FT2008

11th INTERNATIONAL CONFERENCE ON THERMOCHRONOLOGY

PRE-CONFERENCE FIELD-TRIP

TECTONICS AND NEOTECTONICS OF SOUTH-CENTRAL ALASKA

SEPTEMBER 12-14, 2008

Denali (Mt. McKinley 6,194 m) from the south, near Talkeetna. Photo by Paul Fitzgerald

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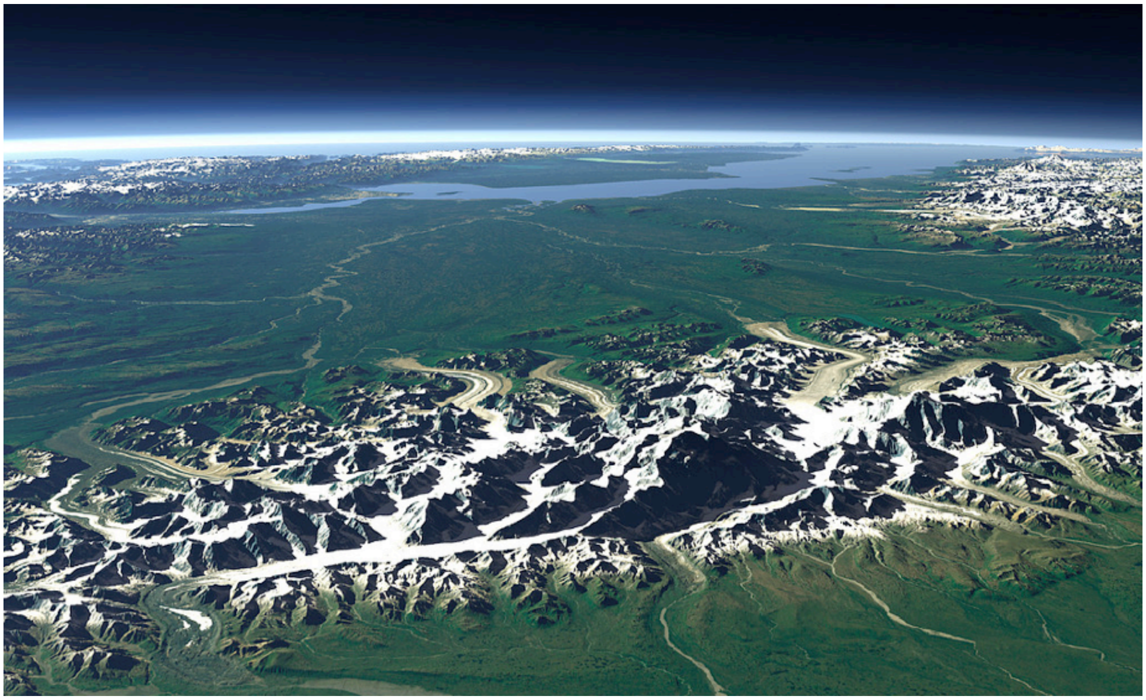
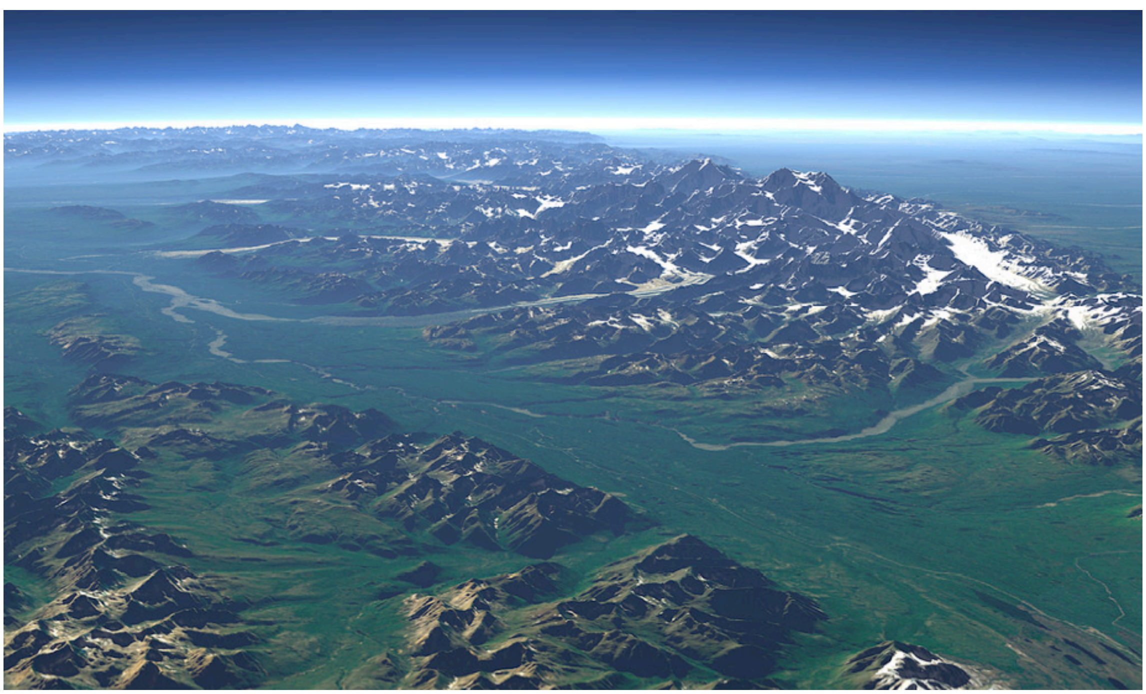


View looking southward across the Alaska Range with Denali (Mount McKinley) at ~6194 m in the foreground casting the largest shadow. The right-lateral strike-slip Denali fault is located beneath the linear glaciers in the foreground. Cook Inlet is the blue string of water in the distance, with the city of Anchorage located near the left side. Behind and in the background is the Kenai Peninsula (earth.imagico.de).



View looking westward across the northern Talkeetna Mountains in the foreground, Broad Pass is the long green valley in the middle distance, and the central Alaska Range is the region of high peaks on the right. The twin summits of Denali (Mount McKinley), the tallest mountain in North America, are on the right (earth.imagico.de). The Western Alaska Range is in the far distance.

SUMMARY OF TRIP

This fieldtrip travels from Anchorage to Healy, just north of the central Alaska Range and then back again, essentially remaining on the Parks Highway. En-route we will look at some geological features associated with terrane accretion, mountain formation, neotectonics and glaciation. Another objective is to gain an appreciation of the majesty of the Alaska wilderness and the influence of plate tectonics on the assembly and modification of southern Alaska. This field trip guide is not exhaustive and we take advantage of many previous publications and field trip guides, as acknowledged. We also include some thermochronologic information from various mountain belts and terranes along our route: Chugach Mountains, Talkeetna Mountains, central and eastern Alaska Ranges.

September 12th (Friday)
Sunrise: 7.18 am; Sunset: 8.30 pm
Depart Anchorage - est. 9.00 am from the loading zone on the south side of Captain Cook Hotel - on 5th Ave (between K and I Streets), bags can be left at the Captain Cook.

1. Overview stop - Arctic Valley Road (mile 6). Theme - Overview, southern Alaskan convergent margin, active volcanoes, accretionary complex, Chugach Mountains, Border Ranges fault, accreted terranes, Cook Inlet. General aspects of geology and tectonics around Anchorage including glaciation (end moraine).

Buy lunch at Carrs (supermarket in Palmer) - eat at Hatcher Pass

2. Castle Mountain Fault

3. Hatcher Pass - southern Talkeetna Mountains. At this location we see not only the beautiful mountain vista of the southern Talkeetna Mountains and northern Chugach Mountains but also rocks of the Peninsular terrane and the Independence Gold Mine (closed for the season).

Dinner: Salmon Bake, Denali Park (mile 239)
Stay: Motel Nord Haven (mile 248.7)

Sept 13th (Saturday)
Sunrise: 7.22 am; Sunset: 8.33 pm
Breakfast: Salmon Bake
Lunch: Denali Park (Bag Lunch)
Dinner: Salmon Bake, Denali Park (mile 239)
Stay: Motel Nord Haven (mile 248.7)

1. Denali Fault (if not done the day before)
2. Park Road and visitor center, drive road to Savage River, Hines Creek Fault, Cantwell Formation
3. View of small thrust on west side of Walker Dome (east of road) - about mile 255
4. Suntrana Creek - Usibelli Group, Nenana Gravels - walk up Creek.

Sept 14th (Sunday)
Sunrise: 7.24 am; Sunset: 8.26 pm
Breakfast: Salmon Bake
178.1 Honolulu Creek - see those conglomerates with southward paleocurrent indicators
134.9 Denali viewpoint south (has toilets)
162.3 Denali viewpoint north (has toilets)

Lunch at the scenic village of Talkeetna - take-off point for entry into the mountains of the central Alaska Range.
Castle Mountain Fault scarp in Wasilla
Return to Anchorage - arrive at least by 5 pm (co-ordinate with registration etc.)

Trip log

Note: the trip log provides summary information on where we stop and sights along the way, much more information is provided within the background material, after this trip log.

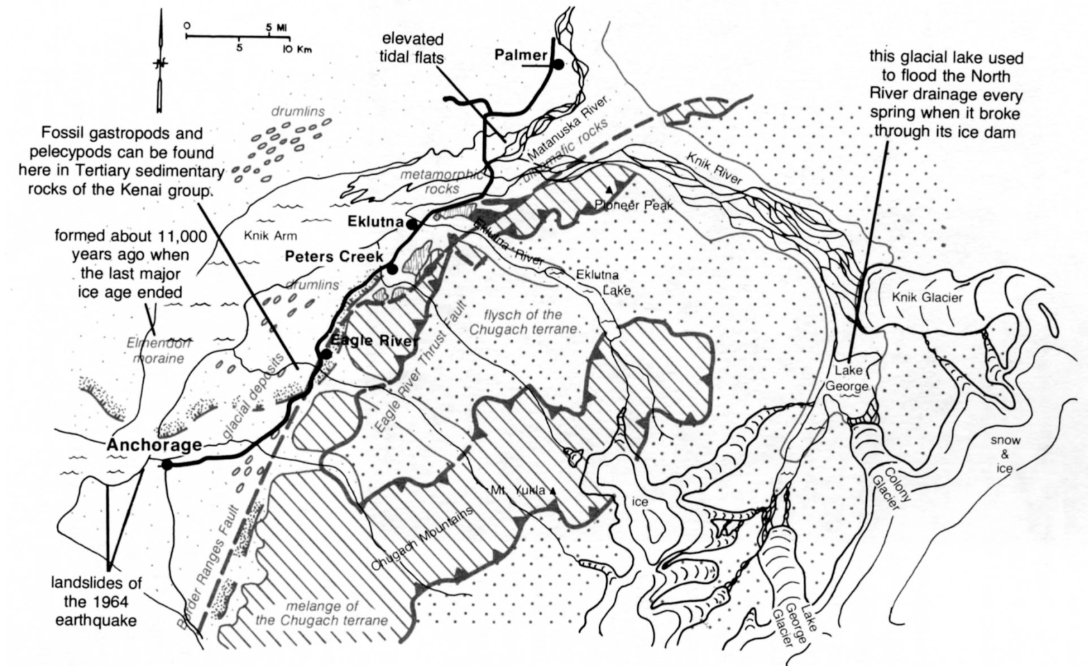


Fig 1. Geological sketch map of the Glenn Highway area between Anchorage and Palmer (from Connor and O'Haire, 1997): Roadside Geology of Alaska.

Anchorage to Palmer (north of the Denali National Park)

1. Overview stop - Arctic Valley Road (mile 6). Theme overview, southern Alaskan convergent margin, active volcanoes, accretionary complex, Chugach Mountains, Border Ranges Fault, terranes, Cook Inlet. General aspects of geology and tectonics around Anchorage including end moraine.

As we drive from Anchorage to Palmer along the Glenn Highway, Cook Inlet is to our left (west), the Chugach Mountains to our right (east) with the Border Ranges fault running along the northern margin of the mountains, forming the eastern edge of the Cook Inlet. The Border Ranges fault separates the Chugach terrane to the east from the Peninsular terrane (these are the basement rocks you will see along the highway) (Fig. 1).

The Elmendorf moraine (Fig. 2) about 10 miles north of Anchorage is the end moraine of the Knik and Matanuska Glaciers that advanced ~30,000 years ago, before retreating ca. 12-14,000 years ago. Much of the region around Anchorage is composed of Pleistocene till and glacial silt and outwash.

[0.0] Anchorage. Miles start at the junction of 6th Avenue (Glenn Highway) and Ingra Street (New Seward Highway). There are very few mileposts for the first 30 miles, set your car odometer here for the first part of the road log until the Knik River bridge.

[6.1] Ship Creek. Traveling north from Anchorage, the mountains to the right (east) are the western Chugach Range, part of the accretionary prism (Southern Margin composite terrane) (Fig. 1). The nearby hills are underlain by mélange of the McHugh Complex. The McHugh Complex is composed of intensely deformed Late Triassic to mid-Cretaceous marine sedimentary and volcanic rocks, and was accreted against the Wrangellia composite terrane to the north between Middle Jurassic and early Late Cretaceous time (Winkler, 1992; Plafker et al. 1994).

On the left (west) is the Cook Inlet Basin. Tertiary sedimentary rocks of Cook Inlet are underlain by the accreted Talkeetna oceanic arc (Peninsular terrane segment of the Wrangellia composite terrane). Paleocene-Oligocene rocks in the upper Cook Inlet basin are equivalent in age and lithology to strata that have been uplifted and exposed in the Matanuska Valley to the northeast. Cook Inlet contains a more extensive Tertiary stratigraphy, including Miocene to Pliocene fluvial-lacustrine deposits. The most recent period of deformation in upper Cook Inlet basin may have started in late Miocene time, but the most significant folding and faulting is Pliocene or younger, and some structures are likely still active (Haeussler et al. 2000). Many of these structures produce oil and gas.

We are driving more or less along the Border Ranges fault, which here is a complex zone of deformation several kilometers wide. In the Anchorage area the Border Ranges fault is covered by Tertiary and Quaternary deposits. As originally defined, the Border Ranges fault was conceived as a single fault, the plate boundary separating the Southern Margin composite terrane accretionary prism from the Wrangellia composite terrane (MacKevett and Plafker 1974). More recent studies (e.g. Pavlis, 1983; Little and Naeser, 1989; Burns et al. 1991) demonstrate that the Border Ranges fault has been extensively and repeatedly overprinted by more recent tectonic activity, including both vertical and strike slip faulting. Pavlis and Roeske (2007) propose referring to the entire zone as the "Border Ranges fault system", and the reader is referred to their paper for a more detailed discussion.

[9.2] Green building on west side of highway is the Alaska National Guard headquarters. From Clardy et al. (1984) - The ridge visible above the trees at 10 o'clock, approximately two miles away, is the Elmendorf end moraine of the most recent glaciation (Naptowne). This moraine marks the terminus of the coalescent Matanuska and Knik glaciers and various tributary glaciers. In late Wisconsin time (about 11,000 years ago) the ice retreated from this moraine. Between mile 7.7 and 11.5 (to the Eagle River hill) the highway traverses the northern boundary of the Anchorage gravel plain, which flanks the southern side of the Elmendorf Moraine (Fig. 2). The gravel is in regional contact with the Naptowne till and the surface gradient of the plain, in general, parallel the till contact. The relationship with the Elmendorf Moraine suggests an outwash origin although formation in a proglacial lake environment has also been suggested.

[12.9] **Eagle River Bridge.** To the left, visible just downstream from the southbound bridge on the west bank of the river, an outcrop of Tertiary sedimentary rocks is exposed in a cut bank. Based on plant fossils these outcrops are early Seldovian Stage (Wolfe et al. 1966), and they are considered to be part of the Tyonek Formation (Miocene) of upper Cook Inlet (Winkler, 1992). The Tyonek Formation is defined as a subsurface unit (Calderwood and Fackler, 1972), and this location is one of only a very few places where the Tyonek Formation is known to outcrop on the east side of Cook Inlet.

[15.3] **Old Glenn Highway.**

[16.0] **Right - Fire Lake.** Limit of Elmendorf (Naptowne) Moraine is ridge on mountainside above Upper Fire Lake.

[17.0] **South Birchwood exit.** Outcrops on right are undivided Jurassic to Middle Paleozoic metamorphic rocks. These are part of a narrow belt of outcrops along the western front of the Chugach Range that have been exposed by activity along the Border Ranges fault system. These rocks are discussed further at mile 29.4.

Good views to the north of the southern Talkeetna Mountains. The mountain front consists of Jurassic-Tertiary plutons and metamorphic rocks overlain by the Paleocene Arkose Ridge Formation. The Castle Mountain fault is located along the base of the mountain front.

[26.0] **Eklutna Lake exit.** Road to Eklutna Lake and dam, in mountains southeast of highway. An old Russian Orthodox church and cemetery may be visited in the village. The road through the village leads to a large quarry a short distance beyond. Jurassic quartz diorite from this quarry has been dated at 165 Ma ± 5 (Clark, 1972).

[26.8] **Alaska Railroad crossing**. Panoramic view of the Matanuska Valley.

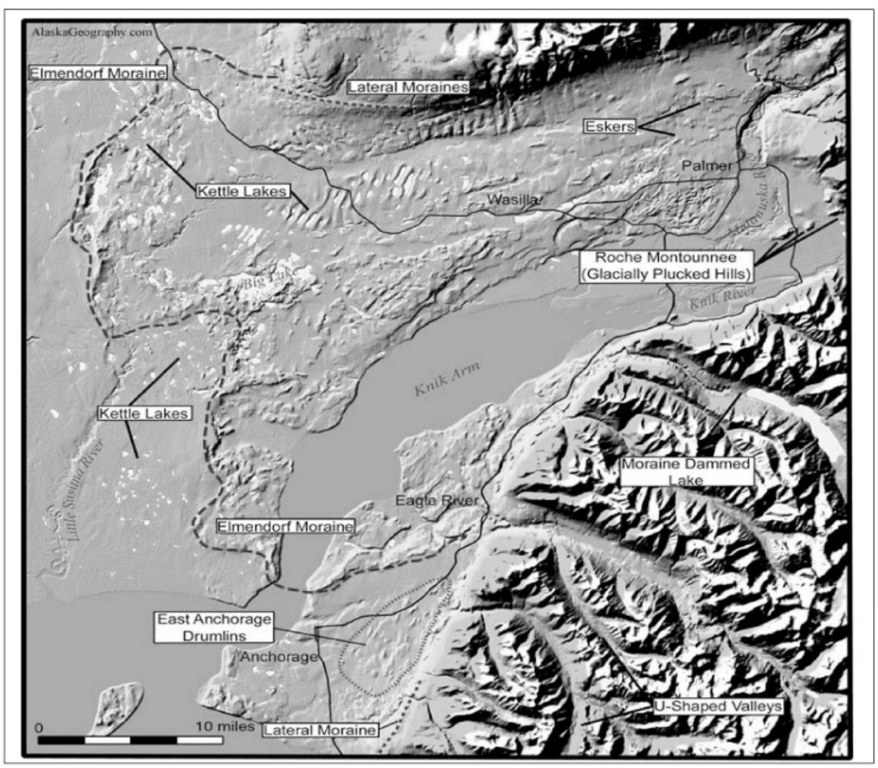


Fig 2. The Elmendorf moraine forms part of the Cairn Point Formation and was deposited between 13.7 to 11.7 thousand years ago (Hamilton, 1994). According to Dr. Reger, the date on the Elmendorf moraine was set at 12,400 years ago (Reger and Updike, 1989; Reger, 1990). (SLU Guide).

The Cook Inlet or Nuti is a large inlet of the Gulf of Alaska in south-central Alaska. It stretches for ~195 miles or 310 km southwest to northeast, separating the Kenai Peninsula from mainland Alaska. It branches into the Knik Arm and Turnagain Arm at its northern end, on either side of Anchorage. The inlet was first explored by Europeans in 1778 when James Cook sailed into it while searching for the Northwest Passage. It was named after Cook in 1794 by George Vancouver, who had served under Cook in 1778.

COOK INLET

The Mesozoic stratigraphy of the Matanuska Valley-Talkeetna Mountains basin extends south and west under the Tertiary Cook Inlet basin (Fig. 3). The Talkeetna Formation, Tuxedni Group, Chinitna Formation, and the Naknek Formation are all recognized in the subsurface of Cook Inlet and/or in scattered outcrops along the west side of Cook Inlet (Magoon, 1994a). The Matanuska Formation is recognized in the subsurface of the northern Cook Inlet basin, while correlative rocks farther south are usually called the Kaguyak Formation (Magoon, 1986). This description is from Trop and Plawman (2006).

In the deepest part of the Cook Inlet basin there are more than 7 km (23,000 ft) of Tertiary rocks (Troutman and Stanley, 2003). The Chickaloon Formation has been recognized in wells in northern Cook Inlet (Alaska Geological Society, 1970a, b). The West Foreland Formation and the Hemlock Conglomerate of Cook Inlet are thought to be equivalent to the Wishbone Formation and the Tsadaka Formation, respectively (Clardy, 1974; Magoon et al, 1976). Younger fluvial-lacustrine Tertiary rocks in Cook Inlet are the Oligocene-Miocene Tyonek Formation, the Miocene Beluga Formation, and the Pliocene Sterling Formation. These Miocene and Pliocene rocks are not present in the Matanuska Valley, either due to non-deposition or erosion.

Cook Inlet is an important petroleum basin, with total known recoverable reserves estimated to be at least 1.18 billion barrels of oil and 2.48 trillion cubic feet of gas. The Tuxedni Group is the source rock for oil in Cook Inlet, while most of the gas is biogenic (Magoon, 1994b). The most important oil reservoirs are the Hemlock Conglomerate and the Tyonek Formation. Non-associated gas is also produced from the Beluga Formation and the Sterling Formation.

[29.4] Exit ramp on right leads to the Old Glenn Highway. Continue on the new Glenn Highway (freeway). An excellent outcrop of the undivided Jurassic to Middle Paleozoic metamorphic rocks can be observed by taking this exit and traveling ~0.1 miles to the first road cut. This outcrop is part of a discontinuous belt of metasedimentary and metavolcanic rocks that outcrop along the northern and western flanks of the Chugach Mountains, within and adjacent to the Border Ranges fault. Generally these rocks are recrystallized, although in some places bedding features are preserved. This particular outcrop shows several orientations of faulting, some with striations. Actinolite schist from this vicinity yielded a minimum metamorphic age of 177 Ma ± 7 (Carden and Decker, 1977). Rocks from this belt near Eklutna yielded fusilinid fossils believed to be Permian in age (Clarke, 1972; Winkler, 1992).

[30.4] Knik River Bridge. From Clardy et al. (1987) and Karlstrom (1964a, b; 1965) - Lake George Outburst Floods - The Knik used to flood annually in June, July, or August when Lake George, impounded upvalley by the front of Knik Glacier, overtopped the ice and eroded a gorge along the valley wall. The discharge of Knik River prior to flooding was approximately 5,000 to 6,000 ft^3/s (142-170 ft m^3/s). Since the beginning of the U. S. Geological Survey gage recording at the bridge in 1949, peak discharges of flooding have ranged from 41,500 ft^3/s (1,180 m^3/s), when no lake formed in the Lake George basin in 1963, to 359,000 ft^3/s (10,200 m^3/s) in 1958. Lake discharge has begun as early as June 26 in 1962, and as late as August 13 in 1949. The duration of augmented discharge from the lake has ranged from 8 to 18 days.

The existence and capacity of the ice-dammed lake basin depend on a very delicate balance between the position of the Knik Glacier front and those of the other glaciers extending into the basin. The lake basin could not have come into existence until late Tanya time (9,000 yr B.P.) when the lake basin glaciers had retreated out of the valley prior to retreat of the master Knik Glacier from a position athwart the valley mouth. In all probability during the ensuing Altithermal time, centered around 5,500 yr B.P., Knik Glacier retreated upvalley from the valley mouth and no lake existed. During the extended phases of the Tustumena advances dated between 4,500 yr B.P. and A.D. 500, the tributary glacier appears to have coalesced with Knik Glacier, and the lake basin was completely filled with ice except possibly during the recessional periods between extended advance phases.

The last cycle of Lake George began with the Tunnel I advance, dated ca A.D. 1000. During Tunnel I maximum, Colony Glacier coalesced with Knik Glacier, forming a high ice dam for the upper part of the valley that remained ice-free. Although likely, it is not certain whether water rose high enough in this upper lake to overtop the ice dam periodically. Retreat from the Tunnel I moraines reestablished, at least for a short time, the same conditions existing today in the basin. During the Tunnel II maximum dated A.D. 1600 to 1700, the Colony and Knik Glaciers did not coalesce and a lower lake and upper lake were created in the ice-free portions of the valley. The middle lake portion was created during retreat of the Colony Glacier from its Tunnel II moraines that today form an arcuate island chain during all but the highest lake phases.

[32.7] Matanuska River Bridge. At 12 o'clock, a closer view of the southern Talkeetna Mountains. See Mile 17.0.

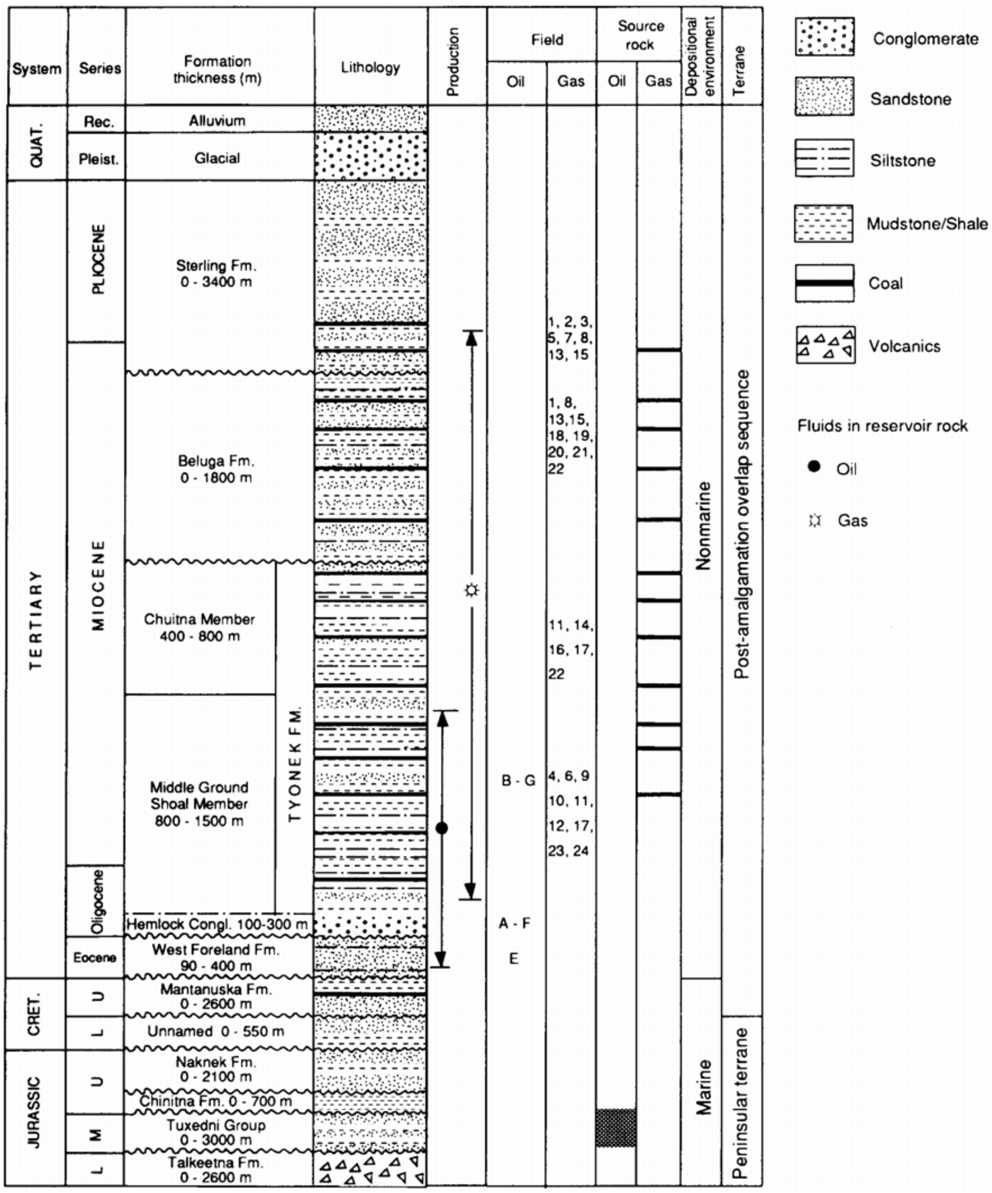


Fig 3. Stratigraphic column of Cook Inlet (from Magoon, 1994).

Castle Mountain Fault

The Castle Mountain Fault is the only known active fault in the greater Anchorage area with identified surface rupture. The fault has had a long history, which likely extends back to late Cretaceous time. Haeussler and Saltus (2005) found evidence from offset aeromagnetic anomalies that the Lake Clark fault, which lies along strike to the southwest, had 26 km of offset since late Eocene time. Thus, the Castle Mountain fault lies along the southern margin of the Talkeetna Mountains and can be considered in two sections. The eastern section is about 100 km long and is seismically active, but lacks a Holocene fault scarp; and there is a western part about 62 km long that is seismically quiet, but has a Holocene fault scarp. This field trip stop is at the western end of the eastern section. A paleoseismic study of the fault indicates four surface ruptures in the past 2700 years, with an average repeat time of 698±90 years ago (Haeussler et al. 2002). The most recent earthquake was about 650 years ago, which suggests the possibility of a significant earthquake (~M6.8+) may be expected in the near future. Willis et al. (2007) determined a late Pleistocene-Holocene slip rate on the fault of about 2-3 mm/yr, based on offset of a post-glacial drainage. Haeussler et al. (2000) found a 4-km-wide anticline paralleling the north side of the Castle Mountain Fault at the Parks Highway crossing. Faults in the core of this anticline may constitute additional seismic sources.

The rocks in this exposure are pervasively slicken-sided, and the fault zone is roughly 50-m wide. Approximately 10 years ago, the State of Alaska started to widen the Hatcher Pass Road. The bulldozer operator working this section soon became intimately familiar with the low shear strength of fault zone rocks. A large landslide covered the road, resulting in closure of the road for most of a year, while more permanent repairs were made. Bunds (2001) infers the rocks at this outcrop were exhumed from 3-4 km depth at temperatures of about 80°C.

Hatcher Pass - southern Talkeetna Mountains. This location is one of the most accessible alpine regions in south-central Alaska. It is popular for hiking in the summer and with backcountry skiers and snowmachiners (Alaskan for "snowmobiles") in the winter. As a result of the maritime influence on climate, these mountain sides can be particularly susceptible to snow avalanches. Jill Fredson's book "Snowstruck" is a good read that describes issues related to snow avalanche hazards and search and rescue, with stories about Hatcher Pass throughout the book. Nordic ski trails are groomed here before anywhere else in the greater Anchorage area, and in the early winter, elite Anchorage skiers will make daily trips to Hatcher Pass. The Hatcher Pass area also has some of the better, but often wet, rock climbing in the Anchorage area, as it is the only granite easily accessible on the road system.

