 Ma (Aalenian–Toarcian) were measured in gabbros from the mafic plutonic belt (three samples near Tonsina) and 180–182 Ma for the high-pressure gabbro of the Border Ranges Ultramafic and Mafic Complex (Onstott et al., 1989). In the Talkeetna Volcanic Formation, there is some biostratigraphic control. The base of the Talkeetna Volcanic Formation is exposed in the Alaska Peninsular and has been dated as Hettangian (Lower Jurassic, 198 Ma; Pálfy et al., 1999), as confirmed by U/Pb ages of zircons in volcaniclastic rocks (Rioux et al., 2003). The top of the Talkeetna Volcanic Formation is overlain in most of the study area by the Tuxedni Formation, dated as Middle Jurassic on the basis of early Bajocian mollusks found in the lower part of the formation (ca. 172 Ma; Gradstein and Ogg, 1996).

STRATIGRAPHY OF THE TALKEETNA VOLCANIC FORMATION

Reconstructing the stratigraphy of the Talkeetna Volcanic Formation is complicated by the fact that a complete section is not exposed in any one area, as a result of tectonic disruption and later transgressive sedimentation. Moreover, those ranges in which thick sections are preserved are commonly separated by strike-slip faults that make correlation from one section to the next difficult. Strong lateral changes in facies also make comparison between ranges hard. In this paper we consider the Talkeetna Volcanic Formation to be those volcanic and volcaniclastic rocks mapped as such in the past, and which lie between midcrustal gabbros to the south and overlying mid-Jurassic–Cretaceous sedimentary rocks.

Some constraints can be placed on the overall thickness and lithologies of the Talkeetna Formation by making several assumptions. The entire arc crustal section, at least east of the Matanuska Glacier, is tilted northward, suggesting that the deeper stratigraphic levels will be exposed toward the south. Indeed, east of the Matanuska Glacier, lavas of the Talkeetna Volcanic Formation are cut by gabbroic intrusions of the middle crust, which in turn overlie the ultramafic lower crustal rocks along the Border Ranges Fault. Thus the units in this region are placed at the base of a composite section as are those from the Stuck Mountain section in the eastern Tonsina region (Fig. 3), since these too are juxtaposed with midcrustal gabbros to the south.

The top of the Talkeetna Volcanic Formation is readily identified in three massifs north of the Matanuska Valley (Fig. 4). South of the Little

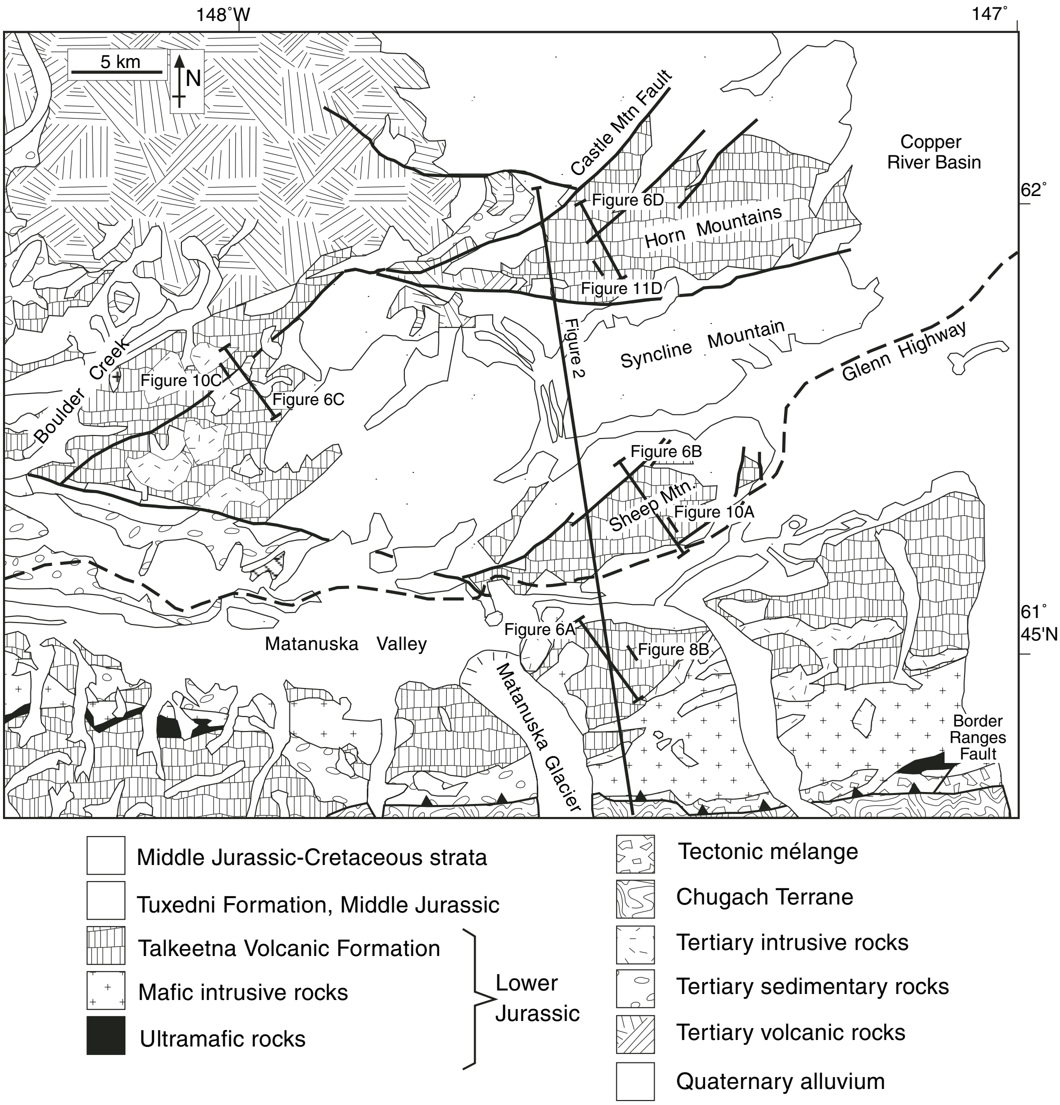


Figure 4. Geological map of the Matanuska Valley and western Copper River Basin showing the exposures of Talkeetna Volcanic Formation studied east of the Matanuska Glacier, on Sheep Mountain, in the region of East Boulder Creek and in the Horn Mountains. The trace of the Matanuska Valley may reflect the presence of a major E-W trending strike-slip fault. Map modified after Beikman (1992).

Oshetna River (Fig. 5), in the Horn Mountains and in East Boulder Creek (Figs. 4 and 6), Middle Jurassic clastic sedimentary rocks rest unconformably over the Talkeetna volcanic and volcaniclastic rocks (Trop et al., 2002). The Tuxedni Formation, which forms the oldest unit of the Middle Jurassic transgressive sequence, does not occur along the Little Oshetna River, implying a later transgression in this region although differences between sections may alternatively reflect lateral facies changes.

The middle of the Talkeetna Volcanic Formation is exposed in the Sheep Mountain massif, immediately north of the Matanuska Valley, and is probably separated from exposures south of the valley by a strike-slip fault that runs along the southern edge of the Copper River Basin, basically along the trend of the Matanuska Valley. The lack of a Middle Jurassic cover suggests that the strata exposed here are not at the top of the section. However, the metamorphic grade of the rocks is less than that seen south of the river and although these strata are intruded, the intrusive-volcanic contact is not a single, continuous stratigraphic horizon, indicating that this section is not at the base of the crustal section either. The sedimentary rocks overlying the Talkeetna Volcanic Formation at Sheep Mountain belong to the Cretaceous Chickaloon Formation (Triplehorn et al., 1984). The section at Sheep Mountain is ~5 km thick, with no evidence for tectonic repetition, which thus provides a minimum estimate for the thickness of the entire extrusive/sedimentary section. This minimum 5 km thickness of the Talkeetna Volcanic Formation is twice as thick as that recorded from the Himalayan Dras-Kohistan Arc (Clift et al., 2000) and is not sliced into nappes, as is the case in the Himalaya.

Reconstruction of a composite section is difficult because the Talkeetna Formation does not contain any distinctive marker beds that can be recognized in different places. In addition, lateral facies changes between sections demonstrates that a simple “layer-cake” model, as might be expected given the lateral changes from lava flows to proximal volcaniclastic debris flows to distal volcaniclastic turbidite sands seen in modern oceanic arc settings (e.g., Underwood et al., 1995) and ancient accreted arc sections (e.g., Dras Arc, India: Robertson and Degnan, 1994; South Mayo, Ireland: Archer, 1984), is inappropriate for the Talkeetna Volcanic Formation. Figure 7 shows some of the large-scale lithological variations between the Sheep Mountain, Little Oshetna, East Boulder Creek, and Horn Mountains sections. Sheep Mountain is characterized by proximal volcanic breccias, lavas, and common intrusions, indicating a vent proximal setting. The Little Oshetna region is dominated by basaltic, amygdaloidal lavas and interbedded tuff breccias, while the Horn Mountains are almost entirely sedimentary, comprising turbidite sandstones and debris-flow deposits (Fig. 8F). In contrast, the top of the East Boulder Creek section exposes minor lavas, proximal volcanic tuff breccias, and debris-flow deposits. Thus in a general sense the Sheep Mountain and Little Oshetna sections have the character of proximal volcanic settings, while the Horn Mountains section occupies a deeper-water, more distal environment and the East Boulder Creek section occupies an intermediate position.

This scenario may be more complex because the Little Oshetna section is located north of the Castle Mountain Fault and thus conceivably derived along-strike from the rest of the Tal-

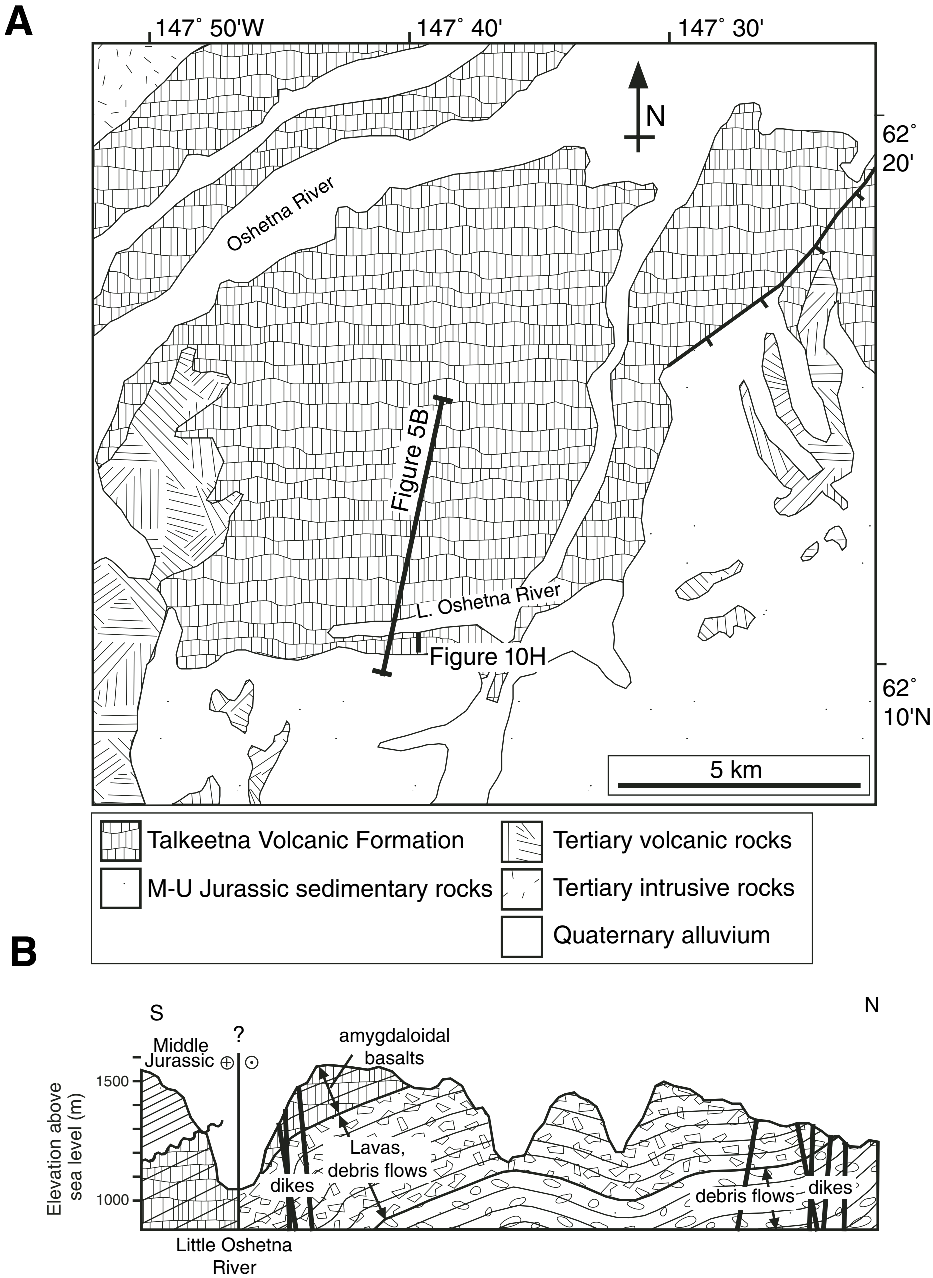


Figure 5. (A) Geological map of Talkeetna Mountains between the Little Oshetna River and the Oshetna River. Map modified after Grantz (1960). (B) Cross section through the top of the Talkeetna Volcanic Formation immediately under marine Middle Jurassic sedimentary rocks. Vertical exaggeration ×2.

