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Late Cenozoic Uplift of Denali and Its Relation to Relative Plate Motion and Fault Morphology

Paul G. Fitzgerald, Edmund Stump, Thomas F. Redfield

Apatite fission-track analysis of samples that cover a 4-kilometer vertical section from the western flank of Denali (Mount McKinley), North America's highest mountain, suggests that the mountain massif was formed by rapid uplift (>1 kilometer per million years) beginning ~6 million years ago (Ma). Uplift was a result of the morphology of the Denali fault and a change in motion of the Pacific plate with respect to North America at ~5 Ma, which created opposing tangential vectors of relative movement along the fault and forced the intervening crustal blocks upward.

Terrane theory provides a framework within which the development of the western Cordillera of North America is perhaps best understood (*1*). Quantification of the geometric interactions between the North American, Farallon, Kula, and Pacific plates can help constrain the geologic history of Cordilleran terranes and the kinematics of their boundaries (*2*). Together, plate motion models and geochronologic studies can place significant constraints on geologic interpretations.

During the late Mesozoic and early Tertiary, the accretion of exotic terranes reshaped the margin of western North America (*1, 3, 4*). In southern Alaska, subsequent thrusting and strike-slip faulting dissected these terranes. Boundaries between terranes and dissected fragments are now complex deep-seated ductile shear zones that may show evidence for recurrent movement (*4, 5*). The Denali fault system (DFS), a major crustal break, has experienced both postaccretionary dextral shear and vertical high-angle reverse movements (Fig. 1) (*5–7*). The still-active McKinley strand of the DFS truncates the Hines Creek fault, along which little major strike-slip movement has occurred since 95 Ma. Some dip-slip and local strike-slip motion may have occurred in the Paleocene and in Recent times along the Hines Creek strand (*8*). Estimates of dextral offset along the McKinley fault strand since Oligocene time vary from <10 to 38 km (*6, 9*). Elsewhere along the DFS, estimates of post-Mesozoic dextral offset vary from ~400 to ~200 km (*7, 8*). Alternatively, apparent horizontal displacement of terranes along the DFS may be a result of thousands of meters of vertical offset combined with only a few kilometers of dextral movement (*4, 6*). In this report we suggest a cause of uplift for the Denali area by integrating apatite fission-track data, relative plate motions, and regional geological and geophysical constraints.

In Denali National Park south of the McKinley strand, granite plutons intrude undifferentiated Jurassic-Cretaceous flysch. Plutonic rocks of south-central Alaska were emplaced in the early and middle Jurassic (176 to 154 Ma), the late Cretaceous and early Tertiary (83 to 56 Ma), and the middle Tertiary (38 to 28 Ma) (*10*). Most of the plutons in the Denali region (the McKinley sequence) are undeformed and of late Cretaceous to early Tertiary age, although some middle Tertiary plutons are also present. By the late Mesozoic, the terranes of south-central Alaska were assembled, although not necessarily in their present location. South of the McKinley strand, the granitic massifs of Denali (6194 m), Mount Foraker (5183 m), and Mount Hunter (4441 m) dominate the Alaska Range. Differential erosion has undoubtedly accentuated these peaks; the rest of the range is composed largely of less competent metasedimentary rocks. Nearby, other largely granitic massifs along the DFS, such as the Kichatna Mountains and the Mount Deborah region, have lower elevations and less relief.

Apatite fission-track thermochronology provides information on the timing, rate, and amount of uplift and exhumation of mountain belts (*11*). The temperature zone of track retention depends on cooling rate and chemical composition. Apatites from the McKinley plutons have compositions similar to that of Durango apatite, an age standard in which tracks are effectively retained at temperatures less than ~110°C for cooling rates of 0.1° to 10°C per million years over geologic time (*12*). In stable thermal and tectonic situations, distinctive apatite age-temperature profiles develop. Tracks effectively anneal instantaneously at temperatures >110°C, but slowly at tem-