Recreation aside, the view to the south is a great view across three main elements of a convergent margin. You are standing on rocks of the Late Cretaceous-early Tertiary magmatic arc looking across the Cook Inlet forearc basin, which includes rocks from Cretaceous to modern and in the distance is the Chugach Mountains (Mesozoic accretionary complex rocks). Most of the higher peaks in the Hatcher Pass area are ~74 Ma tonalite. This pluton is part of a Late Cretaceous-Paleocene arc that developed on top of the previously accreted Peninsular/Wrangellia superterrane. This pluton intrudes amphibolite facies schist, which is inferred to be Jurassic in age and part of the Peninsular terrane. Gold-silver-tungsten veins occur in the tonalite, and have been the target of the various lode-gold mines of the Independence Mine and the larger Willow Creek district.

Hoffman and Armstrong (2006) briefly report evidence for Miocene exhumation of the southern Talkeetna Mountains based on apatite (U-Th)/He data. In the southern Talkeetna Mountains, they obtained AHe ages between 15-20 Ma. In contrast, samples from farther north in the Talkeetnas had AHe ages between 60 and 73 Ma. In the Chugach Mountains, at the base of Pioneer Peak, which is the tallest peak close to the Knik River, Hawley et al. (1984) obtained an apatite fission track age of 68±8 Ma.

Palmer to Cantwell

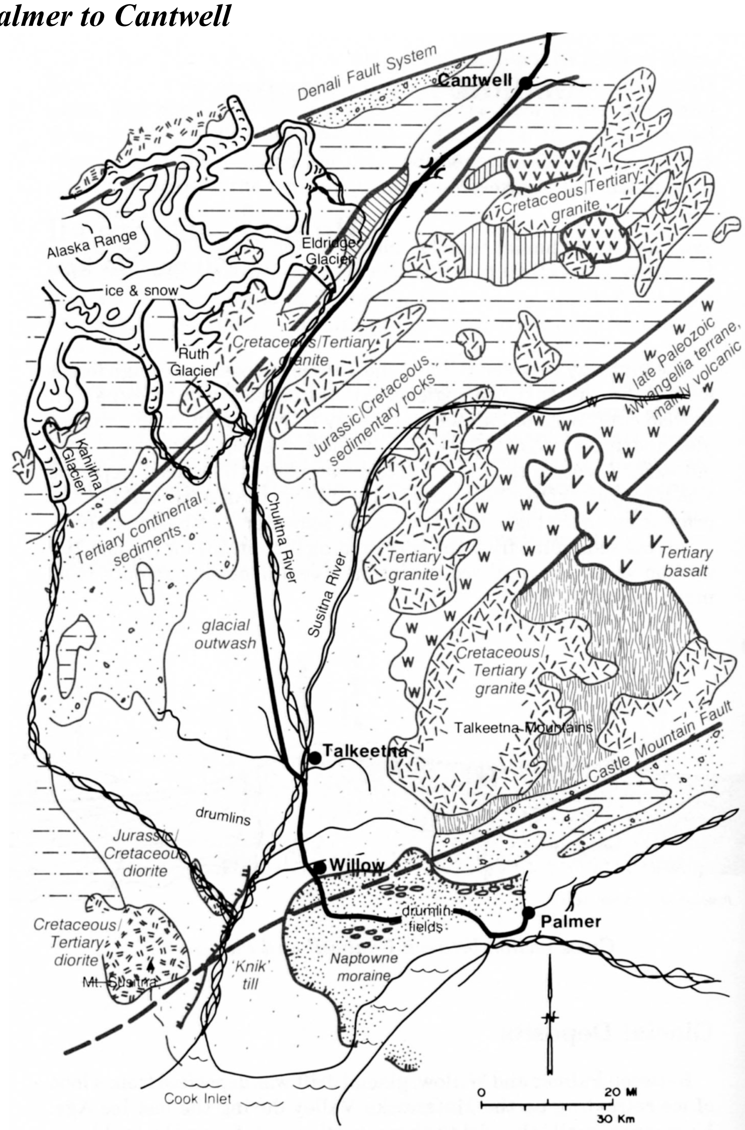


Fig 4. Geological sketch map of the Parks Highway area between Palmer and Cantwell (from Connor and O'Haire, 1997): Roadside Geology of Alaska.

Between Palmer and Willow (if we do not go over Hatcher Pass), the road is over glacial deposits and loess (Fig. 4). Willow is on the edge of a huge glacial outwash plain, that extends from the Alaska Range south to Willow. Rivers draining the Alaska Range merge with the Susitna. As we drive north from Willow - more or less along the Chulitna River and then into Broad Pass to Cantwell the central Alaska 'should' be visible to the west. Much of the Alaska Range we will see will be Jurassic and Cretaceous metasediments, except for the granitic massifs of Foraker and Denali (Mt. McKinley). To the east are the Talkeetna Mountains - also mainly Jurassic-Cretaceous metasediments and metavolcanics of the Wrangellia composite terrane as well as Cretaceous and Tertiary granites.

[134.9] Denali viewpoint south (has toilets) **- STOP HERE**
[162.3] Denali viewpoint north (has toilets) **- STOP HERE**
[178.1] Honolulu Creek - Conglomerates - on return?
[188.6] The Igloo.
[200.0] - Summit Lake - view of the Eastern Alaska Range, Summit Lake drains south into the Cook Inlet via the Chulitna River and north into the Yukon River via the Nenana River. **- STOP HERE**

Cantwell - Healy

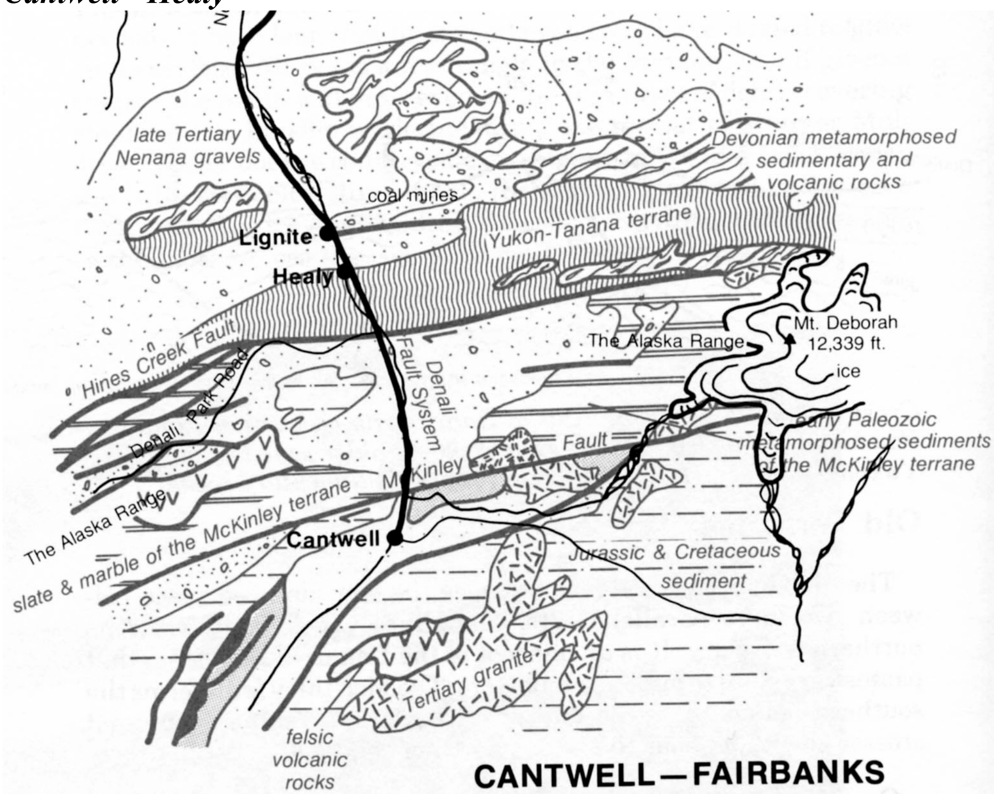


Fig 5. Geological sketch map of the Parks Highway area between Cantwell and Healy (from Connor and O'Haire, 1997): Roadside Geology of Alaska.

[209.9] Cantwell. The town of Cantwell (population 145) sits at the north end of Broad Pass where the Nenana River curves north and cuts through the Alaska Range (Fig. 5). Highway services are available around the intersection of the Parks and Denali Highways. The Cantwell Road heads west 3 km to the actual settlement, located along the Alaska Railroad tracks.

[209.9] Denali Highway Junction. Turn east to take the 136-mile route across the high country between the crests of the Alaska and Talkeetna Mountains.

[237.3] Denali National Park and Preserve Entrance. Turn west into the park. The Hines Creek fault runs very close to the Denali Park Road, although it crosses the Parks Highway about 1.5 km north of the intersection.

[215ish] Denali fault crossing. The right-lateral Denali fault crosses the Parks Highway at about this location (Fig. 6). However, the fault trace has not been identified on the flood plain of the Nenana River, which we are driving on. The fault is well defined to the east and west. If you look in both directions, you can see the axial valley that the Denali fault lies within, but it is difficult to see the fault trace. The epicenter of the 2002 M7.9 earthquake on the Denali fault (Eberhart-Phillips et al. 2003) lies approximately 70 km east of here. This earthquake was preceded by a M6.7 foreshock 12 days before the main shock. The foreshock earthquake ruptured a 45-km-long segment of the fault just east of here. There was no evidence of surface rupture in an overview flight the day of the earthquake. InSAR modeling of the foreshock indicates 40 cm of displacement at a depth greater than 5 km. The rupture in the foreshock propagated unilaterally westward. As a result, residents in this area (between Cantwell and Healy) felt the foreshock earthquake much more strongly than the M7.9 main shock.

This part of the Denali fault likely has a slip rate of

7-9 mm/yr. Matmon et al. (2006) report a slip rate of about 9 mm/yr, based on cosmogenic dating of offset moraines at a site about 20 km east of the Parks Highway. Mériaux et al. (2004) report preliminary results of a cosmogenically dated moraine about 30 km west of here, and obtain a slip rate of 7 mm/yr. It appears the slip rate on the Denali fault decreases westward, from a high of roughly 14 mm/yr near the Denali-Totschunda intersection. It seems likely that thrust faults that splay off the Denali fault may bleed-off slip. Also, a GPS estimate of slip rate on this part of the Denali fault prior to the 2002 earthquake indicated about 5 mm/yr (Fletcher, 2002), which is significantly smaller than the cosmogenically derived rates.

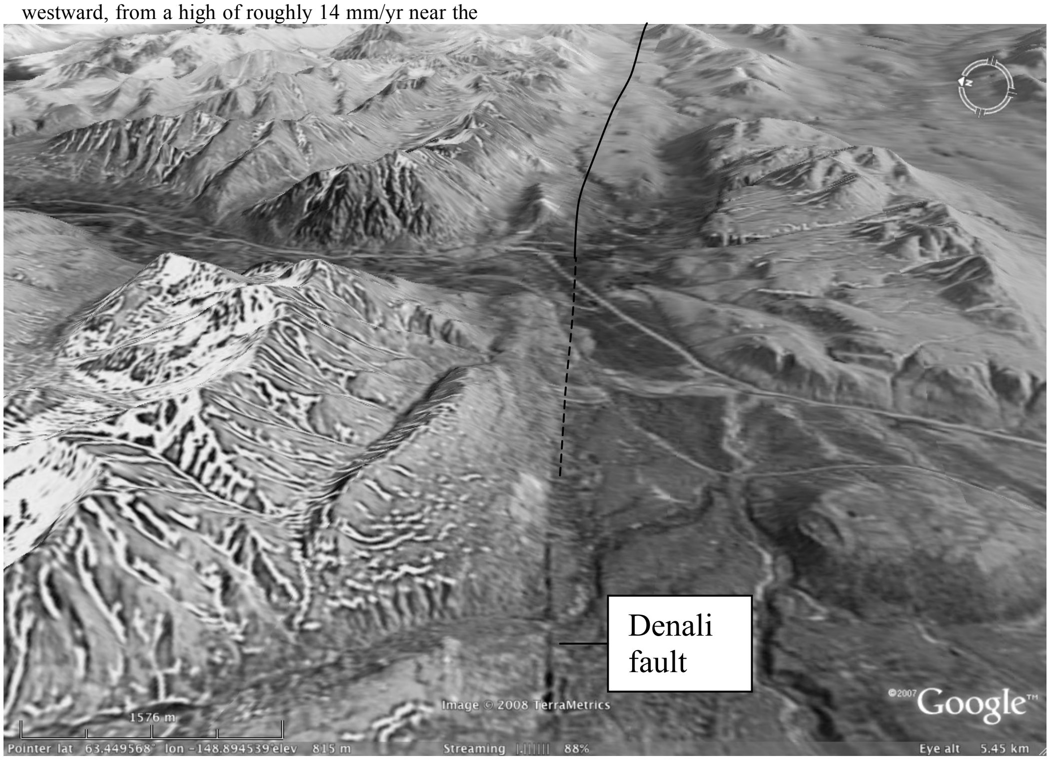


Fig 6. View looking eastward along Denali fault. The Holocene fault scarp can clearly be seen in the foreground. The Parks highway is in middle distance. The 2002 M7.9 earthquake on the Denali fault was preceded by a M6.7 foreshock on a 45-km-long length of the fault east of the Parks Highway.

We will drive along the Denali Park Road, likely as far as Savage River, which is the end of open road access for Denali National Park. On the drive in, we will follow a long, linear ridge of the "Birch Creek Schist" to our right and the Hines Creek fault to our left. The fault forms the southern boundary of the metamorphic basement that underlies the northern foothills. When we leave park HQ and the Nenana River, we will follow essentially east-west oriented drainages until we find a north flowing stream at Savage River. As the park road continues to the west, it crosses the Sanctuary, Teklanika, and Toklat Rivers, all of which have relatively parallel NNW-trending courses. To flow north, these streams have to cross two large east-west trending ridges, clearly indicating the youth of these ridges relative to these major streams.

Denali Park Road - Geology Log

(Park Entrance to Savage River [MP 0 to MP 14.8])
Modified from a summary by P. Brease dated October, 2007
Set odometer at zero at park entrance feature.

Trip OD Mileage Markers on Park Road

[0.0] (MP-0) Park Entrance – (set trip odometer to 0)

Bedrock Geology: Heading east for the next ~32 km or so (~20 miles), the park road traverses the Yukon – Tanana terrane or Birch Creek Schist (the old name), which are some of the oldest rocks in the state, and the "basement complex" of Denali National Park and Preserve (Fig. 7). Mts. Healy and Sugarloaf (~5,000 ft high peaks located on each side of the main highway), are principally comprised of Birch Creek Schist (BCS) which also is suspected to underlie the glacial materials beneath this pull-out. Although no BCS is exposed nearby this point, it is well exposed in the canyon just south of the park entrance (see Parks Highway log) and also at Savage River, 13 miles ahead on the park road. The rocks of the Birch Creek Schist (BCS) were originally deposited at least some 400 Ma as shallow marine sediments that were intruded and interbedded mostly by basic volcanic material. Near continuous tectonic metamorphism has altered these rocks to become a suite of schist, phyllites, quartzite, gneiss, greenstone, and other lithologies of the greenschist faces.

To the east, and across the Parks highway and slightly to the south, is the rugged rampart ridge of Mt. Fellows. The upper portion of this 4212' peak consists of ~56 Ma volcanic rocks of the Upper Cantwell Formation. Named after USGS Geologist, Bob Fellows, the saw-toothed ridge is made up of mafic volcanics (basalt flows), but the unit is comprised of many varieties of mafic to silicic rocks, both flow and air-fall deposits. Underlying the volcanic rocks are the continental sedimentary rocks of the Lower Cantwell Formation. These rocks are primarily sandstone, shale, and conglomerates that filled an interior basin in late Cretaceous and early Tertiary. The older metamorphic

BCS rocks to the north are separated from the younger Cantwell rocks to the south by the Hines Creek fault.

Glaciation: Major glacier expansions in the Nenana River Valley advanced from three feeder valleys including the Yanert Fork to the east, Riley & Hines Creeks to the west, and the main stem of the Nenana River to the south. During the Pleistocene, major ice flows southward from the Yanert and Nenana Rivers coalesced here near the park entrance, and flow continued north through the "outside" range via the Nenana River, forming recessional piedmont lobes from Healy to Clear/Anderson in the Nenana Valley vicinity. This parking pull-out is built upon gravels of Riley Glacial outwash.

[0.7] Wilderness Access Center (Campground reservation and bus transportation)
The center is built on a terrace of the Healy glacial surface that is capped by Riley outwash gravels.

[1.1] Railroad Crossing and Trailhead for Horseshoe Lake Trail
Horseshoe Lake trail is an easy to moderate hike that descends some 200 feet over 0.7 miles through dissected Riley Creek outwash material. The lake itself is an oxbow that was once a meander of the Nenana River.

[1.4] Roundabout

[1.5] Murie Science and Learning Center

The Murie Science and Learning Center (MSLC) is an education and research facility representing America's eight northernmost national parks. They provide innovative hands-on programs for students, teachers, families, Alaskans, and visitors. Most notable in the geologic world, is the dinosaur footprint display (the actual footprint found in the field in the summer of 2005), which is housed here.

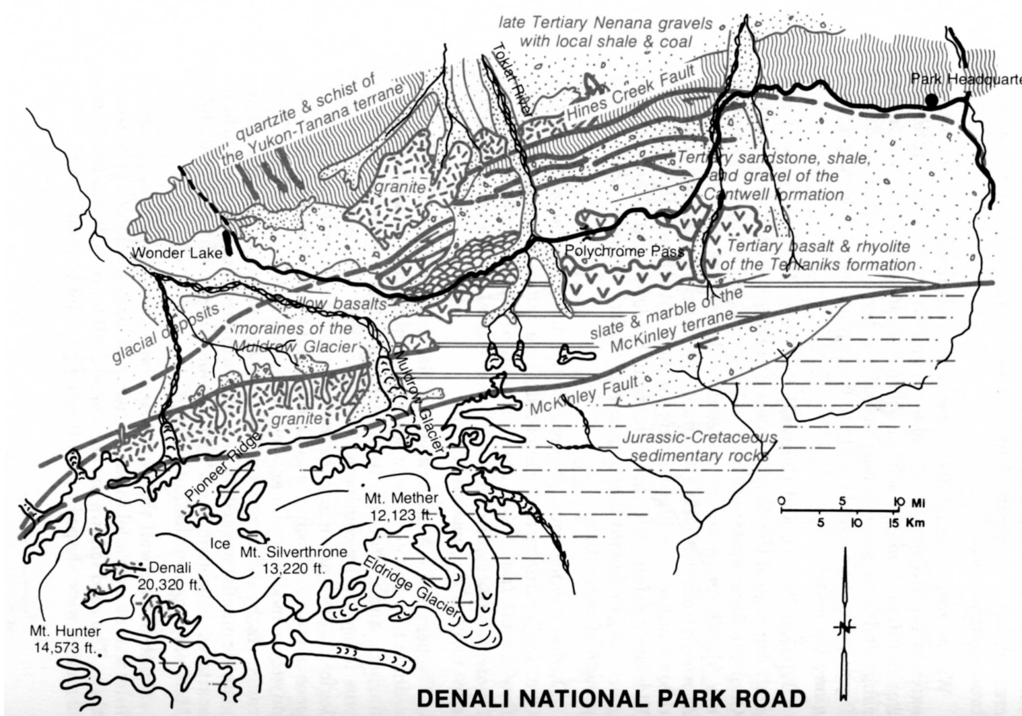


Fig 7. Geological sketch map of Denali National Park Rd. From Connor and O'Haire (1997).

[1.6] Visitors Center – Morino Grill – ANHA Bookstore - Railroad Station
The park visitor center is worth a stop for it's geology display, as well as park history, biotic components, mountaineering displays, and other cultural-historical items. Don't miss the stairway down to the main displays where the plaster outcrops were textured and painted to represent a typical section of "Birch Creek Schist" in contact with basalts of "Upper Cantwell Formation" style.

Trails from the visitor center allow one to wander around and stay low on the Healy glacial fluvial terraces (McKinley Station Trail, Morino Loop, Taiga, and Roadside trails), to climbing high into Birch Creek Schist on the Healy Mountain trail. For a good cross-section of geologic and glacial features in the area, the McKinley Station Trail is most recommended.

Bedrock Geology: As described above, rocks in this area are of two different types, separated by the Hines Creek Fault (fault axis centers roughly on the course of Hines Creek). On the north of Hines creek is the 400+ Ma "Yukon-Tanana rocks or Birch Creek Schist", while on the south side of the creek are 70 to 100 Ma sandstones, conglomerates and shales, with overlying volcanic rocks of the Cantwell Formation. The fault zone runs through Hines Creek Valley, visible from high terraces in the area. The fault trace follows Montana Creek, then continuing up Hines Creek, and out of sight westerly to eventually tie into the McKinley Strand of the Denali Fault system near the northern face of Denali. Altered schist blocks can be seen near the

Riley/Hines confluence (along the McKinley Station Trail), and whitish fault gouge is visible at the mouth of Montana Creek. The Hines Creek fault is considered part of the Denali Fault System, a complex network of faults that arc east-west through southern Alaska.

Glaciation: The Riley Creek Glacial limit is marked by a terminal moraine 70 - 180 feet high for about 3/4ths of a mile along the south bank of Riley Creek (also visible along the McKinley Station Trail). The moraine is deposited behind an irregular ridge of Y-T or Birch Creek Schist. The Denali Railroad station is built on the outwash terrace of the Riley Creek Glaciation, where it is estimated to be 80 ft thick. From the RR bridge, an old channel cut (in BCS bedrock) can be seen south of the bridge in the south wall of the Riley Creek stream cut which is filled with Riley or earlier glacial outwash gravel.

At the railroad through-cut, (across the Hines Creek bridge) the railroad construction has dissected the terminal moraine of the Riley advance. The moraine exhibits various cobbles and clasts of many rock types, all found as bedrock south of this location.

Although the gravel structure in this cut is frequently obscured by rubble and gravel material, the east wall of this cut displays an interesting advance-retreat episode. In the fresh wall of this cut are recumbently folded till and gravel, as well as horizontal clay, sand and peat layers. The sequence of events has been interpreted by Wahrhaftig (1958) as follows:

1. Glacial till and outwash gravel is deposited on site during an advance.
2. The glacier retreats.
3. The ice readvances, pushing and folding the previous layers into a recumbent syncline, and terminates here for a short period of time.
4. The glacier retreats, and a meltwater lake develops between the moraine and the ice limit, depositing clay and peat.
5. Coarse till material is deposited on the lake sediments probably by grounded icebergs.

Radiocarbon dating of plant materials buried in the lake deposits indicates an age of ~10,600 YBP (Wahrhaftig, 1958). This age and general interpretation is consistent with Ten Brink and Waythomas's four advance and retreat events they identified (in Ritter, 1982) and attributed to Wahrhaftigs Riley Creek Glaciation. This places the Riley Creek end moraine in an age range of 15,000 to 13,500 YBP, according to Ten Brink and Waythomas (in Thorson and Hamilton, 1977), which they have named the Riley II advance. The carbon dated lake sediments thus fit in the Riley III advance (12,800 to 11,800 YBP), or the Riley IV advance (10,500 to 9,500), both of which presumably terminated upvalley (south) of this site.

[3.3] Park Headquarters – Healy Glaciation

Park headquarters was moved to this location by Superintendent Harry Karstens in 1925 to get out of the Hines/Riley Creek valley bottom where wintertime temperatures were frequently 20-30°F colder than this location on the Healy glacial terrace.

Glaciation: Park Headquarters is built on morainal materials of the Healy Glaciation (~70,000 YBP) where an embayment, or tong of ice, flowed westerly from the Hines Creek – Nenana River Junction. A terminal moraine "ridge" exists behind the dog kennels, and Hines Creek has breeched the moraine in the vicinity.

After the retreat of the Brown event (~15,000 BP) valley glaciers of the Nenana, Savage, Sanctuary, Tekalnika and the Toklat were not connected, (the passes between drainages were ice free). Glacial erratics (rocks transported by glacial ice) of granite, schist and conglomerate are found in various locations around the park entrance area. On the ridge directly south of Headquarters (known by some locals as "Erratic Ridge") are two exceptionally large house-sized granitic boulders from the Brown Glaciation (150,000+BP) that currently reside at 3400 feet elevation, 1200 feet above the Headquarters area. These erratics were brought to this location by ice-flow down the Yanert River from the Nenana Mountain pluton some 40 miles away. The large boulder at the HQ flagpole is an erratic of Nenana Mountain granite as well.

[3.8] Healy Glacial Limit

Approx limit of Healy Glaciation (70,000 BP). This is recognized by air photos as a continuation of the ice limit (terminal moraine) that is found at the dog kennels at park headquarters. A line of larger tree growth (dominate white spruce?) marks the near east-west crossing of the road. A portion of the park road in this vicinity has been a subsidence problem for many years (often left unpaved) and it is suspected that a kame deposit (fine grained deposit at the ice margin) may be responsible. The park road is being relocated uphill (in 2008) in attempt to remedy the situation.

[5.3] Drunken Forest (Paved Pull-out on left)

Mass Movement: An approximately 1.6 km long, 180 m wide slump-earthflow, informally called the "Drunken Forest," is located across the valley from this turnout. Long attributed to vegetation mat slippage on permafrost, investigations in the late 1980's, including some stratigraphic analysis and refraction seismic traverses, suggests there is no permanently frozen ground involved in the movement of the Drunken Forest.

The mass movement consists of an upper source area basin, characterized by rapid slump-mudflow/slurry movement, and a lower basin that is dominated by slump-block migration. Displacement rates in the upper source basin averages 4.76 m/yr, while rates in the lower basin have averaged 0.33 m/yr for normal precipitation years from monitoring efforts from a 10 year period begun in 1987.

Greater than normal precipitation in 1990 increased the downslope displacement rates to 7.95 m/yr in the lower basin for 1990 and 1991 combined. Displacement rates in the upper basin are poorly constrained because of the loss of monitoring stakes, but are estimated to exceed 100 m/yr for the combined years.

Bedrock geology in the area consists of sandstones, shales and conglomerates of the Cretaceous to Eocene Cantwell Formation, which is overlain by glacio-fluvial deposits of the Wisconsin Browne Glaciation and possibly later glaciations. The Hines Creek Fault is possibly responsible for a weakened zone, which diagonally traverses the mass movement and supplies fault gouge material in the source area basin. Additionally, movement on the fault may have contributed to the initial over-steepening of the Drunken Forest system.

[7.2] Lignite/Dry Ck Glacial Limit (Nenana Flow) (pull out on left)

This is the approximate limit of Lignite/Dry Creek Glaciation (70,000 to 125,000 BP). The road-cut on the right, when climbing out of the drainage, cuts a remnant of the Lignite/Dry terminal moraine. Recessional moraine features, including possible ice marginal drainages, are found on the north side of the road just a few 100's of feet ahead. On the left (south side of the road) are vegetated mounds and water filled depressions (kettle ponds) of ice waste topography. Post Browne event ice separated here receding south and easterly towards Hines Creek, and westerly towards Jenny Creek and the Savage River, stranding ice and morainal material in the "pass" area about 70,000 years ago, leaving this hummocky surface.

[10.5] Mt McKinley Viewpoint (Pull out on right)

[12.7] Savage Campground Entrance

[13.4] "Red Rocks" upslope from the road.

The `red rocks' on the north side of the road & upslope between the Savage Campground and Savage River is bedrock material is the Yukon-Tanana, or Birch Creek Schist. The rock has been altered by *hydrothermal deposition* (hot water circulation through the rocks) that has left deposits of iron staining (*hematite)* and possibly other metallic minerals. Red, rusty areas such as this (called gossans) were common targets for prospectors and miners looking for the more precious minerals such as gold, silver, lead, zinc, and others. Prospectors definitely disturbed this area, probably by hand working the exposures, but mineral values were probably not very rich, and the site was abandoned many years ago.

[13.9] Gravel Ridge (Dry Creek Terminal Moraine)

To the west about 1/3 mile and across the Savage River is a mid-valley ridge where the northern end is exposed gravel. Long thought by many to be an "esker" (subglacial stream deposit), the gravel ridge is the remnant of the terminal moraine of the Dry Creek/Lignite glacial advance of about 125,000 years ago. Glacial ice flowed from the Alaska Range covering the Savage valley to the south in a large lobe shape, with ice probably extending across where the park road is now located (about at Savage Campground).

[14.8] Savage Check Station- Parking Area – Picnicking – Restrooms - Hiking

This is as far as the public can travel on the park road in private cars without a permit. Travel into the park beyond this point is either by the park shuttle service or by tour bus.

Bedrock Geology: Bedrock in the Savage River canyon consists entirely of BCS, including the large outlier known as "Savage Rock" located just above the east-side parking lot. A 2 mile long loop trail, starts (or ends) from either side of the river, and traverses the river valley walls to a rustic log connector bridge just downstream from this trailhead location. The trail traverses good examples of quartz-rich schist, phillites, and quartzite seclusions, occasionally crossing short steep slopes with large massive outcrops. Large and small-scale folds, foliations, kink bands and other evidence of ductile and brittle deformation can be found in many locations along this trail. In some locations, the rocks exhibit folded folds that are folds upon folds. In this place, one can witness the many scales of nature's application of earth crunching tectonic pressure. Differential weathering along fractures or other zones of weakness provide a great mix of ragged buttress ridges that traverse the valley, mostly in an apparent east-west orientation.

Parks Highway Geology Road Log (South to North)

From the Park Entrance (MP237.5) to Healy (MP 248.8)
Modified from a summary by P. Brease dated October, 2007

(MP 237.5) Denali Park Road entrance

(MP 238.0) Cross Nenana River Bridge (Rest Stop on North Side)

Glaciation: From this point, at least two glacial terrace levels can be recognized. The highest terrace would be the Healy glacial bench where the Grand Denali Hotel site is perched high above on the east slope. Although the rock outcrop was leveled for hotel construction, a discontinuous terrace runs from the hotel site back south and into Montana Creek near Mt. Fellows. This bench is mostly an erosional remnant of Healy Glaciation. However, the central valley terraces and the terrace remnants just above the railroad tracks (visible across the valley) are on the Healy Glacial "depositional" surface, where outwash gravels from the Healy recession and/or the Riley advance where deposited. This depositional surface also contains sediment remnants of glacial "Lake Moody" which is explained at mp 243.

Bedrock Geology: This is the southern limit of the surface exposures of Birch Creek Schist or Yukon-Tanana Crystalline Rocks. The Hines Creek fault, separates the Precambrian to lower Paleozoic metamorphic rocks to the north, from Cretaceous to Early Tertiary rocks (the Cantwell Formation) on the south. All bedrock at and north of this location is Birch Creek Schist.

(MP 239.0) McKinley Chalets

Bedrock Geology: Southern end of the Birch Creek Schist exposures near the McKinley Chalets.