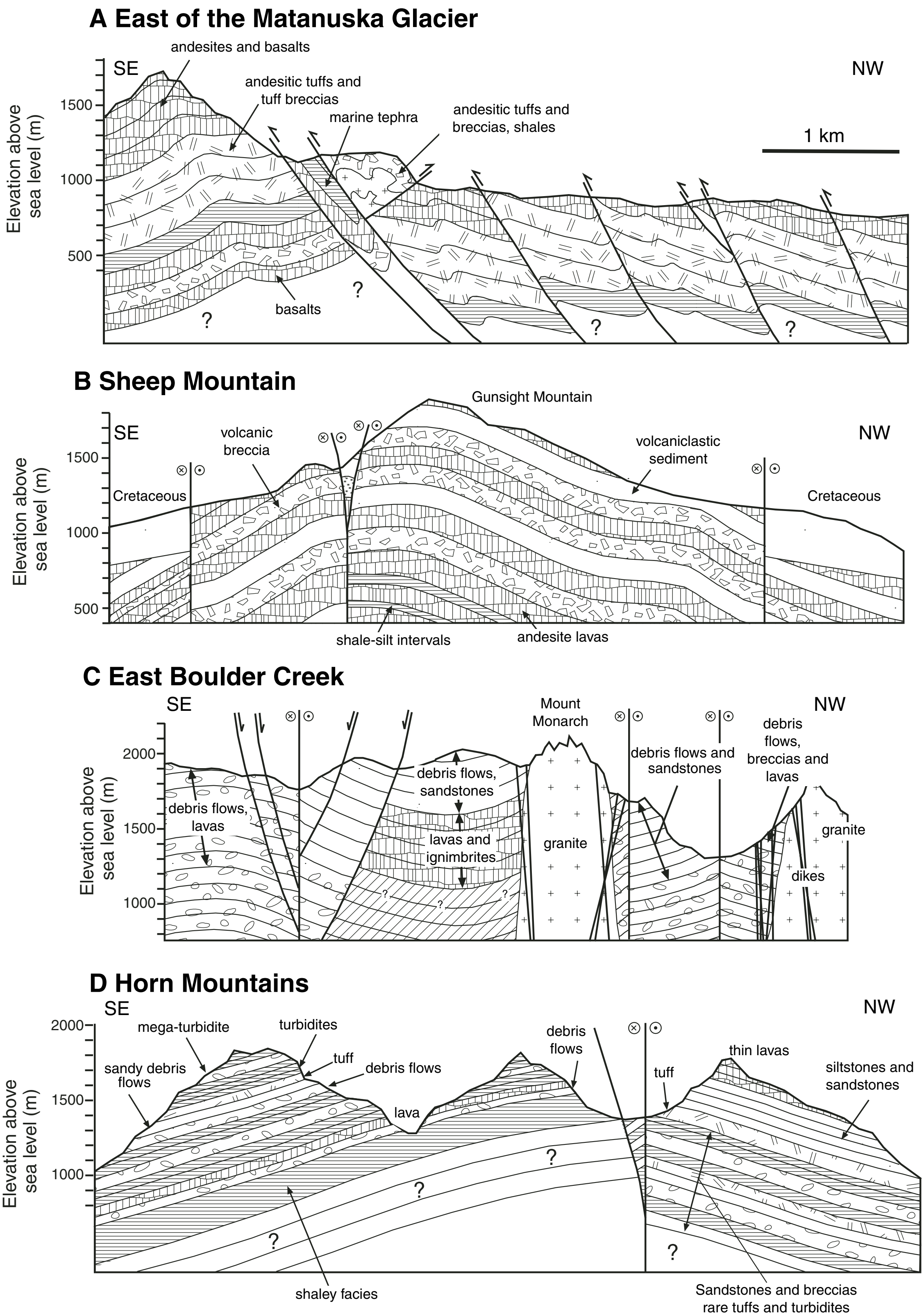


Figure 6. Geological cross sections through the Talkeetna Volcanic Formation at (A) East of the Matanuska River, (B) at Sheep Mountain, (C) in the vicinity of East Boulder Creek, and (D) in the Horn Mountains. See Figure 4 for precise locations. Unshaded stratigraphic levels are not exposed and are unknown. No vertical exaggeration.

keetna Volcanic Formation. The Castle Mountain Fault is a major strike-slip fault, largely active during the early–mid-Tertiary period, though with recent rejuvenation (Parry et al., 2001) and with a total slip likely not in excess of 35 km (Meisling et al., 1987). In this context and given the likelihood of another strike-slip fault between the Sheep Mountain and Matanuska Glacier sections, it is not known whether there is a missing section between the logged sections. However, the Sheep Mountain section has few lithological similarities with the Talkeetna rocks immediately east of the Matanuska Glacier, being much more volcaniclastic and reworked in places, compared to the lavas and primary tuffs and tuff breccias that dominate south of the river. Consequently, we infer that these sections do not significantly overlap in time.

The transition from the top of the Sheep Mountain section into those units known to be at the top of the Formation is more difficult to determine because the stratigraphically highest levels logged at Sheep Mountain show interbedded lavas and volcaniclastic sedimentary rocks, similar in character to those seen in East Boulder Creek. Consequently, we reconstruct the section with moderate overlap between the two sections. We have no evidence to show that a large additional, missing sequence was not originally present between the Sheep Mountain and East Boulder Creek sections. Nonetheless, by reconstructing the section in the way described, we are able to make an estimate for the thickness of the Talkeetna Volcanic Formation at ~7 km. Recent paleobarometry work places the uppermost gabbros of the Talkeetna Arc at 7–8 km depth (B. Hacker, 2004, personal commun.), consistent with our estimate of the upper crustal thickness.

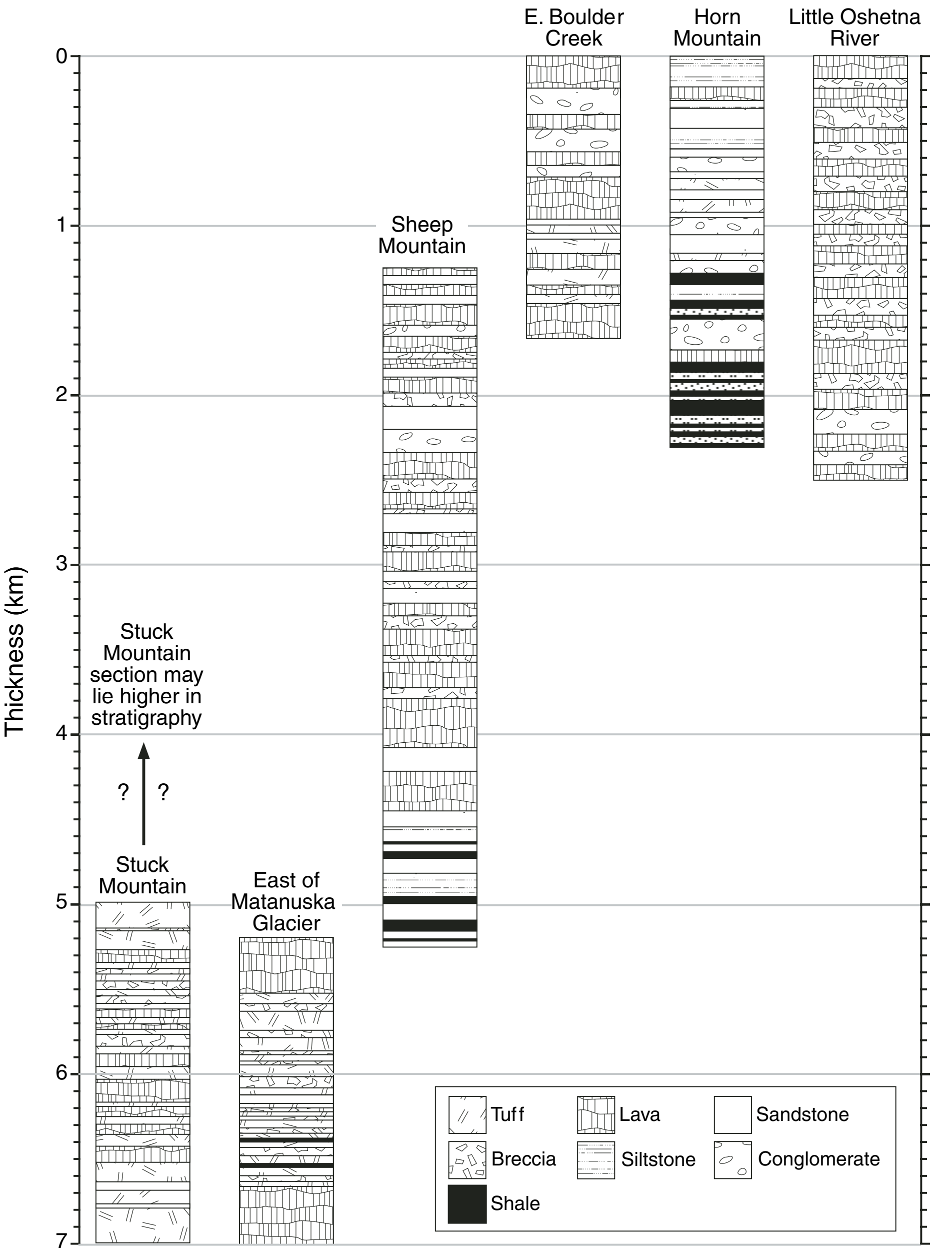


Figure 7. Proposed composite stratigraphy for the entire Talkeetna Volcanic Formation compiled from measured sections on the various massifs considered in this study. Sections are schematic and do not represent individual bed thicknesses, instead showing the overall character of the section.

DEPOSITIONAL ENVIRONMENTS

The rocks of the Talkeetna Volcanic Formation show a wide variety of depositional environments, with both temporal and lateral variation recognized. Nonetheless, a general trend up-section toward more volcaniclastic sedimentation and less lava can be identified. Here we briefly describe the depositional character of the Talkeetna Volcanic Formation in each of the major surveyed massifs in order to describe the evolving nature of arc volcanism.

Stuck and Willow Mountains

These massifs lie at the extreme east of the study area and are dominated by thick bedded lavas (45% of total section) with similar volumes of tuffs and tuff breccias. The section is not very well exposed, but is recognizably folded on a km-scale wavelength. Bedding is on a 1–10 m scale, and the rocks are generally well indurated and slightly metamorphosed to lower green schist facies. Diking is rare and where observed (at location 06V 0591140 6849946) is seen to be a well-cleaved, light-colored, high silica rock with prominent hornblende phenocrysts up to 1 cm across. Lavas tend to be aphyric or with minor pyroxene phenocrysts. Vesicles are rare. Unlike higher in the section, breccias are not common, but instead tuff breccias are present. Rare lapilli tuffs are observed, with well-defined fiammé several cm across. Sedimentary rocks are rare in this area, but medium-grained, well-sorted, massive volcaniclastic sandstones up to 2 m thick are found near the base of the section (Fig. 9D). Mudstone rip-up clasts within the sandstones testify to their redeposited origin in a marine setting.

The lack of vesicles in an arc lava suggests that this section was emplaced in significant water depths, as arc lavas are typically very

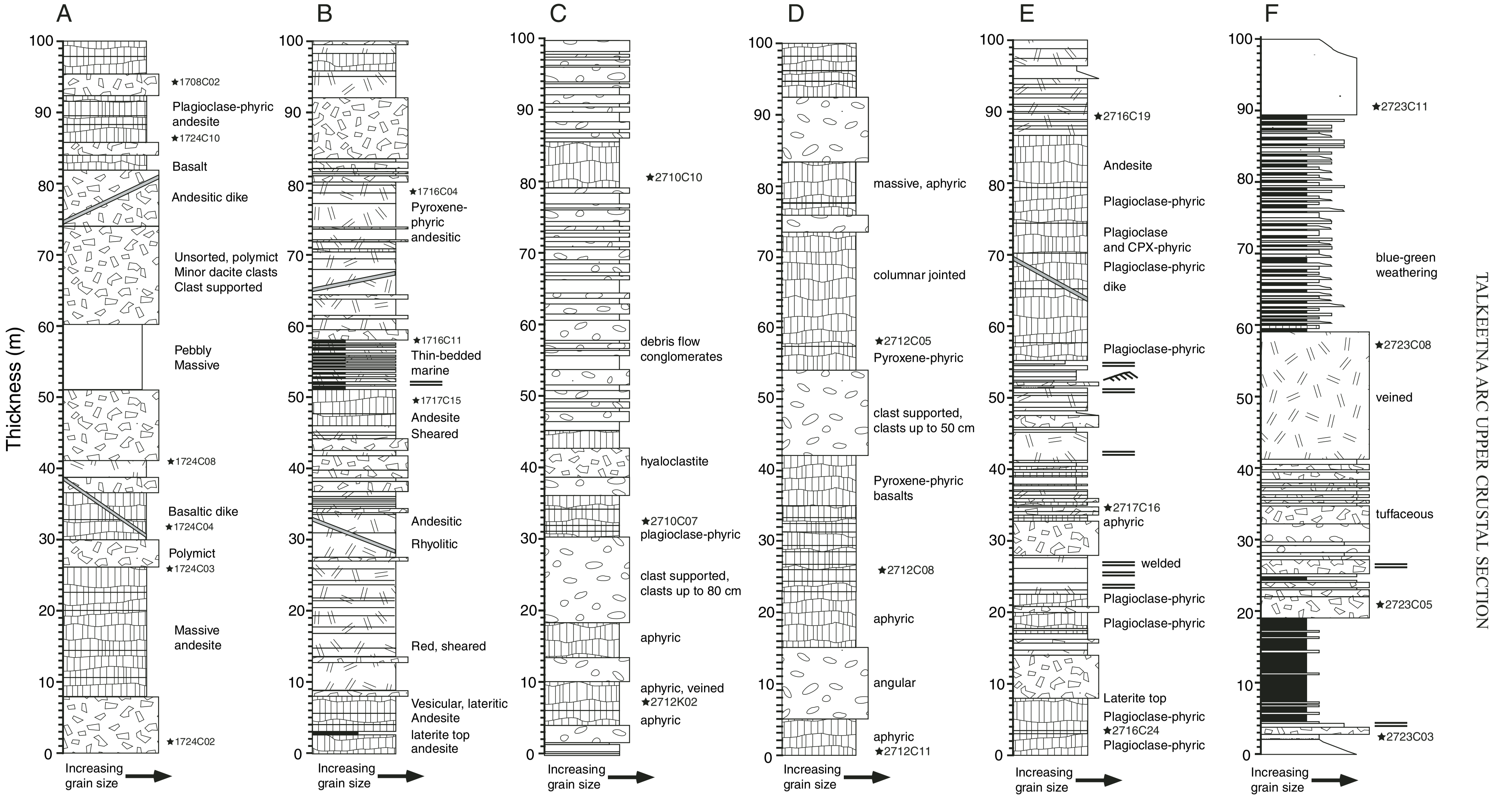


Figure 8. Sedimentary logs from the stratigraphic base of the Talkeetna Volcanic Formation (A) at Willow Mountain and (B) South of the Matanuska River, East of the Matanuska Glacier. The symbols used for the rocks are the same as for Figure 7. See Figure 4 for precise locations. Black stars indicate location of samples. Sedimentary logs from the stratigraphic top of the Talkeetna Volcanic Formation, under the Middle Jurassic Tuxedni Formation, are shown in (C) Sheep Mountain, (D) Little Oshetna River, (E) East Boulder Creek, and (F) Horn Mountains. Note striking facies differences between different areas of similar stratigraphic equivalence.