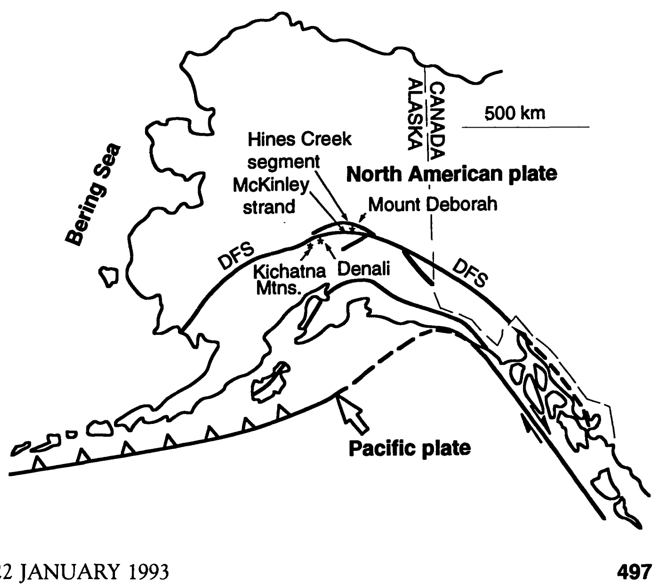
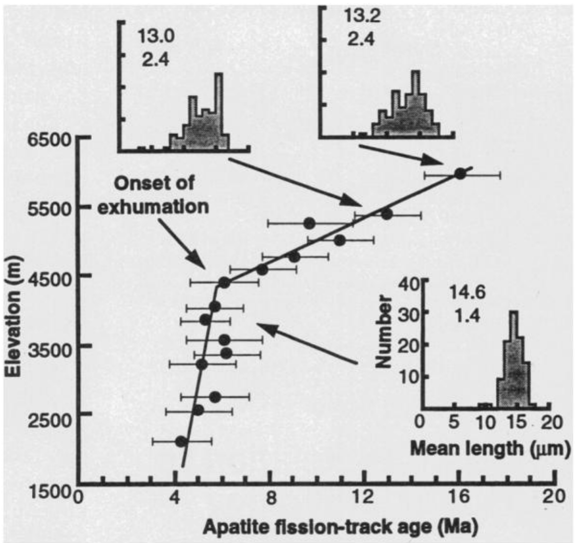


Fig. 1. Location map of Alaska showing the Denali fault system and other major tectonic features. [Modified from (*7*)]

Department of Geology, Arizona State University, Tempe, AZ 85287.

Fig. 2. Variation of the apatite fission-track age ($\pm 2\sigma$) with elevation; also shown are representative track length distributions (mean and standard deviation in micrometers). Ages were determined by the external detector method and zeta calibration, and errors were determined by conventional analysis (*21*).



peratures <60°C. From ~60° to ~110°C, tracks anneal at successively faster rates in the partial annealing zone (PAZ). Tracks are produced continuously; the relative proportions of long and short tracks constrain the time-temperature path (*13*). Sampling over large elevation ranges yields more information because a greater range of crust that cooled at different times can be obtained. A period of relative thermotectonic stability followed by rapid cooling produces a distinctive break in slope in an age-elevation plot that marks the position of the base of a fossil PAZ and the onset of rapid exhumation (*14*).

Samples were collected at vertical intervals of ~100 m between the summit of Denali (6194 m) and the southeast fork of the Kahiltna Glacier (2098 m). Apatite ages range from 16.1 ± 0.8 Ma ($\pm 1\sigma$) to 4.3 ± 0.6 Ma (Fig. 2). Ages vary systematically with elevation and define a profile with a break in slope at ~6 Ma and 4500 m. Samples below the break have simple track length distributions with long lengths (>14 µm) and small standard deviations (<1.4 µm) indicative of rapid cooling. Samples above the break have complex distributions (means of ~13 µm, standard deviations of >2 µm), indicative of annealing within the PAZ before the onset of rapid cooling. The break in slope is interpreted as the base of a fossil apatite PAZ that marks the onset of rapid exhumation accompanying uplift of Denali. In a normal continental geotherm (~25°C per kilometer) the depth to the base of an apatite PAZ (~110°C) is ~4.4 km below mean surface elevation, for a 0°C mean annual surface temperature for the Denali region (Fig. 3).

In order to calculate the mean thickness of crust removed by exhumation, it is necessary to know the initial mean elevation and the present mean elevation (*11*, *15*). The present mean elevation in the immediate area around Denali is ~3 km. The mean surface elevation of tundra to the north of Denali is at an elevation of ~0.3 km, whereas the outwash plains to the south of the central Alaska Range are at an elevation of 0.1 to 0.2 km. Cenozoic nonmarine clastic rocks crop out discontinuously along the McKinley fault strand in basins that have been dissected by later fault movements (*16*). In Oligocene and Miocene units (Coal Bearing Group) in the Healy Basin north of Denali, paleocurrents trend predominantly southward, draining the Yukon-Tanana highlands (*17*). Topography was subdued at that time, with a lowland probably occupying the present position of the central Alaska Range (*18*). In the Pliocene, paleocurrent directions reversed, with sediments (upper unit of the Coal Bearing Group and Nenana Gravels) being derived from the rising Alaska Range (*17*, *18*).