(Park at the Chalets, cross the highway, walk north along the road cut ~200 feet to the first clean vertical exposure)

The schists are mineralogically simple; they are composed of quartz-rich lithologies intermixed with varying amounts of white mica. Minor carbonaceous schist, metasandstone, and metapebbly sandstone are present along with the dominant quartz-mica schist.

The structures in this outcrop are extremely complex. Suites of features typical of both ductile and brittle deformation environments are present. Ductile deformation features include up to 4 foliation surfaces. Two can be recognized with relative ease in most parts of the outcrop: a sub-vertical foliation parallel to lithologic layering, and a spaced crenulation cleavage that is sub-horizontal or dips shallowly to the south. Folded quartz lenses, more common in the northern end of the outcrop, were folded by the spaced crenulation cleavage. Other crenulation cleavages can be observed overprinting the spaced crenulation cleavage, but are apparently domainal.

Relic sedimentary structures can be observed at the south end of the outcrop. Some of the more massive appearing schists contain clear, white, grey and black rounded pebbles up to 1 cm across (most are 2-3mm) and appear to be more resistant to deformation than the mica rich layers.

Shallowly north-dipping faults and kink bands, and folded foliations can be observed in parts of the outcrop and reflect a period of brittle deformation. Faults trend east-west, parallel to the northern range front. Foliation surfaces which are near horizontal at roadside become near vertical at the top of the outcrop. Kink bands are present locally; their geometry indicates a top to the south sense of movement. Faults, folded foliaton surfaces, and kinks MAY have formed at the same time; if so, they apparently record an episode of horizontal compression in approximately a north-south direction.

Diabase dikes cut the schists in the northern part of the outcrop. They are subvertical and generally strike north-south. These dikes are part of a large suite that cuts the metamorphic rocks in this vicinity.

(~MP 239.5) Canyon Slide

Roadside shoulder space is limited here, especially with the guardrails and barriers in place. It is advised to proceed to the north end of the barrier where some pull-over space is available to look at this landslide feature from a safe position.

Mass Movement: The section of road cut just to the north of the Chalets has been continuously unstable since the construction of the road in 1971. Steep slopes with active natural slides made this section of road the most difficult and expensive to construct. Landslides of talus and cobble sized rock continuously pour onto the roadway, and blockslides, including single slabs up to 1000 tons, have battered and blocked the road as well. The highway department has removed about 300,000 cys of rock from the roadway in this area since the opening of the highway (equivalent to about 15,000 cys/yr) and much of it was placed on the east river terrace 0.7 miles ahead.

The site is in quartz-sericite schist with layers of quartzite, carbonaceous schist, and zones of hydrothermal alteration containing dessiminated pyrite cubes. The foliation is well developed, generally striking east and dipping to the south. The schist is irregularly contorted with intervals of intense folding. Steeply dipping vertical joints intersect the rock and typically strike northward. Tertiary age basalt dikes 5 to 100 feet thick intrude the schist along joints, and demonstrate a wide variety of competence.

A large, 100 ft thick vertical basalt dike is visible in the road-cut, which has contributed significantly to the slide problems here. A sub-parallel shear zone on the west face of this dike has formed a prominent scarp, which marks the start zone for some of the slide material.

Note the catchment zone with rock-fall barrier to prevent rockslides from damaging the road. Rocks occasionally bounce over the barrier, but the bulk of the road damage and hazardous conditions have been greatly reduced.

(MP 241.0) Birch Creek Schist Road-cut

Bedrock Geology: Road-cuts along the canyon are all in "Birch Creek Schist" but some variations of mineralogy make them appear slightly different. In most locations, the silvery sericite schist (mica schist) is dominant, however, in some locations the greyish-blackish rock suggests a more carbonaceous schist, while in other locations, the greenish tones suggests a dominant chloritic schist composition. At this location, the hinges of the many scales of folded rock trend east-west, while northerly dominant thrust faults (of a later age?) dissect at low angles.

Glaciation: The Healy Glacial materials (depositional to the Healy recession or possibly the Riley outwash) are visible as the near vertical gravel beds in the railroad cut across the river. The level bench at the top of the gravel strata correlates in elevation to a bench cut/deposition on the east side of the road as well, and is recognized as the Healy Glacial surface.

(~MP 242.2) Moody Pull-out & Dragonfly Creek

Glaciation: The Nenana Canyon is ~50' deep at this location, with the lowermost river incision and U-shaped valley representing the Riley and/or Healy erosional events, the next level representing the Healy depositional surface, the next level up being the lignite and/or Bear Creek event, and the uppermost being the Browne limit.

Glaciation - Mass Movements: Nearly the entire route of the Alaska Railroad through the Nenana Canyon (~10 miles) has been plagued by mass movements at one time or another. The largest, or most troublesome of these movements is the Moody slide, visible here across the river, where the tracks curve to the east just before going under the highway bridge.

The Moody slide is a zone of slumps, earth-flows, and sinkholes that stretches nearly a mile long, from Sheep Creek, nearly to the highway bridge overpass. The movement occurs primarily in the clay and silt materials that were deposited by glacial **Lake Moody.** These lake deposits are ~150 feet thick at this locality, and they form the slope starting just below the vertical standing gravels near Sheep Creek. The overlying vertical gravels are 100 – 150 feet thick, and are outwash and alluvium of the Riley Creek Glacial episode.

(MP 243) Moody Bridge over Nenana River (north side of bridge)

One may choose to park in the pull-out on the south side of the bridge and walk to the north side.

Surficial Geology: On the north and east side of the bridge, note the tan, fine-grained sediments overlying darker grey fine-grained sediments that together cap the glacial gravels or bedrock in the road cut. These are Lake Moody sediments which consist of fine grained, loess-like debris that have accumulated on this perched schist bedrock while Lake Moody occupied the canyon. In places, this material has undergone freeze-thaw alterations (cryoturbation) that has resulted in folded and overturned layers. More on Lake Moody at the next stop.

(MP 244.0) Gravel Pull-Out on left (east) (w/automated weather tower)

At this pull-out, are good views of the Nenana River valley, glacial terranes, Garner Hill**.**

Glaciation: As the Healy glaciation retreated southward, at least as far back as the park entrance area, a lengthy melt-water lake developed in Nenana Valley, extending from Riley Creek on the south end, to the Healy terminal moraine on the north end (just north of us at this point). This lake was ~9 miles long, 1/3 of a mile wide, and some 122 m deep. Named Lake Moody by Clyde Wahrhaftig (1958), it probably remained in place at least several hundred, or even a few thousand years, during which time it was nearly completely filled with sediments.

The sediments are found as lake deposits of varved clay and silt intermittently on both sides of the canyon at elevations as high as 1750 feet (535 m). In most locations, the lake deposits are covered by subsequent Healy outwash or Riley Creek alluvium or outwash. The silt and clay deposits are a continual problem for both the Highway and the Railroad.

At the confluence of Healy Creek with the Nenana River (down near the power plant to the NE of this pull out) at least 14 terraces are visible on the southern banks. The uppermost terrace in is the Healy Glacier Surface terrace, while the three next lowest terraces (#'s 13, 12 & 11) are mostly erosional features attributed to melt-water outflow from the Healy Glaciation (Wahrhaftig, 1958, Ritter 1982). The next lower terraces (#10, 9 & 8) are considered to be primarily depositional terraces of the Riley Creek outwash materials.

Mass Movements: Just behind Garner Hill (hill with three towers to the NE) from our vantage point, is the Garner Railroad Tunnel, where an active rockslide has been an irritation to the railroad since it's initial construction.

Cross Antler Creek

(~MP 247.1) Asphalted Turnout left (East)

Bedrock Geology: From this vantage point, there is a clear view along the northern range front. The mountains to our south (Sugarloaf on left, and Mt. Healy on the right) form an east-west ridge that parallels the Alaska Range, and exceeds 5,000 ft in elevation. This "outside range" (as the locals call it) is underlain by complexly deformed quartz-rich schist that have Precambrian (?) and Paleozoic protoliths. These are the oldest known rocks in the Denali Park area. They can be traced from the Parks highway west along the northern range front for ~100 km; they also underlie the coal-bearing rocks at lower elevations north of the range front. At least four metamorphic events have significantly altered these rocks.

On the horizon in a NE direction at a distance of about 13 miles is a low hill at about 4500 feet in elevation known as Jumbo Dome. Jumbo is a small intrusive body of hornblende dacite which has yielded a Pliocene age of ~1 Ma Ar-Ar whole rock (Paul Layer pers comm.), making it the youngest igneous rock in interior Alaska.

Glaciation: This turnout is on a large plateau area (Healy surface) that continues south for ~3½ miles, and provides the surface for the parks highway. This plateau is the depositional surface of the Healy Glacial Advance. The Healy Advance occupied the entire width of this valley, and is responsible for most of the landforms and surface materials in the Healy – Nenana Canyon vicinity. Garner Hill, the high knob just southwest of this turnout (with antennae and microwave towers) was surrounded, but probably not overtopped by ice during the Healy event.

(MP 246.8) Junction with Otto Lake Road

Approximately ½ mile west on this road is Otto Lake, a popular destination for the locals on those hot (rare) summer days. At 0.9 of a mile is Hilltop road, which traverses the terminal moraine of the Healy ice advance.

Glaciation: The Hilltop road ridge is considered the limit, or terminal moraine of the Healy Glaciation. A relatively stationary piedmont lobe occupied this area about 60,000 to 90,000 years ago, leaving about 10 ridges that parallel Ridge Road and cross Otto Lake Road to pass on the west side of Otto Lake. This terminal lobe of the Healy advance was about 5 miles wide (east-west) at this point, with an ice thickness of at least 500 feet to an Early Wisconsin Nenana valley floor.

(~MP 247.3) Road Grade descends from upper terrace

Glaciation: The road descends glacial-fluvial (mostly outwash) gravels of the Healy Advance (most visible in the west road-cut). Here, melt-waters from the Healy recession, and/or the Riley Glacial retreat, carved the face of the terrace (headwall erosion).

(MP 248.7) Junction at town of Healy

At this point, a turn east on the Healy Spur Road takes you to the Healy Airstrip, the Golden Valley Electric Plant, the entrance to the Usibelli Coal Mine, and the old coal mine location and abandoned town of Suntrana.

Sept 21st (Sunday)

Breakfast: Salmon Bake

178.1 Honolulu Creek - see those conglomerates with southward paleocurrents

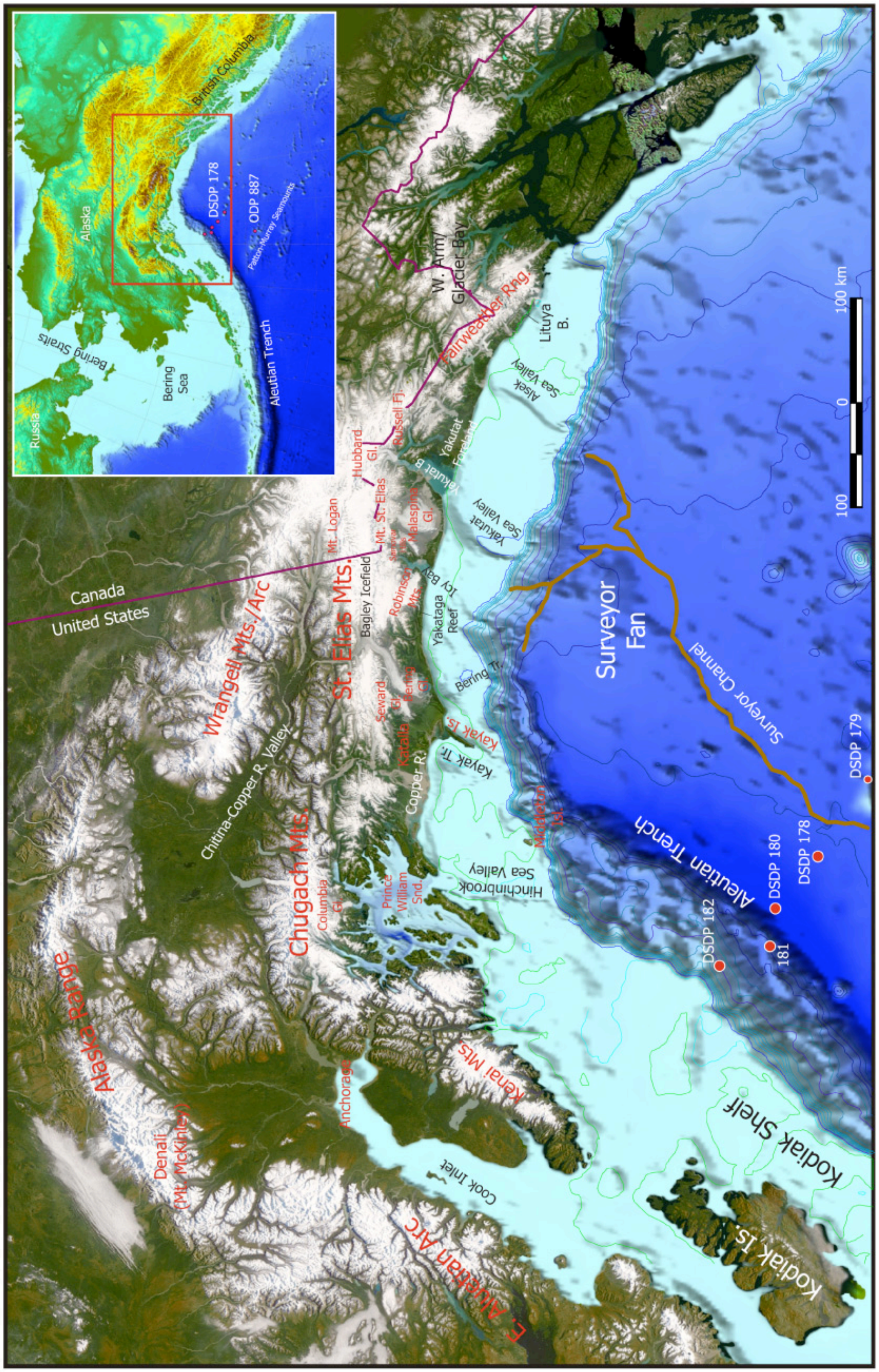
134.9 Denali viewpoint south (has toilets)

162.3 Denali viewpoint north (has toilets)

Talkeetna - lunch

Castle Mountain Fault scarp in Wasilla

Return to Anchorage - arrive at least by 5 pm (co-ordinate with registration etc)



The Gulf of Alaska region: geography and location of DSDP and ODP drilling locations (see inset). Composite of MODIS images for southern Alaska courtesy of MODIS Rapid Response Project at NASA/GSFC. The figure is a composite of many separate images taken at different times. Note the inset map for overall location. Shaded bathymetry from ETOPO2 global elevation data set. (from STEEP Science Plan).

Fig 8. Gulf of Alaska region geography and location map (Gulick and Jaeger, STEEP Science Plan, 2003).

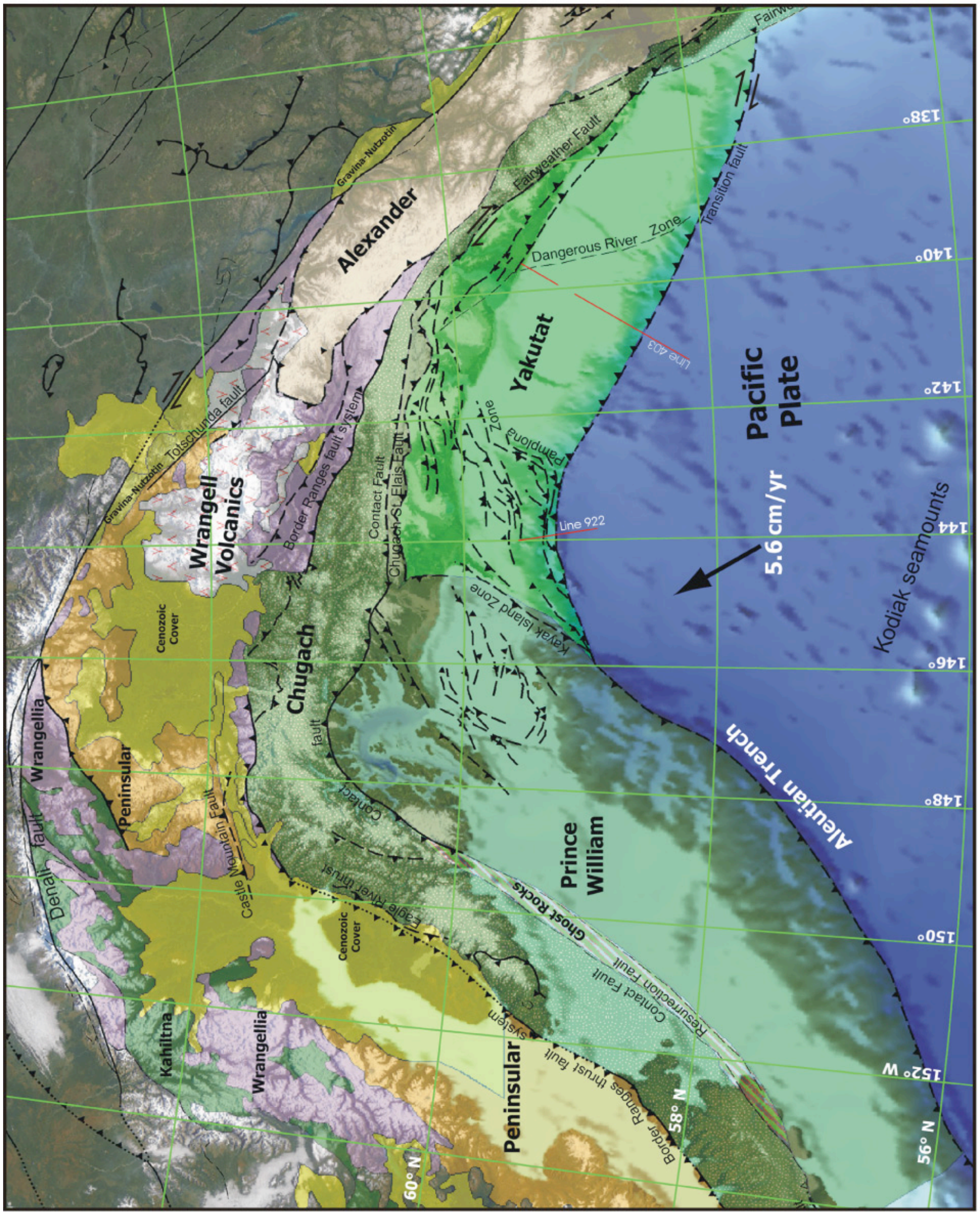


Fig 9. Tectonostratigraphic terrane map of southern and south-central Alaska modified from Plafker (1987) and (1994) (Gulick and Jaeger, STEEP Science Plan, 2003).

INTRODUCTION and BACKGROUND

The southern plate margin zone of Alaska is remarkable for the diversity of geological processes currently operating (Figs. 8 and 9). There are active subduction zones with accompanying volcanic arcs, a buoyant flat slab that extends ~500 km under south-central Alaska, continental-scale strike slip fault systems plus active collision of the Yakutat microplate (Veenstra et al. 2006; Ferris et al. 2003; Fletcher and Freymueller 2003; 1999). Alaska is also well known because this is where the idea of suspect terranes and terrane accretion was largely developed (e.g., Packer and Stone, 1972, 1974; Packer et al. 1975; Jones et al. 1977; Beck, 1980; Stone, 1980, Coney et al. 1980). Alaska consists of a complex amalgamation of accreted terranes, sedimentary basins, magmatic belts and subduction zone strata - these were added to the southern Alaskan margin during the Mesozoic and Cenozoic.

Redfield et al. (2007) have taken the terrane accretion concept one step further, and building upon escape tectonic models, have defined the laterally moving crust of the British Columbia margin, Alaska, and the Bering Sea as the North Pacific Rim orogenic stream (NPRS). Behaving in a similar tectonic and kinematic manner to Anatolia and Southeast Asia, the NPRS illustrates the fundamentally mobile nature of a typical obliquely convergent, plate boundary zone. The NPRS is a composite of crustal terranes undergoing northwestward transport parallel to the British Columbia margin, CCW motion through the Alaskan nexus, and, farther west, escape toward the north Pacific subduction zones of the Aleutian–Bering Sea region. Offsets across the inboard Tintina and Denali fault systems indicate northward transport and southwestward extrusion took place since the earliest Eocene and possibly during the Cretaceous. The Redfield et al. (2007) model implies that the present-day terrane framework of Pacific Rim North America is as much a product of differential flow lines within the NPRS as of individual accretionary events at the margin. This marriage between terrane accretion, entrainment, strike-slip transport, and escape permits the wide variation in magnitude of small block rotation observed throughout southern and central Alaska (Fig. 10). In this scenario relatively rigid crustal blocks acquired their paleomagnetically determined rotations and fault boundaries while moving through the system. Active since at least the earliest Eocene, the NPRS has accommodated a minimum of 800 km of total offset with respect to stable North America. Offset and extrusion may have been accelerated by the collisional impact of the Yakutat block toward the end of the Miocene. The NPRS continues to extrude its leading edge toward the Aleutian subduction zone.

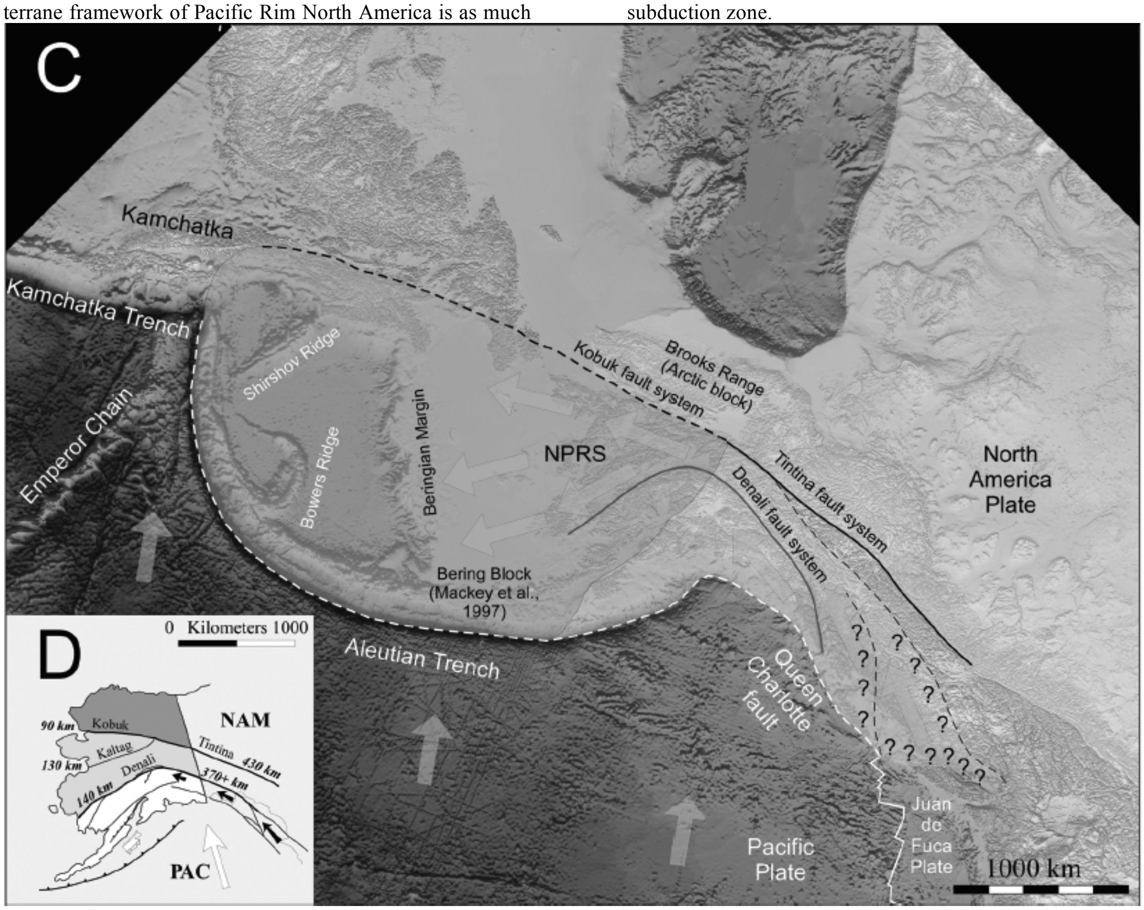


Fig 10. Polar stereographic map showing principal physiography of North Pacific Rim region. Arrows schematically show motion of North Pacific Rim orogenic stream (NPRS) and Pacific Plate relative to fixed North America. Dotted lines delineate the approximate boundaries of the stream. The NPRS comprises all the crustal terranes of the Canadian Pacific, Alaska, and the Bering Sea that are undergoing lateral transport northward toward Alaska and west of the curving nexus of central Alaska's "orocline," southwestward toward the Aleutian subduction zone. D: Offset map illustrating the space problem in central Alaska associated with varying offsets across the great curved fault systems of Alaska. (From Redfield et al. 2007).

South-central Alaska is comprised of three main terranes: Yukon composite terrane, Wrangellia superterrane, Southern Margin composite terrane. The tectonic evolution of southern Alaska is characterized by two main collisional events: (1) Mesozoic collision of the Wrangellia composite terrane (this resulted in a huge addition of juvenile crust to the North American Cordilleran margin), and (2) the Cenozoic collision of the Yakutat terrane (excised continental and oceanic fragment of North America).

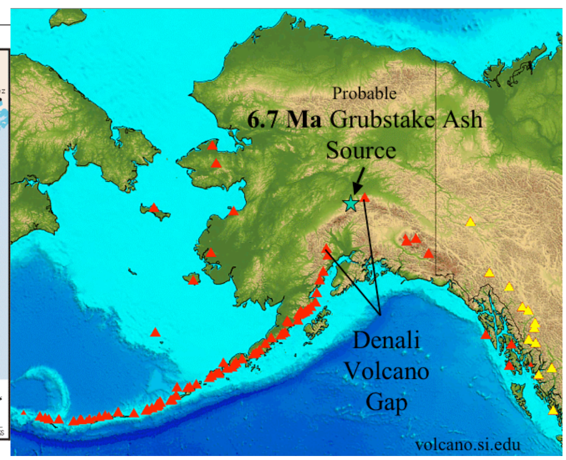
Modern day geological setting

Southern Alaska is located at the northeastern corner of the Pacific Ocean basin. The Pacific plate subducts beneath the southern Alaska margin along the Aleutian megathrust, and it slides past southeastern Alaska along the Queen Charlotte-Fairweather transform fault. The Pacific plate is moving toward the north-northwest relative to North America at a rate of about 5.3 cm/yr. As the Pacific-North America plate motion pole lies to the northeast of Alaska, the relative plate velocity increases westward along the Aleutian arc, and the relative motion becomes more oblique. There are more than

90 volcanoes along the Aleutian arc that have shown activity in Holocene time, and the volcanoes are typically about 100 km above the subducting slab (Figs. 10 and 11). The eastern part of the Aleutian arc is a continental arc built on continental crust, and the western part is an intra-oceanic arc, built upon probable Cretaceous oceanic crust trapped in the Bering Sea basin.

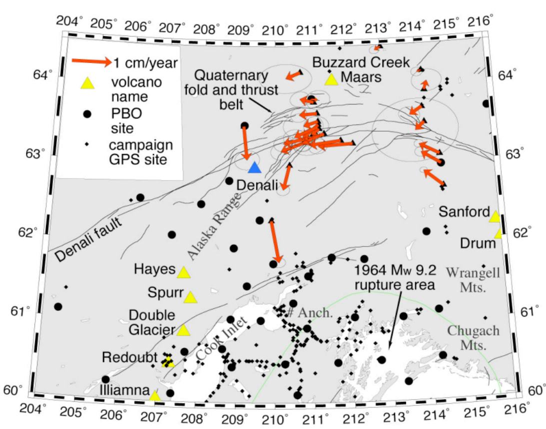
The southern Alaska margin has been convergent since early Mesozoic time, around 200 Ma. A large Mesozoic to early Tertiary accretionary complex rims all of continental southern Alaska. Dates of oldest micas in blueschist facies rocks in the accretionary complex are typically around ~195 Ma, and this seems likely to be close to the time of initiation of subduction beneath the southern Alaska margin. Prior to 50 Ma, the southeastern Alaska margin (the panhandle of Alaska) was also a convergent margin that had an associated arc along the Coast Mountains, and an accretionary complex along the coast. After 50 Ma, the Pacific-North America relative plate motion turned more northwesterly, and the southeast Alaska margin became transform and the magmatic arc shut off. During subduction of oceanic crust beneath southern Alaska, three main components of a convergent margin have been apparent: the magmatic arc, the forearc basin, and the accretionary complex.

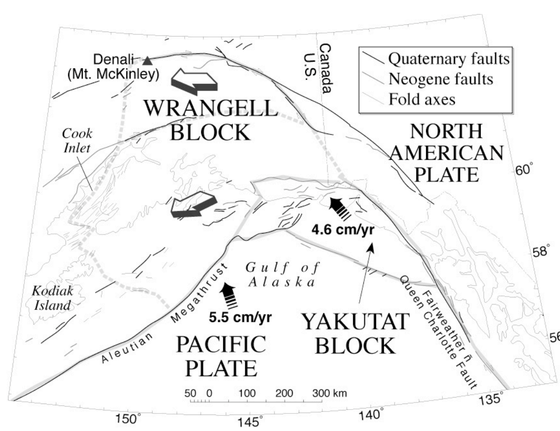
In the armpit of Alaska, in the region between the Aleutian megathrust and the Queen Charlotte-Fairweather fault, the Yakutat microplate is colliding into, and subducting beneath the southern Alaska margin. The Yakutat microplate, or terrane, originally lay off the coast of British Columbia. Most of the area of the microplate likely consists of a thick sequence of mafic volcanic rocks. The eastern edge of the terrane consists of Mesozoic accretionary complex rocks. Sometime after 50 Ma, the Yakutat terrane started moving northward. Between ~15 and 25 Ma, it began to collide with the southern Alaska margin. The distance between the trench and the magmatic arc in south-central Alaska is one of the largest in the world– about 500 km. This is due in part to the shallow angle at which the slab is subducting (Figs. 12 and 13). Seismic tomography reveals the shallowly-dipping slab is in fact the subducted Yakutat microplate, and tomography and receiver function analysis shows the Yakutat slab has been subducted to more than 100 km depth. The shallow dip angle of the slab indicates it is likely buoyant compared to normal oceanic crust. Besides the plate bounding faults, much of the active deformation in southern Alaska appears related to the collision and subduction of the buoyant Yakutat microplate.



Figs 10 and 11. Active volcanoes of the Aleutian Arc. The ~6.7 Ma Grubstake Ash source shown within the Denali volcano gap.

Neotectonics of south-central Alaska





Figs 12 and 13. Neotectonics of south-central Alaska, showing Quaternary faults, volcanoes, and GPS velocities. The GPS velocities show the absolute motion with respect to an external reference frame (from Earthscope proposal, by Haeussler, Freymueller, Moran, Power, Saltus). Lower: Neotectonic setting of southern Alaska. From Haeussler et al. (2000).