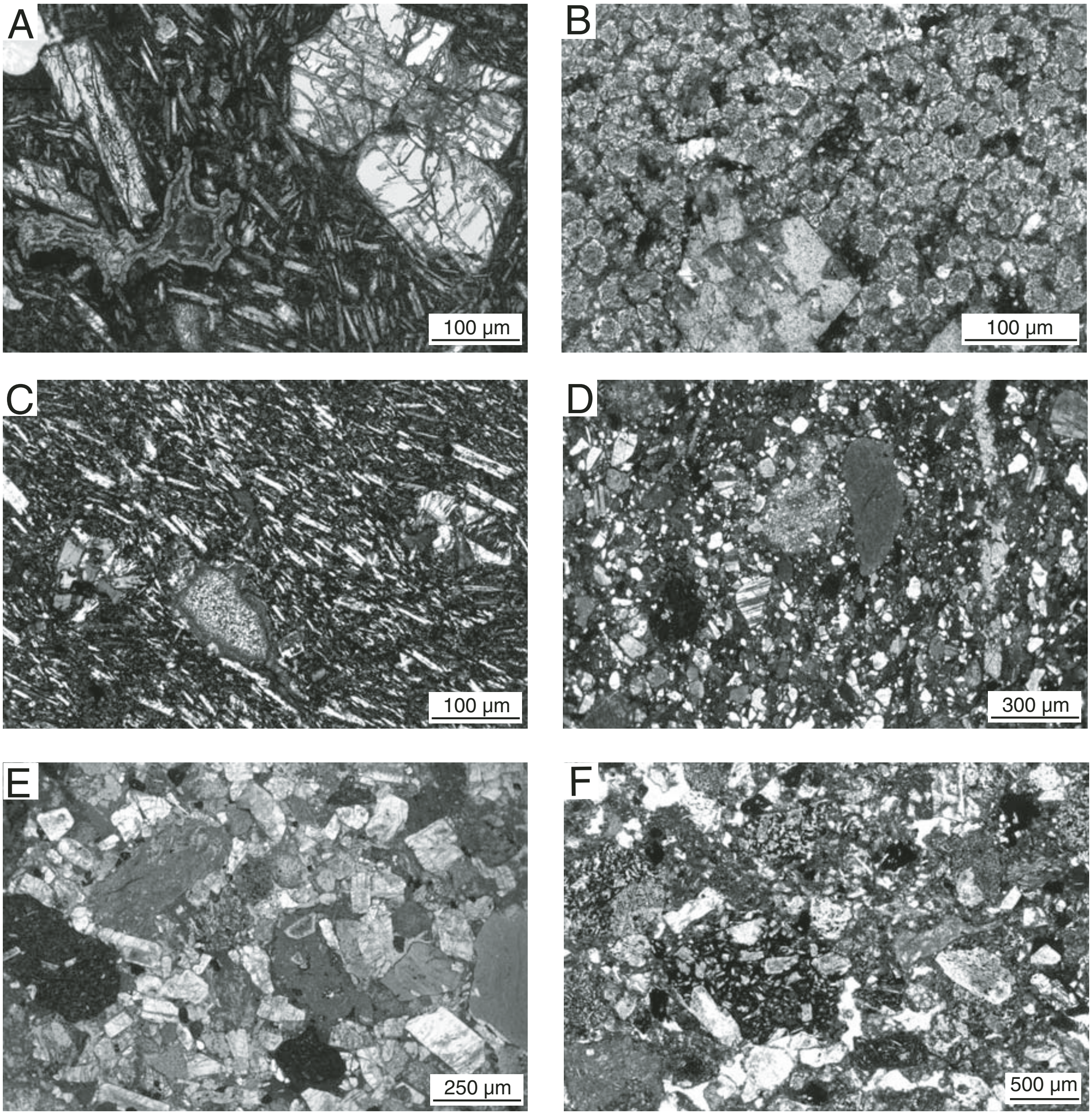


Figure 9. Microscope thin-section photographs of major Talkeetna Volcanic Formation lithologies. (A) Clinopyroxene and plagioclase-phyric basalt, Little Oshetna Valley. Note large clinopyroxene grain, plagioclase microphenocrysts, with clay-lined vesicle. (B) Devitrified rhyolite glass with large altered plagioclase phenocrysts, East Boulder Creek. (C) Plagioclase-phyric andesite with clay and calcite-lined vesicle, Sheep Mountain. (D) Volcaniclastic sandstone, Willow Mountain, Tonsina. Picture taken in cross polars. Note plagioclase grains, calcite-filled vein, and wide variety of clast types. (E) Volcaniclastic sandstone, Horn Mountains. Note the large euhedral plagioclase grains, indicating minimal reworking from a primary tuff. (F) Volcanic breccia, Sheep Mountain.

volatile-rich on eruption. Ocean Drilling Program (ODP) sampling of the Lau Basin and Sumisu Trough, both in the western Pacific, provided examples of deep submarine volcanism, showing that if the volatile content is high then explosive volcanism can occur at great depths whether the lava is basaltic or rhyolitic (~2.5 km; Gill et al., 1990). Water depths during emplacement of the Willow-Stuck Mountain section may have been >2 km.

Matanuska Glacier Area

East of the Matanuska Glacier, a series of mostly north-dipping strata (Fig. 6A) is intruded by and in faulted contact with the adjacent gabbros. This section of the Talkeetna Volcanic Formation comprises ~50% tuffs and ignimbrites, 40% lavas, and 10% sedimentary rocks. The whole outcrop is cut by south-vergent thrust faults. The lowest stratigraphic levels are characterized by aphyric, basaltic lavas, bedded on a 50–150 cm scale, and overlain by andesitic tuffs (Fig. 8B). The tuffs are mostly coarse, massive, and ungraded, 80–200 cm thick. Grading and lamination were observed in around 20% of the tuffs, generally those <40 cm thick. Minor volcanic tuff breccia intervals up to 1 m thick are also exposed. These contain very angular clasts up to 5 cm across, supported in a massive sandy matrix, suggestive of rapid emplacement. As at Stuck Mountain, a large part of the section comprises lavas, tuff breccias, and lapilli tuffs, which are interpreted as submarine deposits of primary volcanic material (Fisher and Schmincke, 1984). Our interpretation of marine deposition is supported by the observation of ~10 m of thin-bedded mudstones (Fig. 8B) containing fine-grained tuffs (1–10 cm thick) intercalated with tuff breccias. The top of the Matanuska section is distinguished by a prominent alternation (1–10 m scale) of dark- and lighter-colored rocks (Fig. 10A). The color is the result of the cyclic deposition of coherent basaltic andesite lavas (1–3 m thick) sharply overlain by basaltic andesitic tuff breccias (2–4 m thick) and finally grading up into a dark tuff (0.5–1.5 m thick). The lavas are typically structureless and fine grained with some pyroxene and/or plagioclase-bearing lithologies, especially seen in the lighter-weathering lithologies.

Sheep Mountain

The central part of the section is best exposed at Sheep Mountain and contains a series of lavas and volcaniclastic rocks with significant evidence for deposition in a marine setting. Volcaniclastic rocks comprise >80% of the section here, compared to <20% lavas, dikes, and sills. Although not common, bivalve-rich sandstone beds are exposed at the western end of the massif (location 06V 0464080 6852605), as well as higher in the section (location 06 V047445 6855355). At the base of the Sheep Mountain section, a medium-bedded facies of carbonate, shale, and medium-grained sandstones dominates, though this is interbedded with thick, proximal, matrix-supported primary volcanic tuff breccias that indicate proximity to an eruptive center. Sedimentary structures are rare, but some shales are parallel-laminated, and sandstones commonly grade up into shales, suggestive of deposition by turbidity currents. Massive sandstone emplaced by gravity-driven mass-flow processes is also present. Minor dikes are present and may also indicate proximity to the vent, though their age is unconstrained. Rare clusters of bivalves, brachiopods, and scleractinian corals within more shale-rich intervals (Sandy and Blodgett, 2000) suggest that water depth shallowed (to upper bathyal–outer shelf, 50–500 m), at least temporarily, compared to the sequences seen east of the Matanuska Glacier. Although remains of cycad plants have been reported from central Sheep Mountain (Knowlton, 1916; Fig. 10G), indicating occasional subaerial exposure, these are only present over short intervals. Marine sedimentation dominates most of the Sheep Mountain section.

Higher in the section, marine volcaniclastic rocks are interbedded with intervals of very thick-bedded, clast-supported breccias, up to 20 m thick, with clasts >20 cm across. Locally, a draping volcanic sandstone overlying rough bed tops appears to have been deposited from a high-velocity current, as evidenced by cross- and parallel-lamination, as well as occasional scoured surfaces within the sandstone. Further up-section, ~3 km above the base of the section, the volcaniclastic rocks are interbedded with massive lavas and volcanic breccias that appear locally to be autobrecciated lavas. The nearby observation of bivalve-bearing sandstones (Fig. 8C) indicates brecciation occurred under water, similar to pillow breccias on modern spreading ridges. Many of the lavas have vesicular tops and show calcite and zeolite filling. In contrast to the quiet carbonate-rich facies seen below, the volcaniclastic rocks are typified by thick-bedded, matrix-supported, ungraded debris-flow breccias, up to 5 m thick and separated by minor shales up to 30 cm thick. Clasts are all volcanic, angular, and ranging up to 70 cm across (Figs. 9F and 10B). The upper 1 km of the section is characterized by a series of structureless, coarse-grained andesitic tuffs (e.g., location 06 V 0492721 6854573), which are interbedded with 1–2-m-thick, massive vesicular basalts and basaltic andesite lavas, which are in turn overlain by a 12-m-thick matrix-supported volcanic tuff breccia, with vesicular clasts up to 60 cm across. A 10-m-thick columnar-jointed basaltic unit caps this exposure, interpreted as a sill because of its geometry. Diking is common in this and many other parts of the Sheep Mountain region, potentially leading to confusion between lavas and sills.

The section at Sheep Mountain is clearly deposited close to the active vents of an arc volcano, but also shows signs of a dominantly marine environment, albeit with occasional red, weathered lava-flow tops and plant fossils that indicate intermittent subaerial exposure. The few intervals of quieter carbonate sedimentation are minor compared to the debris-flow sedimentation that occurred between lava and tuff emplacement.

East Boulder Creek

The Talkeetna Volcanic Formation exposed at East Boulder Creek is mapped as lying under the Middle Jurassic Tuxedni Formation (Fig. 4) and consequently is considered to represent volcanism in the latter part of the arc's development. This section is one of the most disrupted in the region, dissected by NE-SW trending strike-slip faults and intruded by small granite bodies surrounded by 20–50-m-wide alteration aureoles. The granite contacts are also areas of basaltic and andesitic diking. Development of negative flower structures around the strike-slip faults (Fig. 6C) makes a coherent stratigraphy difficult to reconstruct. Nonetheless, the section shows a general trend from more lavas and pumiceous tuffs near the base to more volcaniclastic rocks, especially debris-flow conglomerates, toward the top (Fig. 10C). A volcanic bomb (Fig. 10D) indicates that at least some parts of this section were the products of subaerial, explosive eruption, although the sediment into which the bomb was reworked was likely a submarine mass-wasting deposit. Pahoehoe textures (toes and ropes) were identified on the top surface of several lava flows, associated with vesicular tops. These features may indicate brief subaerial eruption near the base of the section. The pahoehoe lavas are associated with occasional graded, felsic tuffs. Massive basaltic flows 1–5 m thick are interbedded with 2–4-m-thick, angular, clast-supported volcanic tuff breccias and 4–8-m-thick debris-flow conglomerates. The breccias likely represent the brecciated tops of aa-style lava flows. Neither type of sediment shows significant sorting or grading. The upper part of the section, exposed in East Boulder Creek itself, comprises 70% debris-flow deposits and coarse sandstone interbedded with fine-grained, aphyric and plagioclase-phyric basalts up to 5 m thick (30% of the section). Clasts in the debris flows are all volcanic but involve reworking of older altered volcanic rocks. Clasts up to 80 cm across are supported in the sandy and pebbly matrix. The debris-flow sequence grades up into a sandier facies toward the top, more suggestive of mass-flow emplacement.

