# The Denali fault system and the Neotectonic evolution of central Alaska

By

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## Abstract

Alaska's active Denali fault is generally considered to be a statewide, dextral strike-slip structure, more than 1900 km in length, and with a prominent northward-convex surface trace following the Alaska Range. Our 30 years of geologic mapping and studies in central Alaska, including a ca. 240 km segment of the Denali fault, have led us to alternate interpretations. The dextral strike-slip character of the fault extends northwestward from southeast Alaska to near Paxson of eastern Alaska. From there west- and southwestward it gradually changes into a zone of dip-slip faults. Fault kinematics also suggest this change of displacement character. Furthermore, these fault relations are in accord with analyses of seismic motions from the 2002 earthquakes. The epicenters of the two major 2002 earthquakes occured at the apex of this arcuate fault trace in the central Alaska Range.

Along the fault's entire extent as mapped by others, it crosses bedrock exposures at the single locality of Gunsight Pass, about 160 km westward from the 2002 epicentral region. At this locality, the assumed fault is actually an undeformed intrusive contact between the granodioritic McGonagall pluton and the Paleozoic country rocks. There is a dip-slip fault within the Paleozoic rocks along the south margin of the Pass south of the pluton, but there is no evidence of strike-slip motion.

Epicentral first-motion studies and ground-motion analyses of the two 2002 major earthquakes show components of strong compression, and newly formed dip-slip faults were found in the vicinity.This supports the interpretation that the fault changes character in the apex region from a transformlike structure of strike-slip motion into one of compressional character that produced a swarm of subparallel, dominantly dip-slip faults that converge downward and outline a number of upthrust wedge-shaped crustal blocks of regional dimensions.

Structural features of this type would be expected in a zone of transition where the surface course of a strike-slip fault radically changes into multiple dip-slip faults. We interpret the changing character of the Denali fault in central Alaska to be the manifestation, in the relatively thin upper plate, of the junction of trench and transform in the lower plate. We further interpret the wedge-shaped fault blocs in central Alaska to be analogous to the Italian Apennines' composite wedges described and named by Migliorini (1948). The inclined field of compressional force required for the development of these features is inferred to have resulted from an upwardly moving and shallowing position of the subducting plate beneath central Alaska within about the last 6 m.y.

## Introduction

The Denali fault of Alaska is interpreted by many geologists to be an active major strike-

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slip fault with several hundred kilometers of Cenozoic right-lateral displacement, juxtaposing disparate "tectonostratigraphic terranes" of unrelated geologic histories (Beikman, 1980; Jones et al., 1980 and 1981; Nokleberg et al., 1985). Its surface trace is commonly depicted as transecting the entire width of the State, from southeast Alaska through northwestern Canada and central Alaska to the Bering Sea, in a northward-convex manner for over 1900 km (fig. 1). Consequently, the Denali fault is assumed to have played a major role in the tectonic evolution of the southern half of the State (Plafker et al., 1994; also see a number of reports in Ridgway et al., 2007).

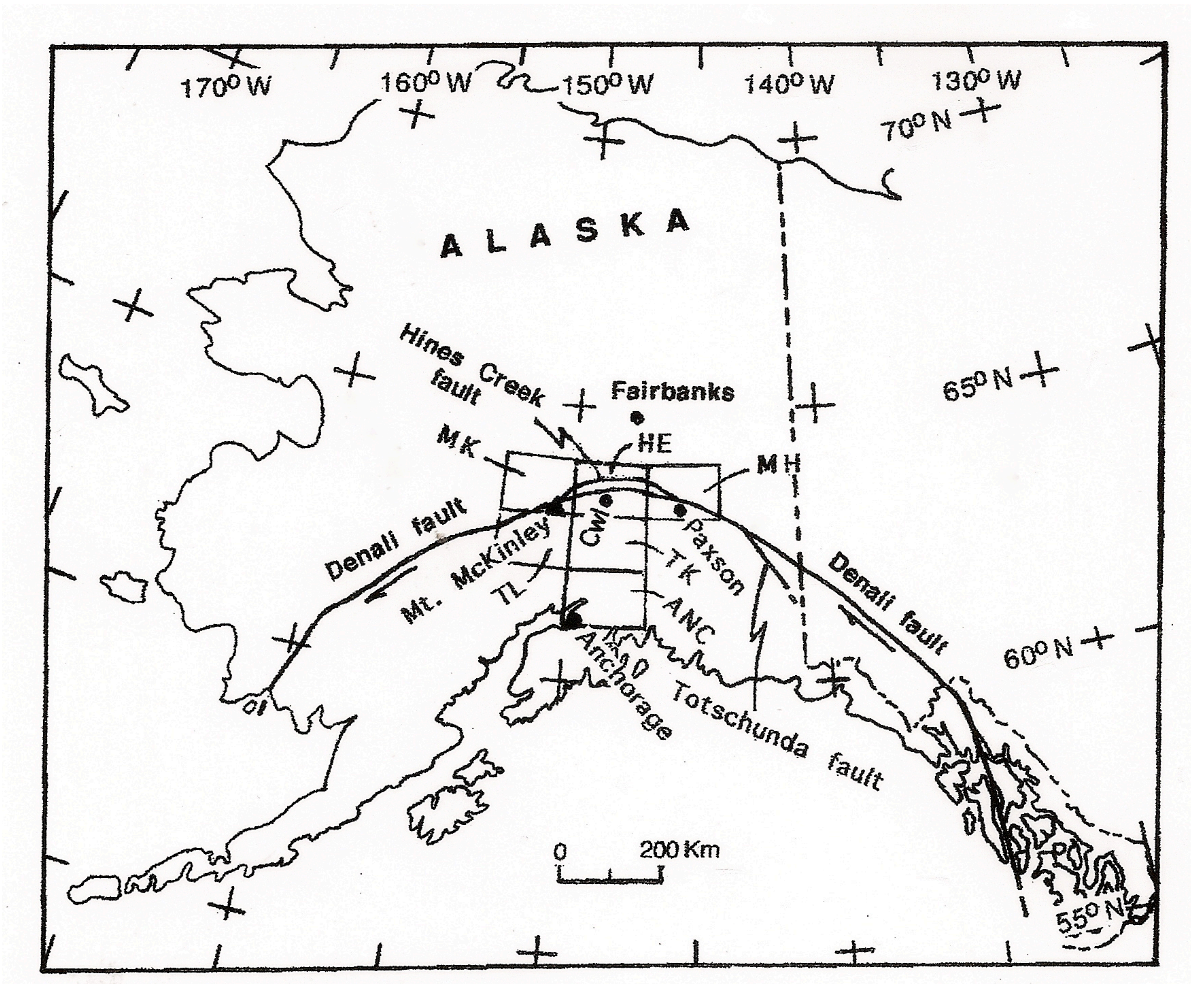



Figure 1. Generalized map of Alaska showing the surface traces of the Hines Creek fault and that of the conventionally interpreted Denali fault, both as they are commonly depicted in the geologic literature at the present (for instance, see in Plafker and Berg, 1994). The map also shows the locations of the six 1:250,000-scaled topographic map quadrangles mentioned in the text. MH - Mt. Hayes quadrangle, longitudes 144° to 147° W; HE - Healy quadrangle, longitudes 147° to 150° W; MK - Mt. McKinley quadrangle, longitudes 150° and 153° W; all three quadrangles are between latitudes 63° and 64° N. TK - Talkeetna Mountains quadrangle, longitudes 147° to 150° W; TL - Talkeetna quadrangle, longitudes 150° and 153° W, both quadrangles between latitudes

62º and 63º N. ANC - Anchorage quadrangle, between longitudes 147º to 150º W and latitudes 61º and 62º N. Cwl - Town of Cantwell.

Seismic studies and associate rupture features of the two large-magnitude earthquakes near the apex of the fault-trace in 2002 are considered by many researchers to support the State-wide strike-slip concept of the Denali fault (Eberhart-Phillips et al., 2003). However, without any further explanation some recent publications (for instance, Harp et al., 2003) show the Denali fault to extend westward only as far as the area of Mt. McKinley.

Before delving into problems of the Denali fault, we would like to briefly point out the inadequacy of evidence for the State-wide strike-slip concept of the fault.

The Denali fault was first named and described by St. Amand (1954, 1957) as a regional strike-slip feature. The concept was based on scattered reconnaissance geologic mapping primarily in eastern and much less so in central Alaska. Topographic features, observed mostly from aerial photographs, provided evidence for the fault in the western half of the State. St. Amand cautioned about embracing the Statewide strike-slip fault concept without additional substantive field work, especially in western Alaska. Nevertheless, little work was done in west Alaska before the strike-slip concept became widely accepted. The Denali fault was further described as a strike-slip feature by Grantz (1966), but again without relevant additional field investigations. Nearly all subsequent studies accepted the State-wide major strike-slip concept, and as such it has discouraged considering other possible interpretations for the Denali fault system.

Our evidence and interpretation of the Denali fault presented in this paper, namely that westward from near Paxson this single strike-slip fault changes into a swarm of dip-slip faults, is based on the cumulative results of over 30 years of geologic mapping and field investigations in a large tract of central Alaska. Our investigations include approximately 40,000 square km, covering all or parts of the Mt. McKinley, Healy, Talkeetna, Talkeetna Mountains and Anchorage quarter-million-scaled topographic quadrangles (fig. 1). This area includes a 240 km-long segment of the conventionally interpreted Denali fault. The relevant results of our central Alaskan work can be found in the following publications: Csejtey, 1974, 1976, 1979, 1992; Csejtey and Griscom, 1978; Csejtey and St. Aubin, 1981; Barnes and Csejtey, 1985; Mullen and Csejtey, 1986; Hillhouse and others, 1985; Stanley and others, 1990; Csejtey and others, 1978, 1980, 1982, 1992, 1994, 1996, 1997, and 1999.

For ease of geographic reference we retain the name Denali fault with the proviso that westward from Paxson (fig. 1) under this name we mean only one of several subparallel faults of a fault swarm. When we refer to the Denali fault as it is commonly interpreted by the geologic community at present, namely as a Statewide strike-slip feature, we use the term ‘conventional’ Denali fault.

New interpretation of the Denali fault system and the related earthquakes of 2002

Our geologic mapping and investigations in central Alaska indicate that the Denali fault is undoubtedly a Cenozoic dextral strike-slip feature in the eastern and southeastern portions of Alaska and intervening region of Canada. However, near Paxson (fig. 1) the fault, just before its surface trace turns southwestward, breaks up and changes into several subparallel and upward diverging faults of dominantly dip-slip displacements (figs. 2 and 3). These faults outline downward narrowing and generally westward widening crustal blocks, very similar to the structural phenomenon of "composite wedges" of Migliorini (1948), and are part of a structurally complex transition zone from a dominantly strike-slip displacement mode into a dominantly dip-slip tectonic regime. In this transitional zone and westward the Denali fault is just one of a swarm of faults. Field evidence at Gunsight Pass near Mt. McKinley (fig. 1) and nearby regions, to be discussed later, indicate that strike-slip

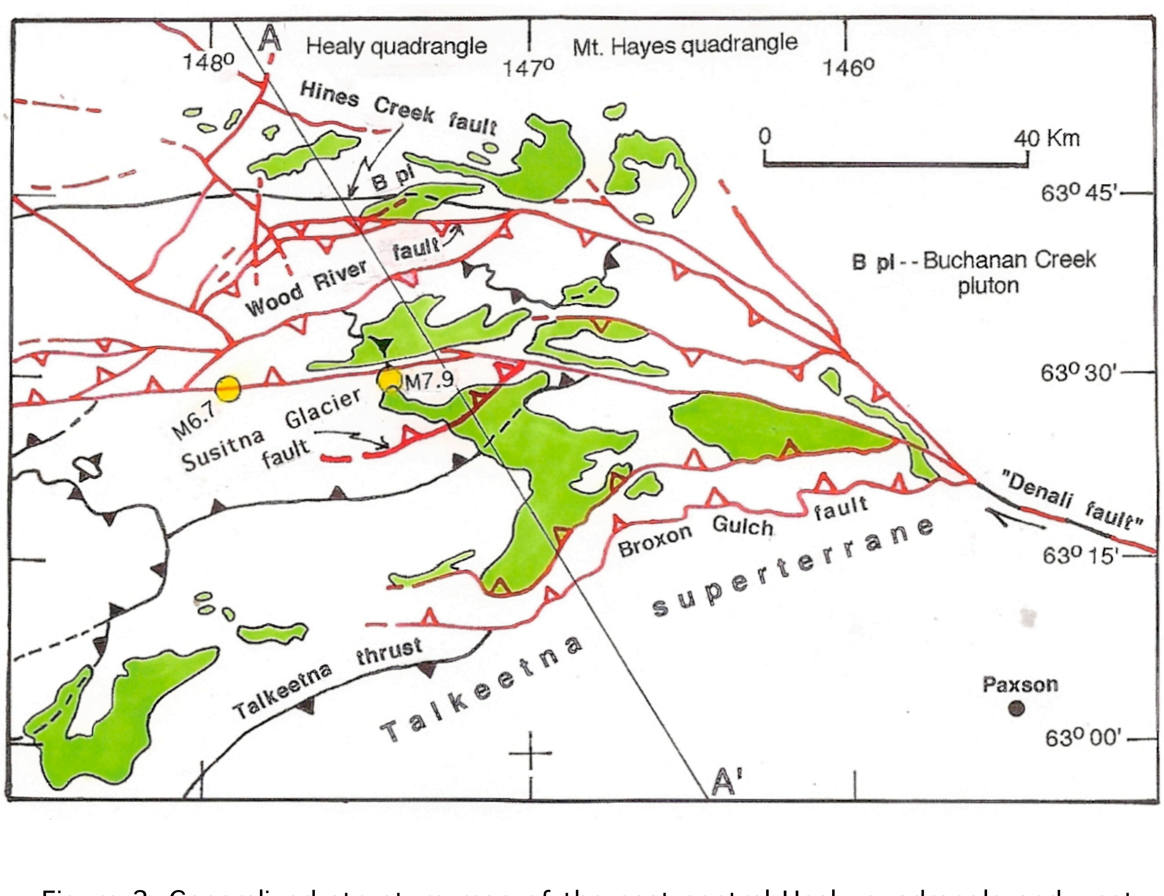



Figure 2. Generalized structure map of the east-central Healy quadrangle and west-central Mt. Hayes quadrangle, showing the principal Cretaceous and Late Cenozoic faults of the area. The Cretaceous faults are shown in black, Cenozoic in red. Solid teeth indicate thrust faults, open teeth high-angle reverse faults. Line A A' indicates the location of a schematic cross-section shown on figure 3.