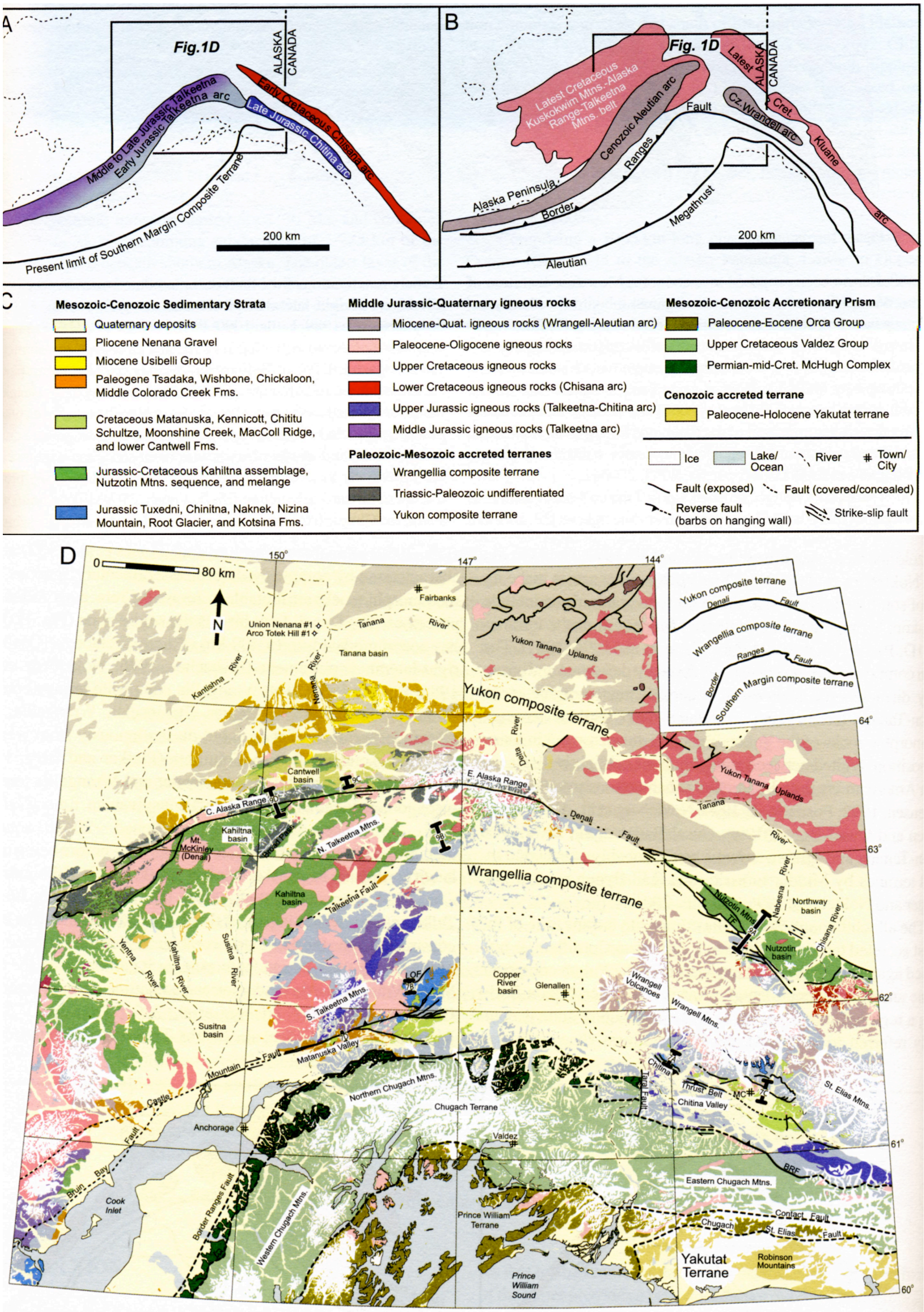


Fig 14A and 14B. South-central Alaska in the context of Jurassic-Cretaceous (A) and Cretaceous-Cenozoic magmatic belts. C: Map units. Figure from Trop and Ridgway (2007), which is adapted from Plafker et al. (1994). D: Simplified geological map showing terranes, magmatic belts, faults, Mesozoic-Cenozoic sedimentary basins etc. From Trop and Ridgway (2007) based on Wilson et al. (1998) and Bradley et al. (2003).

Geologic and tectonic background of south-central Alaska

The following description of geologic and tectonic units is summarized from Trop and Ridgway, 2007; GSA Special Paper 431) (Figs. 14A and 14B).

Yukon Composite terrane: ductilely deformed and structurally dismembered Proterozoic-Paleozoic metamorphic rocks (Yukon-Tanana terrane) and arc-related rocks (Stikine terrane). These terranes were emplaced against inboard terranes, probably by the middle Jurassic.

Wrangellia composite terrane: a very large terrane, accreted against the southern margin of the Yukon composite terrane and smaller continental terranes (Dillinger, Nixon-Fork) along a regional suture (known as the Alaska Range regional suture or the megasuture zone) characterized by complexly deformed sedimentary, igneous and metamorphic rocks attributable to collision in the Jurassic-Cretaceous. The suture zone is bisected by the Denali fault, a structure that has accommodated 400 km of right lateral Cretaceous-Cenozoic strike-slip movement. The Wrangellia composite terrane consists of three allochthonous terranes: Peninsular, Wrangellia, and Alexander terranes. The are two models proposed to account for Mesozoic accretion of this terrane (i) Talkeenta arc (Peninsular terrane) collides in the Early-Late Jurassic against the southern margin of Wrangellia-Alexander terranes, followed by juxtaposition in the early Cretaceous against the former continental margin (Clift, 2005) and (ii) Juxtaposition of the combined Wrangellia, Alexander and Peninsula terranes against the former continental margin in the Late-Jurassic-Early Cretaceous (Ridgway et al. 2002, Trop et al. 2002, 2005).

Border Ranges fault: separates the southern (outboard) margin of the Wrangellia composite terrane and the northern (inboard) edge of the Southern Margin composite terrane. Likely a paleo-subduction zone thrust, the Border Ranges fault accommodated northward underthrusting of oceanic crust beneath the Wrangellia composite terrane during the Early Jurassic-Late Cretaceous. Reactivation of the fault occurred in the latest Cretaceous and Tertiary with hundreds of km of right-lateral strike-slip motion.

Southern Margin composite terrane: includes the Mesozoic Chugach terrane and the Cenozoic Prince William and Yakutat terranes. Chugach and Prince William terranes are metamorphic rocks, melange and scraped off oceanic sedimentary and volcanic rocks (i.e., a subduction complex). The age of the rock strata, the level of deformation and the metamorphic grade decrease systematically southward across the subduction complex indicating northward subduction. The Chugach terrane consists of, from north to south (i) blueschists with late Triassic-early Jurassic metamorphic ages, (ii) melange (McHugh-Uyak complex), <125 Ma, has Triassic-Upper Cretaceous fossils, (iii) marine metasediments (Valdez Group) with latest Cretaceous fossils and latest-Cretaceous-Paleocene uplift ages. The Prince William terrane is juxtaposed against the southern-most side of the Valdez Group; it is comprised of scraped-off Paleocene-Eocene marine metasediments and volcanics.

Yakutat terrane: a sliver of continental North America, is colliding with the southernmost part of the Southern margin terrane (Chugach and Prince William terranes) along the Chugach-St Elias and Fairweather faults. Likely transported ~600 km by dextral translation along the Queen Charlotte fault starting about 30 Ma. The leading edge (initially an oceanic plateau) has been subducted several hundred km under southern Alaska, with the more buoyant, continental, part of the terrane entering the subduction zone ca. 10 Ma. At 5-6 Ma the angle of convergence changed and the rate of convergence increased leading to more orthogonal collision. The Yakutat terrane is presently moving 45-50 mm/yr in the NW direction (with respect to a fixed North America) while being internally deformed, partially subducted and accreted to the North America plate.

Magmatic belts

Magmatic rocks occur mainly as linear belts of plutonic and volcanic rocks associated with north-dipping (present-day co-ordinates) subduction with inward migration of magmatism from Early Jurassic to Late Cretaceous (Talkeetna, Chisana and Chitina arcs) followed by outward (southerly) migration in the Cenozoic (Wrangell and Alaska-Aleutian arcs) (Figs. 14A and 14B). From the Talkeetna Mountains to the central Alaska Range, Paleocene-Eocene rocks (up to 3 km thick) overlap the Peninsular and Wrangellia terranes. Geochemical signatures indicate these rocks likely formed due to slab-window magmatism, likely associated with subduction of an oceanic spreading ridge. Miocene-Recent plutonic and volcanic rocks of the Aleutian-Wrangell arc cut the margin of the Wrangellia composite terrane and are associated with subduction of the northern edge of the Pacific plate and leading edge of the Yakutat terrane beneath southern Alaska.

Sedimentary basins (on our route)

Inboard margin basins: Along the northern (inboard) margin of the Wrangellia composite terrane, Mesozoic sedimentary strata are discontinuously exposed in the Alaska Range and northern Talkeetna Mountains as well as within the regional suture zone between the Wrangellia composite terrane (accreted Mesozoic and oceanic island arc rocks) and the Yukon-Tanana terrane (Paleozoic and older continental margin rocks).

Kahiltna Basin: The Kahiltna assemblage is exposed in south-central Alaska, notably in the central Alaska Range (~100 km wide, ~300 km long belt) and the northern Talkeetna Mountains (~60 km wide, ~150 km long belt), with the two regions of Kahiltna assemblage separated by Broad Pass, a major topographic lineament.

In the northern Talkeetna Mountains, the Kahiltna assemblage overlies (disconformably) Upper Triassic marine sedimentary and volcanics. Deposition continued into the Albian (middle Cretaceous). The assemblage is metamorphosed to kyanite-garnet schist and gneiss (McLaren Glacier metamorphic belt) in the NE Talkeetna Mountains.

In the Alaska Range, the Kahiltna assemblage (characterized by submarine fan strata >5.5 km thick) is juxtaposed against the Yukon-Tanana terrane along the Denali and Hines Creek faults, and while the lower contact is not seen in this region, to the southwest it conformably overlies Upper Triassic to Lower Jurassic marine volcanic/volcanoclastics) (Fig. 15). This assemblage is unconformably overlaid by Late Cretaceous marginal marine and Oligocene non-marine strata south of the Denali fault and Late Cretaceous marginal marine and non-marine strata (Lower Cantwell Formation) north of the Denali fault.

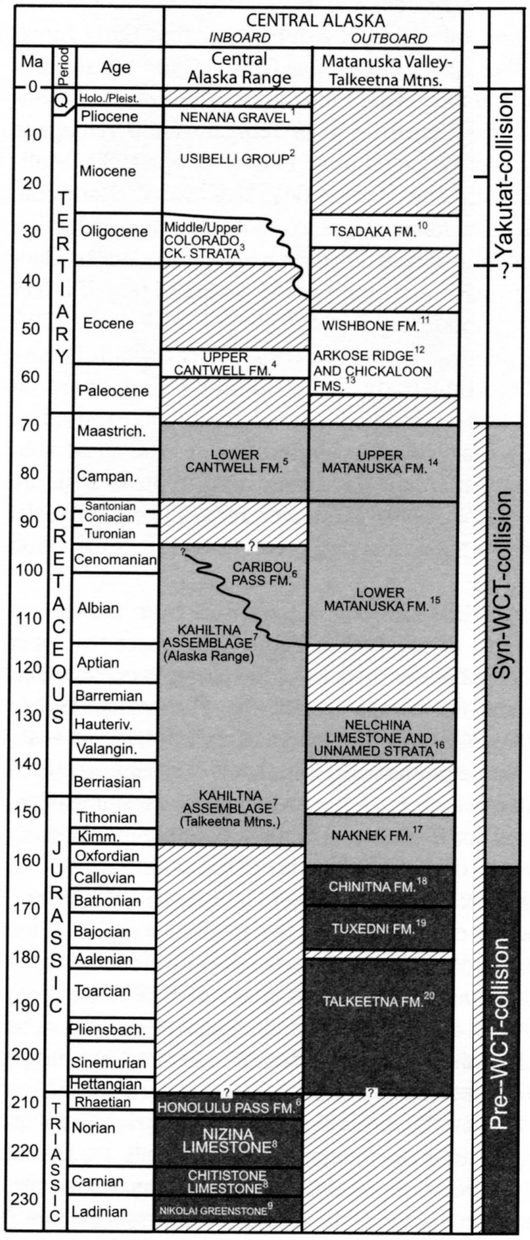


Fig 15. Stratigraphic chart of Mesozoic-Cenozoic basins. "Inboard" (towards the craton) and "outboard" refer to margins of the Wrangellia composite terrane. From Trop and Ridgway (2007).

Cantwell Basin: This basin lies within the central Alaska Range, but north of the Denali fault. The southern structural limit is defined by south-dipping thrust faults that are cut off by the E-W trending Denali fault. To the north, basinal strata are juxtaposed against the Yukon-Tanana terrane (Paleozoic metamorphics) along the Hines Creek fault. There are two distinct units: lower Cantwell Formation - >3 km thick Upper Cretaceous non-marine to marginal marines sedimentary unit, unconformably overlaid (10-20 my hiatus) by the upper Cantwell Formation, >3 km thick Paleocene-Eocene volcanics.

Dinosaur footprints within the Lower Cantwell Formation

Modified from Fiorillo et al. (2007). Dinosauria and fossil aves footprints from the lower Cantwell Formation (latest Cretaceous), Denali National Park and Preserve (Fig. 16).

Denali National Park and Preserve is new area for dinosaur studies. The Cantwell Formation within the park contains the first record of dinosaurs in the Alaska Range. This record consists of tracks of small, medium, large, and very large-sized theropods, as well as hadrosaurs. In addition, the Cantwell Formation contains the first record of fossil Aves. Further, this occurrence of fossil birds records feeding behavior in these presumed ancient shorebirds. Combined this new suite of Mesozoic fossil vertebrate sites add to the understanding of biodiversity in Alaska during the Cretaceous at the beginning of the land bridge referred to as Beringia (Hopkins 1967, Fiorillo in press) because the Cantwell Formation correlates with other rock units in Alaska that produce dinosaur remains such as the ~ 69.5 Ma $^{40}Ar/^{39}Ar$ Prince Creek Formation of northern Alaska (Parrish et al. 1987; Fiorillo and Gangloff 2000, 2001; Gangloff et al. 2005, Flaig, et al. unpublished age) and the Chignik Formation of southwestern Alaska (Fiorillo and Parrish 2004). Thus, further work will provide the opportunity for a more detailed regional paleoecological and paleoenvironmental understanding of an ancient high latitude terrestrial ecosystem on a greenhouse Earth.

Tanana Basin: This basin is located north of the Alaska Range and south of the Yukon-Tanana highlands. A number of large rivers flow transverse to the Alaska Range (Nenana River in the region we visit) draining to the north and merging with the Tanana River that joins the Yukon River further to the north. Lacustrine, fluvial and alluvial sediments, >1.6 km thick, form the Usibelli Group (Oligocene-Miocene), Nenana Gravels (Pliocene) and Quaternary surficial deposits. These deposits, notably the transition from Usibelli Group to the Nenana Gravels are crucial to understanding the evolution of the present-day Alaska Range, as is discussed later. These units form part of the northern foothills of the Alaska Range. North of the Hines Creek Fault, the Usibelli Group unconformably overlies metamorphic rocks of the Yukon-Tanana terrane, whereas south of this fault, limited outcrops unconformably overlie the Cantwell Formation.

Outboard margin basins

Susitna Basin: This Holocene basin is a fluvial and swampy lowland, located between the Cook Inlet to the south, the Talkeetna Mountains to the east, and the Alaska Range to the west and north. Major rivers flowing southward from the Alaska Range (the Kahiltna, Yentna and Susitna Rivers) join as the Susitna River that flows into the Cook Inlet. Bisected by the Castle Mountain fault. Strata in the basin include >4 km of Paleocene-Miocene conglomerate, carbonaceous sandstone, mudstone and coal deposited in fluvial-lacustrine environments unconformably overlying 4-6 km of Paleozoic-Mesozoic sedimentary strata with ~180 m of Quaternary sedimentary and glacial strata.

Fig 16. Dinosaur footprint. Photo by Carla Susanne Tomsich

Matanuska Valley - Talkeetna Mountains Basin*:* This Mesozoic-Cenozoic basin contains >3.8 km Middle Jurassic-Upper Cretaceous marine strata and >2.9 km Paleocene-Oligocene nonmarine strata unconformably overlying the accreted Talkneeta oceanic arc (Lower-Middle Jurassic). These rocks crop out in the Matanuska Valley, southern Talkeetna Mountains and northern Chugach Mountains. To the south, the Border Ranges fault places strata in the southern part of the basin (hanging wall) over subduction complex rocks in the northern Chugach Mountains (footwall). The basin is bisected by the Castle Mountain fault. To the north, basinal strata are juxtaposed against Jurassic arc plutons along the Little Oshetna Fault.

Tectonic and paleogeographic development of south-central Alaska

The following paleogeographic reconstructions and cross-sections from the Late Cretaceous to Recent are from Trop and Ridgeway (2007) and emphasize development of sedimentary basins and related structures as well as collisional tectonics, magmatic belts and orogenesis (Figs. 17 and 18).

TABLE 2. EXPLANATION FOR PALEOGEOGRAPHIC MAPS AND CROSS SECTIONS SHOWN IN FIGURES 3 AND 4

Geographic references
- A - Anchorage
- F - Fairbanks
- M - McCarthy
- N - Nabesna

Inboard Margin Basins
- CB - Cantwell
- CCB - Colorado Creek
- DB - Dezadeash
- KB - Kahiltna
- MCB - MacCallum Creek
- NOB - Northway
- NB - Nutzotin
- TB - Tanana
- WCB - Watana Creek
- (Prefixed with U=Uplifted)
- (Prefixed with F=Future position)

Outboard Margin Basins
- CIB - Cook Inlet
- CRB - Copper River
- CVB - Chitina Valley
- MB - Matanuska - S. Talkeetna Mtns.
- SB - Susitna
- WB - Wrangell Mountains
- (Prefixed with U=Uplifted)
- (Prefixed with F=Future position)

Terranes
- AT - Alexander
- CT - Chugach
- PT - Peninsular
- PWT - Prince William
- WT - Wrangellia
- YT - Yakutat
- YTT - Yukon-Tanana

Faults, Shear Zones
- BHF - Border Ranges-Hanagita fault
- BLF - Bruin Bay-Little Oshetna fault
- CMF - Castle Mountain fault
- CTB - Chitina thrust belt
- DF - Denali fault
- HCF - Hines Creek fault
- LD - Lost Creek decollement
- TF - Totschunda fault
- TAF - Taral fault
- TKF - Talkeetna fault
- VCS - Valdez Creek shear zone

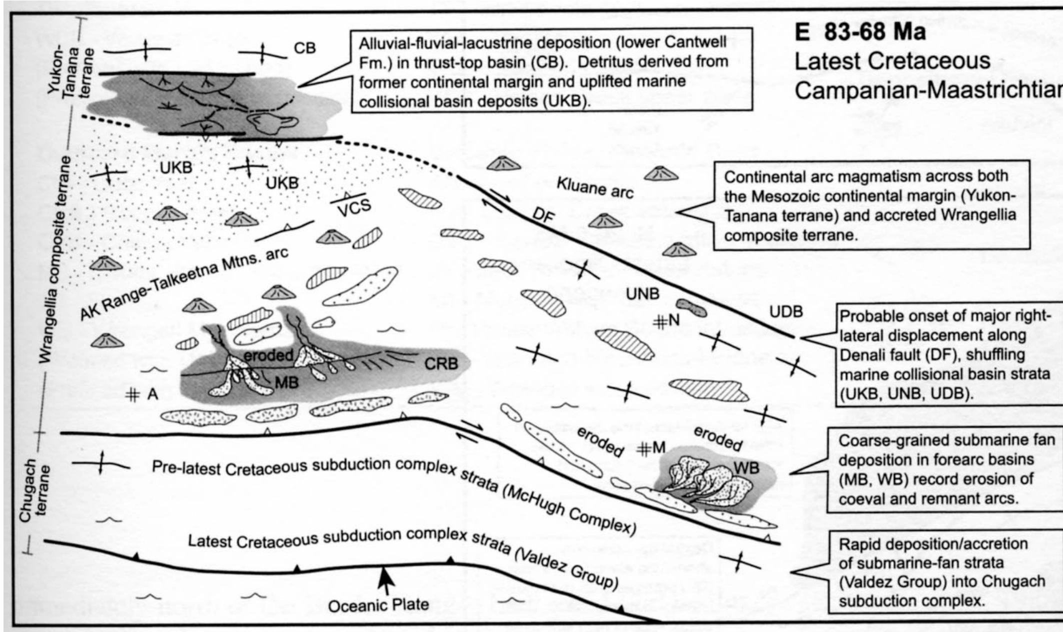
Volcanic Fields, Plutonic Belts
- AA - Aleutian-Alaska arc
- CV - Caribou Creek volcanics
- CTV - Central Talkeetna Mtns. volcanics
- JV - Jack River volcanics/plutons
- MI - Matanuska Valley intrusives
- PI - Prince William Sound intrusives
- TK - Talkeetna Mountains-Kluane arc
- WV - Wrangell volcanic field

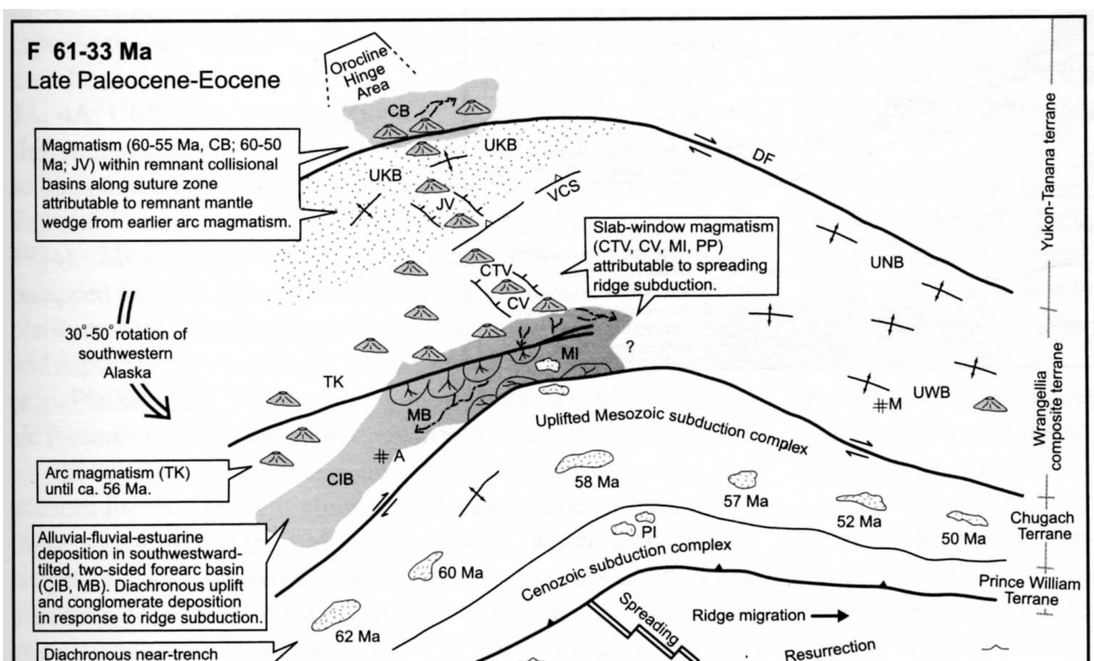
Magmatism
- Locus of active volcanism
- Paleocene-Eocene intrusives
- Mid-Cretaceous Chisana arc rocks
- Upper Jurassic Talkeetna-Chitina arc rocks
- Middle Jurassic Talkeetna arc rocks
- Lower Jurassic Talkeetna arc rocks

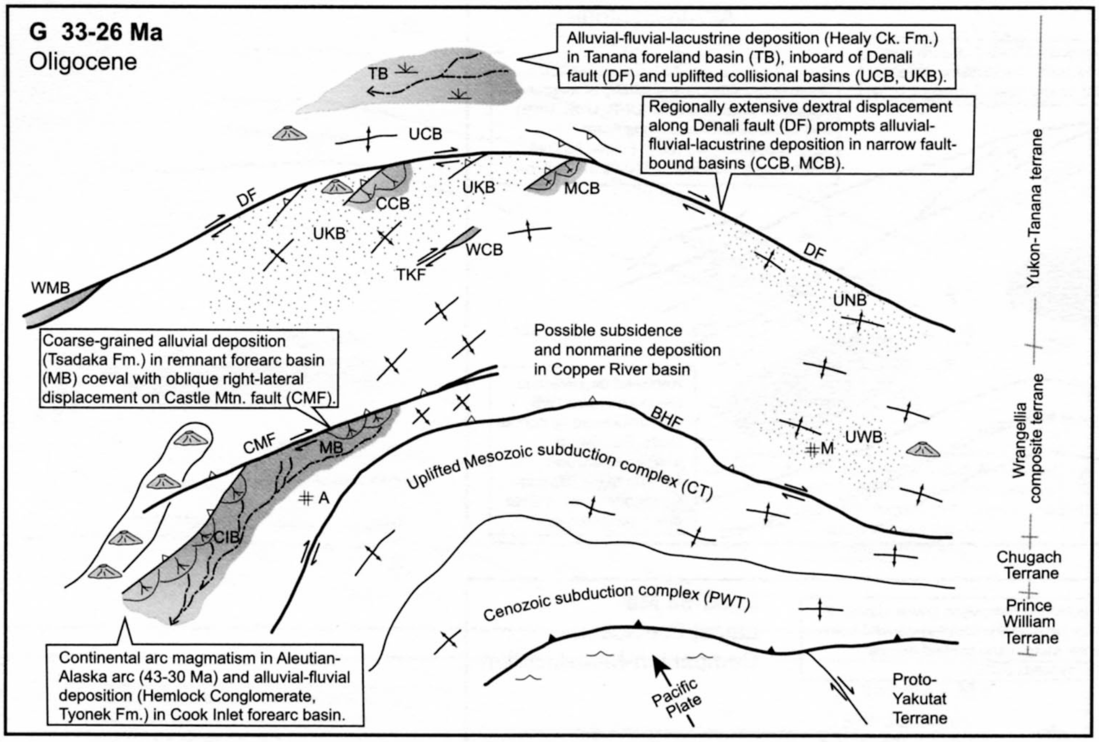
Deformational Features
- Active subduction zone (barb on downgoing plate)
- Active crustal shortening (barb on thrust sheets)
- Regional topographic uplifts via folding/faulting
- Active crustal extension via normal faults
- Regional dextral strike-slip fault
- Strike-slip movement away (⊗) or toward (⊙)

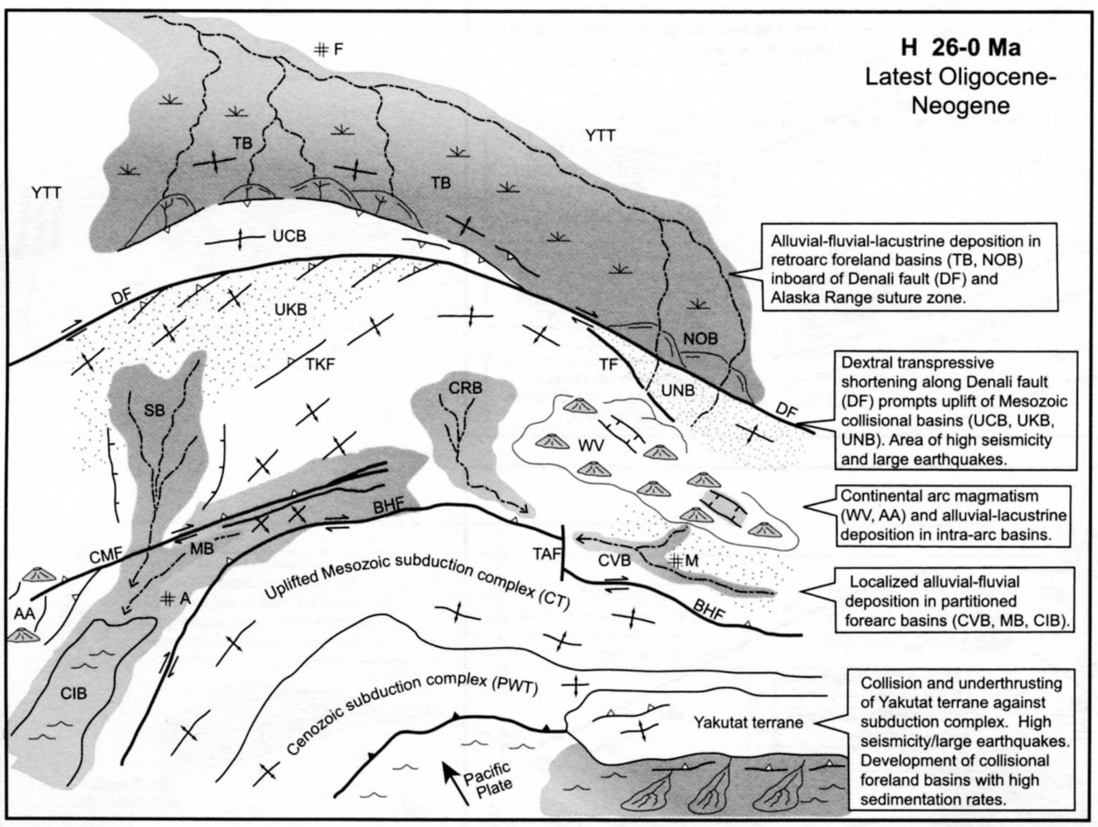
Depositional Features
- Alluvial
- Fluvial
- Lacustrine
- Fan-Delta/ Prodelta Slope
- Marine Shelf
- Submarine Fans
- Marine environments
- Active depositional basin
- Uplifted basinal strata

Fig 17. Explanation for paleogeographic maps and cross-sections (Trop and Ridgway, 2007). See above and below.