Horn Mountains

The Talkeetna Volcanic Formation exposed in the Horn Mountains is unique in this area as an almost completely (>99%) volcaniclastic sequence, largely comprised of tuffs and sedimentary rocks (Fig. 8F). A single 10-m-thick aphyric basaltic lava was identified in the middle of the section. Compared to other sections, turbidite sandstones form a large part of the sequence (40%), with some thicker-graded beds (>2 m) showing a near-complete Bouma cycle (Bouma, 1962). Massive, ungraded sandstones, interpreted as high-density turbidite units, are also abundant. Although not fossiliferous, the sedimentary facies in this region are clearly marine, with mass-wasted facies dominating and shale intervals common (Fig. 10F). Rare dewatering structures, such as flame or loading structures, were recorded. A pale green mudstone unit ~60 m thick, located low in the measured section, contains sandy interbeds (50–70 cm thick) that

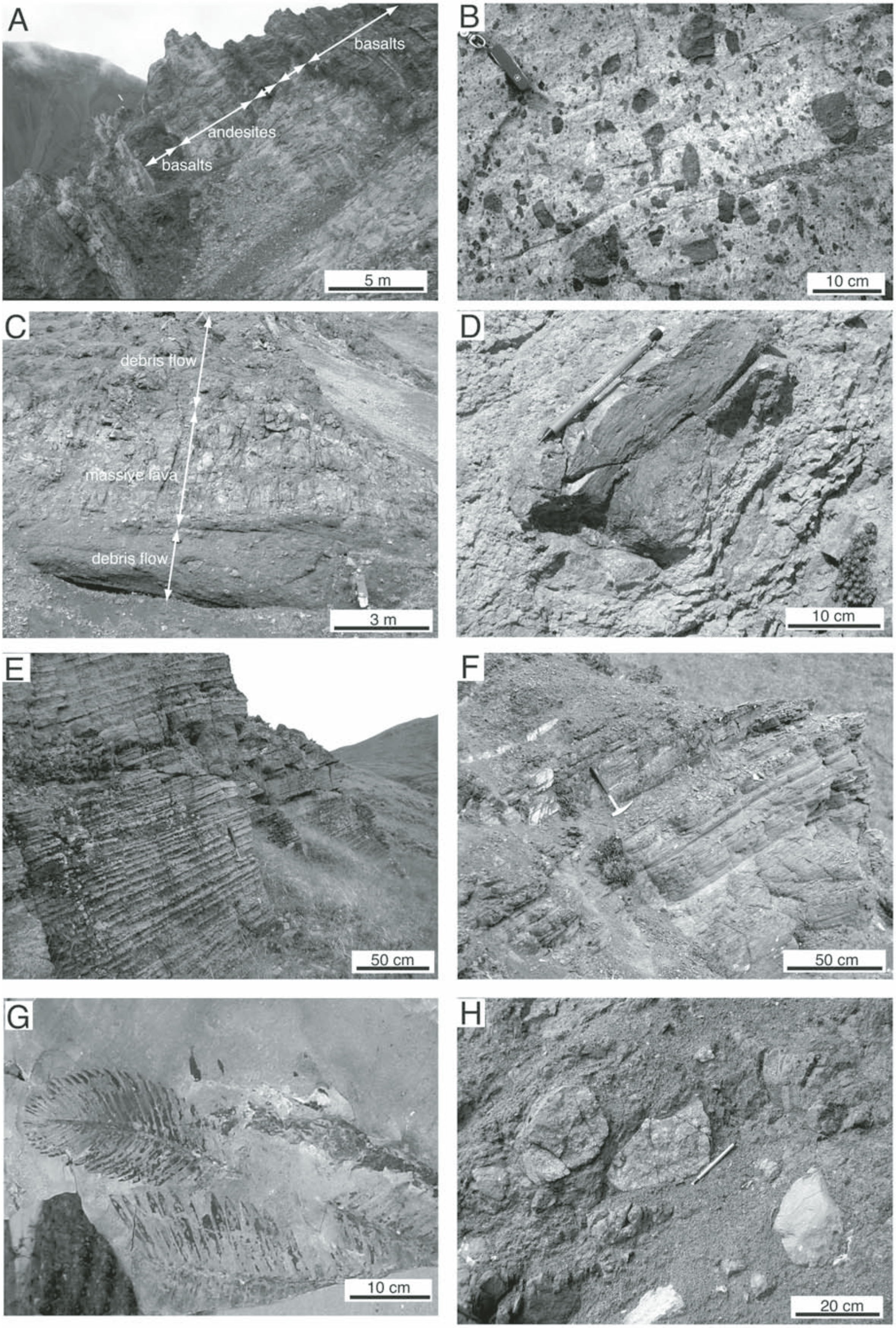

A
basalts
andesites
basalts
5 m
B
10 cm
C
debris flow
massive lava
debris flow
3 m
D
10 cm
E
50 cm
F
50 cm
G
10 cm
H
20 cm

Figure 10. Field photographs of representative Talkeetna Volcanic Formation lithologies. See Figures 4 and 5 for precise locations. (A) Interbedded basalts and andesites, 3 km east of the Matanuska Glacier. (B) Primary volcanic breccias, indicative of explosive eruption, Sheep Mountain. (C) Interbedded basalts and debris-flow conglomerates, East Boulder Creek. (D) Subaerially erupted andesitic volcanic bomb in sedimentary rocks, East Boulder Creek. (E) Medium-bedded tuffs, Horn Mountains. (F) Shales with minor volcanic sandstones, (G) Lower Jurassic cycad leaf from SE Sheep Mountain (61°52′ N; 147°50′30″ W), (H) Close-up of the matrix-supported character of the basalt clast debris-flow deposits, Little Oshetna Valley.

have experienced soft-sediment slump folding. Up-section, these facies coarsen into a series of 10–40-cm-thick, sandy, occasionally conglomeratic, turbidite sandstones. These in turn are overlain by 1–5-m-thick, angular, tuff breccias and volcanic breccias, with clasts up to 20 cm across suspended in a muddy sandstone matrix in the case of the conglomerates. Volcanic clasts are commonly monomict in the breccias and are either light-colored andesites or darker basalts. Debris-flow breccias tend to be more polymict.

Although it is composed entirely of marine and largely reworked strata, the Horn Mountains section was still relatively close to volcanic eruptive centers, as demonstrated by rare, very thick- to medium-bedded tuffs, totaling up to 20 m thick (Fig. 10E), as well as individual tuffs exceeding 2 m in thickness. Toward the top of the measured section the facies first become more shale rich, then sandy and turbiditic, with a single 12-m-thick turbidite forming a ridge-capping unit (Fig. 8F). There is no evidence for subaerial or even shallow marine sedimentation in the Horn Mountains section, and the depositional environment is interpreted as mid–lower bathyal (>500 m water depth).

Little Oshetna River Valley

In the Little Oshetna River valley the Talkeetna Volcanic Formation is unconformably overlain by Middle Jurassic sandstone of the Chinitina Formation (Trop et al., 2002). Unlike the Horn Mountains, which also lie at the top of the stratigraphy, the Little Oshetna section is dominated by lavas and debris-flow breccias (Figs. 8D and 10H). Compared to the sedimentary rocks described at Sheep Mountain and in the East Boulder Creek, the volcanic units commonly appear dark, aphyric, and basaltic. Abundant vesicles, typically infilled by calcite, clay minerals, and zeolites, characterize the tops of beds, indicating that they are flows and not sills. Dikes are noted in several areas and range up to 5 m across, comprising <5% of the total section. These weather into a lighter color than the lavas and are readily identified in outcrop. Reddened flow tops are recorded in several locations, and the conglomerate units themselves are typically reddened, presumably by fluid flow during diagenesis. Lack of reddening on flow bottoms implies that this red coloration was not caused by baking around sills injected into volcaniclastic sediments. Lighter-colored andesites with common pyroxene and plagioclase phenocrysts are noted but appear less common. Light-colored, parallel-laminated tuff units, 30–150 cm thick, form <10% of the uppermost part of the section.

Bedding is on a 3–20 m scale and involves an alternation between massive, occasionally columnar-jointed, basaltic flows and more readily eroded, ungraded matrix-supported volcanic breccias with clasts up to 50 cm across (Fig. 10G). Lavas are commonly pyroxene and/or plagioclase-phyric (Fig. 9A). The breccias are comprised only of angular lava clasts and are relatively altered (Fig. 10H). We interpret these rocks to be primary volcanic deposits, i.e., block-and-ash-flow tuffs. Lavas comprise ~40% of the section at the top, a proportion that decreases gradually down-section, reaching ~20% toward the base of the measured section. Significant lateral variability in the thickness of lava units is apparent over distances of 10 m, caused in part by ponding within the rough surfaces of the underlying tuff breccias. Evidence for marine sedimentation is apparent, especially lower in the section. The proportion of volcanic sandstone and even siltstone increases to ~40%. Evidence for deposition under current activity is noted; grading, parallel-, and cross-laminations suggest sedimentation from submarine sediment gravity flows. Deposition appears to have been rapid and episodic, consistent with submarine mass wasting close to a volcanic center.

TABLE 1. ND ISOTOPIC DATA FROM THE TALKEETNA VOLCANIC FORMATION

Sample	Nd (ppm)	Sm (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd	Location
2712C08	6.90	2.33	0.20	0.512942 ± 18	5.9	N of Little Oshetna River
2709C09	15.60	4.43	0.17	0.512922 ± 7	5.5	Little Oshetna River
2722C16	16.72	4.68	0.17	0.512919 ± 3	5.5	Horn Mountains
2710C10	10.28	3.52	0.21	0.512957 ± 9	6.2	NE side of Sheep Mtn
1721C04	13.80	4.34	0.19	0.512919 ± 8	5.4	Sheep Mountain
1725C03	13.80	4.38	0.19	0.512951 ± 6	6.1	Sheep Mountain
2718C13	12.41	4.02	0.20	0.512933 ± 13	5.8	W of Monarch Mtn
1722C15	9.00	3.20	0.22	0.512976 ± 4	6.6	E of Matanuska
1723C10	6.37	2.20	0.21	0.512861 ± 46	4.3	W of Tazlina
1724C02	21.92	6.55	0.18	0.512927 ± 4	5.6	Willow Mountain
1710C11	11.26	3.66	0.20	0.512929 ± 8	5.6	Stuck Mountain

Note: ε_{ND} is calculated assuming an age of emplacement at 180 Ma. Results corrected for La Jolla standard = 0.511847.

GEOCHEMISTRY

Analytical Techniques

A representative set of 84 samples was selected for chemical analysis. These were chosen from the freshest samples available and are distributed to cover the full range of lithologies and localities in order to derive a robust image of the composition of the Talkeetna upper crust. Samples from the Matanuska-Tonsina areas described above were included as well as four samples from a series of Talkeetna Formation lavas exposed in the Johnson River of the Iliamna area, lying to the SW of the main study region (Fig. 1). After being cut and cleaned, the rocks were powdered and dried before analysis. A suite of 10 major elements and 17 trace elements was analyzed by X-ray fluorescence (XRF) at the GeoAnalytical Laboratory of Washington State University. An additional 27 rare earth elements (REEs) and trace elements were also analyzed by inductively coupled plasma mass spectrometer (ICP-MS), also at Washington State University. U.S. Geological Survey standard BCR-1 was used to determine internal and external precision of these analyses. Uncertainty, as determined from duplicate analyses of the samples and standards, is generally <3% for the REEs and <5% for the other trace and major elements. The full analytical results are shown in Table DR1 (Table 1).[1] Major-element data are shown in non-normalized percentages measured after ignition and loss of most of the volatiles.

[1]GSA Data Repository item 2005101, X-ray fluorescence, is available on the Web at http://www.geosociety.org/pubs/ft2005.htm. Requests may also be sent to editing@geosociety.org.

A subset of 12 samples was selected for Nd isotopic analysis. After dissolution, Nd was concentrated using standard column extraction techniques, and isotopic compositions were determined on a VG354 mass spectrometer at Woods Hole Oceanographic Institution. We calculate the parameter ε_{Nd} (DePaolo and Wasserburg, 1976) using a depleted-mantle model age from the method of DePaolo et al. (1991). A $^{143}Nd/^{144}Nd$ value of 0.512638 for the Chondritic Uniform Reservoir (CHUR; Hamilton et al., 1983) was used.

Interpretation of the geochemistry concentrates on the lavas and especially on the less-evolved volcanic rocks. We do, however, also consider the chemistry of the volcaniclastic deposits, because they constitute a large portion of the upper crustal mass. In practice the volcaniclastic rocks found around submarine arc volcanoes represent fragmented and mass-wasted volcanic material, but they are not mixed to any significant degree with continental material or pelagic sediment. It should be noted that these are not eroded volcanic rocks, but typically result from explosive submarine eruptions followed by mass wasting. As a result they can be considered to be another form of volcanic material with significance for arc petrogenesis.

Major-Element Chemistry

The major-element chemistry allows the general character of the Talkeetna erupted section to be assessed. Alteration is seen on a microscopic scale in almost all samples, which suggests that fluid-mobile elements were partially remobilized and may not yield much information of petrogenetic significance. Loss on ignition (LOI) varies from 1%–11% and likely represents alteration in rocks of this age, despite the fact that arc lavas may contain a significant amount of primary magmatic water (e.g., Gill et al., 1990; Newman et al., 2000).