Late Cenozoic faults constitute the complex zone where the recurring Cenozoic dextral strike-slip movement along the Denali fault of eastern Alaska changes into a swarm of faults with dominantly dip-slip movements. See text for further explanation. The map also shows in green the distribution of a tight cluster of about 100 Ma old granitic plutons, including the Buchanan Creek pluton (B pl). The tight cluster of these plutons across the Cenozoic faults indicate no appreciable strike-slip motion along any of these faults in the last about 100 Ma. Note the new high- angle reverse fault, the Susitna Glacier fault of Eberhart-Phillips et al., 2003 , which has developed near the epicenters of and during the 2002 earthquakes of central Alaska (also see fig. 4). Geology of the Healy quadrangle is after Csejtey et al. (1992) and Sherwood and Craddock (1979); and that of the Mt. Hayes quadrangle has been modified after Nokleberg et al. (1992). Small yellow circles with the designations M6.7 and M7.9 are the epicenters of the two major earthquakes of 2002.

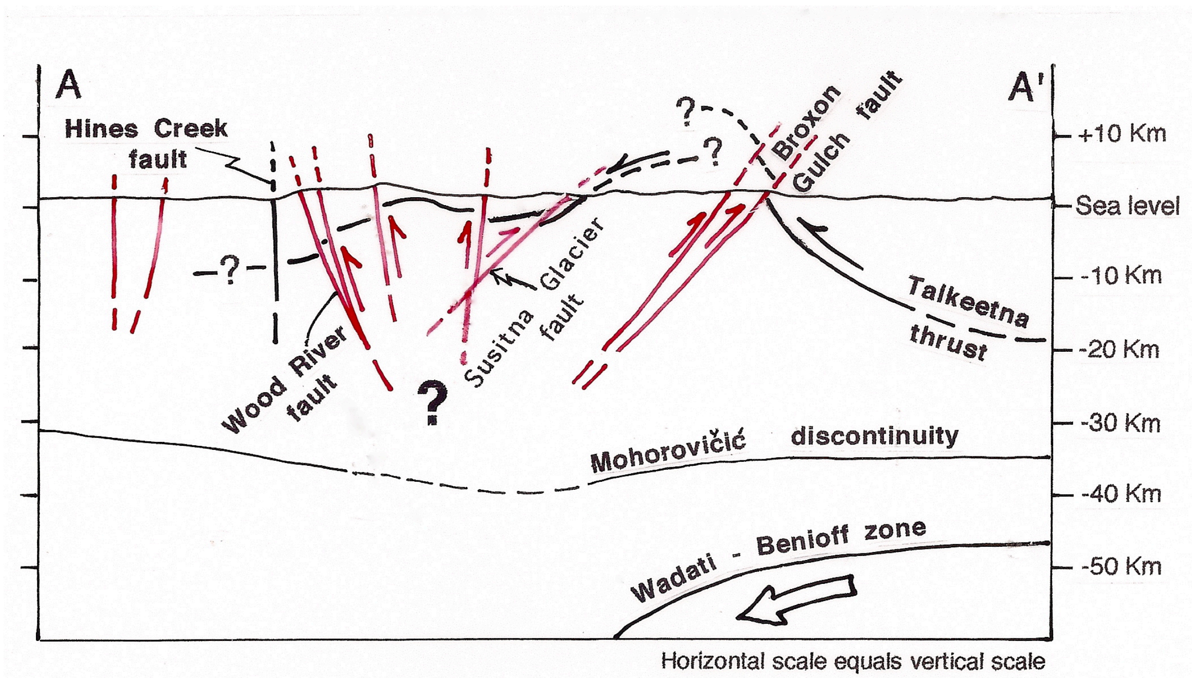
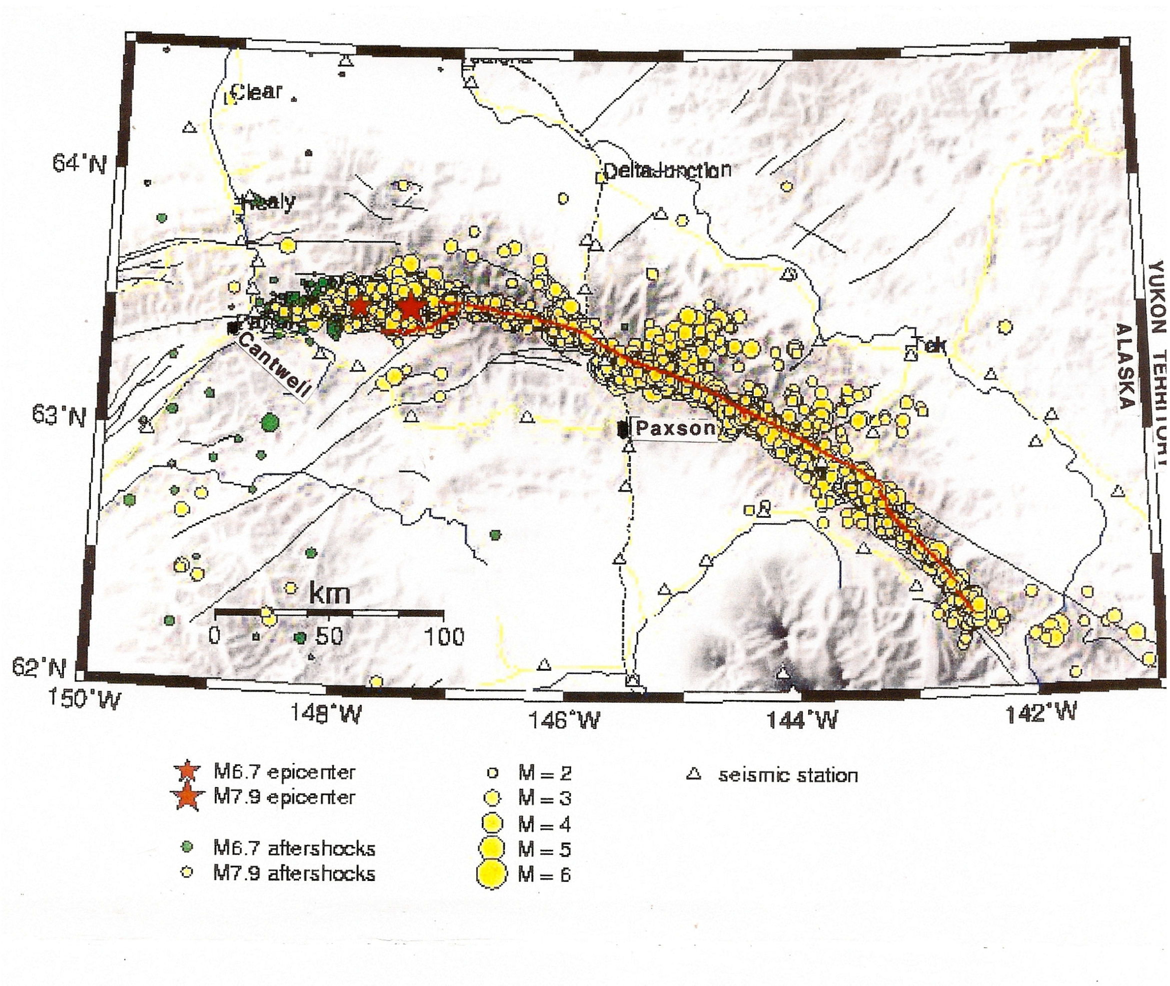



Figure 3. Schematic cross-section across the area of figure 2 (line A A'). The Late Cenozoic faults, shown in red, outline concentrically upthrust wedge-shaped crustal blocks. Displacement along the recently formed Susitna Glacier fault of Eberhart-Phillips et al., 2003, is exaggerated. Faults similar to the ones shown on this cross section have been described by Migliorini (1948) from the Italian Appenines. We interpret these upward diverging faults to constitute the terminus for the Cenozoic dextral movements along the Denali fault of eastern Alaska. See text for further discussion. The approximate position of the Talkeetna thrust is from Csejtey et al. (1992), and that of the Mohorovicic discontinuity from Barnes (1967) and Csejtey et al. (1992). The position of the Wadati-Benioff zone has been extrapolated into the cross-section from Plafker et al. (1993). These last two features are shown for background information only. In order to keep the cross-section focused on the faults, the Cretaceous plutons are not shown.

displacement along the conventionally depicted Denali fault dies out some distance east of the Pass, somewhere near the apex of its surface trace (fig.1). Our field investigations west of the apex also indicate that the transitional zone ends somewhere west near the town of Cantwell (fig. 1). West of the apex area the northwestward movement of the crustal block along the dextral strike-slip eastern Denali fault is accommodated essentially by crustal shortening in a roughly southwest-trending wide zone of dip-slip faults, many outlining composite wedges, and large-scale folds. Very limited local strike-slip components along some of these dip-slip faults are also possible due to compressional slippage between the wedge-shaped crustal blocks. The upheaval of the central and western Alaska Range in the last 6 Ma is the result of still ongoing crustal deformational processes.

Two large earthquakes and numerous aftershocks occurred along and near the conventionally depicted Denali fault in central Alaska in the Fall of 2002 (figs. 2, 3, 4, and 11; the following summary is after Eberhart-Phillips et al., 2003; Lu et al., 2003; and




Red line - mapped rupture; solid black lines - mapped fault traces; dashed black line - Trans-Alaska Pipeline; yellow lines - roads; blue lines - major rivers

Figure 4. Seizmic map of southcentral and eastern Alaska, showing the epicenters of the M6.7 and M7.8 magnitude earthquakes of 2002, and the epicenters of the aftershocks of those two earthquakes. The map also shows the locations of the

surface ruptures along the Denali and Totschunda faults, as well as the location of the Susitna Glacier fault. Note that the strike-slip movement along the Denali fault ends about where the newly developed Susitna Glacier high-angle reverse fault buts into the Denali fault. We consider this spatial relationship to be indicative of Cenozoic strike-slip movement along the Denali fault of eastern Alaska changing into dominantly dip-slip movement along a number of faults in southcentral and western Alaska. Seizmic map from the website http://www.aeic.alaska.edu/Denali_Fault_2002/ updated October 19, 2003, of the Geophysical Institute, University of Alaska.

Geophysical Institute, University of Alaska, earthquake website, 2003). The first and smaller of the two earthquakes on October 23, the Nenana Mountain event of M6.7, did not cause any known surface ruptures. It occurred along the Denali fault, and first motion studies implied strike-slip motion. But the second and larger earthquake of M7.9 on November 3, about 25 km east of the Nenana event, resulted in a massive dextral slip-partitioning east of the epicenter of this event for over 250 km along the eastern Denali fault and then sidestepping onto the Totschunda fault (figs. 1 and 4). Seismic studies indicate the hypocenter of the M7.9 earthquake is a short distance south of the Denali fault on a newly developed co-seismic high-angle reverse fault which dips toward the northwest (figs. 2 and 3). Some of the earthquake literature (for instance, Eberhart-Phillips et al., 2003) has referred to this structural feature as a thrust fault. The surface trace of this fault, named the Susitna Glacier fault, buts the Denali fault at the western end of its long dextral co-seismic surface rupture (fig.4). The observable surface trace of this new fault is about 40 km in length, and a north-side up vertical separation of nearly 4 m has occurred.

The spatial distribution of the surface ruptures along the Denali fault and the location of the Susitna Glacier fault, and possibly along with some reactivated and tectonically northward-verging thrust faults in the northern foothills of the central Alaska Range (Hanson et al., 2002), are not only consistent with but support the concept of the Denali fault transforming from strike-slip into a dip-slip feature in the region of the apex of its surface trace, thus becoming part of a compressional orogenic regime. The right-lateral strike-slip motion deduced from seismic studies for the hypocenter of the Nenana Mountain M6.7 foreshock -- no surface ruptures were found due to this event -- is equivocal. We believe the indicated lateral motion is probably caused by oblique compression on one of the wedge-shaped crustal blocks delineated by the previously mentioned dip-slip faults.

The northward convex southern coastline of Alaska closely parallels the plate boundary between the North American plate on the north and the Pacific plate to the south (Plafker et al., 1993). The approximate western half of this plate boundary is a trench where the northwest-moving Pacific plate dips under the continental North American plate, but the eastern half is a northwest-trending transform boundary. The downgoing Pacific plate has a shallow dip under central Alaska, the top of this downgoing plate is significantly less than 100 km deep in the general area of the 2002 October and November earthquakes (fig. 11).

We interpret the westward change of the Denali fault from strike-slip to dip-slip mode as the on-land manifestation of the trench-transform fault junction mechanism in the thin upper plate of central Alaska (also see fig. 12). The forming of the present Alaska Range took place in the approximately last 6 million years. The formation of the central Alaska Range was caused by the relatively quick upward change in the position, that is the shallowing of the northward moving lower plate beneath central Alaska. In our interpretation this shallowing caused an upward inclined compressional field in the upper plate which, in turn, produced the upward widening "composite wedge"-type structures of Migliorini (1948). We will discuss the development of these structures in the central Alaska Range in a later part of this paper.

## Problems with the conventional concept of the Denali fault in central Alaska

The conventional State-wide major strike-slip Denali fault concept has been extrapolated by earlier earth scientists from eastern Alaska into the central and western portions of the State without sufficient field evidence. We do not question the presence of a fault or faults at or near the depicted trace of the conventional Denali fault in central Alaska. Many of those faults belong to swarms of subparallel Cenozoic faults in the region. (figs. 2, 11, and 12). Nevertheless, as our field investigations progressed along the Denali fault in the Healy and Mt. McKinley quadrangles of central Alaska (fig. 1) since the early 1970-s, we found more and more field evidence against a continuous major strike-slip terrane boundary fault with hundreds of km of dextral displacement.