E 83-68 Ma
Latest Cretaceous
Campanian-Maastrichtian
Alluvial-fluvial-lacustrine deposition (lower Cantwell Fm.) in thrust-top basin (CB). Detritus derived from former continental margin and uplifted marine collisional basin deposits (UKB).
Yukon-Tanana terrane
Wrangellia composite terrane
Chugach terrane
CB
UKB
UKB
VCS
Kluane arc
DF
Continental arc magmatism across both the Mesozoic continental margin (Yukon-Tanana terrane) and accreted Wrangellia composite terrane.
AK Range-Talkeetna Mtns. arc
UNB
N
UDB
Probable onset of major right-lateral displacement along Denali fault (DF), shuffling marine collisional basin strata (UKB, UNB, UDB).
eroded
CRB
MB
A
eroded
M
eroded
WB
Coarse-grained submarine fan deposition in forearc basins (MB, WB) record erosion of coeval and remnant arcs.
Pre-latest Cretaceous subduction complex strata (McHugh Complex)
Latest Cretaceous subduction complex strata (Valdez Group)
Rapid deposition/accretion of submarine-fan strata (Valdez Group) into Chugach subduction complex.
Oceanic Plate


F 61-33 Ma
Late Paleocene-Eocene
Orocline Hinge Area
CB
UKB
UKB
Magmatism (60-55 Ma, CB; 60-50 Ma; JV) within remnant collisional basins along suture zone attributable to remnant mantle wedge from earlier arc magmatism.
JV
VCS
DF
Yukon-Tanana terrane
Slab-window magmatism (CTV, CV, MI, PP) attributable to spreading ridge subduction.
CTV
CV
UNB
30°-50° rotation of southwestern Alaska
MI
?
TK
UWB
M
Wrangellia composite terrane
MB
Uplifted Mesozoic subduction complex
Arc magmatism (TK) until ca. 56 Ma.
A
CIB
58 Ma
57 Ma
52 Ma
50 Ma
Chugach Terrane
PI
Alluvial-fluvial-estuarine deposition in southwestward-tilted, two-sided forearc basin (CIB, MB). Diachronous uplift and conglomerate deposition in response to ridge subduction.
60 Ma
Cenozoic subduction complex
Prince William Terrane
Spreading Ridge
Ridge migration
62 Ma
Diachronous near-trench plutonism within subduction complex during northeastward subduction of spreading ridge oriented obliquely to trench.
Kula Plate
Resurrection Plate


G 33-26 Ma
Oligocene
Alluvial-fluvial-lacustrine deposition (Healy Ck. Fm.) in Tanana foreland basin (TB), inboard of Denali fault (DF) and uplifted collisional basins (UCB, UKB).
TB
UCB
Regionally extensive dextral displacement along Denali fault (DF) prompts alluvial-fluvial-lacustrine deposition in narrow fault-bound basins (CCB, MCB).
DF
CCB
UKB
MCB
UKB
WCB
TKF
WMB
DF
UNB
Coarse-grained alluvial deposition (Tsadaka Fm.) in remnant forearc basin (MB) coeval with oblique right-lateral displacement on Castle Mtn. fault (CMF).
Possible subsidence and nonmarine deposition in Copper River basin
CMF
MB
BHF
M
UWB
A
Uplifted Mesozoic subduction complex (CT)
CIB
Cenozoic subduction complex (PWT)
Continental arc magmatism in Aleutian-Alaska arc (43-30 Ma) and alluvial-fluvial deposition (Hemlock Conglomerate, Tyonek Fm.) in Cook Inlet forearc basin.
Pacific Plate
Proto-Yakutat Terrane
Yukon-Tanana terrane
Wrangellia composite terrane
Chugach Terrane
Prince William Terrane


H 26-0 Ma
Latest Oligocene-Neogene
F
YTT
TB
TB
YTT
UCB
Alluvial-fluvial-lacustrine deposition in retroarc foreland basins (TB, NOB) inboard of Denali fault (DF) and Alaska Range suture zone.
DF
UKB
NOB
TKF
TF
UNB
Dextral transpressive shortening along Denali fault (DF) prompts uplift of Mesozoic collisional basins (UCB, UKB, UNB). Area of high seismicity and large earthquakes.
SB
CRB
DF
WV
Continental arc magmatism (WV, AA) and alluvial-lacustrine deposition in intra-arc basins.
BHF
CMF
MB
TAF
CVB
M
A
Uplifted Mesozoic subduction complex (CT)
BHF
Localized alluvial-fluvial deposition in partitioned forearc basins (CVB, MB, CIB).
AA
CIB
Cenozoic subduction complex (PWT)
Yakutat terrane
Collision and underthrusting of Yakutat terrane against subduction complex. High seismicity/large earthquakes. Development of collisional foreland basins with high sedimentation rates.
Pacific Plate

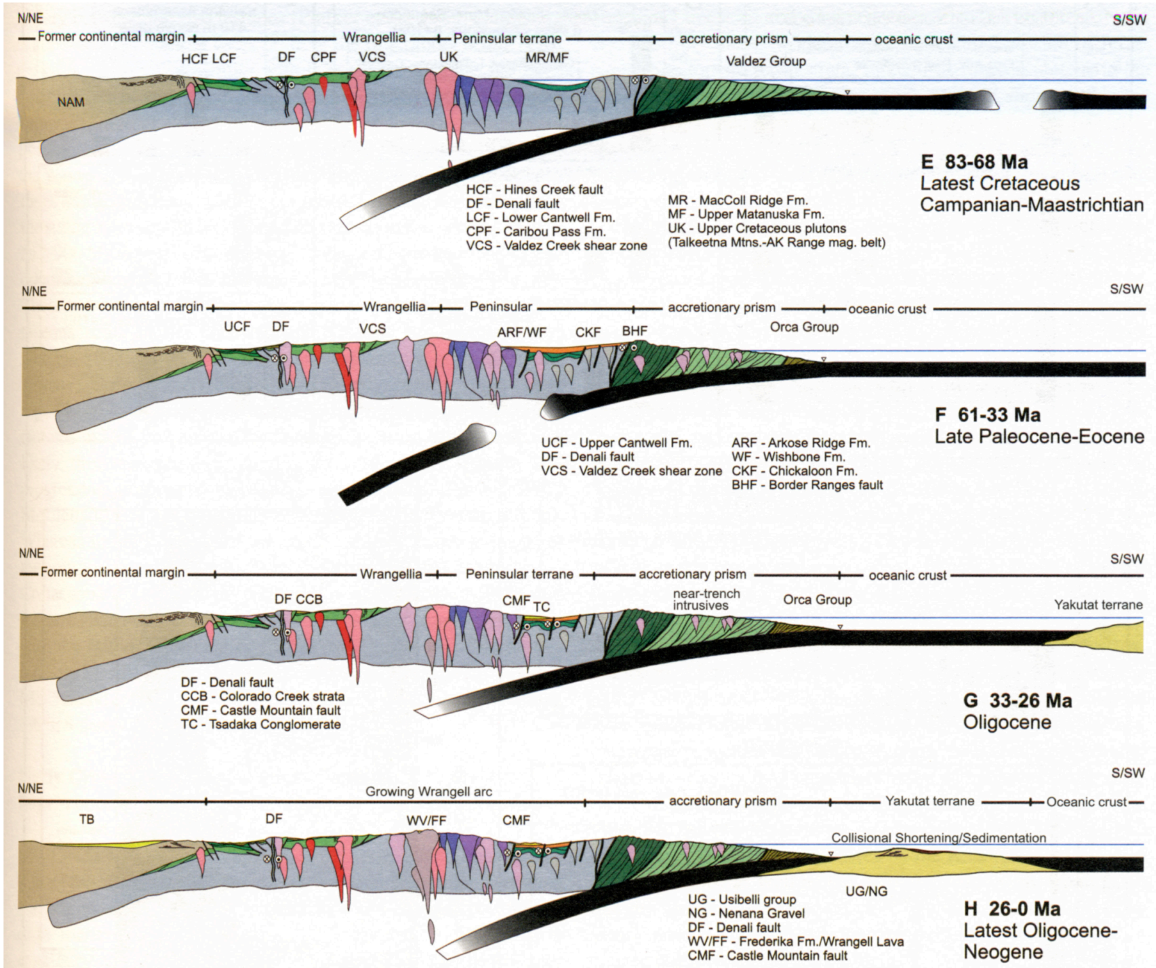


Fig 18. Cross-sectional view of tectonic evolution of the Alaskan margin through time (Trop and Ridgway, 2007).

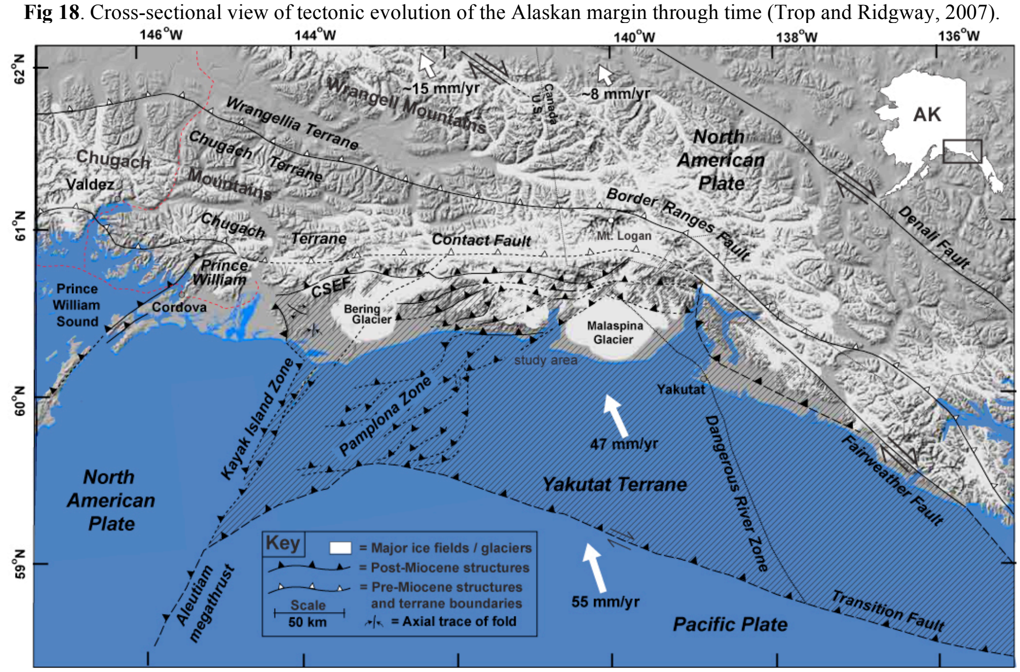


Fig 19. Schematic map of the southern Alaska continental margin with major structural components and boundaries.

Collision of the Yakutat Block with North America

The Gulf of Alaska margin is on of the most seismically and tectonically active regions in the world due to interactions between the combined Pacific plate and overlying Yakutat microplate with the North American plate. Some of the following is from "Living on the Edge", Garver and Cockburn, (2008) which has been modified from the STEEP Science plan - a National Science Foundation Continental Dynamics program.

The basement of the Yakutat microplate is thought to consist of Mesozoic continental crust in the eastern one-third and Eocene oceanic crust in the western two-thirds overlain by up to 10 km of Cenozoic sedimentary strata. Along its eastern margin, the Yakutat microplate moves northwest with the Pacific plate relative to interior Alaska at 40-50 mm/yr along the Queen Charlotte-Fairweather transform fault system (Fig. 19). The Transition fault, which marks the southern boundary of the microplate and its contact with the Pacific plate, is characterized by sparse historic seismicity that suggests a low rate of relative plate motion. At the leading western and northwestern edge, oceanic Yakutat microplate basement is actively subducting beneath North America along the extension of the Aleutian megathrust onto the continental margin. As a consequence, off-scraping of the sedimentary cover has developed a wide fold and thrust belt (Pamplona Zone) in which the deformation front has migrated progressively southward and eastward some 50 to 100 km from the microplate boundary.

The Yakutat microplate formed at about 30 Ma at which time the Queen Charlotte-Fairweather transform stepped inboard to its present position. Subsequently, the microplate moved northwestward and subduction of the leading edge of the microplate to a depth of ~100 km resulted in onset of arc volcanism in the Wrangell Mountains at ~25 Ma. Abrupt shoaling (shallowing) and upward coarsening of marine sediments record uplift of the Yakutat microplate beginning in the Miocene.

Development of the modern Chugach/St. Elias orogen is related to the northwestward translation, collision, and subduction of the Yakutat terrane along the North American plate margin since ~25 Ma (Plafker, 1987). Motion of the Yakutat terrane is closely tied to northwestward motion of the Pacific plate with respect to North America.

Castle Mountain Fault

The Castle Mountain fault is one of several major east-northeast-striking faults in southern Alaska, and it is the only fault with historic seismicity and Holocene surface faulting (Lahr and others, 1986; Detterman and others, 1974). The Castle Mountain fault is approximately 200 km long, and is one of the longest structures in the Cook Inlet basin. Martin and Katz (1912) first noted the fault, but it was delineated on a regional scale by Detterman and others (1974, 1976). They mapped and divided it into two physiographic segments: the western Susitna Lowland and eastern Talkeetna Mountains segments (Fig. 20). Haeussler (1994, 1998) mapped and examined the 30-km-long region between the two Detterman and others (1974, 1976) maps (Fig. 21). Thus far, there are no land use or building regulations associated with proximity to the Castle Mountain fault.

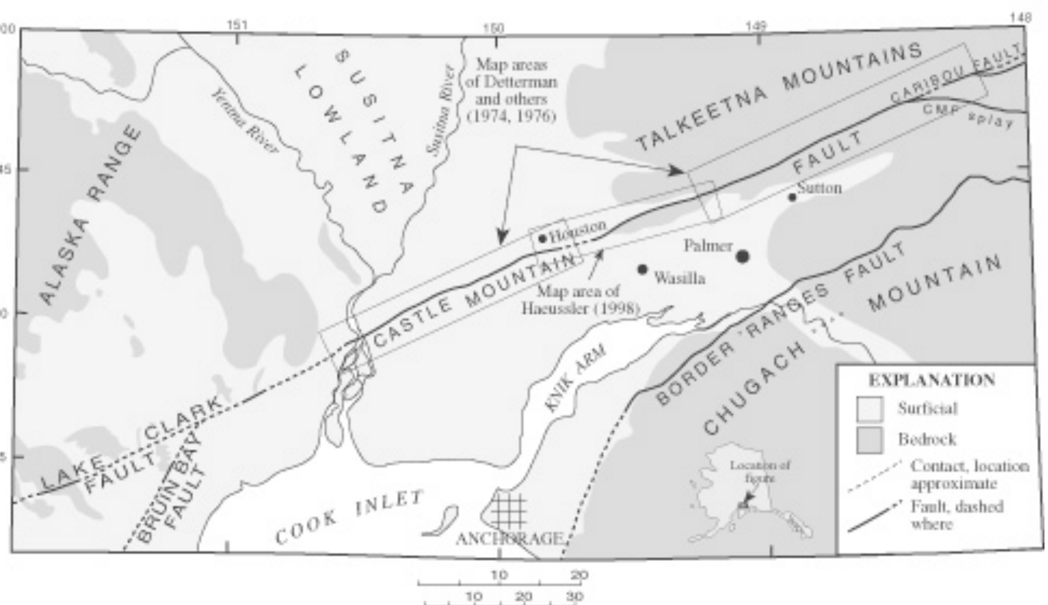


Fig 20. Location of Castle Mountain fault in south central Alaska, and previous USGS maps along the fault (figure and text: LaBay and Haeussler, U.S. Geological Survey Open-File Report 01-504, 2001).

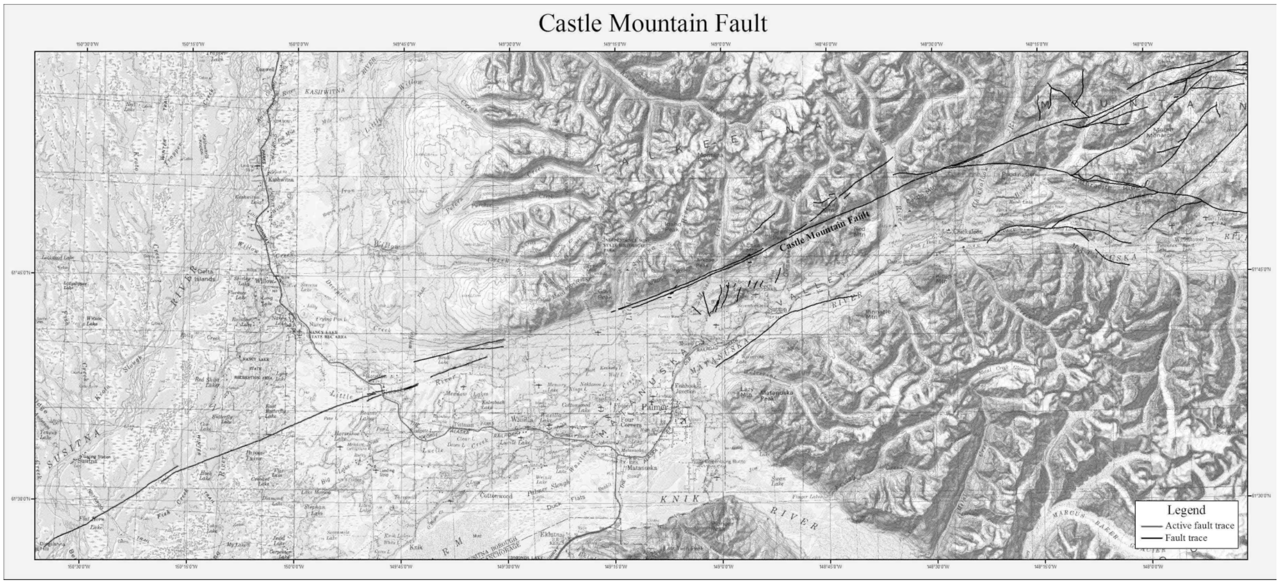


Fig. 21. Map of Castle Mountain Fault (from LeBay and Haeussler, 2001).

The surface trace of the Castle Mountain fault is not the only earthquake hazard associated with the fault. The two historic earthquakes on the Castle Mountain fault were located on the part of the fault where there is no surface expression (Lahr and others, 1984), and thus even the part of the fault with no scarp should probably be considered active. In addition, Haeussler and others (2000) showed there is a 3-4 km wide fault-cored anticline on the north side of the fault near Houston. The faults in the core of the anticline do not crop out at the surface, but certainly also represent a seismic hazard. Saltus and others (2001) use aeromagnetic data to show that this anticline continues for the length of the Castle Mountain fault in the Susitna Lowland. (USGS).

The Alaska Range and Denali Fault System

The ~650 km long, Alaska Range incorporating North America's highest mountain (Denali - also known as Mt McKinley at 6,194 m elevation) is a spectacular, but narrow range that follows the curved Denali Fault System (DFS) across south-central Alaska. The DFS is a major intracontinental strike-slip fault that is still active as shown by its morphology and the 2002 magnitude 7.9 earthquake with an epicenter 22 km east of Mount Nenana (in the Eastern Alaska Range) (Fig. 22). The Alaska Range lies ca. 500 km inland of the modern day plate boundary, and can be divided into the Western, Central and Eastern Alaska Range (Fig. 23). The Central Alaska Range is dominated by Denali while peaks in the Eastern Alaska Range exceed 4000 m.

The following section was modified from: Haeussler (2008), An overview of the neotectonics of interior Alaska: far-field deformation from the Yakutat microplate collision.

The Denali fault has been an important feature in Alaskan tectonics, probably for more than 100 million years. Mid-Cretaceous rock units are offset about 370 kilometers across the fault in Canada (Lowey, 1998), and the Denali fault had a significant role in the accretion and northward transport of Mesozoic allochthonous terranes along the southern Alaska margin (Plafker et al. 1994b, Ridgway et al. 2002).
Another important offset constraint is in the Mt. McKinley (also referred to as Denali) region, where the Mt. Foraker pluton is 38 Ma old and is offset 38 km (Reed and Lanphere, 1974). This implies an average slip rate of 1 mm/yr for this time period. Matmon et al. (2006) used cosmogenic isotopes to date moraines and other features offset by the Denali fault in the last 17,000 years. At 14 localities they found rates that average about 12 mm/yr, but the rates are higher to the east at about 14 mm/yr and decrease to the west to about 9 mm/yr. In preliminary results, Mériaux et al. (2004) used cosmogenic dating to determine a slip rate of 7 mm/yr at a site west of Matmon's in Denali National Park. It is interesting that the slip in the 2002 earthquake mirrors the same pattern of higher co-seismic slip to the east and lower to the west (Haeussler et al. 2004; Mériaux et al. 2004).

InSAR and GPS also provide constraints on the Denali fault slip rate. Biggs et al. (2007) used a new multi-interferogram method for measuring the Denali fault slip rate prior to the 2002 earthquake. For a region along the Richardson Highway, they deduce a rate of 10.5 ± 5.0 mm/yr, which is in agreement with the cosmogenically-derived rate. These slip rates show that slip on the central part of Denali fault is about $1/5^{th}$ the Pacific-North America or the Yakutat-North America convergence rate.

Both the eastern and western Denali fault are active, but have a slip rate lower than central part of the fault. The western Denali fault, southwest of Mt. McKinley was examined by Cady et al. (1955), Fernald (1960), and Plafker et al. (1977) (see also Plafker et al. 1994a). They found discontinuous scarps, shutter ridges, and vegetation linears along the fault trace. About 140 km west of Mt. McKinley, the major north-flowing drainages (Kuskokwim River, Windy Fork, Big River) are not noticeably offset along the fault trace. This stands in contrast to major north-flowing glaciers (Foraker, Straightaway, Peters, Muldrow), about 20 km southwest of Mt. McKinley, which have right-lateral dog-leg bends of 5.5 km or more. Thus, it appears likely the Western Denali fault has a fairly low slip rate, perhaps 1-2 mm/yr, in contrast to the ~10 mm/yr for the central segment, and the decrease in slip rate occurs a few tens of kilometers southwest of Mt. McKinley.

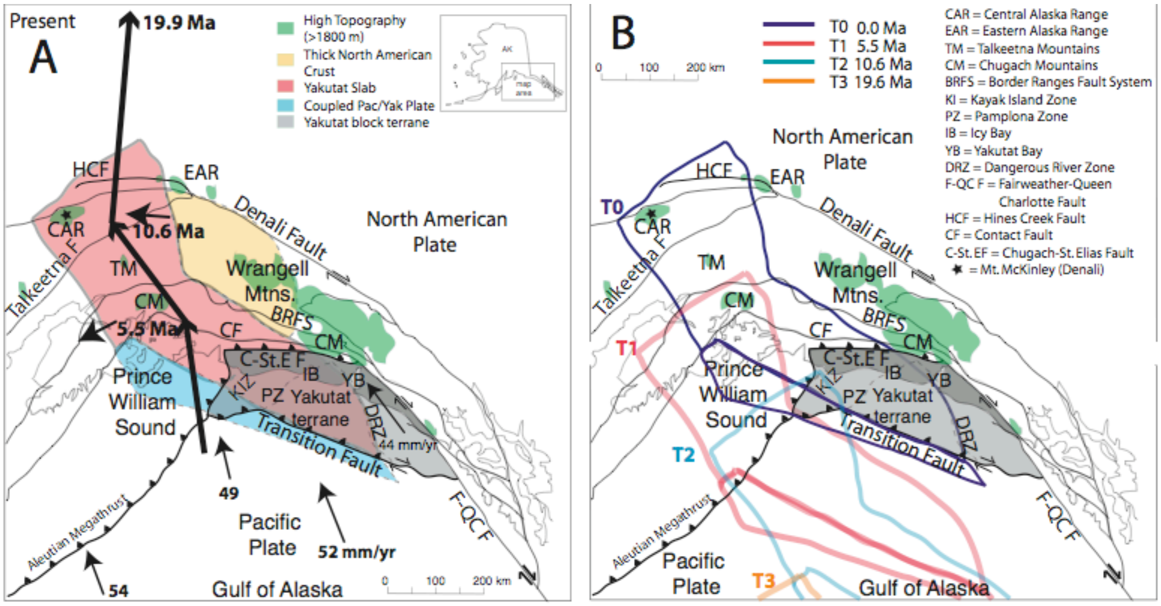


Fig 22. Tectonic map of southern and central Alaska with plate motion vectors depicting the relative position of the Yakutat slab beneath the southern Alaska continental margin through time based on relative plate motion directions and velocities. Note that the buoyant Yakutat slab does not extend beneath the Central Alaska Range until after ~5.5 Ma (modified from Eberhart-Phillips et al. 2006).

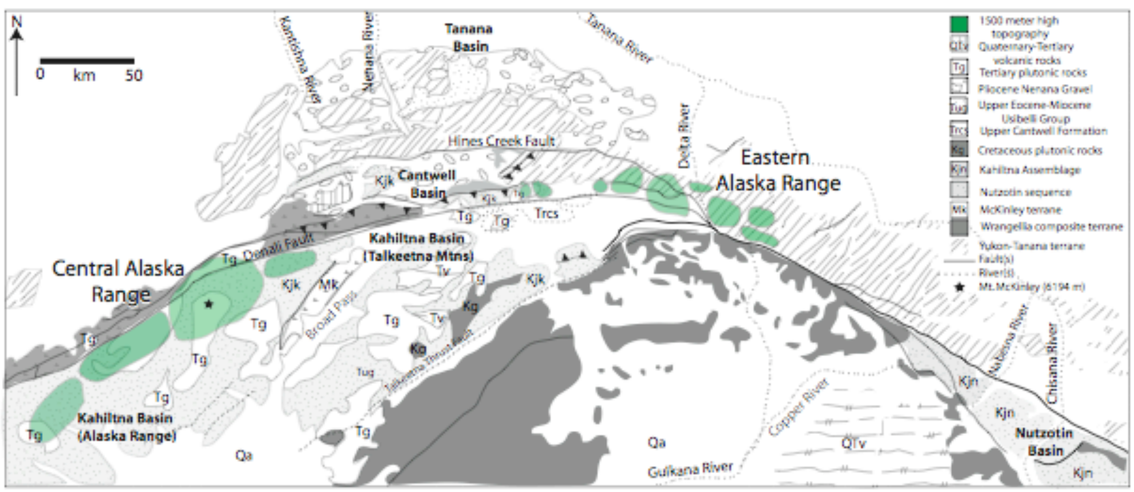


Fig 23. Above: Regional geological map of south-central Alaska showing basins, major faults and topography (>1500 m). Modified from Washburn (1980), Ridgway et al. (2002, 2007) and Eberhart-Phillips et al. (2006). The high topography within the central Alaska Range is located mainly to the south of the DFS whereas the high topography within the eastern Alaska Range is located to the north of the DFS at the junction between the strike-slip Denali fault and the Talkeetna thrust fault, south of the Hines Creek strand of the DFS. Below: Regional geological map of the Tanana, Cantwell and Kahiltna basins, south-central Alaska, with major structural components superimposed on the regional stratigraphy (Ridgway et al. 2002, 2007).

The eastern Denali fault is also active. Lahr and Plafker (1980) estimated its slip rate at 2 mm/yr. Horner (1983) suggested a slip rate of less than 1 mm/yr based on the rate of moment release. Leonard et al. (2001) use GPS geodesy and estimate its slip rate at less than a few mm/yr. Uncertainties in fault geometry and in modeling glacio-isostatic rebound make more precise calculations difficult. Clague (1979) documented geomorphic evidence for Holocene movement along the fault. He found a series of discontinuous scarps and aligned sediment mounds, as well as sachungen on nearby mountain ridges. All these features are indicative of late Quaternary-Holocene faulting, but he did not find clear evidence for late Holocene offsets. Moreover, the Holocene fault scarp on the Eastern Denali fault appears to die out south of Kluane Lake (Clague, 1979). The Hines Creek strand of the Denali fault, was the principal trace prior to 95 Ma (Wahrhaftig et al. 1975; Hickman et al. 1977), and a significant part of the ~370 km of displacement was likely on this fault trace (Hickman et al. 1978). There is about 1.5 km of vertical offset across the fault in Cenozoic time, and 6 m of south-side-down movement in Quaternary time (Wahrhaftig et al. 1975). Veenstra et al. (2006) found that the crust south of the Hines Creek strand was 35-45 km thick, whereas the crust to the north was typically about 26 km thick. The disparity between thick crust beneath the mountains and thin crust to the north suggests a fundamental change in material properties or mode of compensation. This change may be associated with geophysical disparities between terranes. To the north is metamorphosed continental margin, Yukon-Tanana; to the south is deep marine and island arc, Kahiltna and Wrangellia.

High topography (>2000 m) in the central Alaska Range is all south of the DFS system, where as in the eastern Alaska Range the majority of high topography is sandwiched between the Hines Creek and McKinley Strand of the DFS (Fig. 23). The Hines Creek strand, a major tectonostratigraphic boundary, maybe acting as a backstop for deformation in the region (Fig. 24).