If the mean surface elevation of the central Alaska Range in the late Miocene before the onset of uplift and exhumation was ~0.2 km above sea level, then the base of the PAZ has been uplifted 8.7 km because it is now at an elevation of 4.5 km. The rate of uplift would be >1 km per million years. However, because the mean surface elevation around Denali is now ~3 km, compared to ~0.2 km before the onset of uplift, mean surface uplift is ~2.8 km. The amount of mean exhumation to produce this mean surface elevation is therefore ~5.9 km. Mean exhumation is less than uplift of the base of the PAZ because the uplifted PAZ (break in slope) is now at a higher elevation than the mean surface elevation. Total uplift is the sum of the tectonic component and the isostatic component. The tectonic component is the residual uplift component of the mean surface (isostatic or dynamic) uplift after the isostatic rebound caused by exhumation has been subtracted (*14*). For the immediate area around Denali, the tectonic component (*11*) is ~3.7 km, which is large as

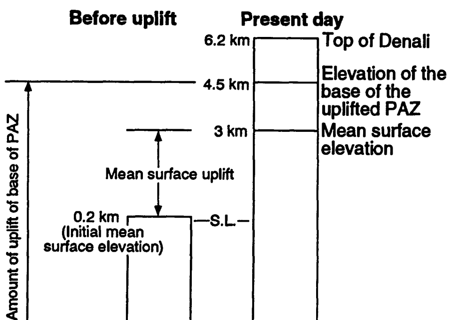


Fig. 3. Schematic showing the uplift model for Denali; S.L., sea level. The base of the PAZ is estimated to reside at a depth of −4.2 km before uplift. The base of this uplifted PAZ is now at an elevation of 4.5 km, which implies that this point has undergone 8.7 km of uplift since ~6 Ma.

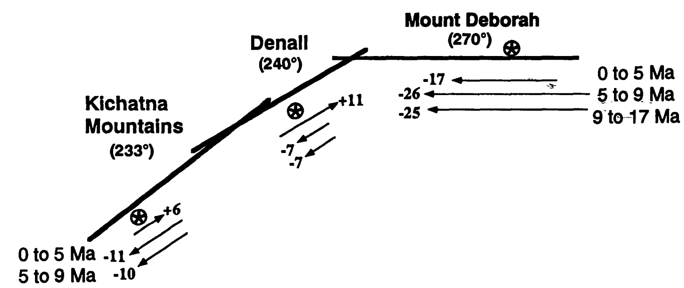


Fig. 4. Diagrammatic trace of the McKinley segment of the DFS showing the tangential components (in kilometers per million years) of the relative plate motion vectors (*2*) plotted for three locations. Selected fault azimuths are assumed to have remained constant. Closest to Denali (azimuth 240°), source vectors from Kodiak Island and the southern Chugach Mountains were averaged. Source vectors for the Kichatna Mountains (azimuth 233°) and the Mount Deborah region (azimuth 270°) were from Kodiak Island and the southern Chugach Mountains, respectively. The relative motion vectors should not be interpreted to require absolute offset across the DFS as sinistral or dextral. Rather, the vectors reflect relative compression if the crust is a coherent, rigid block and if plate-to-plate coupling is 100% effective. In this analysis, the vectors are qualitative. Circled stars designate the positions of the Kichatna Mountains, Denali, and Mount Deborah.

compared to the amount of exhumation and explains why Denali is so high. If we consider the central Alaska Range as a whole, rather than the immediate Denali area, assuming that the fission-track data from Denali apply to the whole range, mean surface elevation is ~1 km and the amount of tectonic uplift is ~1.7 km. This calculation is a limiting case because the timing of uplift and the amount of uplift and exhumation may vary, for example, with distance from the DFS. Pebble studies in the Nenana Gravels indicate that uplift and exhumation started in the south and proceeded northward (*18*).