<u>Rock units crossing the conventional Denali fault.</u>

The most convincing evidence contradicting the terrane boundary and major strike-slip concept of the Denali fault in central Alaska is the close correlation of six rock units and a metamorphic belt across the trace of the fault (fig. 5). These geologic phenomena have been described before, including detailed maps showing their areal distributions, thus here only a brief summary of them is given, along with their principal references. The six features correlating across the fault are (also see fig. 5):

1) A thick, dominantly marine flyschoid sequence of deep basin, slope, shallow shelf and subordinate terrestrial rock assemblages, ranging in age from Ordovician(?) to Middle Pennsylvanian (Csejtey et al., 1996, 1994, 1992 [unit DOs]; Mullen and Csejtey, 1986; Reed and Nelson, 1980);

2) A thick Upper Triassic calcareous sedimentary sequence of continental-slope type turbidite and capping-shelf type deposits (Csejtey et al., 1996, 1992 [unit TRcs]; Umhoefer, 1984; Jones et al., 1981, 1983; Sherwood and Craddock,1979);

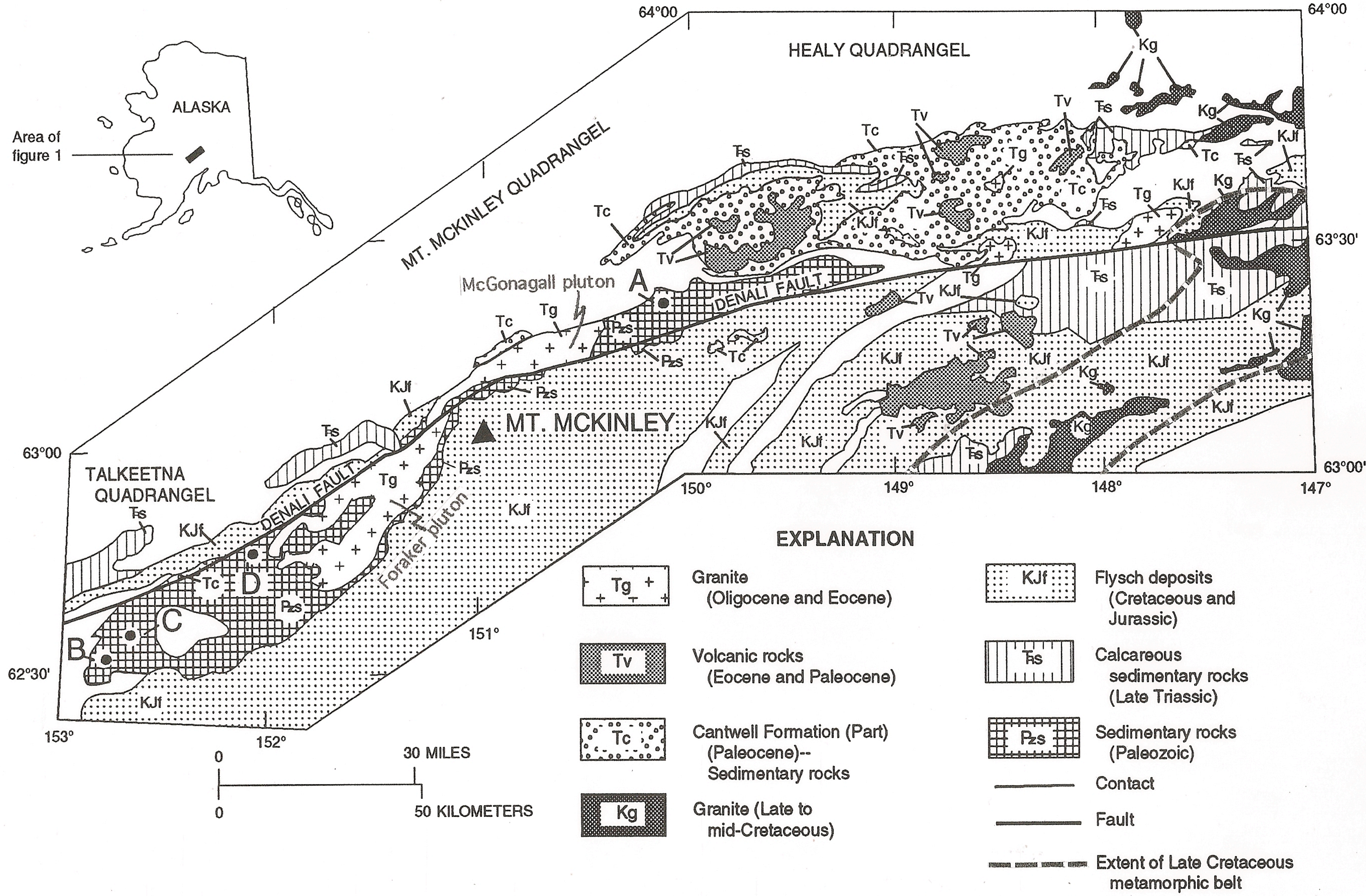



Figure 5. Map showing generalized distribution of correlative rock units across the conventionally interpreted Denali fault between longitudes 147° W and 153° W.

Figure reproduced from Csejtey et al., 1996. Distribution of rocks is from Reed and Nelson, 1980; Csejtey et al., 1992; B. Csejtey, Jr., unpub. data, 1994 and 1995. Surfacial deposits and noncorrelative rocks are not shown. Of the seven rock units shown on the map, the correlations of five units (Tv, Kg, KJf, T̄s, and Pzs) are considered to be very good, that of the Cantwell Formation (Tc) is somewhat debatable. The correlation of the Tertiary granitic rocks (Tg), primarily the Foraker and McGonagall plutons, is somewhat ambiguous, because while their ages are similar, their chemistry, especially their trace element components, are sufficiently different (Ford et al., 1998) to consider them unrelated intrusives. Nevertheless, the areal distribution of the rocks of the five units of very good correlation, especially those of units Kg and Tv, reliably indicate that there was no appreciable lateral movement along the conventional Denali strike-slip fault in the map area within the last about 95 Ma. Dots and capital letters within unit Pzs indicate locations of paleontolagically examined samples discussed in the original publication of Csejtey et al., 1996.

3) A very thick, intensely deformed monotonous sequence of dominantly dark gray to black turbiditic flyschlike rocks, ranging in age from Late Jurassic to Late Cretaceous, underlying large areas of southcentral Alaska, interpreted to have been deposited in an oceanic basin between and onlapping onto the margins of the ancient North American continent and the approaching allochthonous accretionary continental blocks (Csejtey et al., 1996, 1992 [units KJf, KJfk, KJcg, KJa, and KJfl], 1982, 1978; Jones et al., 1981, 1983; Reed and Nelson, 1980);

4) The occurrence of an areally tight group of mid- to Late Cretaceous epi- to mesozonal (Buddington, 1959) granitic plutons straddling the Denali fault (figs. 2 and 5) in the eastern Healy and adjacent western Mt. Hayes quadrangles (fig 1; Csejtey et al,. 1996, 1992; Barker et al., 1994; Nokleberg et al., 1992, Sherwood and Craddock,1979; Wahrhaftig et al., 1975);

5) A narrow, northeast-trending in situ metamorphic belt of mid- to Late Cretaceous age in the eastern Healy quadrangle (fig. 1), part of the regional Maclaren metamorphic feature of Smith (1974), the isograds and metamorphic facies boundaries of which appear to cross the Denali fault without appreciable horizontal offsets (fig. 5; Csejtey et al,. 1992 [Sheet 2, Map C], 1982);

6) Scattered outcrops of Paleocene and Eocene, in part possibly latest Cretaceous, felsic to mafic, subareal to hypabyssal volcanic rocks in the western two-thirds of the Healy quadrangle (fig. 5; Csejtey et al,. 1992 [units Tvv, Tvif, Tvim, and Tcv]). The tight grouping of the areal outcrop patterns of these in situ volcanic rocks across the Denali fault preclude any significant strike-slip offsets.

Although none of the above rock units provide a definite piercing point to determine exactly how much strike-slip displacement may or may not have occured along the Denali fault in southcentral Alaska, these units clearly indicate that the Denali fault in the region is definitely not a terrane boundary fault, and that total post mid-Cretaceous strike-slip displacement along it, if any, must be quite small. The tight areal distribution of both the early Tertiary volcanic rocks and the Cretaceous plutons, and the apparent continuity of the narrow, Cretaceous metamorphic belt across the fault strongly suggest that total post mid-Cretaceous dextral displacement, if any at all, could not be more than a few km.

In addition, there are four other rock units, three of sedimentary and one granitic, which either correlate or probably correlate across the conventional Denali fault in central Alaska (figs. 5 and 11). However, their very limited areal distribution on one or the other side of the fault precludes determining post mid-Cretaceous horizontal offsets, if any, along the fault. Nevertheless, the occurrence of these rock units on both sides of the Denali fault is further indication that in southcentral Alaska this traditionally so interpreted fault is not a terrane-boundary feature.

The oldest of the above sedimentary rock units consists of a cluster of small erosion remnants of an early Tertiary fluviatile sequence south of the fault in the western Healy quadrangle (figs. 1 and 5 (shown on fig. 5 as Tc). These outcrops are part of unit Tfv of Csejtey et al., 1992 ). These fluviatile rocks may correlate with similar strata of the extensive Late Cretaceous and Paleocene Cantwell formation north of the conventional Denali fault (fig. 5; Ridgway et al., 1994, 1995, and 1997; Csejtey et al., 1992; Wolfe and Wahrhaftig, 1970).

Another sedimentary unit of limited areal extent consists of Oligocene coal-bearing strata in the southwestern Healy quadrangle south of the fault (unit Tcb of Csejtey et al., 1992; J.A. Wolfe, oral commun., 1984; Hopkins, 1951; Wahrhaftig, 1944). These coal-bearing rocks are considered correlative with the areally more extensive Eocene to Miocene, in part coal-bearing sequence north of the fault in the Healy quadrangle (Csejtey et al., 1992 [also shown as unit Tcb]). The outcrop areas of these rocks are too small to be shown on fig. 5.

The third possibly correlative sedimentary unit south of the Denali fault comprises a small patch of unconsolidated and unfossiliferous, pebble to boulder conglomerate and coarse-grained sandstone in the south central part of the Healy quadrangle (Csejtey et al., 1992 [unit Tn?]). This conglomerate is lithologically very similar to the Miocene and Pliocene Nenana Gravel (Inyo Ellersick, oral commun.,1984) covering large areas along the northern flank of the central Alaska Range, north of the Denali fault (fig. 5; Csejtey et al., 1992 [unit Tn]; Wahrhaftig, 1975, 1970a, 1970b, 1970c; Wahrhaftig et al., 1969; Capps, 1940).

The fourth rock unit occurring on both sides of the Denali fault in southcentral Alaska comprises the Paleocene McKinley sequence of granitic rocks described by Reed and Lanphere (1973). The McKinley sequence plutons underlie large areas of southern Alaska, but at least three small plutons of the sequence occur north of the Denali fault in the Mt. McKinley and Talkeetna quadrangles (fig. 11; Lanphere and Reed, 1985).

The possibility of yet another geologic affinity between rocks on both sides of the Denali fault is provided by the results of a geochemical survey of stream sediment samples in the Healy quadrangle (Light et al., 1990). A unique, greisen-type tin mineralization, associated with the Paleocene McKinley granitic sequence of Reed and Lanphere (1973), is known to occur near the southwestern corner of the Healy quadrangle (Howley and Clark, 1974) and adjacent areas of the Talkeetna quadrangle (Reed et al., 1978). Anomalous values of tin and other elements, associated with this tin mineralization, have been detected in sediments of unrelated stream systems in contiguous areas surrounding and extending, beyond the known tin mineralization occurrences, across the Denali fault in the southwestern region of the Healy quadrangle (Light et al., 1990). Quite possibly, the areal extent of the tin anomalies may indicate a tectonic cohesiveness between the two sides of the Denali fault in the region since Paleocene time.

In conjunction with the above-discussed correlative rock units there is an additional problem to consider: Were the Denali fault in southcentral Alaska a major, terrane-boundary strike-slip fault, separating lithologically divergent rock packages, one would expect to see some geophysical expressions of such a tectonic break. However, definitive aeromagnetic and Bouguer gravity expressions of the assumed strike-slip fault in southcentral Alaska are lacking (Barnes and Csejtey, 1985; Barnes, 1977; Decker and Karl, 1977; R. W. Saltus of U.S. Geological Survey, oral commun., 1998).

Seismic surveys parallel with the Alaska and Richardson Highways north of Paxson and north of the traditional Denali fault, investigating the deep crustal structure of central Alaska (Beaudoin et al., 1992), provide additional supportive, although somewhat interpretive evidence that the traditional Denali fault is not a terrane boundary fault. The seismic line of Beaudoin et alii runs northwesterly for about 130 km from a point about 30 km southeast from Delta Junction (fig. 4). Interpreting the seismic data Beaudoin and his coworkers conclude that along the line of the seismic section the exposed Paleozoic and Precambrian?, mostly metamorphic rocks of the Yukon-Tanana terrane (original definition after Jones and Silberling, 1979) extend to a depth of only about 10 km below sea-level. Then for about another 10 km the Yukon-Tanana rocks are underlain by an underthrust subhorizontal unit of Mesozoic flyschoid rocks (unit KJf of Csejtey et al., 1992), which in turn are underthrust by a 10 to 12 km thick, subhorizontal slab of rocks of the Wrangelia? terrane of Jones et al., 1977. The few km interval between the base of the Wrangellia? slab and the Mohorovičić discontinuity (about 29 to 33 km below sea level) is interpreted to be composed of a variety of mafic rocks. If the identification of the composing rocks of the seismic section is correct, then the presence of the same Mesozoic flyschoid and Wrangelia? rocks on both sides of the traditional Denali fault strongly suggest that the fault is not a terrane boundary fault.

In summary, our assessment of the correlative geologic features across the traditional

Denali fault in southcentral Alaska is as follows: Although the degree of reliability of the correlation of the various geologic units and features across the Denali fault varies, ranging from very good to probable or even possible, the reliable correlations indicate that in southcentral Alaska the Denali fault is clearly not a terrane boundary fault. Furthermore, the large number - about 12 - of correlative or probably correlative geologic features across the fault strongly argues that since sometime in Late Cretaceous time, that is since the emplacement or development of at least 6 of the correlative features during the accretionary development of southern Alaska (Csejtey et al., 1982, 1992), there has not been any appreciable lateral displacement on the Denali fault in southcentral Alaska. It seems highly unlikely that so many identical or nearly identical rock packages and other geologic phenomena would simultaneously develop in distant areas, and then subsequently be juxtaposed next to each other by a major strike-slip fault.

In conjunction with the relatively large number of correlative or probably correlative geologic features on both sides of the conventional Denali fault in southcentral Alaska, it should be pointed out here that each previous interpretation of dextral offset along the fault has been based on a single, assumed correlative geologic feature.

<u>Inconsistences between offset interpretations along the conventional Denali fault.</u>

One of the interpretations of offset, the 400 km displacement within the last 80-100 million years, is based on the assumed offset of the metamorphic rocks of the Maclaren metamorphic belt south of the fault from a metamorphic complex in the Yukon Territory of Canada (Forbes et al., 1974; Smith, 1974; Turner et al., 1974; Nokleberg et al., 1985). We have pointed it out in this report and elsewhere (fig. 5; Csejtey et al., 1982, 1992) that rocks of the Maclaren metamorphic rocks are not truncated by but actually straddle, without any obvious offset, the Denali fault in the eastern Healy quadrangle of southcentral Alaska.

The approximately 38 km dextral offset of the McGonagall and Foraker plutons, both of about 38 Ma old, near Mt. McKinley in Denali National Park (Reed and Lanphere, 1974; fig 5) is questionable. In an earlier publication we pointed out (Ford et al., 1998) that the trace element chemistry of the two plutons are sufficiently dissimular to indicate that they are different intrusions instead of the offset halves of an originally single intrusive body. The two plutons appear to be separate intrusions, and thus not indicators for dextral offset, as will be discussed with the geology of the Gunsight Pass area.

The approximately 150 km of apparent dextral separation of the contact between some Paleozoic rock units in southwestern Alaska (Jones et al., 1980, 1981) is similarily, questionable. We have no first-hand knowledge of this geologic feature but suggest that what may appear as considerable right-lateral offset, is quite possibly the result of several hundreds, perhaps even a few thousands of meters of vertical separation along a dominantly dip-slip fault or fault zone in a region of essentially flat-lying strata.