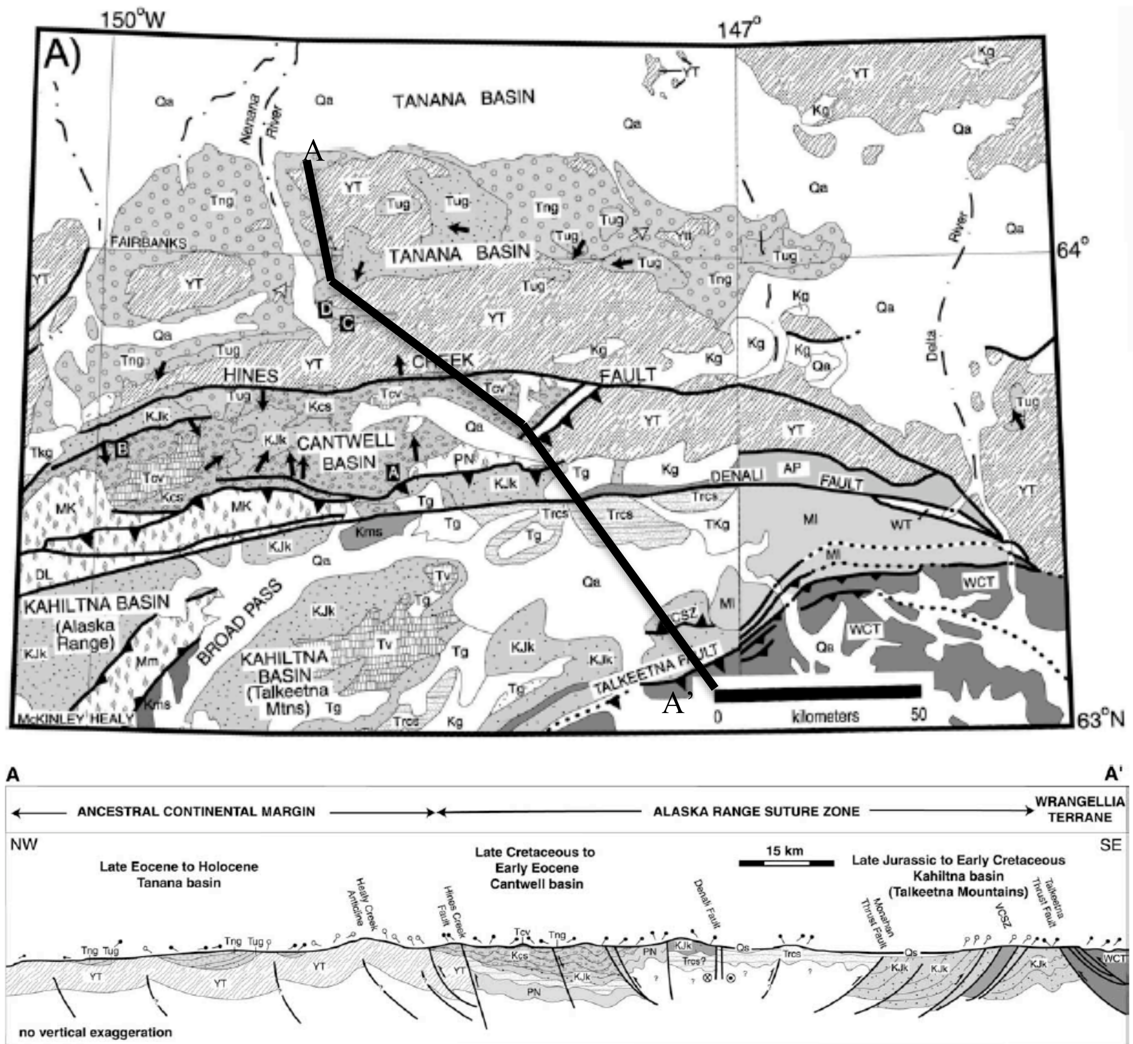
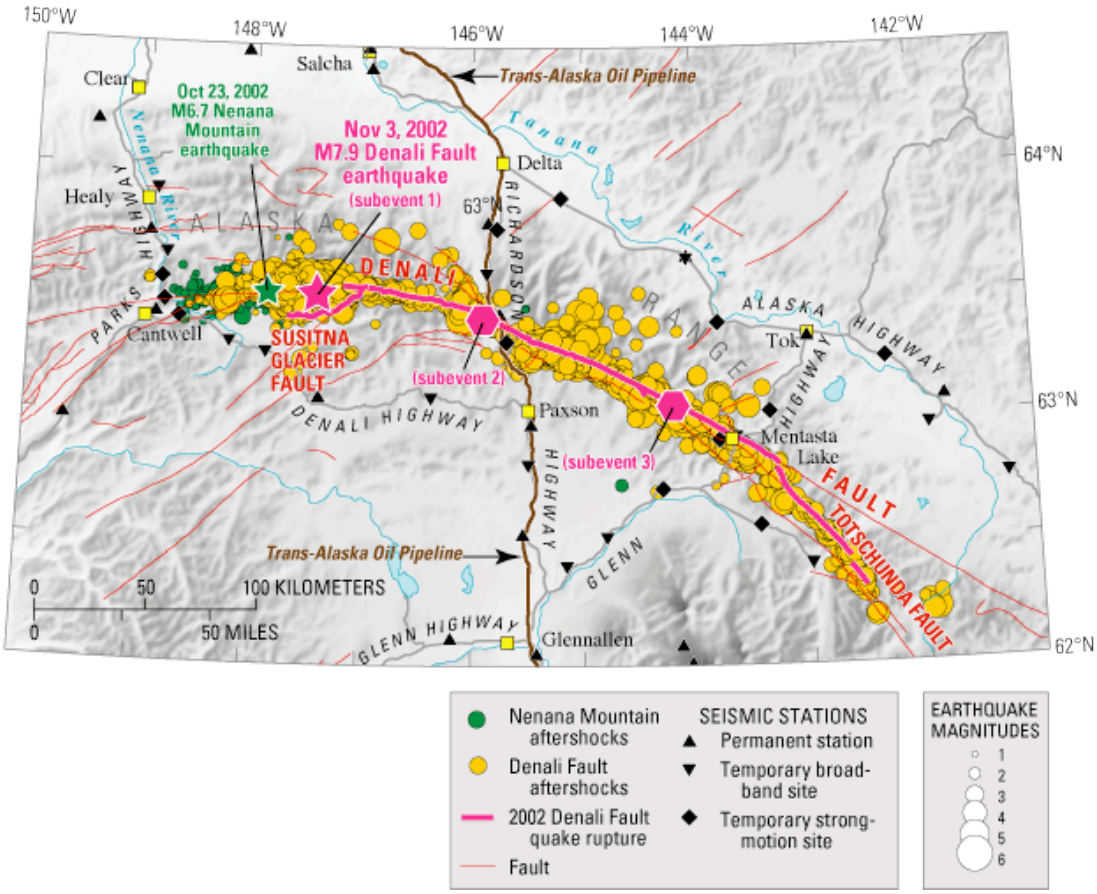
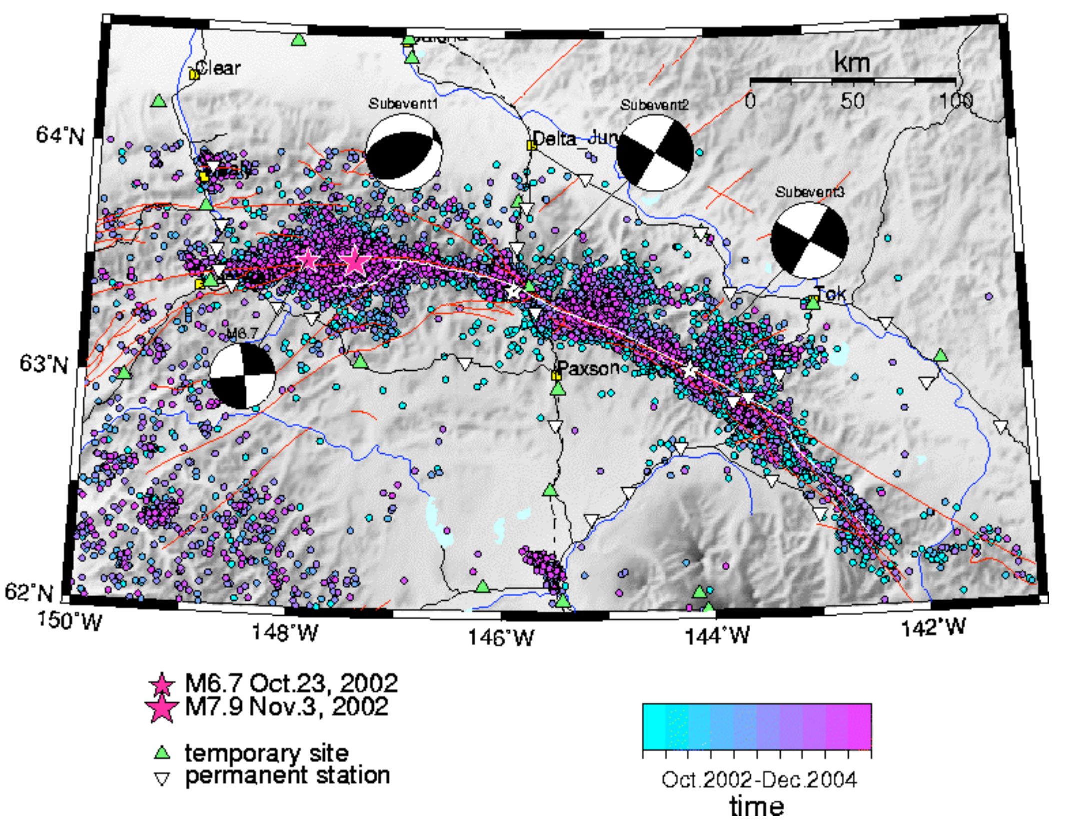


Fig 24. Simplified cross section showing structural relationships between strata of the Kahiltna, Cantwell, and Tanana basins. Cross section is constructed from structural data collected from Ridgway et al. (2007) and mapping data of Csejtey et al. (1992).

Denali is the highest mountain peak in North America, at a height of approximately 20,320 feet (6,194 m). It is the centerpiece of Denali National Park. The mountain was also known as Bolshaya Gora, meaning Big Mountain in Russian. Denali has a larger bulk and rise than Mount Everest. Even though the summit of Everest is about 9,000 feet (2,700 m) higher, measured from sea level, its base sits on the Tibetan Plateau at about 17,000 feet (5,200 m), giving it a real vertical rise of little more than 12,000 feet (3,700 m) (Figs. 25 and 26). The base of Denali is roughly a 2,000 ft plateau, giving it an actual rise of 18,000 feet (5,500 m). Denali means "the great one" in the Dena'ina language. In 1897 the Mountain was officially named Mount McKinley, after U.S. president William McKinley. As the decades progressed Indian-rights activists began increasingly to view this renaming as colonial and disrespectful.



150°W
148°W
146°W
144°W
142°W
64°N
63°N
62°N
Salcha
Clear
Healy
Cantwell
Delta
Tok
Paxson
Mentasta Lake
Glennallen
Trans-Alaska Oil Pipeline
Oct 23, 2002 M6.7 Nenana Mountain earthquake
Nov 3, 2002 M7.9 Denali Fault earthquake (subevent 1)
(subevent 2)
(subevent 3)
SUSITNA GLACIER FAULT
DENALI
FAULT
TOTSCHUNDA FAULT
ALASKA
RANGE
PARKS HIGHWAY
DENALI HIGHWAY
RICHARDSON HIGHWAY
ALASKA HIGHWAY
GLENN HIGHWAY
Tanana River
Nenana River
0 50 100 KILOMETERS
0 50 MILES
Nenana Mountain aftershocks
Denali Fault aftershocks
2002 Denali Fault quake rupture
Fault
SEISMIC STATIONS
Permanent station
Temporary broad-band site
Temporary strong-motion site
EARTHQUAKE MAGNITUDES
1
2
3
4
5
6



Clear
Delta_Jun
Paxson
Tok
Subevent1
Subevent2
Subevent3
M6.7
km
0 50 100
64°N
63°N
62°N
150°W
148°W
146°W
144°W
142°W
M6.7 Oct.23, 2002
M7.9 Nov.3, 2002
temporary site
permanent station
Oct.2002-Dec.2004
time

Figs 25 and 26 (Preceding map). Mainshocks and aftershocks, M6.7 Nenana Mtn. and M7.9 Denali Fault events. Map showing AFTERSHOCKS until 2004 (two years after main shock). White line - mapped rupture, red lines - fault traces; dashed black line - Trans-Alaska Pipeline; black lines - roads; blue lines - rivers (source: AEIC).

M 7.9 Denali Fault earthquake of November 3, 2002.
The largest inland earthquake in North America in almost 150 years struck Alaska on November 3, 2002. It ruptured three different faults ending with a total rupture length of ~330 km (Figs. 25 and 26). It started on the previously unrecognized Susitna Glacier Thrust fault, a splay fault south of the McKinley strand of the Denali fault system (DFS). Then the rupture transferred onto the main strand of the DFS and continued as a right-lateral strike-slip event for ~220 km until it reached the Totschunda fault near 143°W longitude. At that point, it right-stepped onto the more south-easterly trending Totschunda fault and stopped after rupturing nearly 70 km of it. A team of geologists surveyed the total length of the ruptured faults and reported maximum vertical offsets on the Susitna Glacier Thrust of 4 m and maximum horizontal offsets of 8.8 m west of the Denali and Totschunda fault junction. While the fault rupture lasted for approximately 100 sec from its initiation to the arrest, its distal effects were felt for many days.

The November 3, 2002, magnitude (M) 7.9 Denali Fault earthquake was the strongest ever recorded in the interior of Alaska. Like most earthquakes of its size, it was complex, consisting of several subevents. It started with thrust (upward) motion on a previously unknown fault, now called the Susitna Glacier Fault. This rupture continued on the Denali Fault, where largely horizontal "right-lateral" movement (in which the opposite side moves to the right, when you look across the fault) propagated eastward at more than 7,000 miles per hour. As the rupture propagated, it offset streams, glacial ice, frozen soil, and rock, opening some cracks so wide that they could engulf a bus. The rupture crossed beneath the Trans-Alaska Oil Pipeline and terminated on the Totschunda Fault, 184 miles east of the epicenter, about 90 seconds after the quake began. The maximum horizontal movement (fault offset) of about 29 feet occurred in the eastern part of the rupture, near subevent 3 (AEIC).

Of the population centers, the hardest hit were the villages of Mentasta and Northway, located at the eastern end of the rupture zone. This event caused significant damage to the transportation systems in central Alaska. The Trans-Alaska Pipeline suffered some damage, but no oil spills occurred. Multiple landslides and rock avalanches occurred in the Alaska Range with the largest slide on the Black Rapids Glacier.

The Denali Fault event was felt as far as Washington and caused seiches in pools and lakes as far as Texas and Louisiana. There were reports of triggered seismicity in volcanic and geothermal centers in Washington and California and regional seismicity in Utah. The M 7.9 Denali Fault event was preceded by the magnitude 6.7 Nenana Mountain event on October 23, 2002. Its epicenter was located on the Denali fault 22 km east of the M 7.9 event epicenter (AEIC).

Thermochronology of the Alaska Range

In the central Alaska Range, the geology is largely comprised of Jurassic-Cretaceous flysch-type sediments intruded by early Cenozoic granitic plutons (e.g., Reed and Lanphere, 1973; Reed and Nelson, 1980; Dusel-Bacon, 1994). Periods of magmatism occurred at ca. 62-60 Ma (peraluminous) and 57-51 Ma as documented by new U-Pb ages (Hung et al. 2007 AGU). The thermal history following intrusion is quite well documented with information from K-feldspar $^{40}Ar/^{39}Ar$ analyses (West, 1994) and AFT (Plafker et al. 1992; Fitzgerald et al. 1993, 1995) (Fig. 27). Recent MDD modeling of West's K-feldspar data (Benowitz et al. 2007) record rapid cooling following intrusion of these granites, and then cooling events at ca. 47-43 Ma, ca. 25 Ma and ca. 11 Ma (Figs. 28 and 29).

AFT thermochronology in the central Alaska Range records a younger (Miocene to recent) history (Plafker et al. 1992; Fitzgerald et al. 1993; 1995). Results from a vertical profile collected from the top to bottom of Denali (~4 km of relief) yielded AFT ages from 16-4 Ma, that combined with track lengths indicated a change in cooling rates at 5-6 Ma from slow to very rapid (Fig. 27). Exhumation rates since 5-6 Ma are on the order of 1-2 mm/yr. Significant age differences between samples collected at similar elevations in the central Alaska Range indicated (1) that the amount of exhumation decreased in a systematic pattern away from the highest values at Denali located on a significant bend in the DFS, and (2) the presence of major thrust faults. Regional geological constraints (paleocurrents in basins north of the central Alaska Range, heavy mineral suites, paleogeographic reconstruction) were used by Fitzgerald et al. (1995) to constrain the paleo (ca. 6 Ma)-land surface elevation of the central Alaska Range and hence constrain surface uplift and rock uplift. Paleocurrent reversal, provenance and its implications in basins north of the central Alaska Range were explored much more extensively by Ridgway et al. (1999) who confirmed a regional paleo-current reversal from southward flowing rivers draining the quartz-rich Yukon-Tanana terrane (depositing the Usibelli Group) to northward flowing system draining the growing Alaska Range to deposit the Nenana Gravels in the latest Miocene and Pliocene (Ager et al. 1994).

The pattern of surface uplift, rock uplift and exhumation for the central Alaska Range is striking, resembling a flattened bulls-eye against the inside corner of the DFS (Fig. 28). This pattern, plus the correlation of timing for the initiation of rapid cooling with the change in relative plate motion of the Pacific plate (relative to a fixed North America) from a northwesterly to a more northerly trajectory with an increase in velocity, at 5.6 Ma (Engebretson et al. 1985) led Fitzgerald et al. (1993, 1995) to propose that uplift and formation of the central Alaska Range was related to this change in plate motion. Actual uplift of the range was most likely due to thrusting along major northeast-trending faults south of the central Alaska Range (Plafker et al. 1992).

Apatite (U-Th)/He dating (Perry and Fitzgerald, 2007; 2008) from samples from the Denali vertical sampling profile confirm that cooling since 6 Ma has been rapid, with a possible increase in rate at ca. 2.5 - 3 Ma. In addition, multiple single grain age determinations from multiple samples on either side of the DFS just north of Denali at Peters Pass are all <4 Ma, confirming that deformation is occurring on both sides of the DFS there, indicating active thrusting on faults north of the DFS.

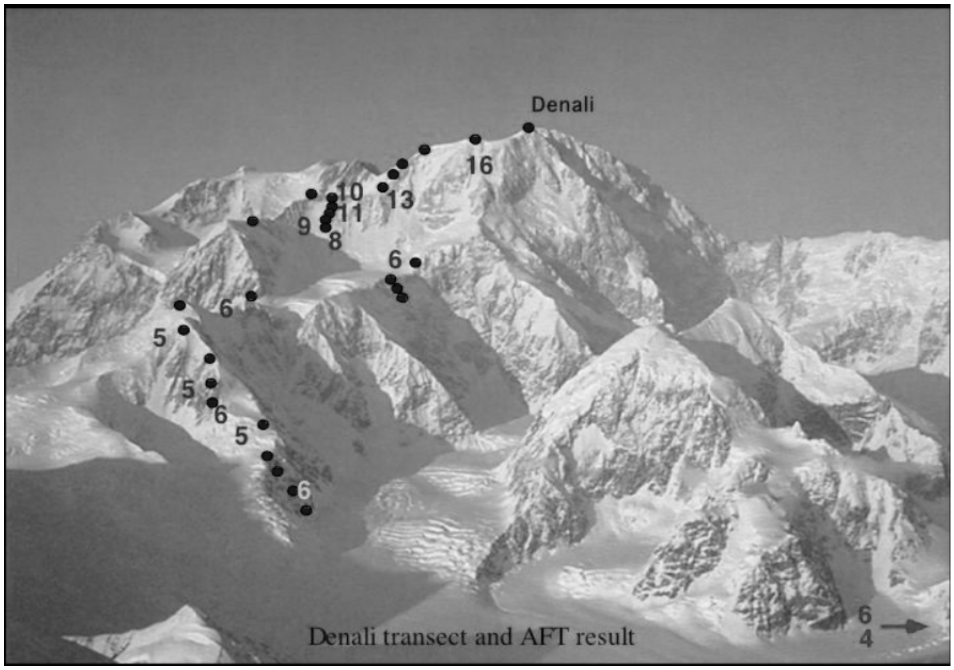


Fig 27. Photo of western flank of Denali with AFT ages in Ma (Fitzgerald et al. 1995).

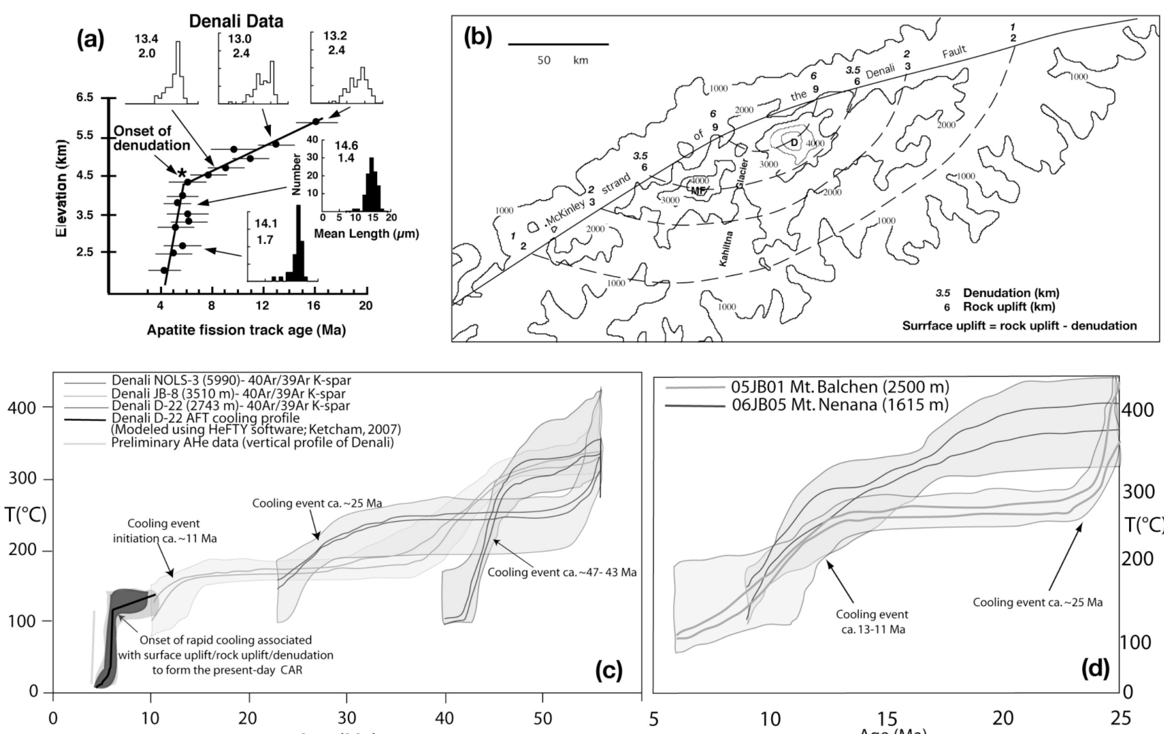


Fig 28. (a) Apatite fission track ages and representative track length distributions (with mean length and standard deviation in microns) from the Denali vertical profile. The onset of denudation associated with rapid cooling is clearly evident at 5-6 Ma (from Fitzgerald et al. 1995). (b) Contours of rock uplift and denudation in the Central Alaska Range (from Fitzgerald et al. 1995). Note that denudation = "the movement of a column of rock with respect to the surface of the Earth" - Rock uplift = movement of a column of rock with respect to a fixed reference frame (e.g., mean sea-level) and surface uplift = change in mean land surface elevation. (c) K-feldspar MDD models for 3 samples from the Denali vertical profile (Benowitz and Layer) showing possible cooling events. Modeled AFT data from D-22 (using HeFTy; Ketcham et al. 2007) can be compared to the vertical profile in (a) and the onset of rapid cooling and denudation associated with formation of the modern day Central Alaska Range. Preliminary apatite (U-Th)/He ages from the Denali vertical profile plot younger than the AFT ages and suggest rapid cooling. (d) K-feldspar MDD models for 2 samples from the Eastern Alaska Range (Benowitz and Layer) showing likely cooling events.

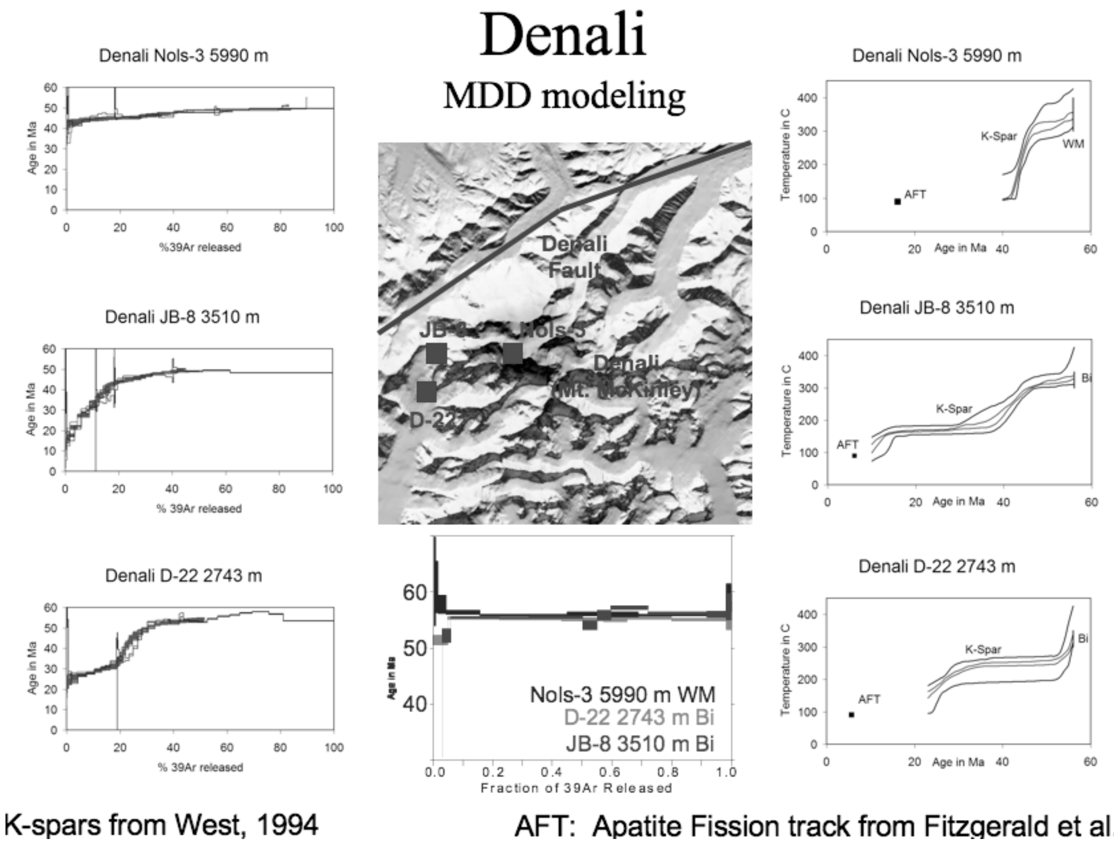


Fig 29. Bulk resistance-furnace K-spar multi-diffusional domain modeling (MDD; Lovera et al. 1989) of a vertical sampling transect on Denali shows classic post shallow-emplacement cooling at high elevations. At lower elevations there is evidence of cooling related to tectonic events. Sample JB-8, the closest to the DFS, shows evidence of a cooling event at 11 Ma. Modified from, West (1994), A petrologic and geochronologic study of the McKinley Pluton, Alaska, M.S. thesis, University of Alaska. Fairbanks, and Benowitz and Layer (2008).

In the Tordrillo Mountains (western Alaska Range), modeled AFT data from a reconnaissance study (Haeussler et. al., 2006; Haeussler and O'Sullivan, in review) suggest an earlier period of cooling at 25-20 Ma, a hiatus and then onset of rapid exhumation at 5-6 Ma (synchronous with the central Alaska Range). These authors suggest that uplift of the western Alaska Range occurred due to counterclockwise rotation of southern Alaska south of the Denali Fault as a far-field effect of the Yakutat microplate collision and flat-slab subduction.

In the eastern Alaska Range, Benowitz and Layer have obtained preliminary K-feldspar data from samples collected by Benowitz. The MDD models suggest periods of more rapid cooling at ca. 25 Ma and also ~11 Ma (Fig. 29). North of the DFS near the Susitna Glacier, Armstrong et al. (2007) obtained several apatite (U-Th)/He and AFT ages (no length data). Their AFT ages ranged from 3-5 Ma and apatite (U-Th)/He ages from 1-4 Ma on the same samples, with results implying much higher exhumation rates in the Quaternary, more recent than in the central Alaska Range. Results from one sample south of the DFS gave older ages and suggests less exhumation there.

Patterns of cooling interpreted as periods of exhumation are starting to emerge in the thermochronology data collected so far from the Alaska Range (Table 2). However we note that much of this data is preliminary and collected as part of what we hope will evolve into a funded NSF project. The results are extremely tantalizing as these periods of cooling appear to be related to periods when there are changes in the plate motion vector of the Pacific Plate (e.g., Engebretson et al. 1985; Atwater and Stock, 1998; Norton, 2000; Raymond et al. 2000; Steinberger et al. 2004; 2007) (Fig. 30).

Periods of cooling in the Alaska Range

Episodes of faster cooling	Western	Central	Eastern
Since 5-6 Ma	AFT modeling[1]	AFT vertical profile and modeling[2, 3, 4] (U-Th)/He data[5]	(U-Th)/He and AFT data[7] (implies Quaternary rapid cooling).
Ca. 11 Ma	-	K-feldspar modeling[6]	K-feldspar modeling[6]
Ca. 25 Ma (K-feldspar) Ca. 35 Ma (AFT)	AFT modeling[1]	K-feldspar modeling[6]	K-feldspar modeling[6]
Ca. 47-43 Ma	-	K-feldspar modeling[6]	

1. Haeussler and O'Sullivan, in press; 2. Plafker et al. (1992); 3. Fitzgerald et al. (1993); 4. Fitzgerald et al. (1995); 5. Perry and Fitzgerald (2007); 6. Benowitz et al. (2007); 7. Armstrong et al. (2007).

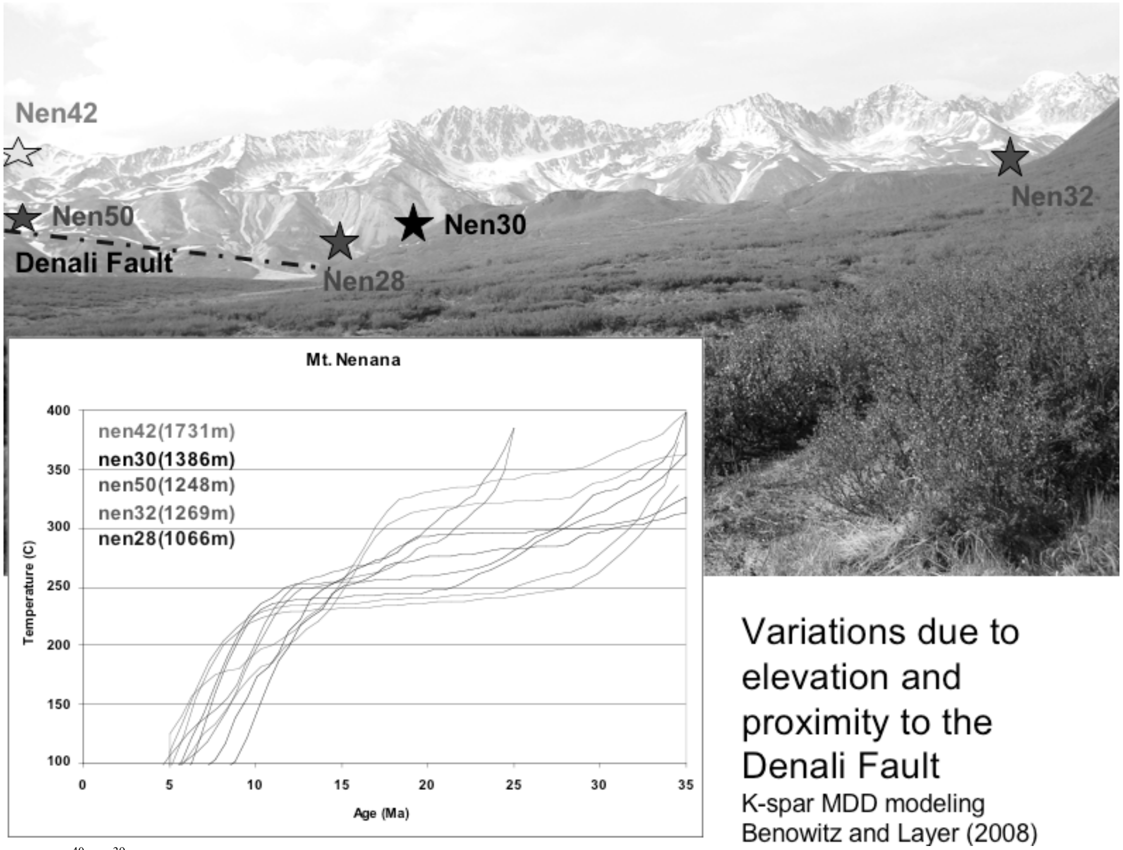


Fig 30. $^{40}Ar/^{39}Ar$ K-feldpar MDD modeling from the Eastern Alaska Range. The highest sample nen42 shows a cooling episode at ca. 16 Ma, whereas all the others have a cooling episode starting at ca. 11 Ma.