Aspects of the major-element chemistry of the Talkeetna Volcanic Formation are shown in Figure 11. Figure 11A shows an alkali/iron/magnesium (AFM) triangular diagram with the Talkeetna volcanic and volcaniclastic rocks falling between tholeiitic and a calc-alkaline trend. This assignment is also shown by the FeO/MgO versus SiO_2 diagram (Fig. 11B). Further dis-

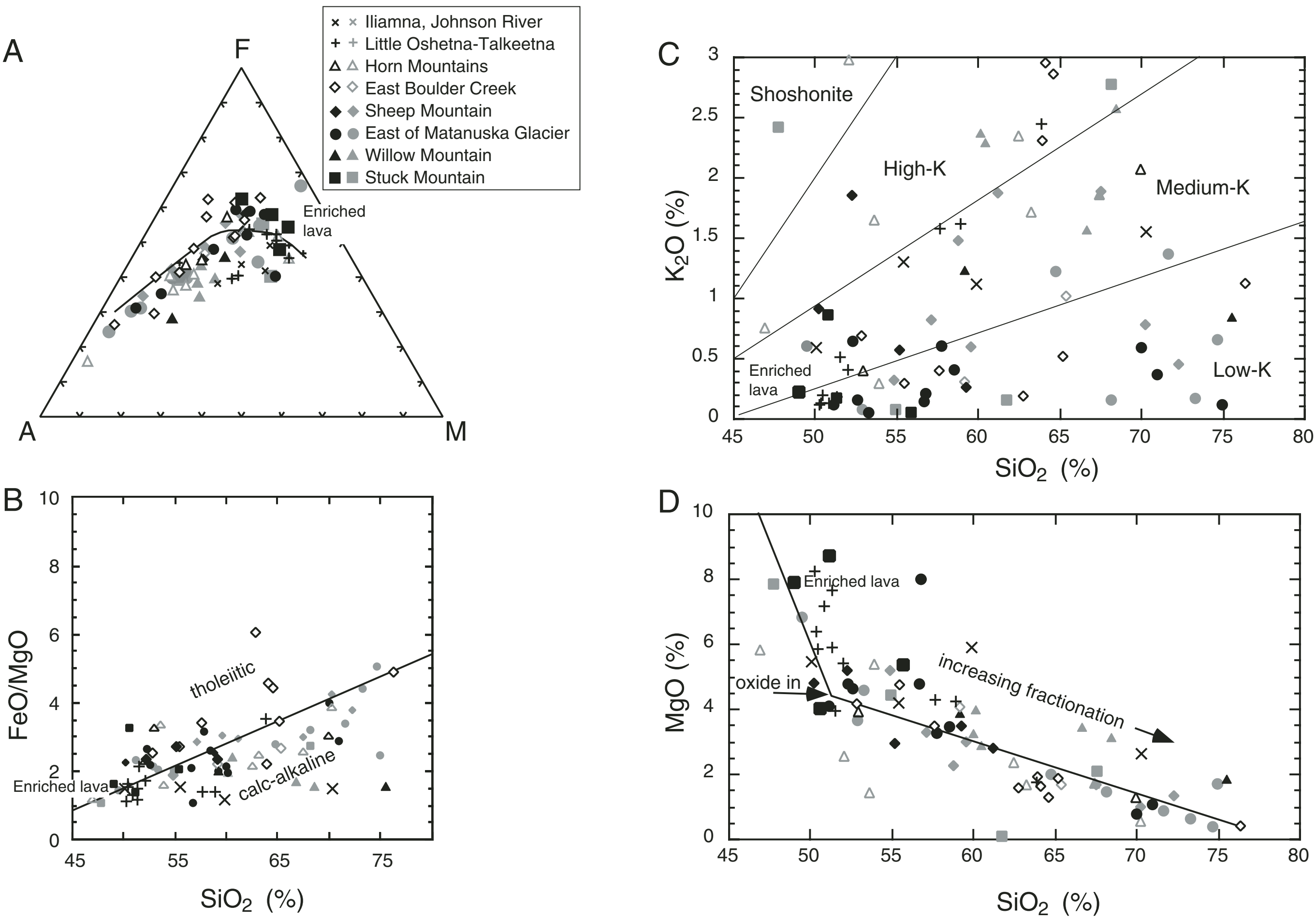


Figure 11. Major element characteristics of Talkeetna Volcanic Formation lavas. See Figure 4 for precise locations. (A) Triangular alkali/iron/magnesium (AFM) diagram as defined by Irvine and Baragar (1971) showing the range of values for Talkeetna lavas and volcaniclastic rocks. Volcanic rocks are shown as black symbols, volcaniclastic in gray color. (B) FeO/MgO versus SiO_2 variation diagram to show the general FeO-depleted, calc-alkaline chemistry (Miyashiro, 1974). (C) K_2O versus SiO_2 diagram showing the wide range of analyzed compositions, though with a dominance of low- and medium-K lavas. Compositional fields are from Peccerillo and Taylor (1976). Analyses labeled "enriched" lavas refer to rocks with unusual high LREE enrichments. (D) MgO versus SiO_2 diagram showing the dominant trend of Talkeetna Volcanic Formation rocks being consistent with an origin by fractional crystallization of a basaltic parent. "Oxide in" label shows point in fractionation series at which mafic iron oxide minerals begin to precipitate.

crimination on the basis of major elements can be made by plotting K_2O against SiO_2 for all rocks (Fig. 11C). A wide variation in composition is noted, although with a predominance of low- and medium-K rocks. However, because potassium is fluid-mobile (Pearce, 1982), the petrogenetic significance of such alkali enrichments must remain suspect.

Plotting MgO against SiO_2 shows a general trend that is consistent with differentiation via fractional crystallization of orthopyroxene, clinopyroxene, plagioclase, hornblende, and magnetite from a basaltic parent (Fig. 11D; Greene et al., 2005). Although this plot does not exclude the formation of andesite and higher silica lavas by remelting of the lower crust (c.f. Honshu Arc; Kimura et al., 2002), a simple fractionation origin from a relatively consistent basaltic parent is possible for most Talkeetna andesites.

No coherent temporal evolution is detected in the major elements in the Talkeetna Volcanic Formation (Fig. 12), with the possible exception of the Little Oshetna River region where basaltic lavas with relatively low consistent alkali contents (0.52%–0.13% K_2O) occur beneath the unconformity with the overlying Middle Jurassic Chinitina Formation.

Trace-Element Chemistry

The trace-element chemistry of the Talkeetna Volcanic Formation is more useful in understanding the petrogenesis of the magmas, because many of the elements considered are not susceptible to alteration and allow separation of influences from the mantle wedge under the arc and those derived from the subducting oceanic slab. Such separation is possible because some elements are mobile in the fluids discharged from the oceanic slab, while others are unique to the mantle wedge. Trace-element analysis was done in order to constrain whether the arc was formed in an oceanic or continental setting and to determine the polarity of subduction during the Early Jurassic. Studies of western Pacific arcs show that the most chemically depleted rocks are typically found in the forearc regions (e.g., boninites; Crawford, 1989), with enrichment increasing into the backarc region. If backarc volcanism occurs, this can extract melt from the mantle wedge before it passes under the arc volcanic front and consequently results in greater relative enrichment of the most incompatible elements compared to the arc volcanic front (e.g., Ewart and Hawkesworth, 1987). Our study also aimed to use the continuous sections available in the Talkeetna Formation to reconstruct the chemical evolution of the arc, as this is known to change in modern systems in response to tectonic events, such as backarc rifting or collision with seamounts (e.g., Arculus et al., 1995; Turner et al., 1997).

The general trace element character of the Talkeetna Volcanic Formation can be viewed using a mid-ocean ridge basalt (MORB)–normalized spider diagram (Pearce, 1982). In this diagram (Fig. 13) elements are arranged along a horizontal axis on which elements that are strongly enriched by flux from the subducting slab occupy the left-hand side (as far right as U), and elements largely derived from melting from the mantle wedge lie on the right (from Nb). Compatibility of the elements in mantle phases is arranged to increase to the right among the wedge-dominated elements and toward the left in the slab-dominated elements. The slab-enhanced elements are typically water-mobile except Th, which is immobile in aqueous solution but enriched in slab flux by sediment melting (e.g., Pearce and Peate, 1995). All the rocks analyzed show typical characteristics of a subduction-related petrogenesis. The slab-derived elements show significant relative enrichment, although both Ta and Nb are depleted compared to the other immobile, incompatible elements. It is noteworthy that although Th is occasionally depleted, the concentrations of the other slab-derived elements are generally coherent and similar to modern arc lavas (e.g., Pearce, 1982), implying that these elements have not been strongly modified from their original concentrations during alteration. The Sheep Mountain section in particular shows a remarkably consistent trace-element pattern. However, in some lavas from Stuck and Willow Mountains, Rb, K, U, and Th are variously depleted, possibly implying significant remobilization during alteration. This implication is consistent with the higher degrees of alteration observed in hand specimen and thin section and in turn with the inferred deeper burial of that part of the volcanic section.

The similarity between the trace-element character of the volcaniclastic sedimentary rocks and the lavas is noteworthy. The chemistry is consistent with the petrography in showing no nonvolcanic material mixed with the volcaniclastic sediments. Specifically, there is no indication of erosion from a continental hinterland. Whether the volcaniclastic sediments were primary tuffs or reworked, the chemistry supports our interpretation that they represent the primary production of a submarine arc volcano. The volcaniclastic sediments do not represent erosion of older volcanic rocks but instead reflect mass wasting of brecciated volcanic material on the flanks of a volcano, during or just after an eruption. Consequently, their bulk composition lies very close to primary magmatic compositions.

The overall trend of the water-immobile high field strength elements (HFSEs: Ta, Nb, Zr, Ti) is fairly flat, subparallel to a MORB profile, possibly indicating that the source mantle from which the melt was extracted had a trace-element content similar to a MORB source. The trend is quite distinct from a more enriched continental or plume-type chemistry. HFSEs are generally considered to be dominantly derived from melting of the mantle wedge, with little contribution from the subducting plate. The spider diagrams show differences in HFSEs between different parts of the section, pointing to changes in the composition of the mantle wedge. The Johnson River (Iliamna) samples show the lowest Nb/La ratio, which might indicate the greatest source depletion prior to arc magmatism or the highest degree of partial melting during arc magmatism. The lavas exposed east of the Matanuska Glacier also have slightly lower Nb/La values (i.e., more depleted) than those exposed on Sheep Mountain or in the East Boulder Creek. The Little Oshetna area distinguishes itself in having the highest Nb/La values and a slightly enriched Nb/Zr value, suggestive of a more enriched source than other areas. Although the trend to greater enrichment up-section is also expressed as a trend from south to north, we do not consider this to represent an across-arc chemical trend similar to those known from western Pacific arcs (McCulloch and Gamble, 1991). This is because the total across-arc distance considered in the Talkeetna Arc section is not comparable to that sampled in modern systems and because the structure of the Talkeetna area indicates a tilted fairly continuous section, not a series of independent volcanic centers.

The REE chemistry of the more primitive lavas (<60% SiO_2) in the Talkeetna Volcanic Formation is shown in chondrite-normalized multi-element diagrams (Fig. 14). Many of the trends are relatively flat and straight, with some showing moderate relative LREE enrichment. Slight negative Eu anomalies reflect plagioclase fractionation prior to eruption, although very small Eu anomalies probably indicate the presence of small amounts of accumulated plagioclase in some mafic basalts. Compared to MORB, all the compositions show LREE enrichment, which likely reflects enrichment of the mantle source by recycling of LREEs from subducted sediments and basalt. Just as differences in HFSE enrichment are observed between the different massifs, there is greater relative LREE enrichment on Sheep Mountain and East Boulder Creek compared to lavas from east of the Matanuska Glacier. The Little Oshetna and Johnson River lavas are also slightly enriched in LREEs. Lavas on Stuck and Willow Mountains at the base of the section generally show quite flat REE patterns,