North to northwest motion of the Kula and Pacific plates relative to the North America plate in the late Cretaceous to Holocene provides a driving force for dextral movement along the DFS (*2*). In a model for the uplift and exhumation of the central Alaska Range, the arcuate geometry of the DFS (especially the bend in fault trend near Denali) plus the close proximity of Denali to the DFS must be considered. At some active margins, oblique convergence is accommodated by strike-normal compression and strike-parallel translation (*19*). Dextral transpressive movement along the DFS forces rocks outboard of the fault against the bend and the Yukon-Tanana terrane. Sediments in the Healy Basin and the fission-track data indicate that, at least from ~16 to 6 Ma, this transpressive movement resulted in little, if any, uplift and exhumation of Denali. An acceleration in lateral movement along the DFS or an increase in compressive force could conceivably create space problems at the bend in the fault trend and cause uplift. Relative plate motion vectors calculated for three azimuths of the McKinley strand suggest that, at ~5 or 6 Ma, the tangential component at Denali and the Kichatna Mountains changed direction from dextral to sinistral (Fig. 4). However, the tangential component at Mount Deborah remained dextral. This geometry created a situation in which tangential motion vectors opposed each other along different segments of the fault. In all cases the normal component increased; this change would amplify the space problem and force the intervening crustal blocks upward. The magnitudes of the components are maxima because the outboard collage of terranes probably absorbed some of the strain, and it is unlikely that plate coupling was 100% efficient. The vector resultants are supported by regional paleomagnetic evidence: counterclockwise rotations of individual southwestern Alaska terranes (*20*) could be favored by a temporary, localized sinistral regime. In this context, the observed drainage patterns surrounding the Denali massif that imply right-lateral movement might be attributed to counterclockwise rotation of blocks during uplift and exhumation.

In conclusion, existing geologic, thermochronometric, and paleogeographic data indicate that Denali was rapidly uplifted at ~6 Ma. This uplift was perhaps a direct result of the space problem caused by the ~5 Ma change in motion of the Pacific plate interacting with the DFS.

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15. Apatite fission-track analysis measures the displacement of rock with respect to a thermal reference frame. On the basis of various assumptions, the rate and magnitude of displacements determined with this technique place constraints on the magnitude of displacements with respect to the geoid or mean sea level (*11*). The following definitions are used [P. England and P. Molnar, *Geology* **18**, 1173 (1990)]: surface uplift is the displacement of Earth's surface with respect to mean sea level; uplift is the displacement of rock with respect to mean sea level; exhumation (erosion or removal of overburden due to tectonic processes) is the displacement of rock with respect to the surface. Surface uplift is uplift minus exhumation.
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22. Mugs Stump, C. Anker, and P.G.F. collected the samples. We thank the staff of Denali National Park and members of the High Altitude Medical Research Camp for assistance during the summer of 1989. Samples were irradiated at the Georgia Institute of Technology reactor. We thank R. Grimm, S. Peacock, and S. Reynolds for discussion and two anonymous reviewers whose suggestions improved this manuscript. Supported by National Science Foundation grant DPP 8821937. This study is dedicated to the memory of Mugs Stump, killed while guiding on the south buttress of Denali, 21 May 1992.

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Seismic Structure of the Southern East Pacific Rise

R. S. Detrick, A. J. Harding, G. M. Kent, J. A. Orcutt, J. C. Mutter, P. Buhl

Seismic data from the ultrafast-spreading (150 to 162 millimeters per year) southern East Pacific Rise show that the rise axis is underlain by a thin (less than 200 meters thick) extrusive volcanic layer (seismic layer 2A) that thickens rapidly off axis. Also beneath the rise axis is a narrow (less than 1 kilometer wide) melt sill that is in some places less than 1000 meters below the sea floor. The small dimensions of this molten body indicate that magma chamber size does not depend strongly on spreading rate as predicted by many ridge-crest thermal models. However, the shallow depth of this body is consistent with an inverse correlation between magma chamber depth and spreading rate. These observations indicate that the paradigm of ridge crest magma chambers as small, sill-like, mid-crustal bodies is applicable to a wide range of intermediate- and fast-spreading ridges.

Current models of crustal magma bodies at mid-ocean ridges, as well as the variation in shallow crustal structure with age, have been strongly influenced by a series of seismic experiments that have been carried out over the past decade along a small section of the northern East Pacific Rise (EPR) between 9°N and 13°N (*1–9*). Seismic reflection profiles have imaged a narrow (<1 to 4 km wide), thin (tens to hundreds of meters), sill-like magma body 1 to 2 km below the ridge axis in this area (*3, 10, 11*).

R. S. Detrick and G. M. Kent, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543.
A. J. Harding and J. A. Orcutt, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92093.
J. C. Mutter and P. Buhl, Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY 10964.