It should be considered that the amounts of displacement, and thus the rates of fault movements invoked by the three above-discussed dextral offset stipulations are actually inconsistent with each other. The postulated 400 km offset of the 90 to 80 m.y. old Maclaren metamorphic belt would require an average fault displacement rate of about 4.4 to 5 km/m.y. in southcentral Alaska. The 38 km offset of the two halves of a 38 Ma pluton, about 150 km southwest of the Maclaren metamorphic rocks, would take, again on average, about 1 km/m.y. And in western Alaska, the 150 km apparent offset in not more than 90 million years - since the accretion of the ancient Alaskan continental margin - would require an average movement rate of about 1.6 km/million years. In view of no known major structures south of the Denali fault, to account for the crustal shortening and lengthening in the areas separating the Maclaren metamorphic rocks from the Foraker pluton and then the Upper-Lower Creataceous contact from the pluton, respectively, the three offset proposals along a single, continuous strike-slip fault are incompatible.

Problems with offset topographic features along the conventional Denali fault.

Plafker et al., (1977); Clyde Wahrhaftig, (personal commun, 1982); and many other earth scientist in the past have pointed out that many stream and glacial valleys crossing the Denali fault in southcentral Alaska appear to be offset in a right lateral sense. This has been considered additional evidence of continuing Holocene right-lateral movement along the fault. However, even a quick perusal of the Healy and Mt. McKinley quadrangle topographic maps (for quadrangle locations see fig. 1) reveals that the amounts of the apparent, dominantly dextral offsets vary considerably between topographic features only a few hundred meters or a few kilometers apart. This appears to be incompatible with the effects of a systematically moving dextral strike-slip fault. Much more likely, in the majority of cases the change in the course of the streams and glaciers across the fault has been caused by dominantly vertical movement along the fault. We have actually seen evidence for this along a recently active, small fault that is parallel with and just a few kilometers north of the Denali fault in the Mt. McKinley quadrangle (figs 9 and 10). In a number of cases the change in the course of a stream or glacier along the fault has been a result of contrasting erosive characreristics of the rocks which were vertically juxtaposed by the fault. An excellent and convincing evidence for this is the course of the Muldrow Glacier crossing the Denali fault near Mt. McKinley (fig. 9). The change in the course of that glacier was not caused by dextral offset but, as shown by the small undulations in its course, the glacier was deflected by the hard intrusive rock mass of the McGonagall pluton.

Mechanical problems with strike-slip along a curved fault trace.

The proponents of the State-wide strike-slip Denali fault have failed to account for the mechanical and spatial problems of moving an essentially rigid crustal block, on the southern side of the fault, for considerable distances along a curving fault trace of non-uniform radius. The trace of the assumed State-wide Denali fault comprises long straight segments interspersed with sharply bending short segments, and the closure between the westernmost and easternmost trace of the fault is roughly 70 degrees (figs. 1 and 6A). Where are the structures in the moving southern block resulting from such an arduous journey!? None have been found. (See discussion of this problem in Csejtey, 1992). We believe the flexing of the moving southern block going around each bend would be somewhat similar to that of a long railroad train going through a short but sharp curve between straight stretches of the tracks. Each car entering the curve would rotate, that is change its position, relative to the car behind it, and then rotate back to its original position after leaving the curve and entering the straight stretch of the tracks. Again, no structures resulting from such movements and accompanying rotations have been found in the supposedly laterally southwest-moving southern block of the Denali fault in southcentral Alaska.

In conjunction with the curved surface trace of the conventional Denali fault, an interesting although a somewhat empirical relationship can be deduced when one superposes the surface trace of the fault on a map of inferred maximum horizontal stress trajectories in Alaska compiled by Nakamura et al., 1980; Plafker and Jacob, 1985; and Plafker et al., 1993. In Nakamura et al (1980) it is inferred that along plate boundaries these mapped stress directions represented maximum tectonic compression. If so, by resolving the compressional force at the intersections of the trajectories with the Denali fault into vectors parallel with and perpendicular to the fault (fig. 6A), it appears that along the eastern segment of this interpretedly State-wide dextral fault the vectors parallel with the fault tend to be greater than their perpendicular counterparts. However, near the apex of the assumed surface trace of the fault this ratio between the two kinds of vectors gradually undergoes an inverse change whereby the perpendicular vectors become greater than the parallel ones (fig. 6B). Perhaps the analogy is not far fetched comparing the vector relationships to the brake mechanism of an automobile. As long as the rotational force parallel with the brake shoe - wheel drum contact is greater than the perpendicular force exerted on the drum by the brake shoe, the wheel turns. However, when the ratio between the two forces inversely changes, the wheel stops. Although our vectoring the compressional trajectories is only approximate because of the small scale of the available maps, and intersection no. 9 is a contradictory enigma, we believe it supports our interpretation that only the eastern portion of the conventional Denali fault is a strike-slip feature, but west of its apex it is only one of a swarm of dominantly dip-slip faults being part of a compressional tectonic regime characterized by high angle reverse and normal faults and folds.

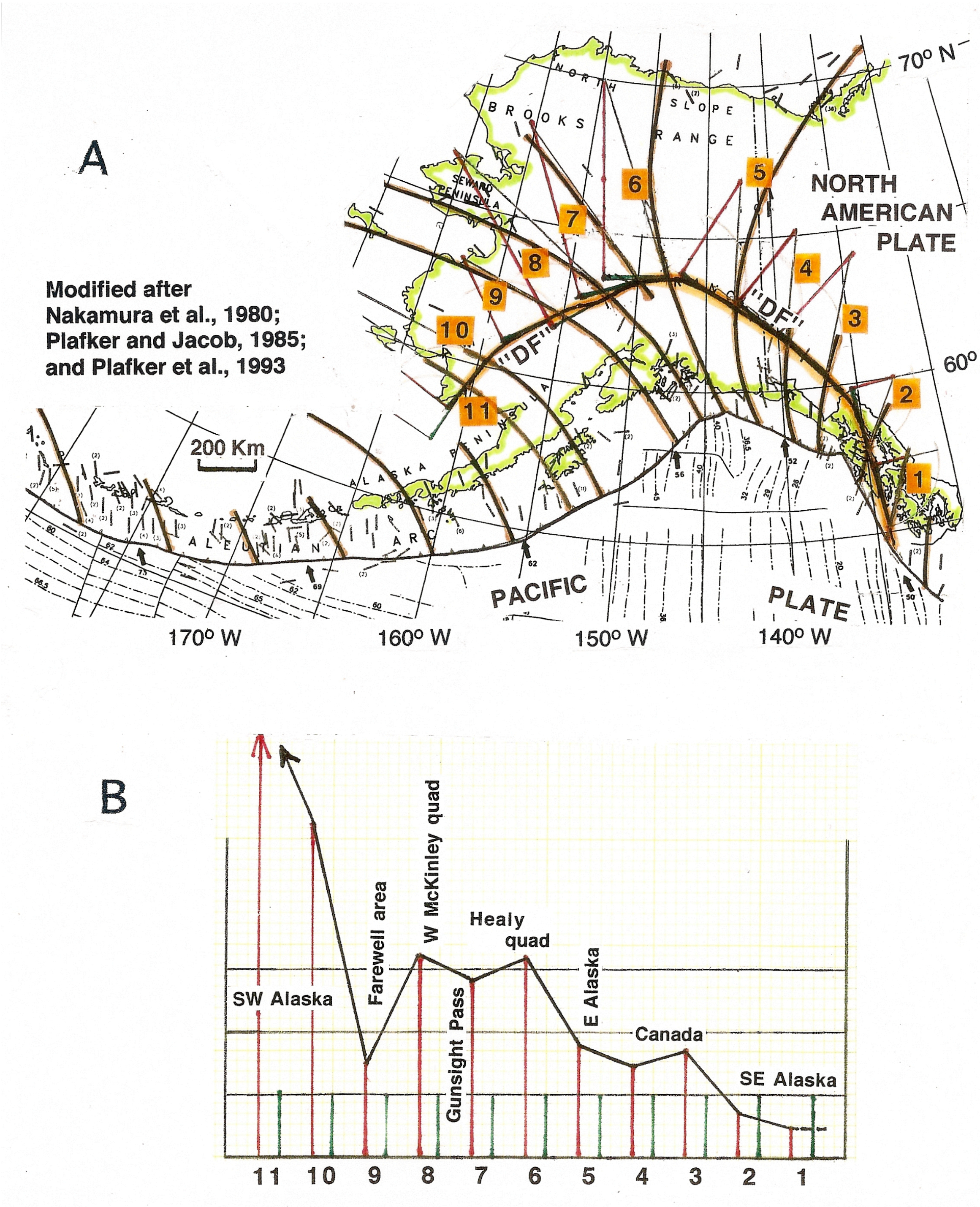



Figure 6. Analyses of regional horizontal compression directions, which coincide with maximum horizontal stress directions (Nakamura et al., 1980), along the conventionally interpreted dextral strike-sip Denali fault cutting across all of Alaska. Part 'A 'shows the inferred horizontal trajectories - curved heavy lines, and the trace of the Denali fault as traditionally interpreted. All but two of the trajectories, and the trace of the Denali fault are taken from Plafker et al., 1993. Where the trace of the Denali fault intersects a compression trajectory, the trajectory was vectored into two components: one parallel with and the other perpendicular to the Denali fault. Comparisons between the two components are shown on figure 'B'. Large numbers on figure 'A'

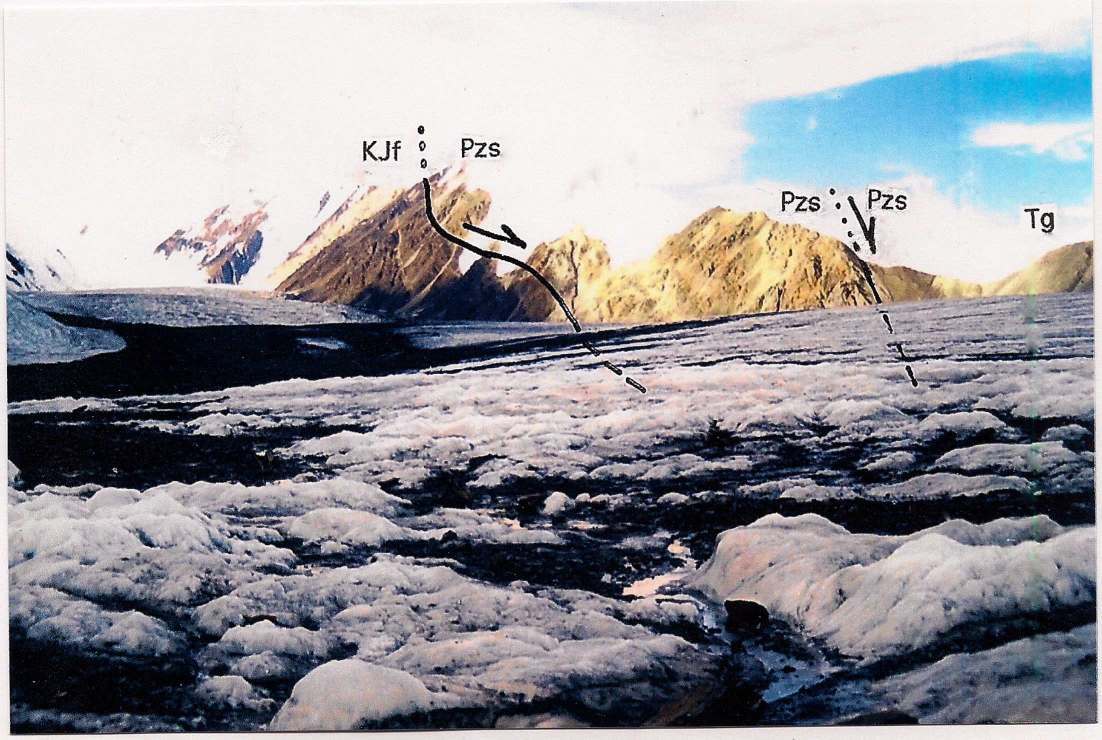
correspond with numbers in figure 'B', and indicate location of analyzed intersection. As numerical magnitude data are not available, at each intersection the parallel vector was assumed to be of the same unit length, and the perpendicular vector was compared to it. Trajectories nos. 1 and 11 have been interpolated from the data by Plafker et al., 1993. See text for further explanation.

## Geology of the Gunsight Pass area: the key to understanding the central and western Denali fault

The best but the previously least studied exposure of the conventionally interpreted Statewide Denali fault in all of Alaska is in Denali National Park and Preserve at Gunsight Pass. It occurs in the steeply carved, approximately 60 m (200 ft) high wall of the valley occupied by the Muldrow Glacier, about a scant 18 km (11 mi) NNE from the summit of Mt. McKinley, in the southern portion of the quarter-million-scale Mt. McKinley quadrangle (figs. 1, 5, 7, 9, 10 and 11). Following St. Amand's (1957) original but conditional (on actual field evidence) concept for a Statewide major strike-slip fault, displayed schematically on a small-scaled map, it was J.C. Reed, Jr. (1961) who first showed on a more detailed map such a fault, the traditional Denali fault, going through Gunsight Pass. Close examination of Reed's "Index to mapping" reveals that locating this fault in Gunsight Pass was not based on field work but on aerial photo interpretations by Clyde Wahrhaftig of the USGS. The fault was also shown by J.C. Reed, Jr. (1961) to juxtapose light-colored Tertiary granitic rocks of the subsequently named McGonagall pluton of Reed and Lanphere (1974) and dark-colored, assumedly Mesozoic sedimentary strata. J.C. Reed, Jr. also reported on the actual field observation of the renowned Alaskan topographer and mountaineer Bradford Washburn that the contact between the two rock types, that is the assumed Denali fault dips toward the north at a moderate angle of 35 to 40 degrees. Unfortunatelly, none of the subsequent earth science investigators field checked this vital information, the only locality where the assumed fault would be actually exposed in a cross section anywhere along its onland surface course of 1900 km. In addition, no one has explained the mechanics of such an uniquely low-angle dip for a major strike-slip fault of continental proportions.