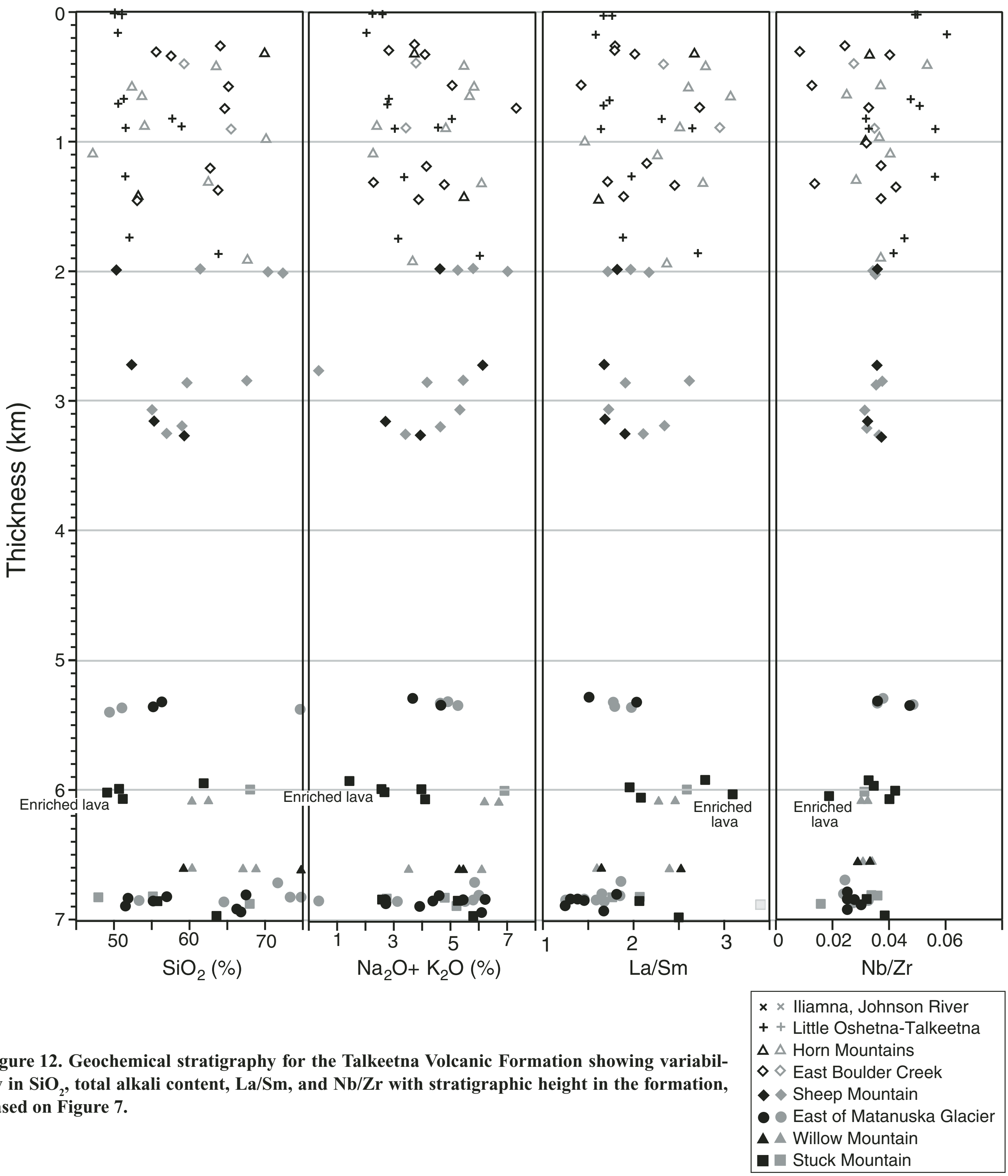
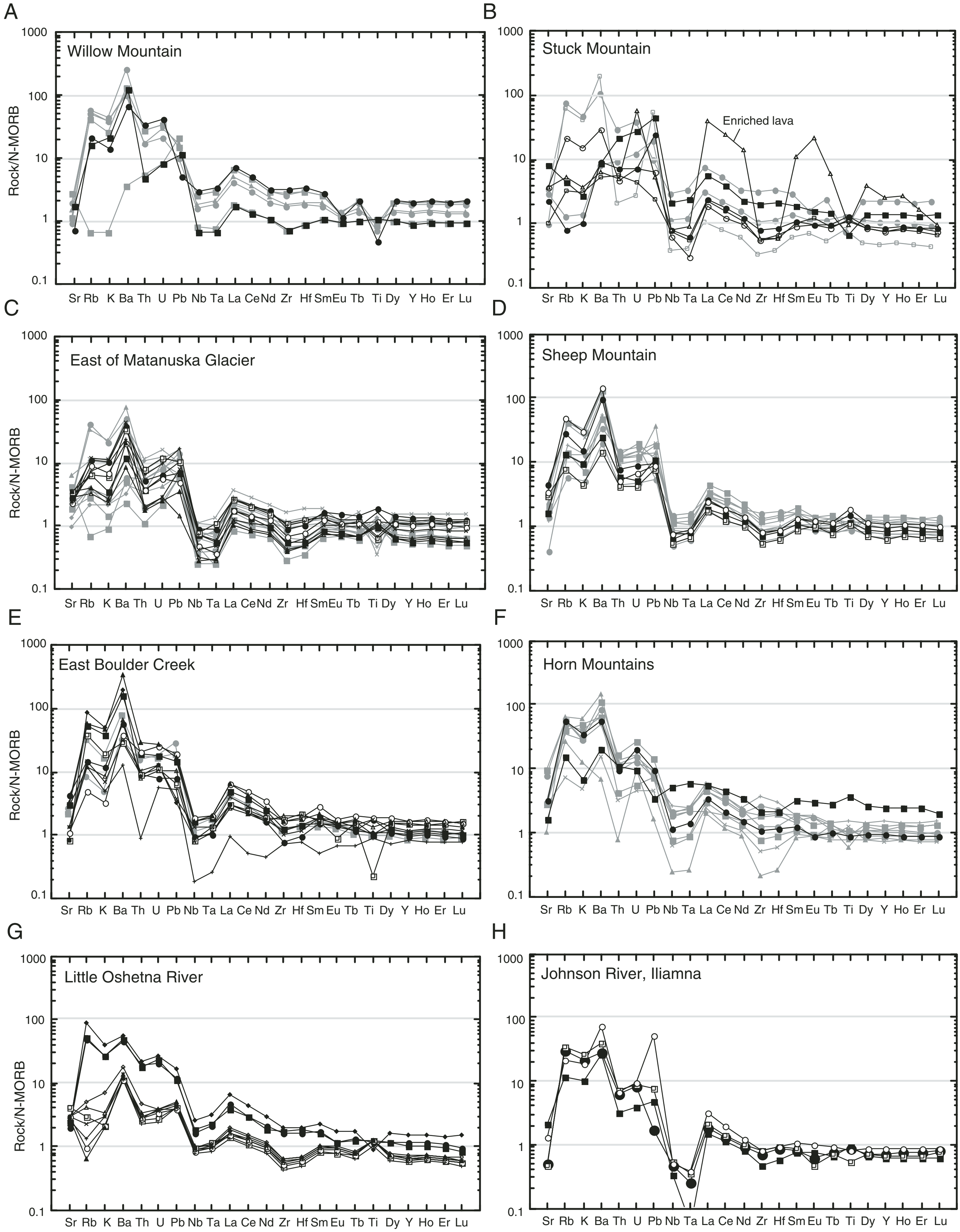


Figure 12. Geochemical stratigraphy for the Talkeetna Volcanic Formation showing variability in SiO_2, total alkali content, La/Sm, and Nb/Zr with stratigraphic height in the formation, based on Figure 7.

Figure 13. N-MORB–normalized multielement spider diagrams for Talkeetna Volcanic Formation rocks collected in different regions of the study area. (A) Willow Mountain; (B) Stuck Mountain; (C) South of the Matanuska River; (D) Sheep Mountain; (E) East Boulder Creek; (F) Horn Mountains; (G) Little Oshetna River and (H) the Johnson River region, Iliamna. N-MORB values of Sun and McDonough (1989). Lavas are shown as black lines, volcaniclastic rocks in gray. Symbols used distinguish different samples from a single area and do not correspond the symbols used in Figures 11 and 12.


A
Willow Mountain
B
Stuck Mountain
Enriched lava
C
East of Matanuska Glacier
D
Sheep Mountain
E
East Boulder Creek
F
Horn Mountains
G
Little Oshetna River
H
Johnson River, Iliamna
Rock/N-MORB
1000
100
10
1
0.1
Sr Rb K Ba Th U Pb Nb Ta La Ce Nd Zr Hf Sm Eu Tb Ti Dy Y Ho Er Lu

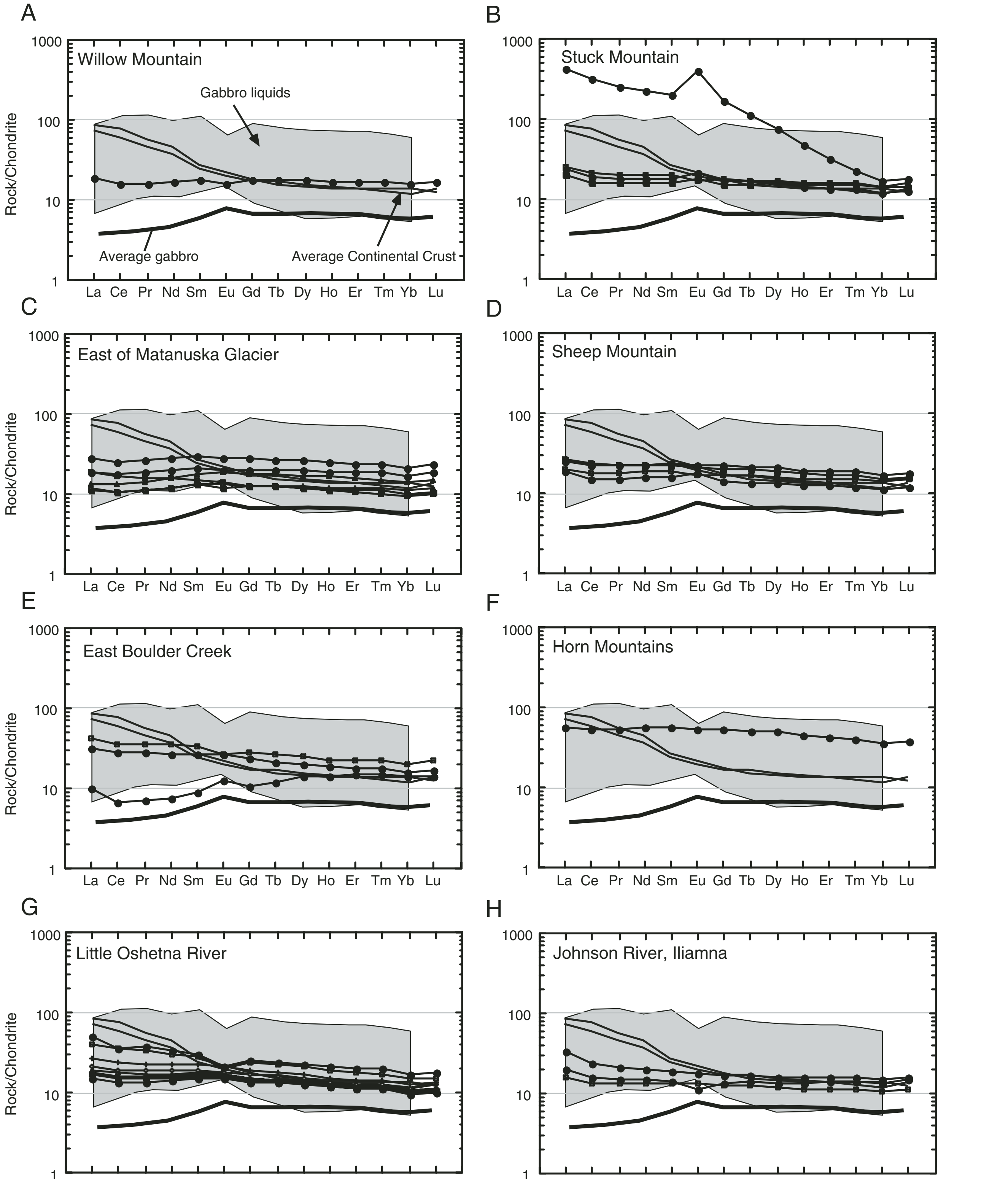


Figure 14. Chondrite-normalized REE diagrams for Talkeetna Volcanic Formation lavas <60% SiO_2. (A) Willow Mountain; (B) Stuck Mountain; (C) East of the Matanuska River; (D) Sheep Mountain; (E) East Boulder Creek; (F) Horn Mountains; (G) Little Oshetna River and (H) the Johnson River region, Iliamna. Chondrite values of Sun and McDonough (1989). Field labeled "gabbro liquids" shows the range of liquids calculated to have been in equilibrium with the Talkeetna Arc mid-crustal gabbros (Greene et al., 2005). The average gabbro line refers to the average bulk rock gabbro composition for the Talkeetna Arc (Greene et al., 2005). Symbols used distinguish different samples from a single area and do not correspond the symbols used in Figures 11 and 12.

though one lava shows extreme relative LREE enrichment together with HREE depletion. The presence of very enriched rocks in the Stuck-Willow area is in accord with the earlier work of Plafker et al. (1989), who published an analysis of a LREE-enriched, HREE-depleted volcaniclastic sedimentary rock from this area. The LREE-enriched lavas are located at the base of the Stuck Mountain section, near the base of the entire Talkeetna Arc section (Fig. 12). However, it is questionable whether these rocks are really of Jurassic Talkeetna affinity because they lie close to highly enriched, siliceous dikes of Eocene age (B. Hacker, 2004, personal commun.), which may have contaminated their chemistry.

Interpretation of the REE chemistry is slightly more complex than for HFSEs because, in addition to being extracted from the mantle source, REEs can also be derived from recycling of subducted sediments and/or basalt. Isotopic data, discussed below, are required to separate the two influences. Nonetheless, it can be seen that overall relative LREE enrichment of any Talkeetna lava is less than that of the bulk continental crust (e.g., Taylor and McLennan, 1985; Rudnick and Fountain, 1995; Christensen and Mooney, 1995). Compared to the midcrustal gabbros, Talkeetna volcanic rocks have greater LREE enrichment (Greene et al., 2005). Only one lava in East Boulder Creek was found to have REE slopes similar to the midcrustal gabbros. However, melt compositions calculated by Green et al. (2005) for the liquids in equilibrium with the pyroxenes in the gabbros indicate that the gabbros are cumulates that formed in equilibrium with melts that had REE characteristics similar to the lavas (Fig. 14).

No well-defined temporal trend is noted in either HFSEs or REEs, beyond a general tendency for the most depleted rocks to occur at the base of the section, east of the Matanuska Glacier, with greater enrichment up-section in the East Boulder Creek and Sheep Mountain sections. Interestingly, the Little Oshetna section is again anomalous in showing higher HFSE enrichment but only moderate LREE enrichment.

The coherence of the REEs and HFSEs can be assessed by plotting La/Sm against Nb/Zr. La/Sm was used as a proxy for the degree of LREE enrichment, while Nb/Zr can indicate the degree of HFSE enrichment. Figure 15A shows the total array of Talkeetna compositions with reference to N-MORB, primitive mantle, and the bulk continental crust. Excluding the anomalous Little Oshetna lavas, there appears to be a wide scattered range of REE enrichment but a more constant degree of HFSE enrichment, indicative of a decoupling between these elemental groups during arc petrogenesis. The Little Oshetna lavas show an independent array trending to higher relative HFSE enrichment.

These new data may also be compared with erupted glass compositions from Neogene arc volcanic sequences (Fig. 15B). The modern arcs are represented by a series of whole-rock volcanic and tephra glass compositions spanning the range of erupted products from each of these systems. It can be seen that the mafic lavas of the Talkeetna Volcanic Formation span a similar range in HFSE and REE enrichments compared to the recent Tonga and Izu volcanic fronts. The range of Talkeetna compositions is, however, more restricted than the entire range of Tonga volcanic rocks, including Eocene forearc boninites and backarc basin basalts, especially if the enriched lava at Stuck Mountain is excluded.

