

Denali fault slip rates and Holocene–late Pleistocene kinematics of central Alaska

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ABSTRACT

The Denali fault is the principal intracontinental strike-slip fault accommodating deformation of interior Alaska associated with the Yakutat plate convergence. We obtained the first quantitative late Pleistocene–Holocene slip rates on the Denali fault system from dating offset geomorphic features. Analysis of cosmogenic ^{10}Be concentrations in boulders ($n = 27$) and sediment ($n = 13$) collected at seven sites, offset 25–170 m by the Denali and Totschunda faults, gives average ages that range from 2.4 ± 0.3 ka to 17.0 ± 1.8 ka. These offsets and ages yield late Pleistocene–Holocene average slip rates of 9.4 ± 1.6 , 12.1 ± 1.7 , and 8.4 ± 2.2 mm/yr $^{-1}$ along the western, central, and eastern Denali fault, respectively, and 6.0 ± 1.2 mm/yr $^{-1}$ along the Totschunda fault. Our results suggest a westward decrease in the mean Pleistocene–Holocene slip rate. This westward decrease likely results from partitioning of slip from the Denali fault system to thrust faults to the north and west.

Keywords: Denali fault, slip rates, cosmogenic isotopes, offset moraines.

INTRODUCTION

The Denali fault system is part of a major zone of right-lateral faulting that extends across southern Alaska (Fig. 1). Modern activity along the Denali fault, including the M 7.9 earthquake in 2002 (e.g., Eberhart-Phillips et al., 2003), is related to the collision of the Yakutat plate into the southern margin of Alaska at a rate of 47 mm/yr $^{-1}$ (Fletcher and Freymueller, 2003). Several researchers recognized the Cenozoic activity and importance of the Denali fault (St. Amand, 1957; Grantz, 1966; Brogan et al., 1975), and Reed and Lanphere (1974) found evidence of at least 38 km of offset in the past 38 m.y. Field evidence for displacement through the Pleistocene and Holocene ranges from right bends of 3–4 km along major glacial valleys that cross the fault (Plafker et al., 1977; Richter and Matson, 1971) to small channels that were offset several meters. On the basis of air photos, Hamilton and Myers (1966) recognized the Totschunda fault and proposed that it transfers strain from the Fairweather fault onto the Denali fault. Richter and Matson (1971) mapped the Totschunda fault and suggested that the Totschunda–Fairweather alignment represents the beginning of a new transform fault that bypasses the southeast section of the Denali fault. Despite the significance of the Denali fault system in the North American plate–Pacific plate boundary kinematics, the Quaternary slip rate on its different sections is unknown. We obtained the first quantitative late Quaternary slip rates along the most active sections of the Denali fault system. These rates are important for understanding the development of this large-scale strike-slip fault and for evaluating its seismic hazard.

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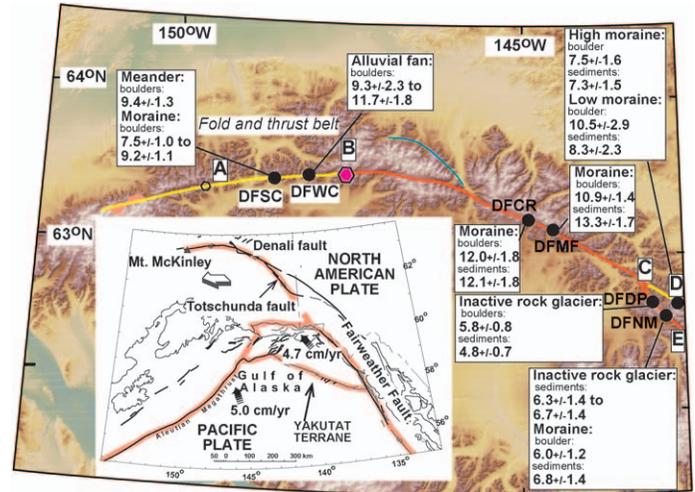


Figure 1. Study area. The Denali fault system was considered in four parts: A–B, western, unruptured segment; B–C, central segment, ruptured in 2002 earthquake; C–D, eastern, unruptured segment; C–E, Totschunda fault. Text boxes give slip rates calculated from boulder or sediment ages (in mm/yr $^{-1}$). Red line—2002 surface rupture; yellow line—unruptured sections of the Denali fault; blue line—McGinnis Glacier fault; solid circles—sampling locations; pink solid hexagon—2002 earthquake epicenter; open hexagon—Bull Creek site (slip rate of ~ 6 mm/yr $^{-1}$; Meriaux et al., 2004); orange solid polygons—38 km offset pluton (Reed and Lanphere, 1974). Sampling sites are denoted by four capital letters—e.g., DFSC. Inset (modified from Haeussler et al., 2000): Denali fault system and North American plate–Pacific plate boundary. Arrows indicate motion relative to North American plate.