Our detailed geologic field investigations at Gunsight Pass and adjacent areas have revealed that the granite-sedimentary rock contact is actually an intrusive one. This contact is roughly parallel with the bedding of the country rock (figs. 7A and 7B), but is irregular and undulatingly cross-cutting in detail. At the contact the plutonic rocks display a fine-grained border facies, the country rocks show evidence of relatively low-temperature hornfelsing, and there is no evidence of shearing due to tectonic movement (fig. 7C). There are also

A




B

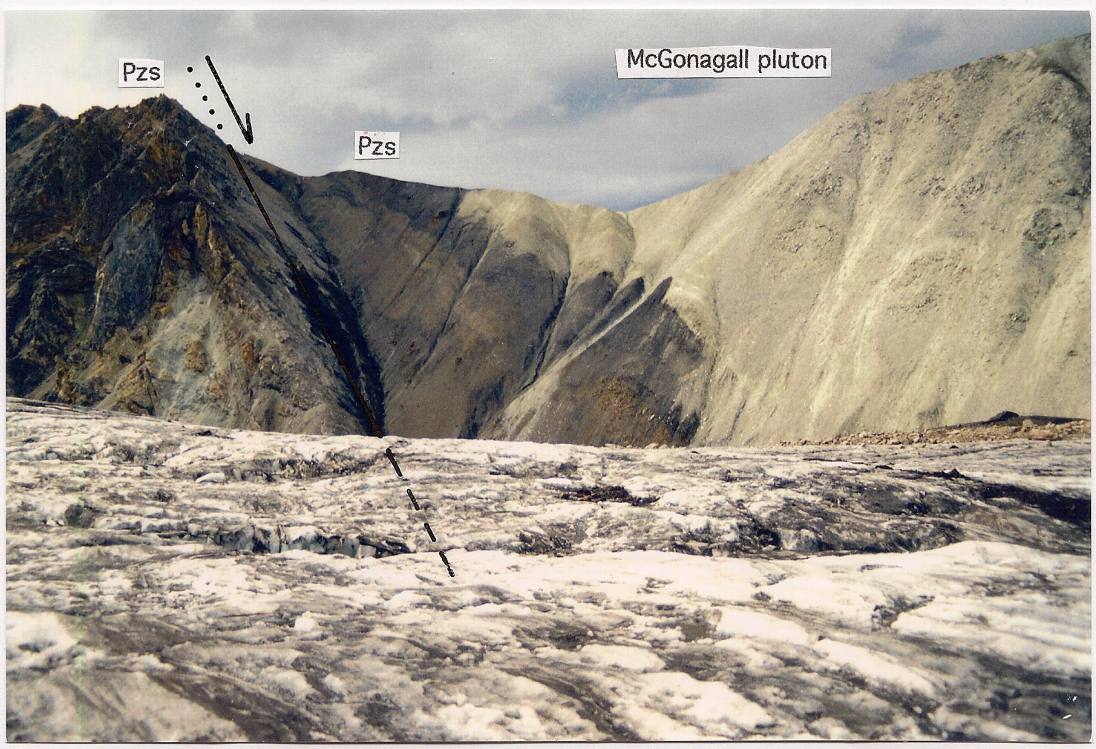



Figure 7. Photos A and B of the Gunsight Pass area in Denali National Park and Preserve, Alaska. Photo captions are given after the photos.

C

D

Figure 7. Photos C and D of the Gunsight Pass area in Denali National Park and Preserve, Alaska. Photo captions are given after the photos.

Figure 7. Captions of photos of the Gunsight Pass area in Denali National Park and Preserve, Alaska.

Photo A - View of Gunsight Pass from the east, about three km away, from the Muldrow Glacier. Mt. McKinley is off the picture, about 20 km to the southwest. Gunsight Pass is near the right edge of the picture. Photo shows well the overall geology of the area around the Pass. Eocene granitic rocks of the McGonagall pluton (Tmg)- in and for about 10 km to the north (right) of the Pass (see fig. 5) - are in intrusive contact with Devonian calcareous sedimentary rocks (unit Pzs on fig. 5). In mid to Late Cretaceous time these Devonian rocks were thrust upon flyschoid rocks of Cretaceous and Jurassic age (unit KJf on fig. 5). In turn, these flyschoid rocks have been intruded by the Mt. McKinley pluton of Paleocene granitic rocks of the McKinley series of Reed and Lanphere, 1973. Mt. McKinley itself is held up by its namesake pluton. There is a northward-dipping normal fault on the south side of the Pass (see figs. 8, 9, and 10), but there is no strike-slip fault. The conventionally proposed course of the Denali fault is through the Pass. The geology of Gunsight Pass and surrounding regions does not permit to postulate the presence of a regional strike-slip fault in or within several tens of km of the Pass (see fig. 9).

Photo B - Closer look at Gunsight Pass, again from the east and from the Muldrow Glacier. Note the irregular and moderately northward dipping intrusive contact of the granodiorite of the McGonagall pluton with the Devonian sedimentary rocks to the south. According to the conventional Denali fault concept, this contact is the Denali fault (Reed, 1961). Note the moderate northward dip of the north-side-down normal fault. With such a moderate dip and the same rocks on either side of it, this fault is highly unlikely to be a major strike-slip feature.

Photo C - Close-up of the granodiorite - sedimentary rocks intrusive contact. Geologic hammer gives scale. Head of hammer is at contact. Note the undulating nature of the contact, the fine-grained border facies of the granodiorite, and the hornfelsic country rocks. Arrow points to a country rock xenolith.

Photo D -. Looking west along the strike of the normal fault at the south side of Gunsight Pass. Were this fault a continuous, regional strike-slip feature cutting across all of Alaska, it would have to bend sharply to the left to clear the mountains in the back. Peters Glacier and the mountains beyond it are about 5 and 7 km distant, respectively. The moderate northward dip and the required sharp bend are strong evidence against this feature being a strike-slip fault. Our structural interpretation of the Gunsight Pass area is shown on figs. 9 and 10.

some rocks which appear to be country rock inclusions. In short, all the classic evidence for an intrusive contact are present. Our investigations has also revealed that the sedimentary country rocks are part of a regionally extensive, thick flyschoid sequence of Ordovician(?) to Middle Pennsylvanian age (unit Pzs on fig. 5; Dumoulin et al., 1998; Csejtey et al., 1996, 1994, 1992 [unit DOs]; Mullen and Csejtey, 1985; Reed and Nelson, 1980).

The nature of the intrusive granitic contact with the Paleozoic sedimentary rocks at Gunsight Pass (figs. 7B and 7C), in conjunction with the fact that the medium-grained core of the pluton lies further to the north, which in turn is bordered by an approximately coeval unit of hypabyssal dacite porphyry (figs 9 and 10), permits the speculation that the McGonagall pluton is an elongated, mushroom-shaped igneous body, that is a laccolith. Accordingly, the contact at the Pass could be the northward-tilted floor of the laccolith, and the dacite porphyry unit could be an earlier phase of the main intrusion which subsequently intruded its own but slightly older subvolcanic rocks. If this speculation is valid, then the intrusive center of the McGonagall pluton is some distance away from the western Denali fault and from the large body of the Foraker pluton (figs. 9 and 10), thus the two plutons could not constitute the offset halves of the same intrusion (Reed and Lanphere, 1974). Consequently, the McGonagall and Foraker plutons cannot be used as evidence for offset along the western Denali fault.

The Paleozoic host rocks of the McGonagall pluton at Gunsight Pass are part of an allochthonous sequence scattered through central Alaska (unit Pzs on fig. 5). During the mid-Cretaceous accretionary orogeny along the margin of the ancient North American continent, these Paleozoic rocks have been thrust upon younger rocks, mostly the thick, dark-colored turbiditic flyschlike rocks of Late Jurassic to Late Cretaceous age, underlying large areas of southcentral Alaska (Csejtey et al., 1996, 1992 [most frequently designated as unit KJf], 1982, 1978; Jones et al., 1981, 1983; Reed and Nelson, 1980). An excellent exposure of this thrust relationship can be seen about 700 m (little less than half a mile) southwest of Gunsight Pass on the sculpted western wall of the Muldrow Glacier valley (fig. 7A and unit DOs on fig. 9). The thrust dips about 30 to 35 degrees to the north, and the bedding of the Jura-Cretaceous turbiditic rocks in the footwall and that of the flyschoid Paleozoic rocks in the hanging wall dip about the same. The similarities of the present dip of the thrust and the enveloping rock units suggest that at the time of thrusting the dip of these features probably was subhorizontal and were subsequently folded or tilted northward.

Our field investigations also revealed that there is a fault at Gunsight Pass, uphill about 150 m (166 yards) toward the south from the lowest part of the Pass and a little less distance from the intrusive granitic contact (figs. 7A, 7B, 7D, 9, 10, and 11). The strike of the fault is about east-west, and it dips to the north at about 55 degrees. Slickensides along the fault plane indicate that the northern fault block moved vertically down or nearly so relative to the southern block (fig. 8). The rocks on both sides of the fault are part of the same Paleozoic unit described as DOs by Csejtey et al., 1992 , and as unit Pzs by Csejtey et al., 1996 (unit DOs on fig. 9, unit Pzs on fig. 5). Sighting down the strike of the fault plane from where it crosses the Pass, looking eastward reveals no particular information, but looking westward along the strike (fig. 7D) it is apparent the trend of the fault has to change sharply, otherwise it would run into a mountain of unfaulted granitic rocks of the McGonagall pluton (fig. 9), only about 6.5 km (4 miles) distant. Were this fault a single continuous feature, the sudden change in its trend would be about 35 degrees, quite unlikely for a regional strike-slip fault of hundreds of kilometers of dextral movement.

Supposing this fault to be a regional strike-slip feature, it would predate the uplift of Mt. McKinley within the last 6 million years (Fitzgerald et al., 1995). In that case, as indicated by the northward-dipping bedrocks and the thrust fault 700 m south of Gunsight Pass, it also should have been tilted northward at least 10 to 15 degrees, making its pre-uplift northward dip at least only 45 to 40 degrees, an impossibly shallow dip for a major strike-slip fault.

The conventional concept of the Statewide Denali fault, as it is generally assumed to project westward from its apex in the central Alaska Range, requires its surface trace to be located, if not at Gunsight Pass proper, then just a few km either to the south or north of the Pass. Just south of the assumed Denali fault trace there are several large granitic plutons in the Talkeetna and Mt. McKinley quadrangles (the Foraker, McKinley, Ruth, and Kahiltna plutons of Reed and Lanphere, 1973; and Reed and Nelson, 1980; for quadrangle locations see fig. 1), that are Paleocene and Eocene in age and extend several tens of km south of the trace of the traditionally postulated strike-slip Denali fault (fig.9; Reed and Nelson, 1980). These plutonic bodies are not cut by any major faults, and thus they effectively void the possibility of a major post-intrusion strike-slip fault being present in that region.

In the region north of Gunsight Pass, in addition to the McGonagall pluton (Reed and Lanphere, 1973) of Eocene age flanking the Denali fault, there are at least six sedimentary and volcanic rock units, ranging in age from Eocene to Ordovician or Devonian, that extend over 30 km north of the fault. This fact makes the postulation of a major strike-slip fault in that region untenable (units Tmgv, Tdp, Kcs, KJf, $\overline{R}$cs, and DOs on fig. 9).

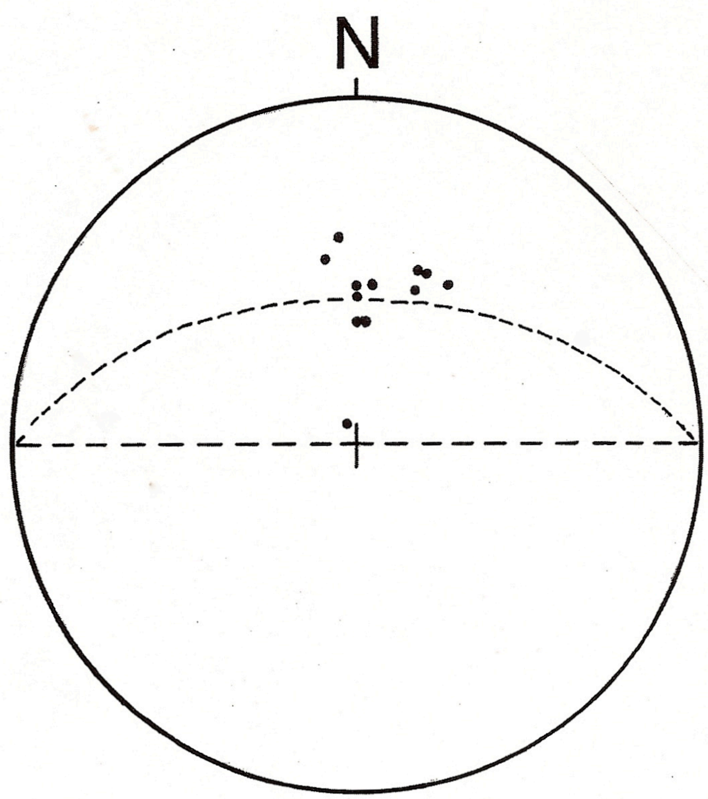



Figure 8. Stereographic plots (lower hemisphere) of slickensides from the normal

fault on the south side of Gunsight Pass in Denali National Park and Preserve, Alaska. Dashed lines show approximate attitude of fault, striking EW, dipping N 55 degrees. Also see figs. 7, 9, and 10.

The results of our geologic field investigations not only failed to disclose any supporting evidence for a major strike-slip fault at Gunsight Pass or in the adjacent regions, but in effect, disprove the existence of such a fault or faults. We raise the hypothetical question: if the formerly postulated major strike-slip Denali fault does not exist near the apex of its southward concave surface trace (fig. 1), near two-thirds of its assumed westward trace, then how can it be a Statewide feature? Clearly, the conventional Denali fault concept needs to be drastically revised.

## An alternative theorem to the conventional Denali fault concept

A major flaw in the conventionall Denali fault concept is that no consideration has been given to the fact that the essentially straight and single fault of eastern Alaska turns sharply in central Alaska, and westward from near Paxson (fig. 1) it gradually transforms into a fault zone of a number of subparallel, regionally discontinuous and essentially coeval faults (figs. 11 and 12). Most of these faults have not only been known for some time, but also were known to be high-angle reverse and subordinate normal faults, accompanied by tight to open folds. Many of these faults and folds are large and extend for tens of kilometers (figs. 2, 11 and 12). Clearly, the active strike-slip Denali fault of eastern Alaska undergoes a change in its structural character in central Alaska near the apex of its surface trace, and from there on westward this fault is only one in a zone of complex, individually discontinuous, dominantly dip-slip faults.