Uplift and denudation of the central Alaska Range: A case study in the use of apatite fission track thermochronology to determine absolute uplift parameters

Paul G. Fitzgerald, Rasoul B. Sorkhabi, Thomas F. Redfield, Edmund Stump

Abstract. Apatite fission track thermochronology (AFTT) on granitic samples collected in the central Alaska Range in conjunction with geologic constraints from basins to the north (Nenana Basin) and south (Cook Inlet) of the range is used to constrain the timing, amount, rate, and pattern of surface uplift, rock uplift, and denudation since the late Miocene. The conversion from a thermal frame of reference (apatite fission track data) to an absolute frame of reference (with respect to mean sea level), which requires constraining the paleo-land surface elevation, the paleo-mean annual temperature, and the paleogeothermal gradient, is evaluated and shown to be viable in the context of an exhumed apatite partial annealing zone (PAZ). Apatite ages at Denali (Mount McKinley) range from 16 Ma near the summit (~6 km elevation) to 4 Ma at ~2 km elevation. A distinctive break in slope in the apatite age profile at an elevation of 4.5 km, also marked by a change in confined track length distributions, marks the base of an exhumed apatite PAZ. Rock uplift and denudation are greatest at Denali, decreasing southward away from the McKinley strand of the Denali fault system as shown by progressively older apatite ages (7–35 Ma) from a suite of samples along the Kahiltna Glacier. A correlative decrease in topography occurs southward from the fault. The central Alaska Range lies within an arc defined by the Denali fault, with the highest peaks (including Denali) concentrated at the arc apex. Patterns of rock uplift and denudation within the central Alaska Range mimic topography. Between early and late Miocene, and possibly earlier, the central Alaska Range was most likely an area of relative tectonic and thermal stability. Rock uplift, denudation, and mean surface uplift of the Denali region began by the Late Miocene (~5–6 Ma), being ~8.5 km, ~5.7 km, and ~2.8 km, respectively, at average rates of ~1.5 km/m.y., ~1 km/m.y., and ~0.5 km/m.y. The amount of rock uplift, denudation, and surface uplift decreases to ~3 km, ~2 km, and ~1 km at Little Switzerland, some 45 km south of the Denali fault. We conclude that the topographic and rock uplift patterns of the central Alaska Range, the shape and proximity of the McKinley strand of the Denali Fault to these patterns, the timing of the onset of rock uplift and denudation at ~5–6 Ma, and a significant change in relative plate motion between North America and the Pacific plates circa 5.6 Ma are all inherently related.

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The thermal history and uplift of the Alaska Range from $^{40}Ar/^{39}Ar$ thermochronology

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$^{40}Ar/^{39}Ar$ laser step-heating of single mineral crystals of hornblende, biotite and potassium feldspar (K-spar) has proven useful in determining detailed thermal histories of igneous and metamorphic terranes, Individual crystals of the same mineral within a single sample can record different perspectives of that history and can record different 'events' (either thermal or chemical) that might otherwise go undetected or be blurred by 'bulk' step-heating methods. For K-spar, individual crystals can show variations in their complex, multi-domain age spectra due to variations in composition (as seen by Ca/K ratios and densities), grain size, and/or crystal structure. When this single crystal dating is combined with more 'traditional' resistance-furnace K-spar multidiffusional domain modeling, different portions of the cooling history of a unit can be identified. Because the minerals have mid-crust closure temperatures, they can provide insights into faulting and exhumation that are not seen by lower temperature thermochronometers.

We have employed this multi-mineral $^{40}Ar/^{39}Ar$ thermochronologic approach to vertical sampling studies of granitic plutons throughout the Central and Eastern segments of the Alaska Range. The Alaska Range is a ~650 km long topographic barrier that is believed to be related to the active transpressive Denali Fault system as well as to the collision and subsequent underplating of the Yakutat microplate with southern Alaska. Our results show differential episodic exhumation and uplift along the Range. Biotite age spectra from the McKinley Pluton (Denali) in the Central Alaska Range are undisturbed and reflect pluton emplacement cooling starting at 60 Ma, while K-spar data suggest episodic cooling at ~43 Ma, ~25 Ma and ~11 Ma, in addition to uplift at ~5-6 Ma (apatite fission track ages - Fitzgerald et al. 1995). In contrast, in the Eastern Alaska Range, biotite, K-spar, and in some cases hornblende, show evidence of post-emplacement open-system behavior or slow cooling. For example, Mt. Nenana (167 km east of Denali) has a 37 Ma biotite closure age, while K-spar ages range from 9 to 35 Ma with youngest ages at lower elevations and nearest to the Denali Fault, where ~25 Ma and ~12 Ma cooling events are identified. These cooling ages are also reflected in changes in subsidence and sedimentation rates in basins north of the Alaska Range.

Miocene Exhumation of the Southern Talkeetna Mountains, South-Central Alaska, Based on Apatite (U-Th)/He Thermochronometry

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The Talkeetna Mountains, bounded by the Chugach Mountains to the south and the Alaska Range to the north, are in a key location to study the effects of Cenozoic shallow subduction of the Yakutat microplate in southern Alaska. Apatite fission-track data from the Chugach Mountains suggest that uplift/exhumation coincided with the collision and underthrusting of the Yakutat microplate about 16-22 Ma. AFT data along the Castle Mountain fault at the southern boundary of the Talkeetna Mountains suggest cooling about 10 Ma. Farther north, in the Denali area of the Alaska Range, AFT data suggest rapid cooling about 5-6 Ma. To address the exhumation timing of the region between the Chugach Mountains and the Alaska Range, apatite (U-Th)/He ages were determined for granite and granodiorite samples collected along a generally north-south transect at elevations ranging from approximately 600 to about 2000 m. Most samples south of the Kashwitna River are 15-20 Ma and show slight increase in age with increasing elevation, suggesting rapid cooling of this area 15-20 Ma. Farther north, (U-Th)/He ages are 60 to 73 Ma indicating that there is considerable complexity and spatial variability in the timing of the Talkeetna mountains. The early Miocene (U-Th)/He ages suggest that the most recent exhumation event of the southern Talkeetna Mountains occurred 10-15 My prior to uplift/exhumation of the Denali area farther north, perhaps associated with the early stages of Yakutat microplate subduction and prior to development of shallow subduction beneath the Talkeetna area.

Geological Society of America Abstracts with Programs, Cordilleran Section, 102nd Meeting, Paper No. 6-5, 2006

Rapid Quaternary Exhumation of the Eastern Alaska Range

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The Denali Fault is the dominant structural feature of the Alaska Range in central Alaska. The southern Alaska block, located south of the Denali Fault, is moving north and west as a result of subduction of the Yakutat microplate 400 km to the south. The Denali Fault cuts across the Alaska Range (AR), which we separate into central and eastern regions near Broad Pass. The eastern AR was the site of the M7.9 earthquake on the Denali Fault in 2002. Most of the high topography in the central AR, including the highest peak in North America (Denali – 6188m), is located south of the Denali Fault. In contrast, peak elevations in the eastern AR near Mt. Hayes and Deborah are lower (highest at 4215m), and most of the higher elevation is on the north side of the Denali Fault. Published apatite fission-track ages from Denali show an exhumed partial annealing zone that indicates rapid exhumation beginning 5-6 Ma. We produced new apatite fission-track ages from the Hayes range in the eastern AR. The samples were collected just north of the Denali Fault, span 800 m of elevation, and the ages increase with elevation from 2.8 to 5.1 Ma. Same-sample apatite (U-Th)/He ages increase with elevation from 1.4 to 3.7 Ma. The age-elevation slopes for the AFT and He ages are similar to the exhumed partial annealing zone slope for the Denali data, but are offset to lower elevations. South of the Denali Fault in the Hayes range, He and AFT ages for one sample are three and five times higher, respectively, than same elevation samples north of the Denali Fault, implying higher exhumation rates north of the Denali Fault in the Quaternary. AFT and He age profiles from north of the Denali Fault suggest exhumation rates of ~1.5-2.0 mm/yr beginning ca 1.4 Ma in the Hayes range, which is more recent and more rapid than in the Denali area. This region of rapid rock uplift and exhumation is coincident with the edge of a tomographically identified NE-trending zone of thick crust in the southern Alaska block that projects north of the Denali fault and under the Hayes range. An interpretation of this rapid Quaternary exhumation in the Hayes range is that it was caused by impingement of the thick Wrangellian crust against thinner Yukon-Tanana crust, located north of the Denali and Hines Creek fault systems, as the southern Alaska block moved NW as a result of Yakutat microplate subduction.

Geological Society of America Abstracts with Programs, Cordilleran Section, 103rd Meeting, Paper No. 29-6, 2007.

Thermotectonic Evolution of the central Alaska Range: Low-temperature Constraints from Apatite Fission-Track Thermochronology and (U-Th)/He dating

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The southern Alaska continental margin represents a tectonically complex region where various driving mechanisms, such as changes in plate motion and/or microplate rotation and/or collision of the Yakutat terrane, may have contributed to the uplift and formation of the Alaska Range. The Alaska Range is located along a major continental strike-slip fault system, the Denali Fault system (DFS), and is host to the highest mountain in North America, Mt. McKinley (~6194 m). The Alaska Range is located ~500 km inland of the active plate margin. The high topography of the central Alaska Range occurs where the McKinley strand of the Denali fault system changes from a mainly east-west orientation to a southwest-northeast orientation. Our objective in this study is to date apatites using (U-Th)/He (AHe) dating from a suite of samples (Fitzgerald et al. 1995) previously collected over ~4 km of relief on the western flank of Denali (Figure 1). Combining the new AHe ages with the previously determined apatite fission-track (AFT) data, our goal is to further constrain the patterns and timing of denudation within the central Alaska Range. As apatite (U-Th)/He dating is a lower temperature technique as compared to AFT thermochronology, the new data provide information on the more recent exhumation history.

Previous Apatite Fission-track results

Previous work within the central Alaska Range included an age elevation profile (~4 km relief) from the west flank of Denali (Mt. McKinley). Thermochronology yielded AFT summit ages of ~16 Ma down to ~4 Ma at the lowest elevation (Fitzgerald et al. 1995). This AFT age - elevation profile shows a significant break in slope (exhumed base of the PAZ) at ~6 Ma that indicates the onset of rapid denudation at that time, continuing to the present, at an average rate of ~1 km/my (Fitzgerald et al. 1995). Fitzgerald et al. interpreted the formation of the range associated with the significant increase in denudation rate at ca. 6 Ma as caused by the change in plate motion of the Pacific plate with respect to the North American plate and the far-field microplate rotation induced by variations in the concentration of partitioned stress along the arc-like Denali Fault system. In essence, the Yukon-Tanana terrane, separated from the Wrangellia terrane to the south by the Denali Fault system, acted as a tectonic backstop along which the central Alaska Range has been formed in the arc of the Denali fault. Changing plate motion vectors are likely to have contributed to the change in translational motion of the Yakutat terrane at ~5-6 Ma from a dominantly strike-slip motion to a more oblique-slip motion as the terrane continued to subduct with the Pacific plate beneath the southern Alaska continental margin (Fitzgerald et al. 1995). Changes in the cooling rate through time have been modeled using previously determined AFT ages with associated track-length distributions, and new Dpar measurements (Figure 2). Results from multiple samples show the onset of rapid cooling beginning ~6 Ma. The uppermost sample (D39) from ~5,956 m, indicates rapid cooling through the apatite partial annealing zone beginning at ~10 Ma. If so, this suggests an earlier cooling event at ca. 10 Ma, followed by relative thermal and tectonic stability and then a more significant cooling event at ca. ~6 Ma associated with the formation of the modern day Alaska Range.

Apatite (U-Th)/He: Age-Elevation Vertical Profile

AHe results from samples from the ~4 km vertical profile of Denali are compatible with previously dated AFT ages (i.e. ages are generally younger). Single grain ages range from ~9-2 Ma with the age-elevation trends compatible with post ~6 Ma rapid cooling. There is some spread of (U-Th)/He single grain ages in each sample with some single grain ages older than their corresponding AFT ages. Such a variation in single grain ages occurs for a number of reasons: 1. The U and Th concentrations within the grain may be non-homogeneous possibly resulting in an inaccurate α-particle ejection correction, 2. U and Th-rich inclusions within the grain exist, 3. Variations in crystal size, 4. The grain boundary does not represent a zero-concentration boundary and any factors that may impede He diffusion from the crystal are possible, 5. Implantation of He from adjacent phases (Farley, 2002; Ehlers and Farley, 2003; Fitzgerald et al. 2006). All of these factors could result in a significant spread in single grain age variation within a particular sample, including single grain ages slightly older than corresponding AFT determined ages. In these situations the "correct age will be closer to the minimum (U-Th)/He age (Fitzgerald et al. 2006). An inflexion in the minimum (U-Th)/He age-elevation profile at 2-3 Ma suggests an increase in the rate of denudation at that time.

Apatite (U-Th)/He: Ages Across the Denali Fault System at Peter's Pass

The relief in the foothills on the north side of Denali fault system near Peters Pass is on average ~800 m with an average peak elevation of ~1400 m. The relief to the south of the pass is even more dramatic with an average of ~2000 m and average peak elevation of ~2575 m, from the pass at ~2439 m to the summit of Denali. Single grain (U-Th)/He ages were determined from samples on both the north and south sides of the Denali fault near Peter's Pass. These samples have no complimentary AFT determined cooling ages. (U-Th)/He ages to the north and south of the Denali fault are all <6 Ma suggesting a history similar to that determined from the Denali vertical profile, i.e., rapid cooling due to rapid denudation was ongoing after ~6 Ma. Ages on either side of the fault are within 2σ error of each other indicating that denudation is occurring on both sides of the McKinley strand of the Denali Fault system. However, single grain (U-Th)/He ages to the south (~1.7-4 Ma) may be slightly older than those to the north (ages are ~1.5-2.6 Ma). Given the more subdued topography north of the fault, this raises the possibility that there is more recent active denudation to the north of the fault, perhaps associated with the onset of more rapid denudation as suggested by the ~2-3 Ma inflexion in the Denali (U-Th)/He age-elevation profile.

FT2008 Extended Abstract

Synchronous Exhumation of the Tordrillo Mountains and Mt. McKinley (Denali), Alaska, Around 6 Ma

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There are three high sections of the Alaska Range. The tallest is near Mt. McKinley (or Denali, height: 6194 m), with a 95 km length of the range above 2500 m. The Hayes range, east of Denali, has a length of 55 km above 2500 m (Mt. Hayes is 4216 m), and the Tordrillo Mountains, south of Denali, has a 43 km length above 2500 m (Mt. Gerdine, the tallest peak is 3,431 m). In order to understand the timing of mountain building in the Tordrillo Mountains, we collected a preliminary suite of 10 samples from Paleocene granite in a vertical transect between 295 and 3231 m for apatite fission track thermochronology. This approach is particularly powerful for reconstructing thermotectonic histories of the upper continental crust of crystalline terranes, especially where the use of traditional stratigraphic and structural evidence is severely limited.

Apatite fission-track ages range between 5.8 and 35.5 Ma. Kinetic modeling of the single-grain age and track-length data, utilizing the Dpar parameter for each grain from which age and/or length data was acquired, indicate early slow cooling, followed by an initial phase of rapid cooling around 25 Ma, followed by a period of relatively slow cooling until at least 10 Ma. The data and kinetic models record a second period of rapid cooling sometime between 10 and 5 Ma; the 5.8 Ma apatite age represents a minimum recorded age for the timing of this event. Differences in cooling history between some samples near the crest of the range, in combination with geologic mapping, indicate west-side-up reverse faults active after 5-10 Ma. Previously published apatite fission-track thermochronology from samples in the Denali area indicates rapid cooling after 6 Ma. Thus both the Tordrillo Mountains and the Denali area experienced rapid cooling at approximately the same time. We infer this also represents surface uplift, because voluminous Pliocene sediments of the Sterling Formation fill the Cook Inlet and Susitna basins. The onset of Sterling sedimentation predates global cooling in mid-Pliocene time, and therefore, the initiation of sedimentation is not related to climate change. We suggest synchronous uplift of the central and western and Alaska Range occurred as a result of counterclockwise rotation of southern Alaska south of the Denali Fault as a far-field effect of the Yakutat microplate collision.

Geology of the Northern Foothills

The Suntrana Creek section within the Tanana Basin (the northern foothills of the Alaska Range) and unroofing of the Alaska Range

Deposition of the Pliocene Nenana Gravels is directly correlated with the unroofing of the central Alaska Range (beginning ~5-6 Ma) (Wahraftig, 1969; Wahraftig, 1994; Ager et al. 1994; Leopold and Liu, 1994; Fitzgerald et al. 1995; White et al. 1997; Ridgway et al. 1999a; Ridgway et al. 2007). The stratigraphy of the Neogene strata located within the Tanana, Cantwell and Lignite Creek basins records the sedimentation of units from the Cretaceous to the Pliocene, so it has a rich record of the surrounding geologic events (Ridgway et al. 2002) (Figs. 31 and 32).

Paleogeography (taken from Ridgway et al. 2007)

Interpretation of stratigraphic, compositional, and geochronologic data from Neogene strata of the Tanana basin provides a continuous record of regional transpressional foreland basin development on the north side of the Alaska Range orogenic belt; foreland basin development was coeval with strike-slip displacement on the Denali fault system (discussed in more detail later in this section). Previous studies have treated the Usibelli Group and Nenana Gravel as unrelated and representing very different basinal configurations. The pioneering work of Wahrhaftig et al. (1969), for example, interpreted the Usibelli Group as being deposited on a broad, low-relief alluvial plain that stretched from the north side of the modern Alaska Range to the Cook Inlet of southern Alaska. In this interpretation, deposition of the Usibelli Group was not influenced by a Miocene Alaska Range and the Pliocene Nenana Gravel represented the beginning of exhumation of the Alaska Range (Figs. 33 and 34). We, in contrast, interpret the Usibelli Group and Nenana Gravel to be intimately related and products of regional shortening in what is now the modern-day central Alaska Range. Since the study of Wahrhaftig et al. (1969), there has been considerable work on understanding the stratigraphy of foreland basins and their tectonic configuration (e.g., Dickinson, 1974; Jordan, 1981, 1995; Lawton, 1986a, 1986b; Flemings and Jordan, 1989; Bradley and Kidd, 1991; DeCelles and Currie, 1996; DeCelles and Giles, 1996; Chen et al. 2001; and others); we use the conceptual framework developed from these studies to evaluate the relationship between the Usibelli Group and Nenana Gravel and to reconstruct the regional basinal configuration of the Neogene Tanana basin.

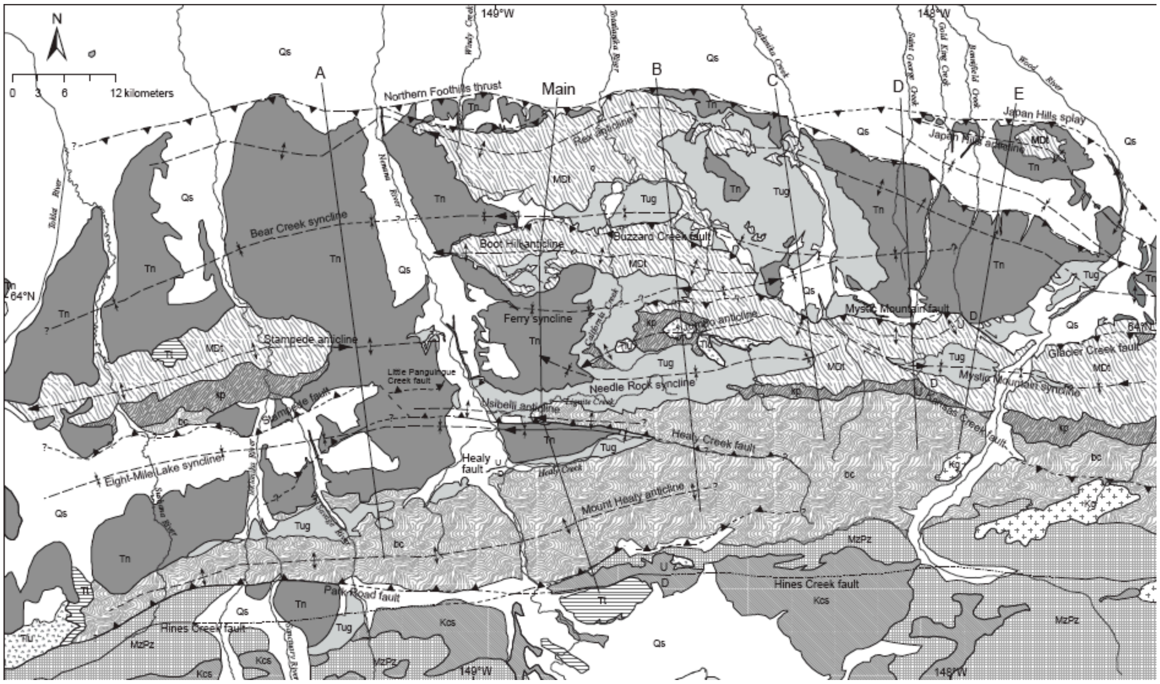
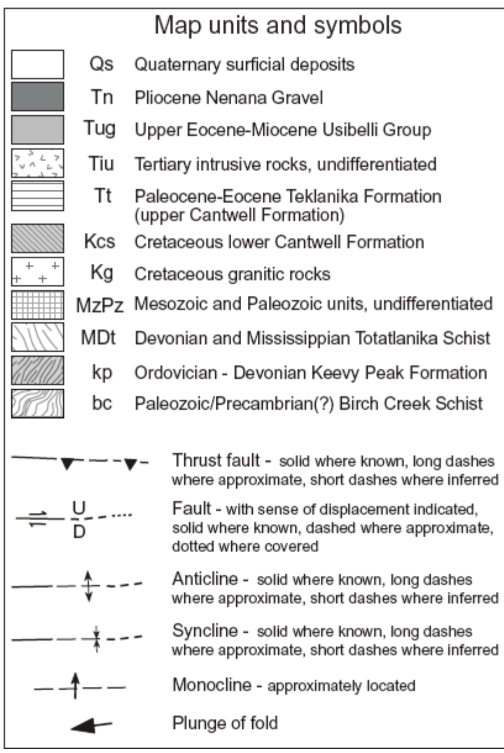


Fig. 31. Map of the geologic and neotectonic features in the central Alaska Range northern foothills. See key below.



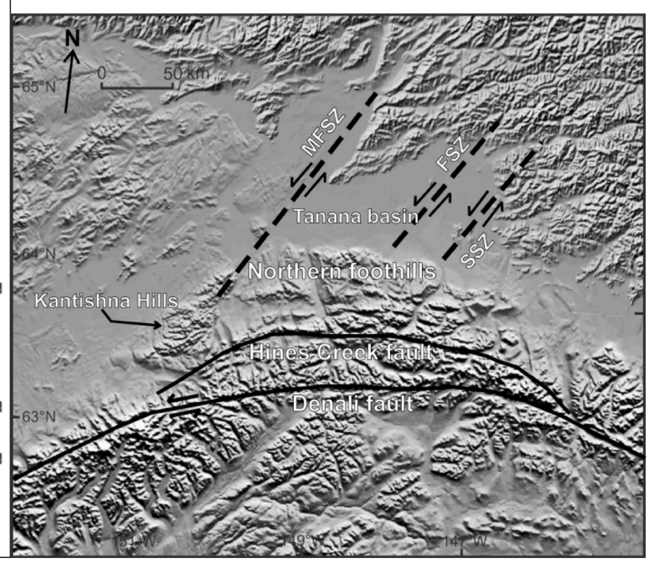


Fig 32. Regional tectonic elements of interior Alaska. MFSZ = Minto Flats Seismic Zone, FSZ = Fairbanks Seismic Zone, SSZ = Salcha Seismic Zone. Note how the MFSZ separates the E-W grain of the northern foothills from the more NE-trending topography of the Kantishna Hills (Bemis, 2004).

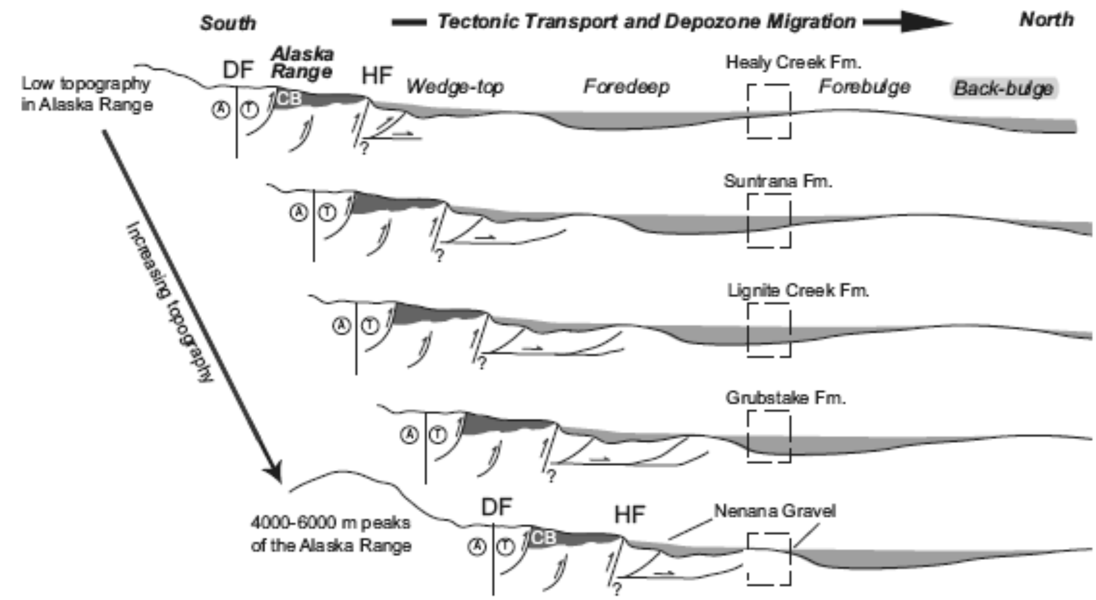


Fig 33. Above. Schematic cross sections showing the development of the Tanana transpressional foreland-basin system. In our interpretation, the Usibelli Group and Nenana Gravel represent a continuum of deposition through several specific depozones within a foreland-basin system. The Healy Creek Formation represents deposition in the Oligocene-Early Miocene distal foredeep and proximal forebulge depozones. The Sanctuary and Suntrana Formations are interpreted to have been deposited in the late Early and Middle Miocene medial/distal parts of the foredeep depozone. The Lignite Creek and Grubstake Formations are interpreted to have been deposited in the Late Miocene proximal foredeep depozone. The Nenana Gravel, in turn, is interpreted to have been deposited mainly in the Pliocene wedge-top and proximal foredeep depozones. In our interpretation, northward propagation of thrust faults along the southern margin of the Tanana basin resulted in a related northward propagation of depozones that is recorded in the stratigraphy of the Usibelli Group and Nenana Gravel. See text for additional discussion. This figure uses both the terminology and the conceptual configuration described for foreland basin systems in DeCelles and Giles (1996). This model is different from the DeCelles and Giles (1996) model in that we emphasize the importance of strike-slip deformation and basement-involved (thick-skinned) reverse faults in a transpressional setting. Abbreviations: DF = Denali fault; HF = Hines Creek fault; circled A next to the Denali fault represents displacement away from the reader; circled T represents displacement toward the reader. Figure from Ridgway et al. (2007).

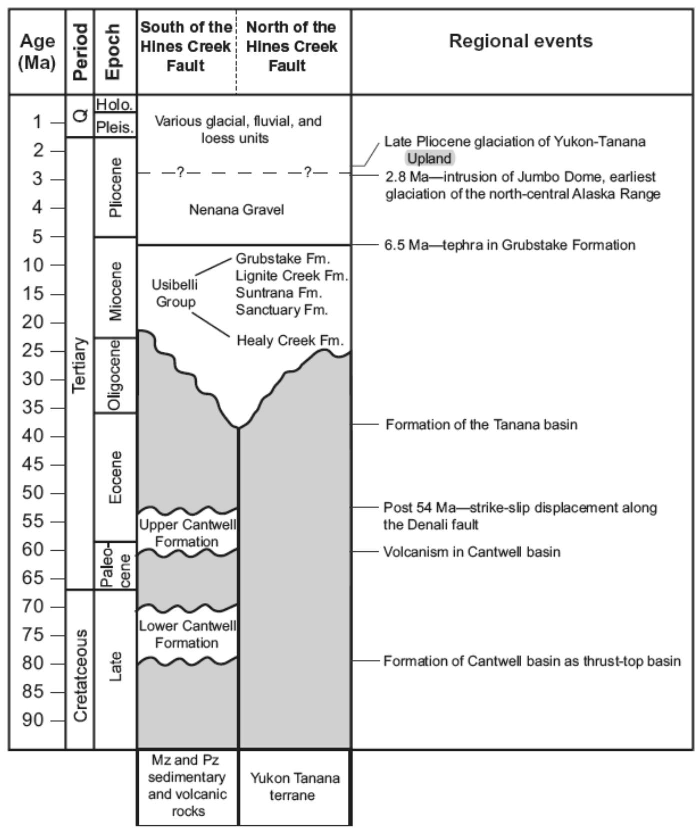


Fig 34. Timeline for the general geologic evolution of the northern foothills. From Ridgway et al. (2007).

Suntrana Creek Section

Directions: The Cenozoic section at Suntrana in the Nenana coal field is located at Lat.63°52'N, Long.148°51'W, Healy D-4 Quadrangle, 3 to 3.5 mi (5 to 6 km) east of the Nenana River, on the north bank of Healy Creek and on Suntrana Creek, its 1.2-mi-long (2 km) tributary at this point (Fig. 35). It is approximately 6.7 mi (10.8 km) east, by automobile road, of mile 248.8 on the George Parks Highway. Mile 248.8 is 7 mi (11.5 km) north on the highway from the entrance to Denali National Park (Fig. 36). Suntrana Creek is narrow and shallow and is easily crossed dryshod most of the year. Its upper 1.5 km is usually dry. The road is now gated beyond the creek, so you can't miss it. Park on the west side of the creek. Debris flows sometimes fill in the creek and present a deceptive surface that may, in fact, have the consistency of quicksand.