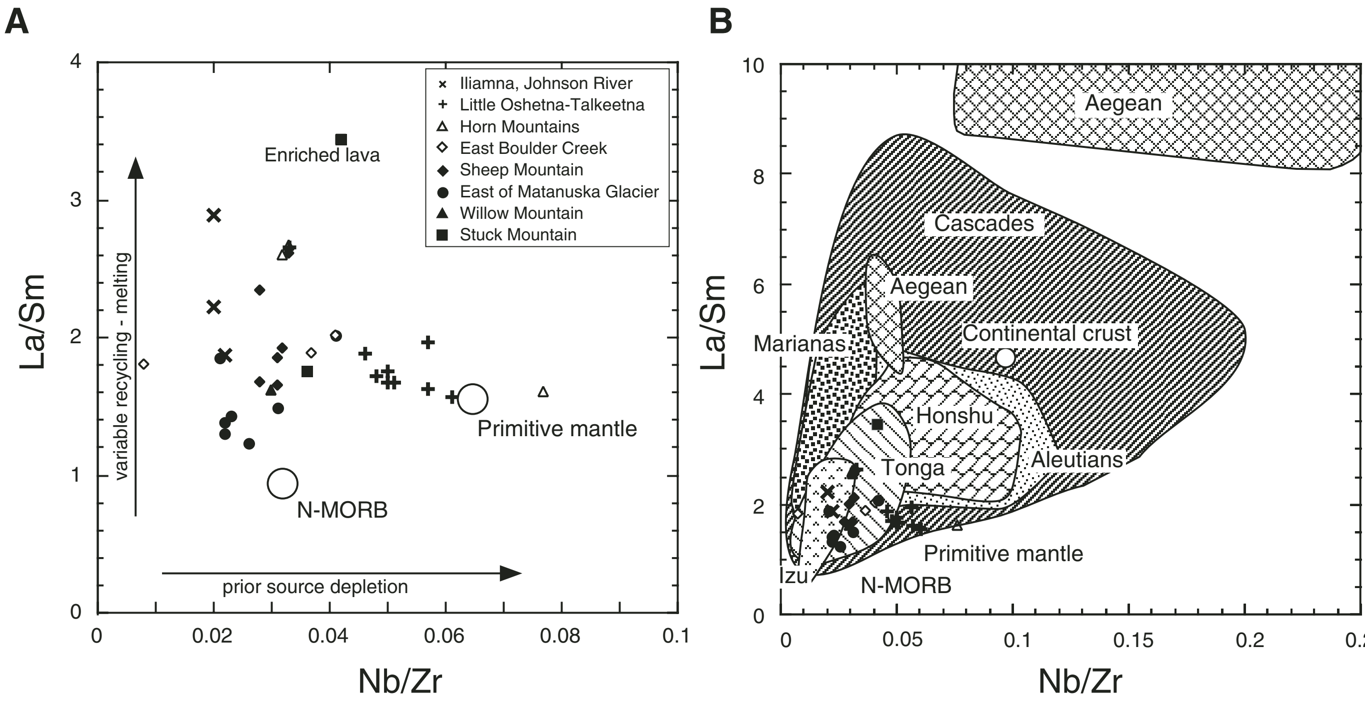


Figure 15. (A) Diagram showing variation in La/Sm versus Nb/Zr in all Talkeetna Volcanic Formation lavas and tuffs, relative to N-MORB, primitive mantle (values of Sun and McDonough, 1989) and the average continental crust (values of Rudnick and Fountain, 1995). Lavas <60% SiO_2 are shown as black symbols, evolved and volcaniclastic rocks are shown in gray. (B) Range in La/Sm versus Nb/Zr compared to measured ranges from volcanic glass from active and Neogene arc systems. Aegean data from Clift and Blusztajn (1999). Izu and Honshu data from Clift et al. (2003), Taylor and Nesbitt (1998), and Straub and Layne (2002). Mariana data from Lin et al. (1990), Straub (1995), Lee et al. (1995), Elliott et al. (1997), Clift and Lee (1998), Peate and Siems (1998), and Kent and Elliott (2002). Tonga data from Ewart and Hawkesworth (1987), Regelous et al. (1997), Ewart et al. (1998), and Clift et al. (2001). Aleutian data from Kay et al. (1982), Morris and Hart (1983), Singer et al. (1992), and Yogodzinski et al. (1993).

The modern Mariana, Honshu, and Aleutian arcs also seem to show a greater spread of enrichment than that sampled in this Talkeetna study. Nonetheless, Figure 15B clearly shows the similarity of the Talkeetna upper crust and explosive output from depleted modern oceanic island arc systems. Although similar compositions are found in a number of continental arcs, such as the Cascades, the Talkeetna Volcanic Formation does not show the spread to more enriched compositions, which is also seen in these settings.

Trace elements may be used to determine the influence of sediment recycling on petrogenesis. In particular, we follow the work of Plank and Langmuir (1998) in using Th/La as a proxy for involvement of a recycled sediment and/or basaltic component. Th/La is known to correlate well with other measures of subduction recycling in many modern arc systems. Figure 16 shows the general positive correlation of La/Sm with Th/La in the more mafic lavas of the Talkeetna Volcanic Formation; this indicates that, for much of the arc's duration, recycling of subducted basalt and/or sediment may have been an important control on LREE enrichment, in addition to the degree of enrichment of the source mantle in the wedge. It is noteworthy that the lavas from east of the Matanuska Glacier show the lowest Th/La values and presumably reflect the lowest degree of sediment recycling.

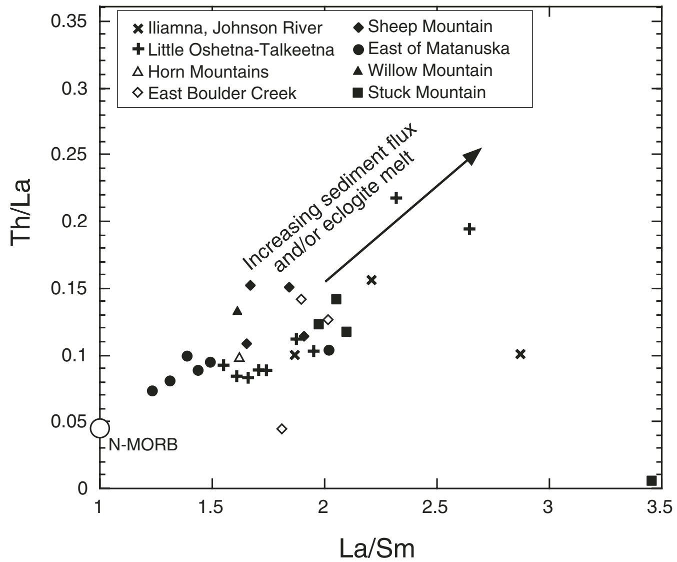


Figure 16. Diagram showing the general positive relationship between Th/La (a proxy for sediment recycling in petrogenesis; Plank and Langmuir, 1998) and La/Sm, indicating a common control by sediment subduction on the LREE enrichment in the Talkeetna Volcanic Formation. N-MORB value is from Sun and McDonough (1989).

Isotopic Chemistry

The petrogenesis of the Talkeetna Volcanic Formation may be further explored through the use of the Nd isotopic system. Because Nd is relatively immobile during low temperature alteration and because of the strong isotopic differences between mantle melts and the continental crust, this isotopic system effectively quantifies the involvement of recycled sediments in melt generation at convergent margins (e.g., Vroon et al., 1993). Nd is especially useful in dealing with both evolved and primitive magmatic liquids because fractional crystallization is not thought to change the isotope ratios. Because of the great similarity in trace-element character, suggesting that the volcaniclastic units are close to magmatic compositions, we chose to analyze a suite of lavas and volcaniclastic rocks to investigate their petrogenesis.

Figure 17 shows a plot of the initial ε_{Nd} against La/Sm. All modern ε_{Nd} values are recalculated to the values at the approximate time of eruption (ca. 180 Ma). If the enrichment in La/Sm in the Talkeetna Volcanic Formation had been dominantly controlled by sediment recycling, then a negative correlation would be expected in this diagram. Little coherent pattern

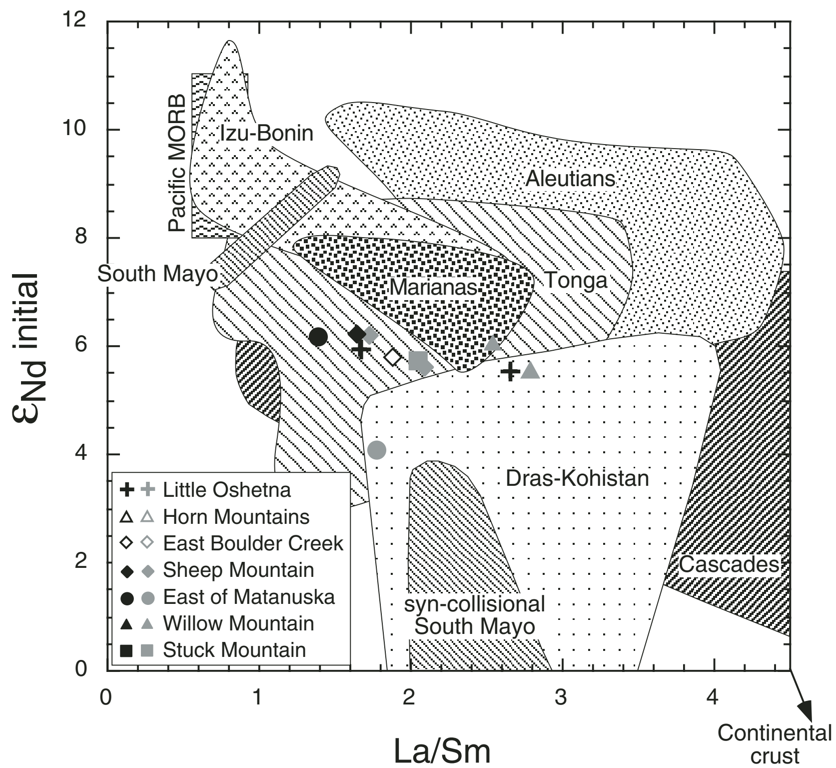


Figure 17. Chemical variation diagram showing the relationship between Nd isotopic character and the enrichment in REEs within the Talkeetna Volcanic Formation. Pacific MORB field is from Castillo et al. (2000) and references therein. Izu field is from Taylor and Nesbitt (1998) and Straub and Layne (2002). Dras-Kohistan field is from Khan et al. (1997), Clift et al. (2002), and Bignold and Treloar (2003). South Mayo fields are from Draut et al. (2004). Other modern arc fields are from sources for Figure 16, largely found in the GEOROC database. Mariana field includes the shoshonitic lavas of northern Mariana Trough (Stern et al., 1990; Sun and Stern, 2001).

is discernable in this diagram, suggesting that the REEs are controlled by several processes. The volcanic and volcaniclastic rocks show a general overlapping pattern, suggestive of a similar petrogenetic history.

The Nd isotope character of the Talkeetna Volcanic Formation can be used to compare the Talkeetna Arc with modern subduction systems and ancient accreted island arcs, as well as mantle sources such as the Pacific MORB source. Although the isotopic composition of the Pacific mantle has evolved since the Early Jurassic (Hauff et al., 2003), the initial ε_{Nd} value of newly erupted MORB has remained strongly positive (>+8) since that time. Because the exact mantle source composition of the Talkeetna Arc is not known, modern Pacific MORB acts simply as a guide to approximate mantle values rather than to a precise composition of the Talkeetna mantle wedge. In contrast, ancient continental crust has negative ε_{Nd} values.

Figure 17 shows that the Talkeetna Volcanic Formation falls within the range of compositions erupted in the recent geologic past in the Tonga Arc and slightly below the ε_{Nd} values recorded from the Mariana and Izu-Bonin arc volcanic fronts. This argues for relatively little recycling of ancient continental material in the Talkeetna Arc. Such ε_{Nd} values are known from the continental Cascade Arc, which involves significant sediment subduction in its petrogenesis, but Cascade samples also show scatter to much lower ε_{Nd} values than are seen here. The degree of sediment involvement in the Talkeetna Arc is smaller than that inferred from the oceanic Cretaceous Dras-Kohistan Arc of the Indus Suture Zone (Khan et al., 1997; Clift et al., 2000) or from volcanic rocks erupted during the Caledonian collision of the oceanic South Mayo Arc with the passive margin of Laurentia during the Early Ordovician (Draut et al., 2004). When compared to the Aleutian Arc, the Talkeetna samples appear to show mixing between a mantle source and a different sediment and/or basaltic end member, although the total contribution is not resolvably greater. There is no evidence to suggest a significant change in sediment recycling up-section in the units analyzed. In constraining the tectonic setting of the Talkeetna Arc, we may infer that it was recycling only a moderate amount of ancient continental sediment, similar to the modern western Pacific arc systems. We cannot rule out involvement of sediment eroded from younger continental crust, such as that formed by the accreted terrains of western North America, but the geochemical evidence does not favor this. We thus infer that the Talkeetna Arc was probably located relatively far from the North American margin at the time of emplacement.

DISCUSSION

Depositional Environments

The depositional environment of the Talkeetna Volcanic Formation shows a general evolution from dominantly lavas and tuff breccias at the base of the section to more gravity-driven sedimentary facies at the top. Nonetheless, all the measured sections were deposited close to an eruptive center, and lava flows and dikes are found at all levels in most sections, except for the Horn Mountains, where sedimentary rocks comprise the most distal sedimentary facies. The Sheep Mountain section in particular appears to have been emplaced close to a volcanic center, based on the coarse, proximal character of the sedimentary rocks and also from the frequent observation of diking and sills, which may form part of a peperite sill complex (Busby-Spera and White, 1987). These complexes are commonly associated with volcanism in thick sedimentary sequences and have been documented in the Gulf of California and the Sea of Japan (e.g., Einsele, 1985; Thy, 1992). Sill complexes form when magmas encounter water-saturated sediment and cannot continue their buoyancy-driven rise through hard rock, driving the liquids laterally into the sedimentary pile.