The age of the individual faults of the fault zone is somewhat conjectural. Clear-cut evidence for recent fault activity is restricted to the surface trace of the conventionally depicted Denali fault, from eastern Alaska westward to about the western edge of the Healy quadrangle, and to an unnamed fault just north of the McGonagall pluton in the Mt. McKinley quadrangle (figs. 1, 10 and 11). On the other hand, many of the faults in the zone are spatially associated with the recently active portions of the Denali fault, and at many localities they cut sections of the latest Miocene to middle Pliocene (roughly 6 to 3 Ma) Nenana Gravel (Csejtey et al, 1992; Csejtey et al., unpub. data). Many of these faults clearly control the present topography of the central Alaska Range and adjacent mountainous areas. The Nenana Gravel is interpreted to signal the onset of rapid uplift of the Alaska Range (Capps, 1940; Wahrhaftig, 1970a, 1975). We conclude that the individual faults and the associated structural features of the active fault zone and evolving topography of the central Alaska Range started to develop about 6 Ma ago, roughly at the same time as the

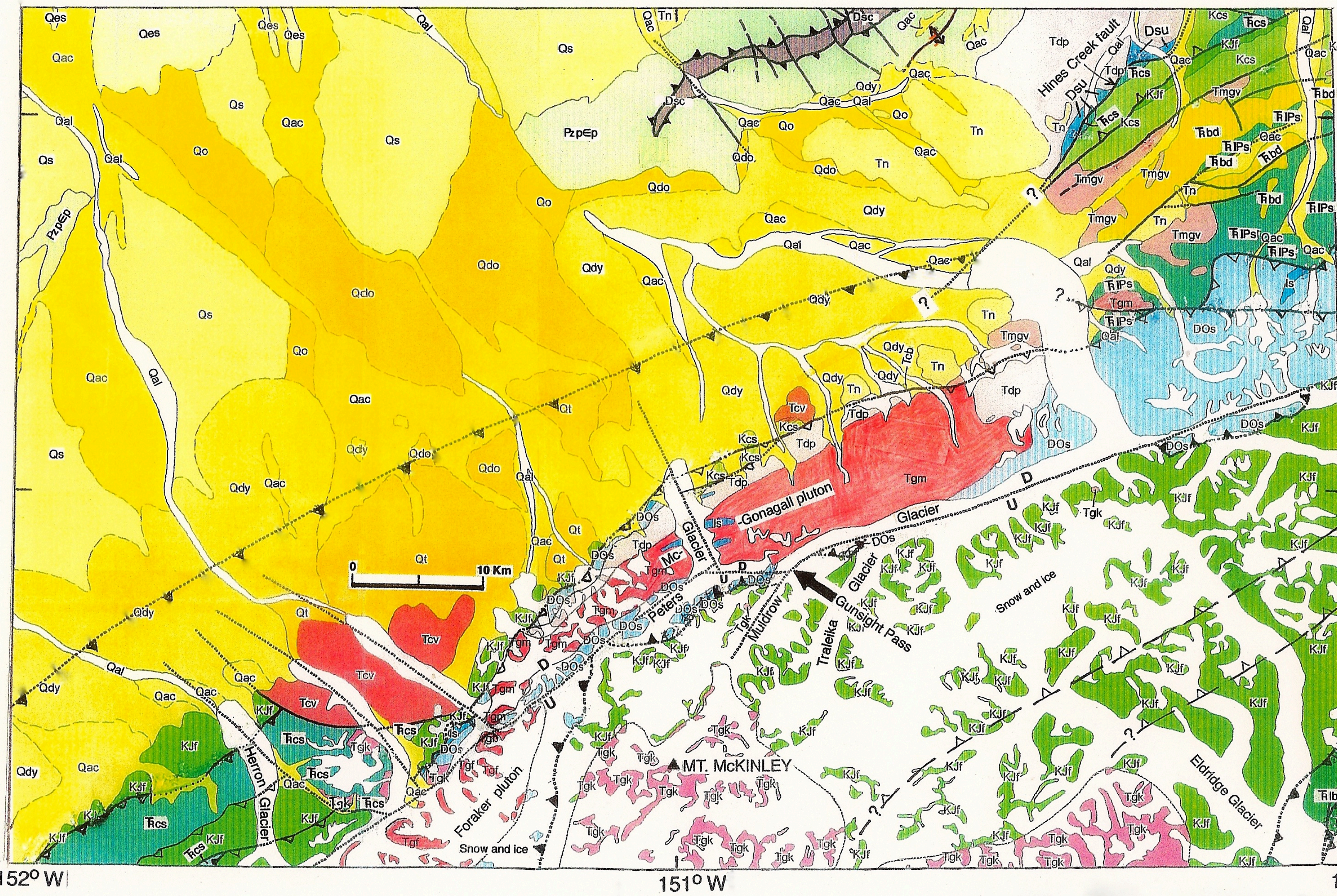



Figure 9. Geologic map of the Gunsight Pass area, Denali National Park and Preserve,

Alaska. Regional geologic considerations require that if there were a presently active, major strike-slip fault cutting across all of Alasks, then it would have to go through Gunsight Pass, or within a few km from the Pass. The presence of large, regionally unfaulted granitic plutons south of the Pass, and continuous, northeast-southwest trending rock units north of the Pass make this most unlikely if not impossible. Mapping by the authors, 1984 - 2004; north-central part of map area modified after Bundtzen, 1981; and northeastern map area modified after Gilbert, 1979.

List of map units for map of figure no. 9

Surficial deposits (after Yeend, 1997):

Qal - Alluvium (Holocene)
Qac - Alluvium and colluvium (Holocene)
Qs - Silt and sand, in part loess (Holocene and Pleistocene)
Qes - Eolian sand (Holocene and Pleistocene)
Qo - Outwash gravel (Pleistocene)
Qdy - Younger drift deposits (Pleistocene)
Qdo - Older drift deposits (Pleistocene)
Qt - Till (Pleistocene)

Note: Unless otherwise indicated, further descriptions and references for the units below can be found in Csejtey et al., 1992

Sedimentary and volcanic bedrock units:

Tn - Nenana Gravel (Pliocene and late Miocene)
Tcb - Coal bearing rocks (Miocene to Eocene)
Tmgv - Mount Galen basaltic to rhyolitic volcanic rocks (early Oligocene to early Eocene; Decker and Gilbert, 1978)
Tcv - Cantwell formation volcanic member ranging from basalt to rhyolite (Paleocene)
Kcs - Cantwell formation terrestrial sedimentary member (latest Cretaceous; new age by Ridgway et al., 1997)
KJf - Thick marine sequence of flyschlike turbiditic rocks (Early Cretaceous and Late Jurassic)
TRcs - Calcareous marine sedimentary rocks (Late Triassic)
TRbd - Submarine sequence of basalt, diabase, and subordinate sedimentary rocks (Late Triassic)
TRIPs - Flyschlike marine sedimentary rocks (Late Triassic to Pennsylvanian)
Dsu - Undivided metasedimentary and metavolcanic rocks of equivalent units Dmf, Dmb, and Dms in the adjacent Healy quadrangle (Late Devonian)
DOs - Thick marine sequence of dominantly slope and basinal turbidites with subordinate shelf deposits, including massive limestone [ls on map] (Middle Devonian to Ordovician)
Dsc - Spruce Creek assemblage of phyllite, mica schist, and metabasalt (probably Devonian; Bundtzen, 1981)
Pzp∈p - Pelitic and quartzose schist sequence (middle Paleozoic to Precambrian?)

Plutonic and hypabyssal intrusive rocks:

Tgk - McKinley series granites (early Eocene and late Paleocene; Reed and Nelson, 1980)
Tdp - Dacite porphyry (early Oligocene and late Eocene; unpub. information by the authors)
Tgm - Granodiorite of McGonagall pluton (late Eocene; Reed and Lanphere, 1974)

Tgf - Granodiorite of Foraker pluton (late Eocene; Reed and Nelson, 1980)

Thrust slices in southeast corner of map area:

J₹rs - Red and brown sedimentary rocks and basalt (Early Jurassic and Late Triassic)
₹lb - Limestone and basalt sequence (Late Triassic)
Dsb - Serpentine, basalt, chert, and gabbro (Late Devonian)

Standard fault and contact symbols.

beginning of deposition of the Nenana Gravel. We also suspect that the individual faults did not develop all at once, and when they did neither did they move constantly nor simultaneously but intermittently and not in unison. Thus, it is probable that a number of the early faults were covered over by deposits of the Nenana Gravel, and when reactivated have cut the same Nenana Gravel. Some faults of the swarm have developed clearly after Nenana Gravel time. The fault swarm as a whole is still active as part of the ongoing orogenic deformation, discussed later, of southern Alaska. The general lack of surface expressions of recent movement along many or most of the faults of the swarm could be the result of ongoing intensive soil movement and surficial erosion due to severe weather conditions in the high latitude and rugged alpine terrains of central Alaska.

The dominant zone of transition from strike-slip to dip-slip movement along the Denali fault extends from near Paxson into the eastern Healy quadrangle, to about longitude 148º W (figs. 1, 2, and 11).. This transitional segment of the fault swarm comprises westward diverging, dominantly high-angle reverse faults, and its northernmost and southernmost faults dip toward the center of the swarm, the northern ones toward the south, and the southern ones toward the north (figs. 2 and 3; also see geologic cross sections in Nokleberg et al.,1992, and Csejtey et al., 1992). The Denali fault is only one of these faults. The individual faults of the swarm eventually either die out westward, some in a fold, or are truncated by other coeval faults (figs. 2 and 11). These faults dying out and truncations occur in the eastern half of the Healy quadrangle, roughly between longitudes 147º and 148º W, approximately between 75 and 125 km (roughly 46 and 78 mi) from the point near Paxson (figs. 1, 2 and 11) where the single strike-slip fault of eastern Alaska starts breaking up. Where the faults of the dominantly transitional zone terminate, other coeval, westward- to southwestward-trending faults take up the apparent crustal shortening of the region (figs. 11 and 12).

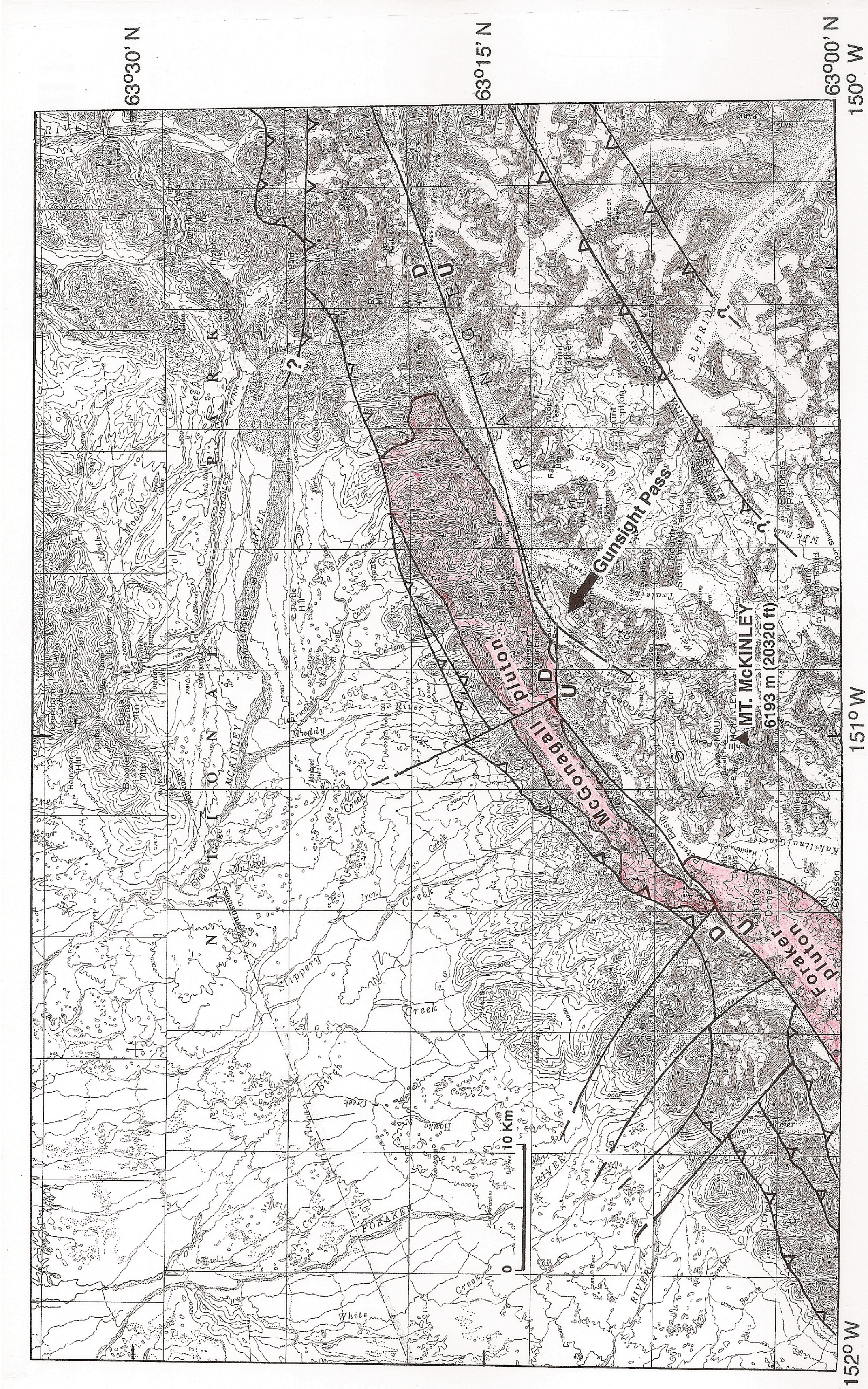



Figure 10. Generalized structural map of the Gunsight Pass area, Denali National Park and Preserve, Alaska. Map shows our interpretation of the Late Cenozoic

fault configuration at Gunsight Pass. Field mapping the southern boundary of the McGonagall pluton, much of it is well exposed, indicates that most of it is not a fault contact, as proposed by the proponents of the conventional Denali fault concept, but an intrusive one. This fact alone is sufficient to negate the interpretation of the McGonagall and Foraker plutons being the offset halves of an originally single intrusive body. Background map is the scaled-down version of the southeast portion of the Mt. McKinley 1:250 000-scaled topographic quadrangle map of the U.S. Geological Survey. Elevations are in feet. Although it is hard to read, it still gives a good indication of the rugged topography of the Alaska Range in the region.

The continuation of the fault swarm southwest of the Mt. McKinley region is less well known due to the lack of detailed geologic mapping. However, available small-scale synthesizing geologic maps ( Beikman, 1980; Plafker and others, 1993) show the continuation of a similar pattern of faults of known or suspected late Neogene age, although fewer in numbers, in the regions southwest of the Mt. McKinley area (fig. 12). Future geologic mapping in southwest Alaska may well disclose additional faults as part of the swarm.

Figure 13 shows a regional geologic cross section drawn across the central Alaska Range in the Mt. McKinley and Talkeetna quadrangles, running from the NW corner of the Mt. McKinley quadrangle to a point on the southern boundary of the Talkeetna quadrangle, about 19 km due west from its SE corner. The line of the cross section runs southwest of Mt. McKinley. The cross section not only shows the structural features, mostly thrusting caused by the mid- to Late Cretaceous accretionary orogeny (Csejtey et al., 1982, 1992), but the dominantly dip-slip faulting of central Alaska as well, taking place within the last 6 million years (Capps, 1940; Wahrhaftig, 1970a; Fitzgerald et al., 1995; this paper). It clearly shows the uplifted crustal block of Mt. McKinley, lying about 35 km to the northeast of the section. The late Cenozoic dip-slip faults show a pattern similar to those of the cross section on figure 3.