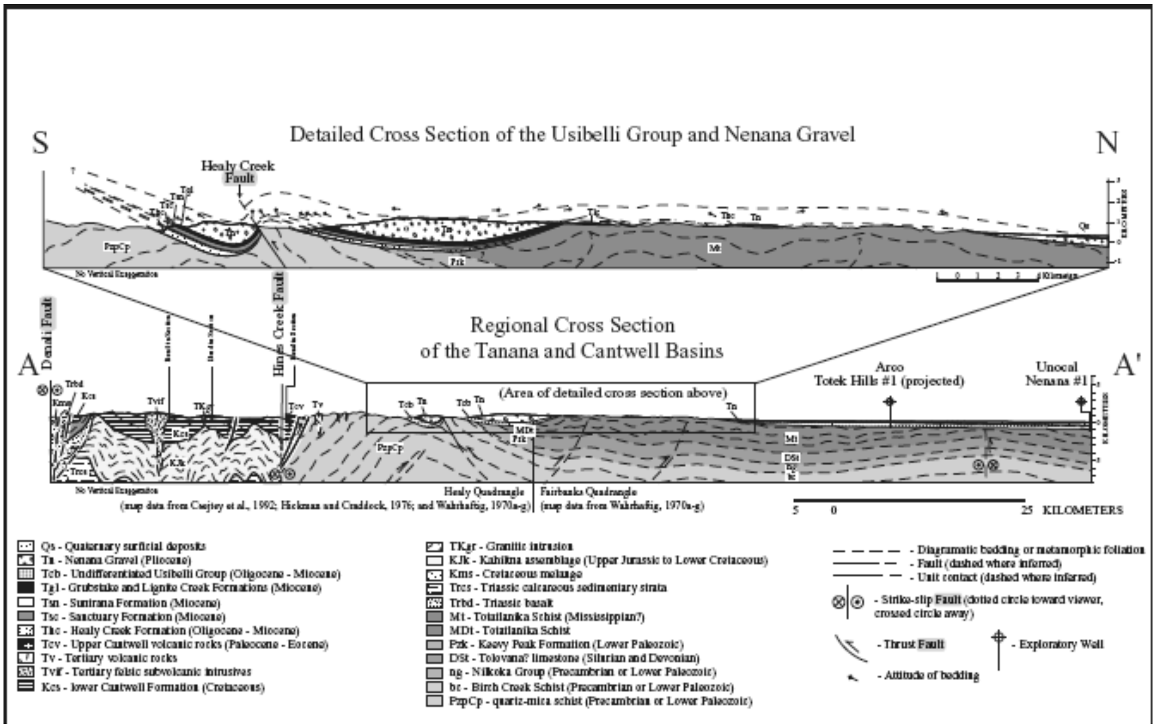


Fig 35. North-south structural cross section through the central Alaska Range and Tanana basin. Note exhumed sedimentary strata of the Cantwell basin (labeled Kcs) that are located between the Denali and Hines Creek faults. Compositional data discussed in the text show that Upper Cretaceous-Paleogene strata of the Cantwell basin provided detritus to the Neogene Tanana basin during deposition of the Usibelli Group and Nenana Gravel. Also note that north of the Hines Creek fault the strata of the Tanana basin were deposited directly on metamorphic rocks of the Yukon-Tanana terrane (labeled PzpCp, Mt, MDt, Pzk). See text for additional discussion. From Ridgway et al. (2007).

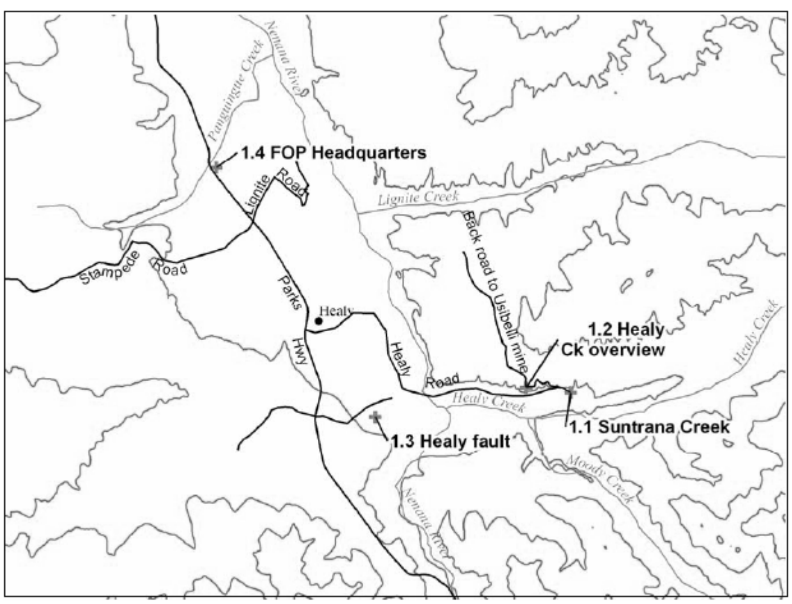


Fig 36. Map indicating points of interest. Note the location of Suntrana Creek, one of the areas considered a type location for the description and identification of the Usibelli Group and Nenana Gravel units. From Thoms (2005).

Photo of the old Usibelli Mine shaft with units marked

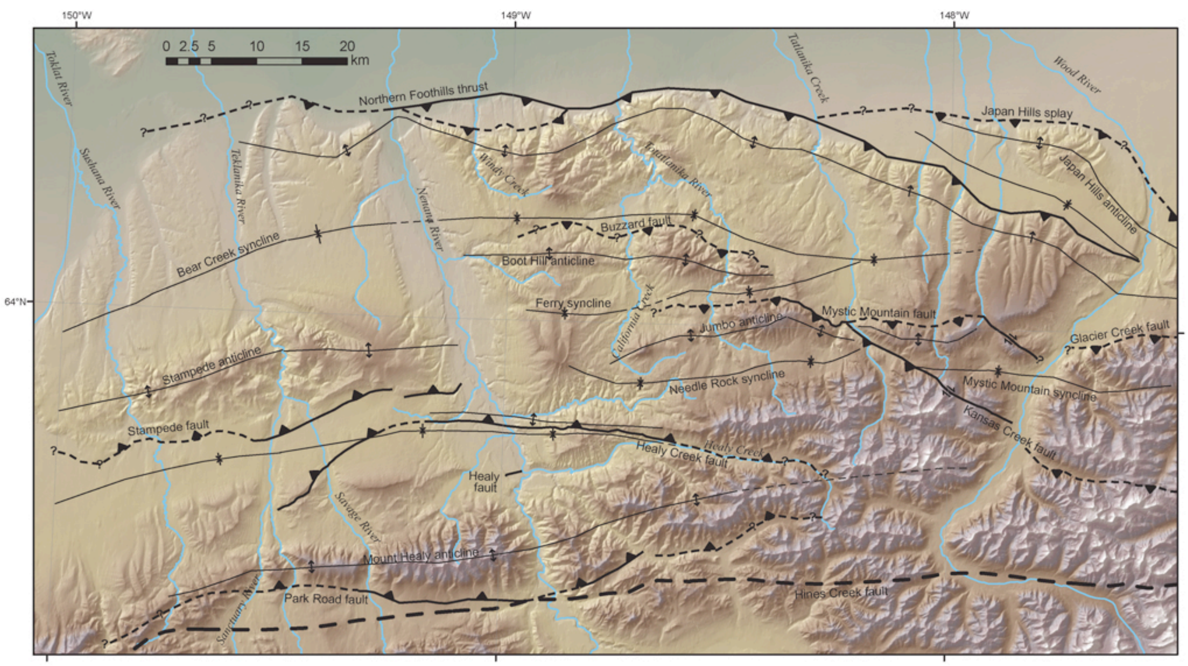


Fig. 37. Map of geologic and neotectonic features in the central Alaska Range northern foothills (Bemis, 2004), showing the most important structural and geologic features in the area north of Denali National Park. The main structures are folds driven by thrusting as can be seen in the cross section (below). In this thrust system, the thrusting verges to the north (the direction of transport), but some thrusts are back thrusts, which verge in the opposite direction (south). Anticlinal cores in this section affect stream flow. Note that most of the north-flowing rivers cut directly across these structural features, which is unusual (from Bemis, 2004).

Overview:
The section exposed here has been described by many people and visited by many more.

Before we begin walking up the creek, notice the knob of schist about 0.3 miles to the SE. The schist, colloquially called the Birch Creek schist, is mostly Paleozoic in age and belongs to the same regional-scale package of rocks that make up the Yukon-Tanana uplands north of the Tanana River (Fig. 37). The overlying deposits, from our vantage point the deposits to the left of the knob, were deposited unconformably onto the schist beginning in the Early Miocene in generally swampy and low-energy depositional systems (Wahrhaftig et al. 1969; Buffler and Triplehorn, 1976; Ridgway et al. 1999). Lying unconformably atop the Birch Creek Schist are two Cenozoic formations that comprise the majority of the Tanana Basin strata with an estimated thickness of ~6,000-8,500 m (Ridgway et al. 2002). From oldest to youngest these units include the Lower Eocene to Oligocene Usibelli Group typically subdivided into five individual formations including: Healy Creek Formation, Sanctuary Formation, Suntrana Formation, and Grubstake and Lignite Creek Formations. Lying conformably atop the Grubstake Formation within the Tanana basin is the Pliocene Nenana Gravel unit (Ager et al. 1994; Leopold and Liu, 1994; Ridgway et al. 1999a, 2007; Trop et al. 2007).

Not only are the deposits indicative of low-energy depositional environments, but paleocurrent measurements indicate the regional stream direction was to the south, indicating the present day Alaska Range did not exist at the time of deposition. In fact, these streams apparently flowed all the way to Cook Inlet because garnets most likely sourced from the Yukon-Tanana uplands have been described from within the Usibelli Group-correlative Hemlock and Tyonek Formations (Kirschner and Lyon, 1973). Thick coal beds in the Usibelli Group presumably record periods of subsidence related to periods of regional shortening (Ridgway et al. 2002).

The Lower Eocene to Miocene Usibelli Group (~57-30 Ma) (Fig. 38) mainly consists of non-marine conglomerate with minor components of sandstone, shale and siltstone that conformably overlie the Cretaceous to Tertiary Cantwell Formation in the Tanana Basin within the Yukon-Tanana terrane (White et al. 1997; Ridgway et al. 2007). The two units of interest within the Usibelli Group include the Lignite Creek and Grubstake Formation and the Healy Creek Formation. These units are of interest because they record a paleocurrent reversal from southward oriented-flow (Usibelli Group) to northward oriented-flow (Nenana Gravels) in the Late Miocene associated with the uplift and denudation of the central Alaska Range (Wahraftig, 1969; Ridgway et al. 2007).

Healy Creek Formation

The Healy Creek Formation is the lowest formation that is here assigned to the Usibelli Group. It is exposed along the northeast wall of the canyon of Healy Creek at Suntrana, from its basal contact with the unconformably underlying quartz-mica schists and associated metamorphic rocks formerly assigned to the now-abandoned Birch Creek Schist, about 750 ft (230 m) south of the road to Usibelli, northward for about 1,000 ft (300 m) to the top of the F coal bed (the coal bed immediately beneath a thick brown-weathering shale). It consists at this locality of 500 ft (150 m) of interbedded poorly sorted and poorly consolidated sandstone, conglomerate, claystone, and subbituminous coal. The basal gravel in this section is interpreted by Buffler and Triplehorn (1976) to be a gravelly braided-stream deposit and the remaining elastic strata to be point-bar deposits (Wahrhaftig, 1987).

Sanctuary Formation

The Sanctuary Formation is here assigned to the Usibelli Group; it conformably overlies the Healy Creek Formation and consists of 130 ft (40 m) of gray shale that weathers to a characteristic chocolate brown or yellowish brown (Wahrhaftig, 1987). It is exposed as a brown band on the cliff east of the old Suntrana Mine adit, and also crops out beside the road at the crossing of Suntrana Creek. It has alternating pale-weathering and dark-weathering laminae a fraction of a cm to 3 cm thick. Triplehorn (1976; 1977) reports the shale to consist 50 percent of kaolinitechlorite, about 35 percent of illite, and about 15 percent of montmorillonite. The Sanctuary apparently accumulated in a large shallow lake (Wahrhaftig, 1987).

Suntrana Formation

The Suntrana Formation rests conformably on the Sanctuary Formation and forms the upper part of the bluff north and northeast of the old Suntrana Mine adit and the canyon walls of the downstream 1,150 ft (350 m) of the canyon of Suntrana Creek (Wahrhaftig, 1987). It consists hereof eight fining-upward cycles of sandstone and pebbly sandstone, overlain by claystone, overlain by one or more coal beds 1.5 to 40 ft (0.5 to 12 m) thick. The eight cycles total 720 ft (220 m) in thickness. The Suntrana Formation contains the major coal resources of the Nenana coal-field. The sandstone of the Suntrana Formation is typically clean, well sorted, cross-bedded, and consists predominantly of quartz. Cross-bedding directions are variable, but suggest current directions toward the south or southwest. Pebbles in the sandstone consist predominantly of quartz, schist, chert, and quartzite, and suggest a thoroughly weathered provenance region (Wahrhaftig, 1987).

Lignite Creek Formation

In general, the Lignite Creek Formation consists of pebbly sandstone with interbedded medium to thick clay and coal beds, and abundant pollen spores (Leopold and Liu, 1994). Locally the unit is deformed (Bemis, 2004; Ridgway et al. 2007). The lower section of the Lignite Creek Formation located in the southeastern portion of the Cantwell basin is ~280 m thick and contains abundant lignite coal deposits whereas the upper portion of the formation is ~180 m thick and lacks abundant coal seams (Wahraftig et al. 1969; Leopold and Liu, 1994). Pollen spores of various species of deciduous trees place the timing of deposition of the formation within the Homerian stage, equivalent to a late Miocene age (Leopold and Liu, 1994).

Grubstake Formation

The youngest formation in the Usibelli Group, the Grubstake, records the formation of a large lake within the northern foothills, presumably due to ponding of south flowing streams against the rising Alaska Range. Estimated thicknesses of the Grubstake Formation, in the Tanana basin area, is ~200-300 meters (Ager et al. 1994; Leopold and Liu, 1994; Wahraftig, 1994; Ridgway et al. 2002). A volcanic ash, which fell into the lake has yielded an ^{40}Ar/^{39}Ar age of 6.7 ± 0.1 Ma (Triplehorn et al. 1999). At this section, the ash first appears about 20 m from the upper, nearly conformable, contact with the Nenana Gravel, so we have a maximum age for the beginning of Nenana Gravel deposition. Pollen spore analysis provides a paleoclimatic age constraint as late Homerian stage in age (Leopold and Liu, 1994; Wolfe and Tanai, 1980). The late Homerian stage has been correlated with units deposited within Cook Inlet where K/Ar and ^{40}Ar/^{39}Ar ages of ash partings deposited within coal-rich units yielded ages of ~11.3-8.0 Ma (Turner et al. 1980, 1977; Leopold and Liu, 1994; White et al. 1997; Ridgway et al. 2002). Paleocurrents within the Usibelli Group record mainly southward-directed drainage as the Yukon River drained across the flat interior of south-central Alaska until ~6.0 Ma (Wahraftig, 1958, 1994; Ridgway et al. 1999a). However, within the Grubstake Formation paleocurrent indicators may possibly begin to record a shift from southward trending to northward-trending flow (Ridgway et al. 1999a). Prior to the uplift of the Alaska Range drainage systems flowed toward the southern Alaska continental margin depositing transported sediment near Cook Inlet of the Kenai Peninsula (Wahraftig, 1975; Fitzgerald et al. 1995; Ridgway et al. 1999a, 2007; Trop et al. 2007).

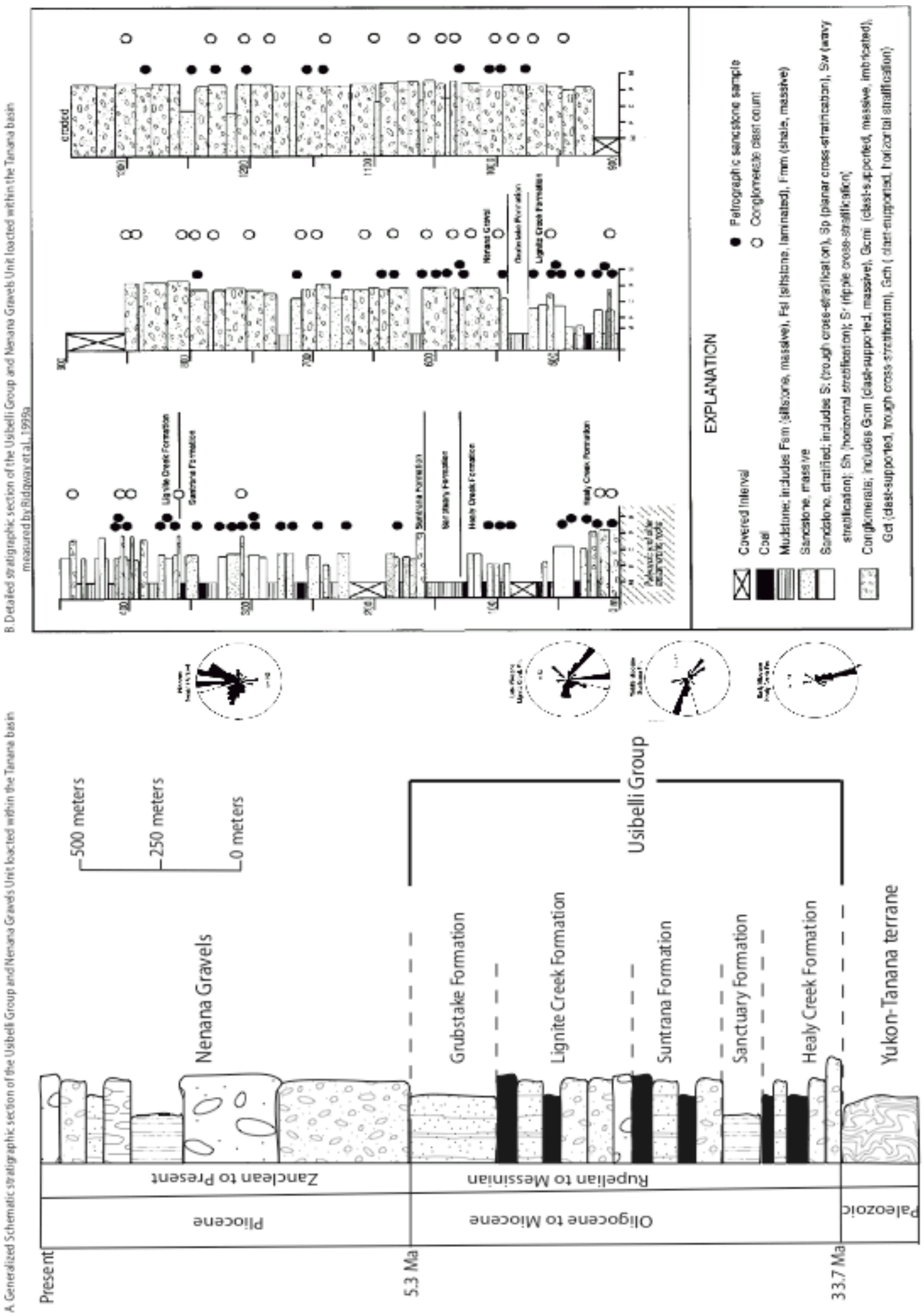


Fig. 38. Simplified schematic stratigraphic column of the Pliocene Nenana Gravels unit and underlying Miocene Usibelli Group located in the Tanana basin to the north of the Alaska Range (modified from Ridgway et al. 2002, 2007) as compared to a detailed stratigraphic section and paleocurrent indicators from Ridgway et al. 1999a.

Nenana Gravels

The Pliocene Nenana Gravel unit conformably overlies the Lower Eocene to Miocene Usibelli Group and consists mainly of well-sorted gravels (Fig. 39). It is estimated to have a thickness of ~1, 000 meters and it is best exposed to the north of Healy Creek, near Suntrana Creek and Nenana coal field (Ager et al. 1994; Leopold and Liu, 1994; Wahraftig, 1994; Ridgway et al. 1999a). Sedimentary petrography of the unit records a shift in the lower section of the gravels dominated by sandstone, conglomerate, and volcanic clasts (identical to the petrofacies of the underlying Lignite Creek and Grubstake Formations) to the upper portion of the unit which is lithic-rich, notably in volcanic grains (Ager et al. 1994; Ridgway et al. 1999a). This shift reflects a change in the main sediment source terrain from the quartz-rich metamorphic terrane of the Yukon-Tanana terrane to the more lithic (volcanic)-rich terrane of the Alaska Range (Ridgway et al. 1999a; Ager et al. 1994).

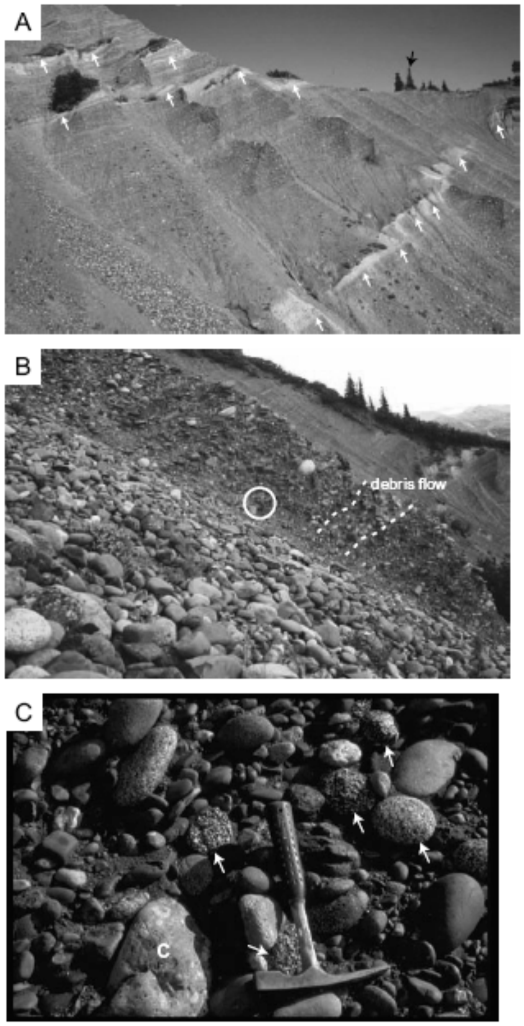


Fig 39. (A) Amalgamated massive and inversely graded beds of boulder and pebble conglomerate that occur in crudely defined beds that are usually less than 0.5 m thick. These lithofacies occur in both Units 2 and 3 of the Nenana Gravel. We interpret these strata as the product of sheetflood and minor debris flow deposition on wet alluvial fans. Note that the interbedded sandstones (white arrows) in the sheetflood lithofacies are laterally continuous at the scale of the outcrop. Spruce trees (black arrow) in upper right for scale. (B) Close-up of thinly bedded boulder and pebble conglomerate with crude horizontal bedding near the top of Unit 3. Hammer (circled) for scale. Dashed lines show bed of rare matrix-supported conglomerate that is interbedded with the sheetflood lithofacies and is interpreted as a debris flow deposit. Spruce trees for scale in upper right corner of photograph. (C) Close-up of clast types in the Nenana Gravel. White arrows point toward granitic clasts. Clast labeled "C" in lower left is a clast of conglomerate that we interpret as being derived from the lower Cantwell Formation. Hammer for scale. From Ridgway et al. (2007).

Age constraints for the Nenana Gravels are based on flora and faunal reconstructions, pollen spore analyses, and K/Ar, ^{40}Ar/^{39}Ar dating of correlative units located in Kenai Peninsula (Triplehorn et al. 1977; Turner et al. 1980; White et al. 1997). Depositional age is partly constrained by palynological data as ~5.4-2.9 Ma and a K/Ar age of ash partings deposited within coal seams of correlative units as ~8.3 Ma (Turner et al. 1980; Ager et al. 1994; Wahraftig et al. 1994; White et al. 1997). The best estimate of when deposition ended within the Nenana Gravel system comes from a K/Ar age of 2.8 ± 0.3 Ma from Jumbo Dome, a rhyolitic plug that intrudes and deforms the post-Nenana Gravel surface (Wahrhaftig, 1969; Albanese, 1980). Paleocurrents within the unit record an important shift to northward-directed drainage within the unit as a consequence of an orographic barrier developing post ~6 Ma (Ager et al. 1994; White et al. 1997; Ridgway et al. 1999a) (Fig. 40). A minimum age constraint of ~2.79 Ma was determined from K/Ar analysis of the Jumbo Dome pluton which locally intrudes the Nenana Gravel unit (Albanese, 1980).

Between 1944 and 1958 Clyde Wahrhaftig made over 500 pebble counts at 80 exposures of the Nenana Gravel throughout the northern foothills enabling him to interpret a sequence of erosion within the Alaska Range (Fig. 41). Briefly, the data suggest a northward progression of source areas starting with rocks located south of the Denali fault and present day range divide, later including plutonic rocks in the eastern Alaska Range, and finishing with the nearby Birch Creek Schist and the underlying Usibelli Group. Ridgway and others (1999) came to similar, though slightly less detailed, conclusions about the Alaska Range unroofing sequence from their analyses of compositional changes within the Usibelli Group and Nenana Gravel. A particularly interesting interpretation from their work is that changes in paleoclimate may have significantly influenced sandstone compositions within the Usibelli Group. That is, quartz is enriched relative to other constituents in sandstones deposited during warm and humid paleoclimates. In sandstones deposited during cooler and dryer paleoclimates, the relative amount of feldspars and lithic fragments is higher. Ridgway et al. (2007) conclude that the Tanana basin is a long-term record of a northward-propagating, transpressional foreland-basin system related to regional shortening of the Alaska Range and strike-slip displacement along the Denali Fault system.

As you walk up the creek, look for these features:

- So-called 'burned shale', which results from fires within the coal seams. On damp days, you can sometimes see, and almost always smell, smoke rising from active fires in the area. This "lithology" appears in the uppermost beds of Nenana Gravel indicating Usibelli Group deposits were being eroded not far upstream.
- Current direction indicators.

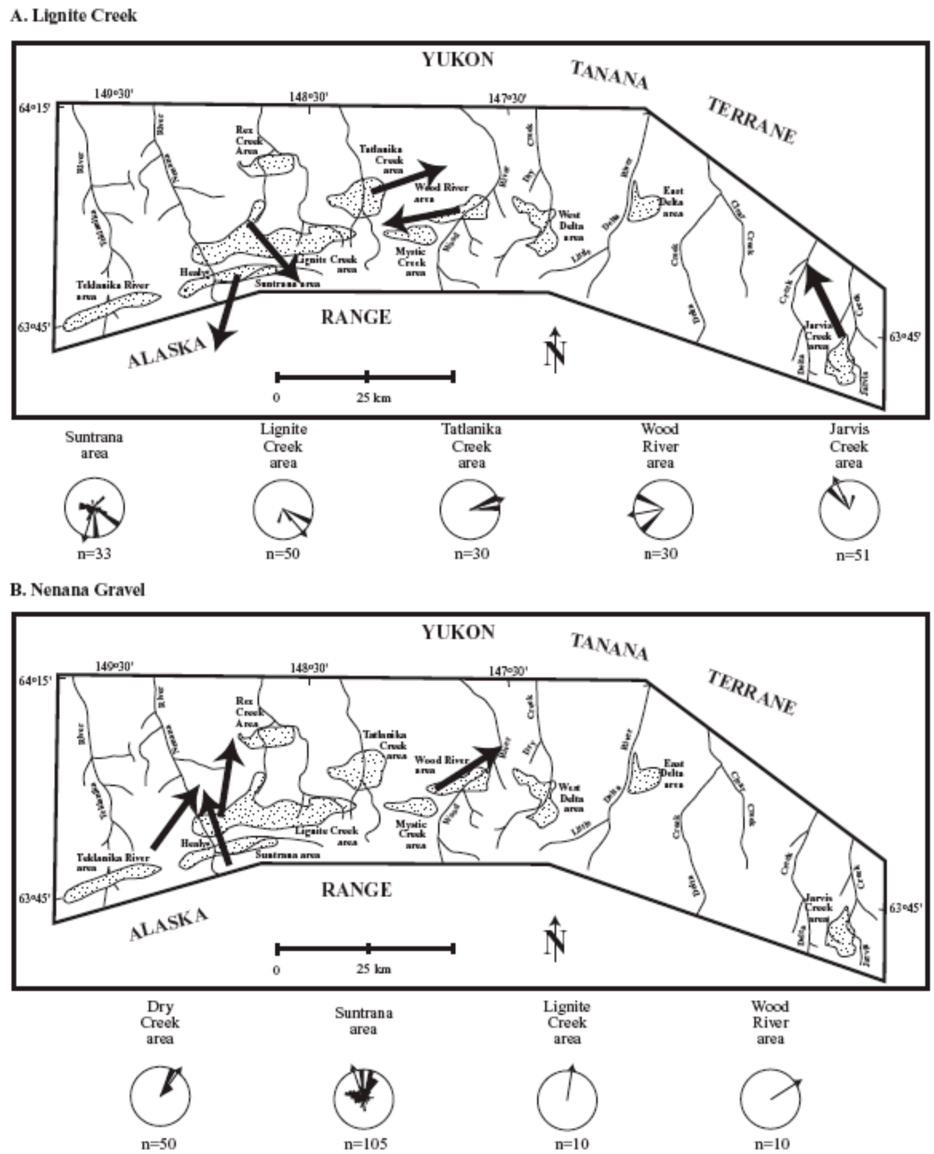


Fig 40. (A) Rose diagrams showing paleocurrent directions for the Lignite Creek Formation from our measured section locations. Measurements from planar cross-stratification in sandstone and clast imbrication in conglomerate. Large black arrows represent mean paleocurrent direction for each area. n = number of measurements. Small black arrows on rose diagrams represent mean paleocurrent direction. (B) Rose diagrams showing paleocurrent directions for the Nenana Gravel. The Dry Creek area is part of the outcrop belt located immediately north of the town of Healy on the west side of the Nenana River (Ridgway et al. 2007).

Correlative gravels south of the Alaska Range?

There are only a few outcrops of suspected Nenana Gravel "correlatives" found south of the Denali fault and the crest of the Alaska Range. One is located in the Honolulu Creek drainage within Broad Pass in the Healy quadrangle. These gravels appear to be thinner than the Nenana Gravels and have southerly paleocurrent indicators. Another possible "correlative" is located in the Hoo Doos east of Isabel Pass in the Big Delta quadrangle. The Hoo Doos section has a maximum age of 4.9 Ma (Ar^{40}/Ar^{39} whole rock) based on a tephra located 51 meters below the base of the gravels. Both sections are easily accessible and deserve more research.

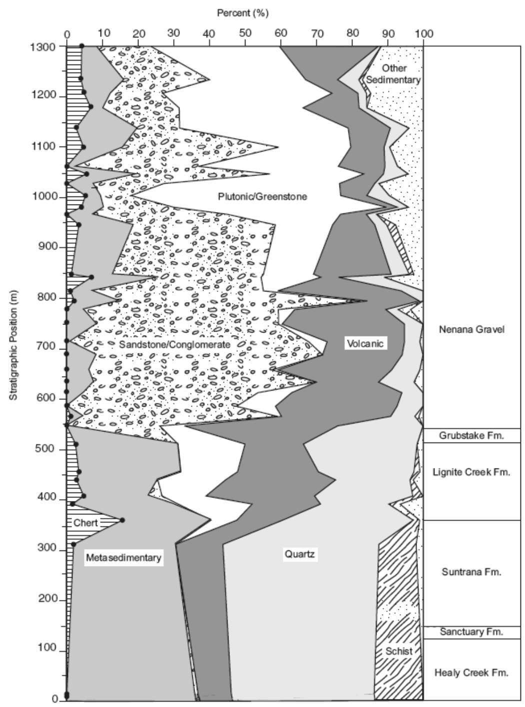


Fig 41. Conglomerate clast composition of the Usibelli Group and Nenana Gravel (Ridgway et al. 1999a). Circle on the left side of the figure mark the stratigraphic position of the 36 clast counts used to construct this diagram. Total clasts counted = 3420.

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