Depositional environments are dominantly deep water and do not change significantly from the base to the top of the section. Most volcanic and volcaniclastic facies indicate eruption at bathyal water depth, likely >500 m and perhaps as deep as 2 km. There is evidence for short intervals of subaerial sedimentation within a shallower water sequence exposed in the middle of the section at Sheep Mountain, where rare coral, brachiopod, and bivalve communities indicate shallow marine conditions punctuated by intermittent subaerial exposure. In general, the sedimentary rocks of the Talkeetna Volcanic Formation indicate mass wasting on rapidly deepening submarine slopes around volcanic centers. There is no overall trend in water depth up-section beyond the temporary shallowing recorded at Sheep Mountain.

Arc Tectonics

Vertical motions in modern arcs are variable and are linked to various tectonic processes. Near the trench, uplift may be driven by collision of the forearc with seamounts on the subducting plate (e.g., Vanuatu: Collot et al., 1985; Tonga: Dupont and Herzer, 1985). Alternatively, subsidence and increased water depth may be caused by arc rifting or subduction erosion (von Huene and Scholl, 1991; Taylor, 1992; Parson and Hawkins, 1994). Continuous magmatic accretion might be expected to lead to long-term crustal thickening and shallowing, yet in the western Pacific, ongoing arc extension has resulted in long-lived bathyal water depths, except for in the immediate vicinity of the arc volcanoes. The lack of a clear bathymetric trend in the Talkeetna Volcanic Formation is similar to the behavior of modern Pacific arcs and is consistent with deposition in an oceanic arc that is undergoing long-term extension driven by tectonic erosion of the plate margin (von Huene and Scholl, 1991; Clift and Vannucchi, 2004).

The preserved Talkeetna Volcanic Formation is a very proximal part of the arc complex, with no distal forearc or trench-slope material preserved. The equivalent deep-water turbidite and hemipelagic sedimentary deposits that characterize the western Pacific forearc basins (e.g., Underwood et al., 1995) and are preserved in the Dras-Kohistan Arc in Ladakh (Clift et al., 2000) are presumed to have been eroded after thrusting of the Talkeetna Arc over the Chugach Terrane in Cretaceous-Cenozoic times. Alternatively, the Talkeetna forearc may have been tectonically eroded and subducted prior to the onset of later subduction accretion in the Chugach Mountains. We consider the Talkeetna Arc to have been in a state of tectonic erosion because of the lack of shallowing seen in the sedimentary record, the lack of a preserved accretionary complex of this age, and because the geochemistry is inconsistent with the subduction of a thick trench sediment column. Clift and Vannucchi (2004) demonstrated that modern trenches with sediment piles <1 km are in a state of long-term tectonic erosion and crustal loss; this seems likely in the Talkeetna example as well.

The distribution of volcanic rocks in the study area is consistent with eruption above a north-dipping subduction zone. If the exposures arranged in an east-west orientation parallel to the Border Ranges Fault represent the trend of the former arc volcanic front as the geochemistry suggests, then the sections in the Little Oshetna region are clearly displaced either trenchward or landward of that lineament by >40 km. Volcanism in forearc regions is unusual because the underlying mantle is generally too cold to melt but may be voluminous in unusual tectonic circumstances, such as during subduction of a spreading ridge or following subduction initiation. In these cases unusual volcanic rocks (boninites, primitive andesites) may be erupted (e.g., Crawford et al., 1981; Rogers et al., 1985; Crawford, 1989). However, Little Oshetna lavas are medium-K basalts and basaltic andesites, quite different from a typical boninite or other depleted forearc rocks. We therefore interpret the Little Oshetna series as having been erupted in a backarc setting, which in turn indicates a south-facing arc polarity (north-dipping slab). It is noteworthy that this polarity is consistent with the development of accretionary complexes within the Chugach Mountains after the Middle Jurassic (Plafker et al., 1989), while a north-facing polarity to the Talkeetna Arc would require collision and polarity reversal to account for development of the Chugach accretionary-wedge material to the south of the Talkeetna Arc; there is no evidence for such a polarity reversal.

Comparison with Other Arc Sections

The 7 km thickness estimated for the Talkeetna Volcanic Formation compares well with the 7-km-thick upper crust inferred by Suyehiro et al. (1996) in the Izu Arc on the basis of seismic refraction data. Similarly, Holbrook et al. (1999) inferred 6–9 km of volcanic rock in the oceanic Aleutian Arc. These observations suggest that the Talkeetna Volcanic Formation is a relatively complete upper crustal section. Other well-preserved volcanic arc sections include a 5-km-thick section preserved in Baja California (Fackler-Adams and Busby, 1998) and the Dras-Kohistan units in the western Himalaya (e.g., Petterson et al., 1991). This latter example is exposed over an outcrop width of ~15 km (~45° dip) at its maximum development in the Suru Valley, Ladakh (Reuber, 1989). This geometry implies an approximate structural thickness of ~11 km for the Dras 1 Volcanic Formation, the precollisional oceanic arc phase of volcanism (Reuber, 1989; Clift et al., 2002). However, strong internal compressional deformation of the Dras 1 Volcanic Formation means that this figure can only be used as a maximum estimate of the original upper crustal thickness. The largest coherent, lightly deformed section of sedimentary rocks from the Dras-Kohistan was estimated at only ~2.5 km thickness by Clift et al. (2000) from the Nindam Nappe of Ladakh. The volcanic and volcaniclastic section of the Talkeetna Arc is therefore the most complete exposure of arc volcanic materials yet documented.

Geochemical Evolution

The trace-element compositions of the Little Oshetna lavas are consistent with eruption in a backarc environment. These lavas are unusual in showing high HFSE enrichment, but moderate REE enrichment compared to other Talkeetna lavas (Fig. 15A). Such a pattern parallels the greater HFSE enrichment in backarc settings observed in the Lau Basin compared to the adjacent arc volcanic front (e.g., Tonga: Ewart and Hawkesworth, 1987). In this type of model, initial melting of the mantle wedge under the backarc generates lavas that are enriched in HFSEs. In contrast, secondary melting under the arc extracts melt from an already depleted mantle source, but additional REE enrichment occurs due to flux from the subducting oceanic slab.

The Talkeetna Arc shows few long-term trends in major-element composition, similar to the continuous eruption of tholeiitic lavas for more than 45 m.y. observed in the western Pacific (Arculus et al., 1995). The trace element and isotopic characteristics of the Talkeetna Volcanic Formation are consistent with an oceanic subduction origin, distinct from any known modern continental arc edifice. Apart from these chemical arguments, Knowlton (1916) demonstrated that the fauna found within the Talkeetna Volcanic Formation was not of any known North American variety, but instead correlates more closely to Tethyan assemblages. While the arc probably did not form as far west as the eastern Tethys, the faunal evidence does confirm an origin for the Talkeetna Arc exotic to North America. The enrichment of the HFSEs and REEs, as well as the relatively stable Nd isotope character, precludes any collision of the Talkeetna trench with a North American passive margin during the time of emplacement of the Talkeetna Volcanic Formation. In contrast, Draut et al. (2004) have shown the strong chemical and isotopic response seen during oceanic arc–continental margin collision in the Irish Caledonides. As a result, large-scale subduction of sediments eroded from ancient continental crust in the Talkeetna Arc can be ruled out. The exposed section does not preserve a geochemical record of the accretion of Talkeetna Arc to Wrangellia nor the later accretion of this composite terrane to North America.

The lack of a Talkeetna-Wrangellia collision record in the volcanic section is consistent with a north-dipping subduction polarity, because an arc located over a north-dipping subduction zone would have been subducting Pacific oceanic lithosphere such that lava compositions might not be affected by a collision to the north involving a second subduction zone. In the Talkeetna Mountains, relatively rapid exhumation of the Talkeetna Arc is documented by the appearance of conglomerate clasts with zircon U/Pb ages of 159–151 Ma in sedimentary rocks of the Naknek Formation, whose fossil assemblages overlap that range (Trop et al., 2005). As a result we conclude that the Talkeetna Arc collided with a second active margin to the north, probably Wrangellia, just before 159 Ma. Whether the collision was with Wrangellia or North America, this model requires that an ocean basin separated the Talkeetna Arc from the continent during its generation.

Interestingly, no short-term excursions in the trace-element chemistry are recognized in the Talkeetna Arc that would correspond to the geochemical and volcanic-productivity excursions seen in the Tonga and Marianas Arcs during arc rifting (Clift, 1995; Lee et al., 1995). This suggests that the Talkeetna Arc did not undergo any major extension events. If any coherent long-term trend may be noted, it is between the relatively LREE-depleted, low Th/La, radiogenic lavas exposed at the section base east of the Matanuska Glacier and the more enriched, higher Th/La and less radiogenic lavas in the Sheep Mountain exposures north of the river. A trend to increasing slight LREE enrichment parallels the general long-term increase seen in the Marianas (Lee et al., 1995), which may be related to a slow decrease in the degree of partial melting in the mantle wedge, possibly driven by growth of the arc crust through time. Such crustal thickening has been proposed to reduce the height of the mantle melting column under the arc volcanic front, thus decreasing the degree of partial melt and increasing the enrichment in incompatible elements (Plank and Langmuir, 1988), though changes in mantle-wedge chemistry may also be important. At the present time we are unable to distinguish between these competing models, though the long-lived deep-water conditions noted in the sediments argue against significant crustal thickening during arc construction.

This study now allows a revised average composition of the Talkeetna Arc crust to be made. Figure 18 shows the composition of the bulk Talkeetna Volcanic Formation normalized against the Rudnick and Fountain (1995) estimate for the composition of bulk continental crust. The new estimate for the Talkeetna upper crust resembles that of the Nindam Formation, which represents the upper crust of the Himalayan Dras-Kohistan Arc (Clift et al., 2000). Moreover, the new estimate of Talkeetna crustal composition compares favorably with that calculated by DeBari and Sleep (1991), supporting their conclusion that the bulk Talkeetna Arc composition departs significantly from that of average continental crust.

CONCLUSIONS

The Talkeetna Volcanic Formation is an ~7-km-thick section of Lower Jurassic volcanic and volcaniclastic rocks exposed in a series of moderately deformed massifs north of the Border Ranges Fault and south and west of the Copper River Basin in south-central Alaska. It forms the upper crust of an oceanic island arc generated above a north-dipping oceanic subduction zone within the Pacific Ocean, with limited recycling of continental sediment, similar to arcs in the modern western Pacific. It is the best-preserved, most coherent example of oceanic arc upper crust known globally.

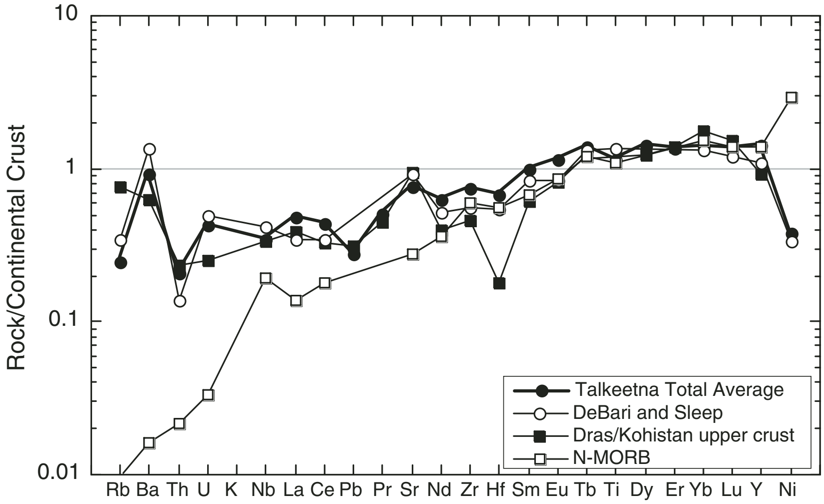


Figure 18. Trace element figure normalized against the bulk continental crustal estimate of Rudnick and Fountain (1995). Figure shows the newly derived average composition of the Talkeetna Volcanic Formation and compares this with that of DeBari and Coleman (1989), as well as the upper crust of the Dras-Kohistan Arc (Clift et al., 2000).

To date, scientific drilling of analogous modern arcs has sampled only a small fraction of their stratigraphy, making the Talkeetna Volcanic Formation the most complete source of information on arc upper crustal lithology and geochemistry known. These sequences appear to largely reflect volcanism close to the arc volcanic centers, followed by mass wasting into bathyal water depths.

Compared to the main arc volcanic sequences exposed north of the Border Ranges Fault, the synchronous volcanic section exposed in the Little Oshetna River region is more basaltic, more enriched in LREEs and HFSEs, and is inferred to have been emplaced in a backarc setting. However, no evidence exists to indicate any major arc rifting or backarc basin formation event. The arc upper crust represented by the Talkeetna Volcanic Formation is slightly more chemically enriched up-section compared to its base exposed east of the Matanuska Glacier. Even if the highly LREE-enriched, HREE-depleted lava recognized in the eastern Stuck Mountain area is Jurassic, these rocks are present in such small volumes that they have no influence on the net composition of the upper crust. Although the Talkeetna Volcanic Formation is more LREE enriched than the corresponding midcrustal gabbros, it is still less LREE enriched and less HREE depleted than the bulk continental crust (Fig. 18). Our new data support the conclusion of Pearcy et al. (1990) and DeBari and Sleep (1991) that oceanic arc crust of the type preserved in this area does not form suitable building blocks for the continents without intracrustal melt differentiation and/or addition of evolved and enriched magma. Unlike several other documented arc-continent collision systems, the Talkeetna Arc appears to have been protected from deformation during collision with North America and Wrangellia by its southward-facing subduction polarity.

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