The overall structural features of the late Cenozoic fault swarm in the central Alaska Range appear to be analogous to the phenomenon called "composite wedge", as named and described by Migliorini (1948) from the Italian Appenines. (An English summary of this structural phenomenon can be found in De Sitter, 1964). In cross section, a composite wedge comprises a number of centrally upthrust wedge-shaped blocks, bounded by upward-diverging faults (figs. 14 and 15). The similarity of the fault swarm to Migliorini's composite wedge feature is especially striking in the area between Paxson and longitude 153º W. Compare Migliorini's figures with the cross sections of figs. 3 and 13.

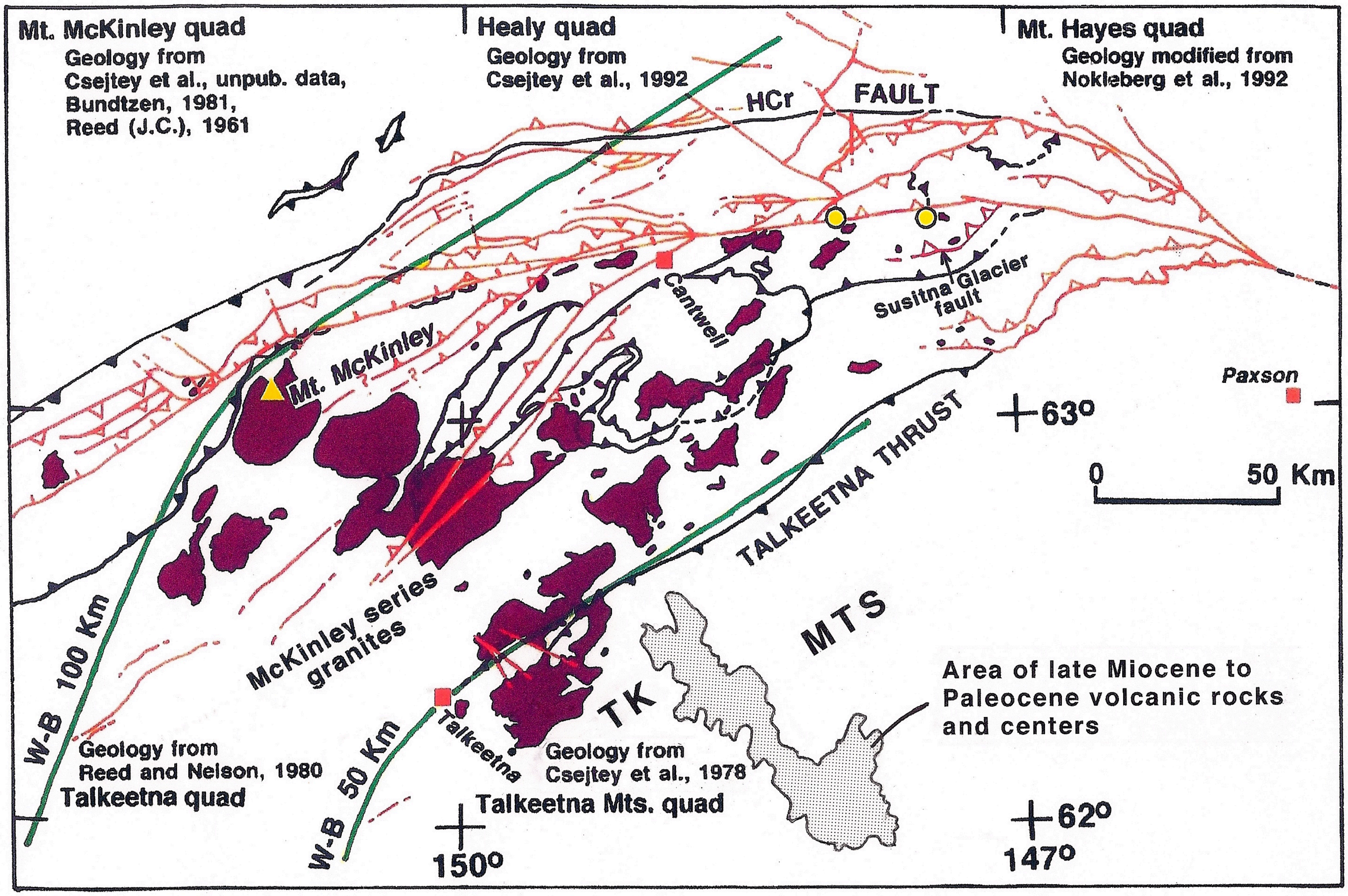



Figure 11. Map showing the major Cretaceous (black) and Cenozoic (red) faults in the central Alaska Range and Talkeetna Mountains regions of central Alaska. Most

of the Cenozoic faults are of late Cenozoic age, and are interpreted to outline structural features very similar to the composite wedges of Migliorini(1948). See text for further explanation. Note the tight cluster of the plutons (maroon) of the early Eocene and late Paleocene McKinley series granites (Reed and Lanphere, 1973), straddling both the Cretaceous and Cenozoic faults, precluding any appreciable strike-slip displacements along them since the intrusions of those plutons. The green lines labeled W-B 100 Km and W-B 50 Km show the 100 km and 50 km below-sea-level contours of the present Wadati-Benioff zone (Plafker et al., 1993). Also note the position of the late Miocene to Paleocene volcanic rocks and centers relative to W-B 50 Km contour. HCr fault -- Hines Creek fault. Black-rimmed yellow dots mark the epicenters of the two 2002 major earthquakes. That of the M7.9 event is on the right, and of the M6.7 event on the left. It appears the M7.9 event was caused by the newly developed Susitna Glacier high-angle reverse fault of Eberhart-Phillips et al., 2003. The immediate cause of the M6.7 event is not clear. TK MTS -- Talkeetna Mountains.

An obvious difference between Migliorini's composite wedge feature and the fault swarm of the Alaska Range is scale. Migliorini's cross section of the Montagna del Murone composite wedge (fig. 14) is barely 10 km wide but the herein proposed composite wedge straddling the Healy and Mt. Hayes quadrangles has a maximum width of about 70 km, and near Mt. McKinley, although less well known, the fault swarm appears to be in excess of 100 km wide. Tha authors cannot perceive any reason why the difference in size would preclude the application of the composite wedge concept in the Alaska Range.

Another difference is that the late Cenozoic faults in central Alaskan not only outline wedge-shaped blocks in cross section, but many of them do so on the surface as well. As a result, it is quite likely that the total displacement along many of these faults also includes a minor horizontal component of a few tens or perhaps up to a few hundred meters at most.

According to Migliorini (1948), an upward inclined field of compressional force is required for the "composite wedge" mechanism to develop (see fig. 15). For such a compressional field in much of central Alaska we propose the following scenario. In the areally extensive Talkeetna Mountains lying just east of the town of Talkeetna, fig. 11), large areas are underlain by a thick sequence of felsic to mafic subaerial and related hypabyssal volcanic rocks of Eocene to late Miocene, possibly of Pliocene age (Csejtey et al., 1978). According to plate tectonic concepts, in a subduction system the undergoing plate should descend to a depth of at least 100 km for magma generation (for instance, see general discussion in Wilson, 1989). However, the present depth of the Wadati-Benioff zone is only 50 km under the middle of the Talkeetna Mountains volcanic area (figs. 11 and 16; Plafker et al., 1993), strongly suggesting that the present depth of the Wadati-Benioff zone is far too shallow to have generated these volcanic rocks. Within the last 5 to 6 million years the position of the subducting lithospheric plate must have flattened out and thus the upper plate became much thinner under most of southcentral Alaska (fig. 16; also discussion and figs. 9, 10, and

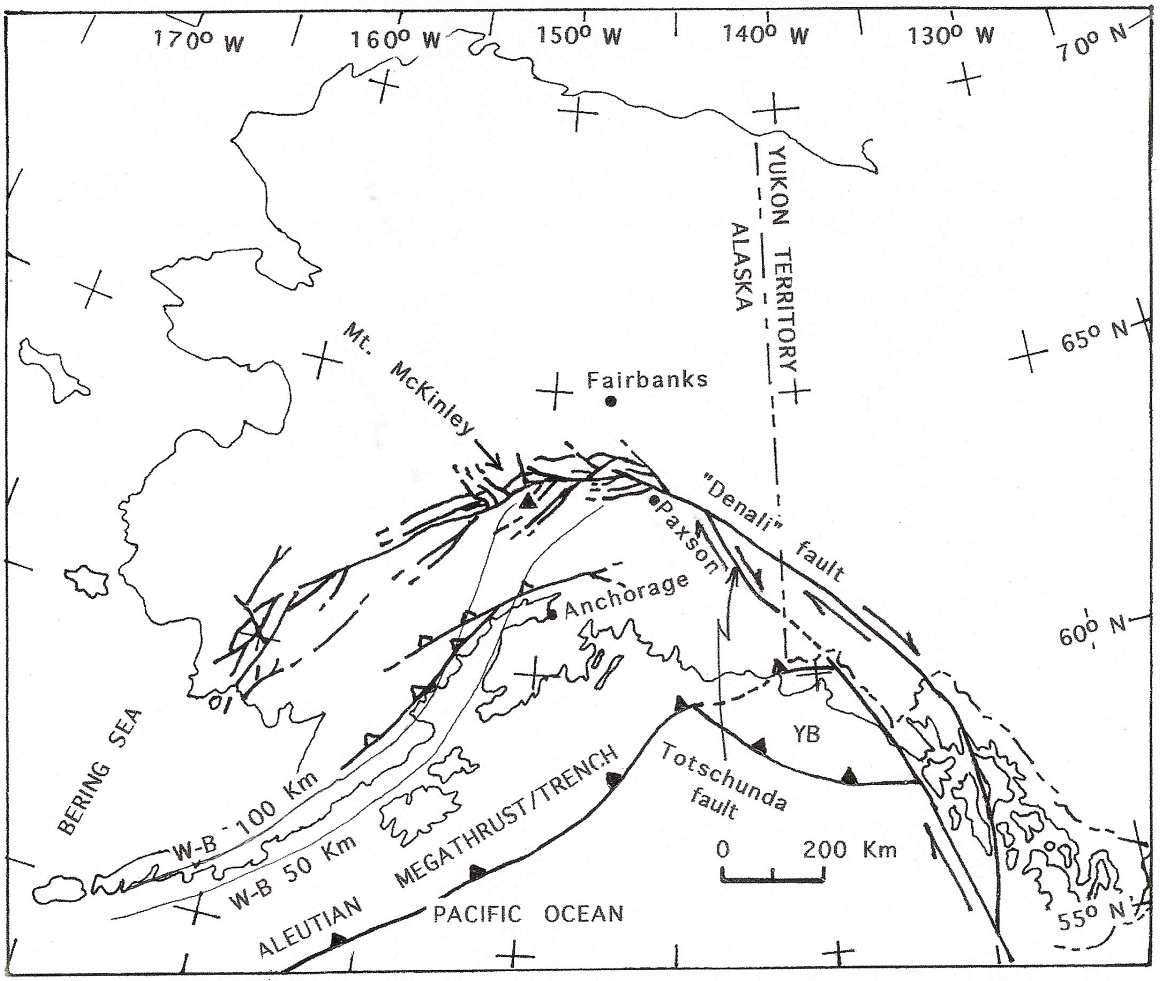



Figure 12. Generalized Neotectonic map of southern Alaska. The map shows how the conventional Denali fault, a single Cenozoic strike-slip feature in eastern Alaska, breaks up into a fault swarm westward from near Paxson. Because of the small scale of the map, only the larger faults of the swarm could be shown, and some of them only in a schematic fashion. Nevertheless, the map is considered to be more than adequate to display the westward change of the conventional Denali fault. The thin lines labeled W-B 100 Km and W-B 50 Km show the 100 km and 50 km below-sea-level contours, respectively, of the present Wadati-Benioff zone. Map compiled from Plafker et al., 1993; Csejtey et al., 1992 and unpub data; Nokleberg et al., 1992; and Reed and Nelson, 1980. YB - Yakutat block. Heavy lines with solid teeth are thrust faults, teeth on upper plate; heavy lines with open teeth are high-angle reverse faults, teeth on upper plate.

11 in Csejtey et al., 1982; and a short dicussion in Csejtey et al., 1978). We propose that this flattening and accompanying thinning and compression of the upper plate provided the northwestward and upward directed compressional field to have produced the composite wedge-type structures in large parts of central Alaska, especially along the Alaska Range

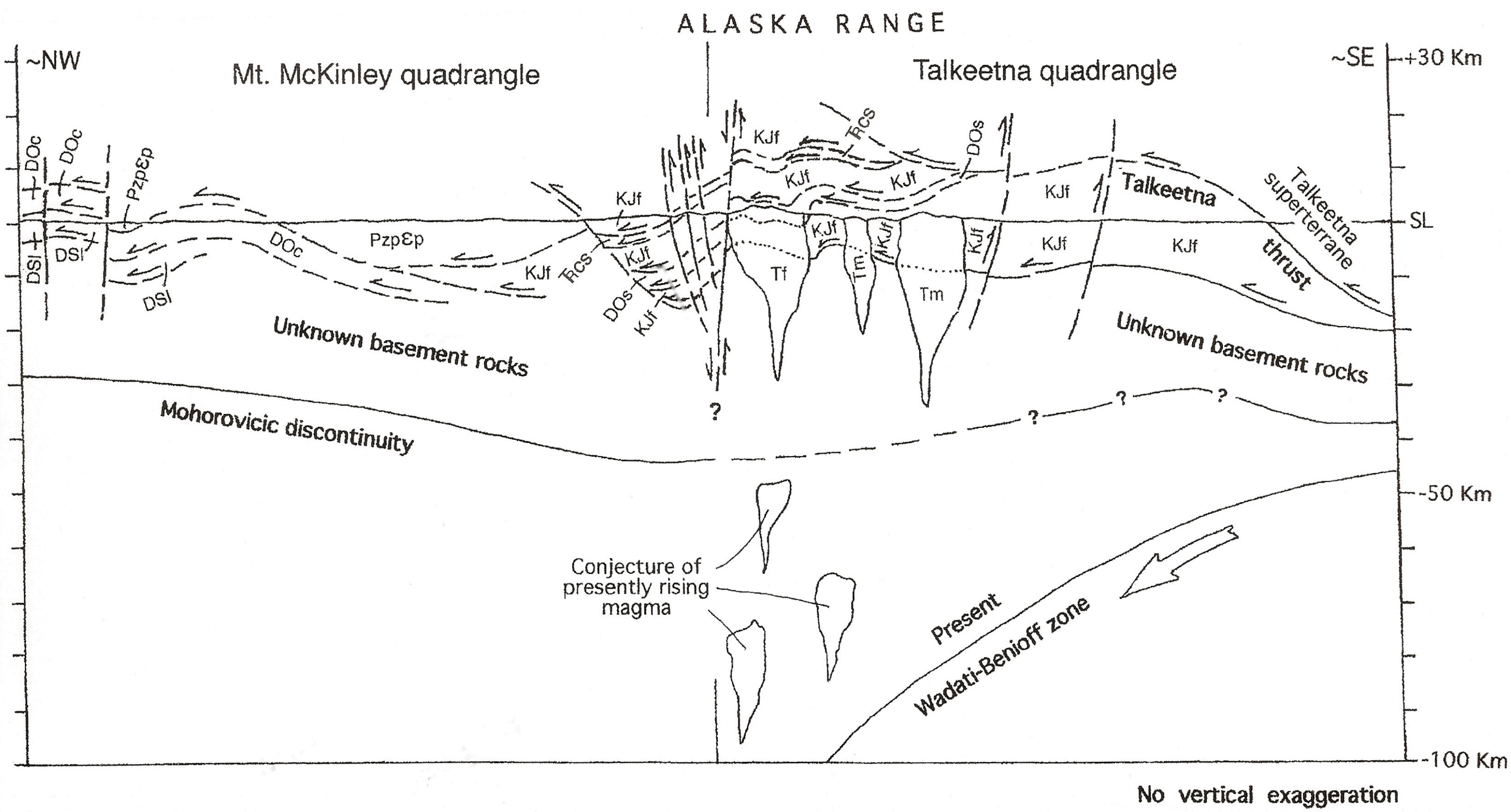



Figure 13. Generalized cross section across the Mt. McKinley and Talkeetna quadrangles, Alaska. Section runs from the northwest corner of the Mt. McKinley

quadrangle across the Alaska Range to the southern boundary line of the Talkeena quadrangle, about 18 km from its southeast corner. See figs. 1 and 11 for quadrangle locations. The section shows the low-angle and folded thrust sheets formed by the mid- to Late Cretaceous accretionary orogeny and the high-angle dip-slip faults in the Alaska Range forming composite wedges of late Cenozoic age. An interesting deduction from this cross section is the possibility of volcanic activity sometimes in the future, along and near the present 100 km below sea-level contour of the Wadati-Benioff zone as far north as Mt. McKinley. For subsurface Wadati-Benioff contours see figs. 11 and 12. Wadati-Benioff zone is after Plafker et al., 1993; and the depth of the Mohorovicic discontuity is after Barnes, 1977; and Veenstra, et al., 2006. Tf - Eocene granodiorite of Foraker pluton (Reed and Nelson,1980). Tm - Lower Tertiary granitoids of McKinley sequence (Reed and Nelson, 1980). KJf - Upper Cretaceous to Upper Jurassic flysch-like rocks (Csejtey et al., 1978; 1992). T̄Rcs - Upper Triassic calcareous marine sedimentary rocks (Csejtey et al., 1992). Talkeetna superterrane - Volcanic and sedimentary rocks of Late Triassic to Pennsylvanian age (Csejtey et al., 1978; 1992). DOs - Upper Devonian to Ordovician marine sedimentary sequence (Csejtey et al., 1992; 1996). DSl - Devonian and Silurian reefy limestone and dolomite (Patton et al., 1980). DOc - Devonian to Ordovician chert and slate (Chapman et al., 1975). Pzpεp - Lower Paleozoic and Precambrian? pelitic and quartzose schist sequence (Csejtey et al., 1992).

(figs. 3, 13 and 16). The timing of the late Cenozoic deformation (within the last 6 m.y.), and the flattening of the Wadati-Benioff zone within the same approximate time interval strongly suggest a "cause and effect" relationship between these two geologic events in central Alaska.

## Tectonic interpretations and conclusions

Geologic investigations by the authors in central Alaska in the last 35 years indicate that the widely accepted concept of the Denali fault system as a State-wide dextral strike-slip system (for example, Ruks et al., 2006; also see figs. 1 and 5), is erroneous. Our conclusion is that in eastern Alaska the Denali fault and the Totschunda fault which joins it are an active strike-slip fault system. But westward from the vicinity of Paxson, near where the surface trace of the conventionally defined Denali fault turns from a northwest-southeast direction to a southwest-northeastern one, that strike-slip fault changes into a fault swarm of dominantly dip-slip displacements (see figs. 2, 11 and 12). Csejtey has proposed as long ago as 1976 that the currently active Denali fault changes into a dip-slip feature in central Alaska. Only recently has a geologic publication (Matmon et al., 2006) expressed a similar interpretation.

In our concept the eastern portion of the conventional Denali fault is an old transform boundary fault that has developed between the northwestward-moving Talkeetna superterrane and the ancient North American continent in mid- to Late Cretaceous time, during the last stages of the superterrane being accreted to the continent (Csejtey et al., 1982). This accretion took place primarily by obduction, that is the Talkeetna superterrane having been thrust over the margin of the ancient North American continent. The remnant of the leading edge of the obducted superterrane is the present Talkeetna thrust (Csejtey et al., 1978, 1982). The dominant form of deformation along the leading edge was thrusting and folding. Through much of the Cenozoic, until about 6 Ma ago, continued subduction of the Pacific plate did exert varying degrees of compressional deformation on the continental margin. The geologic record indicates that the severity of this deformation caused by the continued Cenozoic subduction of the Pacific plate was relatively minor compared to the Cretaceous accretion-related deformation, except for a short period of more intense deformation in the early Cenozoic (Gilbert, 1976).

Starting about 6 Ma ago, the long phase of relatively minor tectonism in the southern parts of Alaska has been superseded by a still ongoing period of much more intense compressional crustal deformation. In eastern Alaska this deformation is primarily manifested, in conjunction with crustal vertical movements of large areas, by recurring northwestward dextral strike-slip displacements along the eastern part of the Denali fault and along the Totschunda fault. We estimate the cumulative dextral displacements along these faults in the last 6 Ma to be at most not more than a few tens of km.

In central Alaska the strike slip movement along the eastern Denali and Totschunda faults translates into a generally southwestward-trending broad zone of compressional features such as subparallel high angle reverse faults, open and tight folds, and large areas of crustal uplift. Subordinate normal faults also occur in this zone. (For an overview of this tectonic changeover see fig. 12). In central Alaska this fault zone coincides quite well with the areal extent of the present Alaska Range. A characteristic feature of the zone is that its faults converge downward toward the center of the zone, and outline a number of upthrust wedge-shaped crustal blocks of regional dimensions (figs. 3 and 13). These fault configurations appear to be analogous to the structural features described and named from the Italian Appenines by Migliorini (1948) as composite wedges, caused by an upward inclined compressional field (figs. 14 and 15).

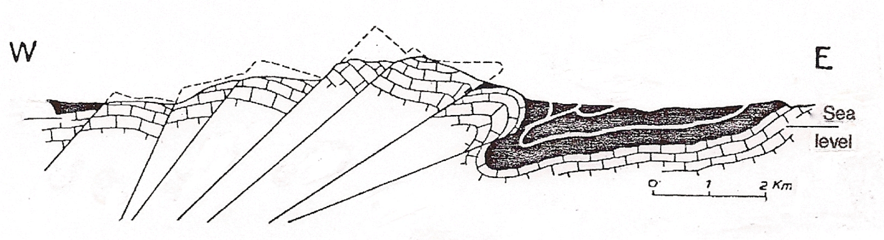



Figure 14. Cross section of a typical composite wedge, the Montagna del Morrone, in the northern Appenine Mountains of Italy. After Migliorini (1948). Triassic to

middle Miocene limestones overlain by Tertiary and Pliocene clastic rocks shown in black. See text for further discussion.

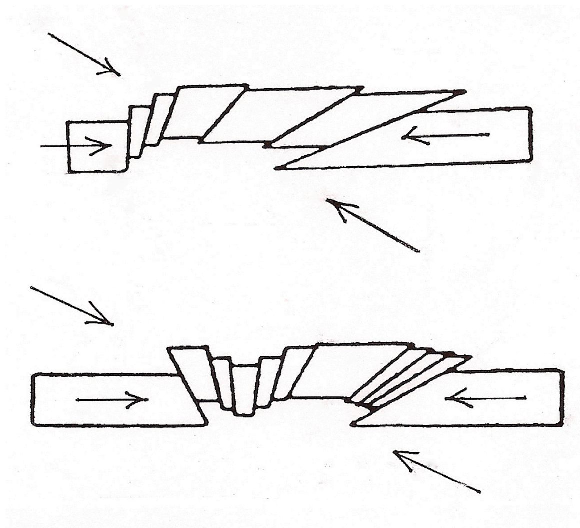


Figure 15. Diagrammatic cross sections of various composite wedge configurations. After Migliorini (1948). These structural features are interpreted to have been caused by an inclined field of compression, as shown by arrows. Most if not all of the present central Alaska Range in southcentral Alaska is herein interpreted to have developed by this structural process within the last 6 Ma.

We postulate that the composite wedge structures were caused by the shallowing of the subducting Pacific plate under central Alaska, that is under a part of the already accreted continental margin of North America, commencing about 6 Ma ago (fig. 16). In order to make space for the upward moving subducting plate, it eroded and compressed the upper plate, producing an upward directed field of compression (see arrows in figs. 15 and 16). It also means that the present 50 and 100 km depth contours of the subducting plate under the upper NorthAmerican plate in central Alaska must have been located considerably further south prior to 6 Ma ago. The best evidence for this is the occurence of a large, late Paleocene to Miocene volcanic center in the central region of the Talkeetna Mountains (Csejtey et al., 1978). This volcanic center, having a northwest elongated outcrop pattern, lies only 50 km or less above the present subduction zone, roughly 80 to 110 km (50 to 70 mi) to the east and east-southeast, respectively, of the town of Talkeetna (figs. 11 and 16). According to petrologic investigations (among others, see in Wilson, 1989), this depth is too shallow to generate magma along a subducting plate.

The Talkeetna Mountains volcanic field occurs along an arcuate line connecting the Aleutian volcanic chain and the volcanic center of the Wrangell Mountaions of eastern Alaska. In view of the observed lack of high grade metamorphic rocks in the Talkeetna Mountains and adjacent regions, the location of the Talkeetna volcanic center along the connecting line between the Aleutian volcanic chain and the Wrangel Mountains volcanic complex, strongly suggests a subduction related origin for the Talkeetna Mountains volcanics. Accordingly, up till the end of the Miocene the 100 km contour of the subducting Pacific plate must have been located somewhere beneath the Talkeetna Mountains volcanic center, and has moved subsequently northwestward to its present location (figs. 11 and 12), exerting the inclined compressional field stipulated in this study. Geophysical investigations by Fuis et al. (2008), show the presence of a northwest-trending tear in the subducting lower plate below the region just east of the Talkeetna Mountains. We interpret this tear as the eastern edge of the flattened portion of the subducting Pacific plate, a process starting in late Miocene time, effectively shuting down volcanic activity in the Talkeetna Mountains.

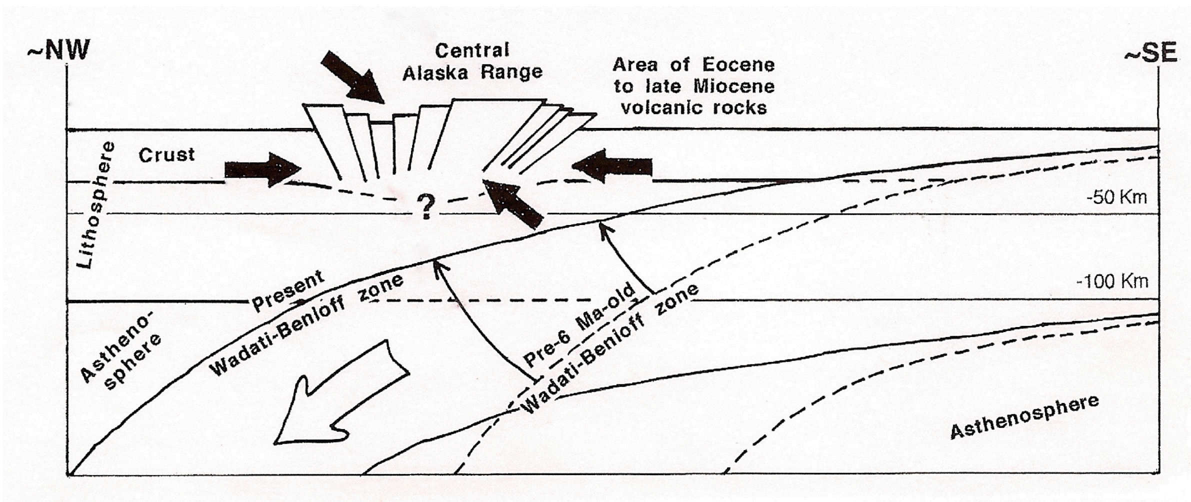



Figure 16. Schematic cross section of southcentral Alaska. Shows our interpretation of how the shallowing of the subducting lithospheric plate within the last approximately 6 million years produced an inclined field of compression (heavy arrows), which in turn caused large-scale composite wedge type structures (Migliorini, 1948) to develop in much of the region, especially in the central Alaska Range. The inclined field of compression is speculated to have been caused by the shallowoing or flattening out of the position of the downgoing or subducting lithospheric plate under central Alaska within the last about 6 million years. The initial compressional field may have been nearly horizontal, but it had became progressively more inclined as the downgoing plate gradually changed its positon.

The composite wedge-type faults and associated compressional features of central Alaska are interpreted in this report to result from the flattening, that is shallowing of the underlying subducting Pacific plate within the last 6 Ma. However, the westward change in the displacement character of the conventionally viewed Denali fault in central Alaska, from strike-slip to a dominantly dip-slip displacement, we interpret as the surface manifestation in the relatively thin upper plate of the westward transition from transform fault to trench movement mode of the underlying subducting Pacific plate. This present transition from transform to trench movement in the Pacific plate can be seen quite well on fig. 12, and on fig. 3 of Plafker et al. (1993).

Since the mid- to Late Cretaceous accretionary development of southern Alaska, the Pacific plate always had a generally north- or northwestward motion relative to the North American Continent (for instance, Csejtey et al., 1982). Thus the transform to trench transition in the subducting Pacific plate appears to have been always present adjacent to southern Alaska. Many of the compressional structural features in central and southern Alaska are the result of this accretionary process. However, the development of the composite wedge-type structural features in central Alaska, superimposed on older features, we interpret to have been the result of the shallowing of the subducting Pacific plate in the last 6 Ma.

In his proposal for the Denali fault, St. Amand (1957) makes the following cautionary remark about the acceptance of the concept of an Alaska-wide strike-slip fault (pages 1368 and 1369):

"... Field studies are needed to determine the sense of motion and the nature of the Denali fault and the rest of the complex. ... It will be years before a reasonably detailed answer will be available or that the whole of the Denali fault system can be considered a single fault, or zone of faulting with certainty, and not a fortuitous concatenation of topographic and structural trends."

As in the case of many conditional proposals in geology, without any further comprehensive geologic field investigations along the entire length of the proposed fault, the Denali fault has been projected from eastern Alaska and widely accepted as a Statewide strike-slip fault. As such, the concept not only became widely accepted but, in our opinion, it has discouraged other possible interpretations for the fault. The probability of some recent tectonic theories of Alaska (for instance, Redfield et al., 2007) actually depend on the validity of the Statewide strike-slip Denali fault concept.

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