METHODS—EXPOSURE AGE DATING AND OFFSET MEASUREMENTS

Slip rates were determined by exposure age dating of geomorphic features crossed by the Denali and Totschunda faults and measurement of their offset. The amount of offset at each site was measured by tape or by calculating the distance between piercing-point locations determined with a handheld global positioning system (GPS) receiver (Table 1; Data Repository item DR1¹). We sampled 10 features at 7 locations (Fig. 1; Table 1). Dating was done by measuring ^{10}Be concentrations in boulders and sediment collected from the surface of each feature. Sediment samples included hundreds of ~ 1 cm clasts collected at the surface. All sites along the central and western Denali fault have numerous exposed quartz-bearing boulders. Sites along the eastern Denali and Totschunda faults are composed of fragments of fine-grained dolomitic shale and quartz vein clasts.

¹GSA Data Repository item 2006132, DR1, offset measurements of displaced features along the Denali fault and error calculations; DR2, snow-cover measurement stations; and DR3, sampling sites and cosmogenic model ages along the Denali fault, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. AGES OF OFFSET FEATURES AND SLIP RATES ALONG THE DENALI FAULT

Fault section	Average age (ky)*	Offset (m) [†]	Slip rate range (mm yr ⁻¹) [‡]	Average slip rate (mm yr ⁻¹) [#]
Western Denali				
DFSC	B (3): 16.8 ± 1.8 (OM)	158 ± 14 (OM)	9.4 ± 1.3	9.4 ± 1.6
	B (2): 17.0 ± 1.8 (M)	127 ± 9–156 ± 9 (M)	7.5 ± 1.0–9.2 ± 1.1	
DFWC	B (2): 2.4 ± 0.3 (AF)	23 ± 5–28 ± 3 (AF)	9.3 ± 2.3–11.7 ± 1.8	
Central Denali				
DFCR	B (9): 12.0 ± 1.3 (M)	144 ± 14 (M)	12.0 ± 1.8	12.1 ± 1.7
	S (2): 11.9 ± 1.3 (M)		12.1 ± 1.8	
DFMF	B (5): 14.1 ± 1.5 (M)	154 ± 12 (M)	10.9 ± 1.4	
	S (2): 11.6 ± 1.2 (M)		13.3 ± 1.7	
Eastern Denali				
DFTR	B (1): 15.7 ± 1.7 (HM)	117 ± 21 (HM)	7.5 ± 1.6	8.4 ± 2.2
	S (2): 16.0 ± 1.8 (HM)		7.3 ± 1.5	
	B (2): 10.4 ± 1.1 (LM)	109 ± 28 (LM)	10.5 ± 2.9	
	S (2): 13.1 ± 1.4 (LM)		8.3 ± 2.3	
Totschunda				
DFDP	B (2): 11.1 ± 1.2 (RG)	64 ± 7 (RG)	5.8 ± 0.8	6.0 ± 1.2
	S (2): 13.3 ± 1.4 (RG)		4.8 ± 0.7	
DFNM	B (1): 13.3 ± 1.4 (M)	80 ± 14 (M)	6.0 ± 1.2	
	S (2): 11.8 ± 1.3 (M)		6.8 ± 1.4	
	S (1): 10.1 ± 1.1 (RG)	63 ± 12–68 ± 12 (RG)	6.3 ± 1.4–6.7 ± 1.4	

*OM—Offset meander, M—Moraine, HM—high moraine, LM—low moraine, AF—Alluvial fan, RG—Inactive rock glacier, B—Boulder samples, S—Sediment samples, Number of samples in parentheses. Average ages consider ages calculated with a maximum snow cover (1 meter over 8 months) and a boulder erosion rate of 1 mm ky⁻¹ (DR3).

[†]Offsets measured with GPS are attributed a 10-m uncertainty to each measured point. This results in a 14-m uncertainty on the distance between the points. Offsets measured by tape are attributed an uncertainty value that correlates with the width of the measured feature. A range of offsets is presented when measurements were done on more than one piercing point. Offsets measured with measuring tape were attributed a 10% error to account for uncertainty in piercing point determination.

[‡]The range of slip rates corresponds to the range of offsets.

[#]Average calculated from all measurements at site.

Postdepositional processes operating on geomorphic surfaces affect the accumulation of ¹⁰Be in boulders and sediment. We were concerned with periglacial processes that cause mixing of surface and subsurface material (cryoturbation), moraine crest and boulder erosion that causes the loss of cosmogenically dosed material, settling of boulders within inactive rock glaciers, and annual snow cover that decreases production rates (Briner et al., 2001, 2002). These processes result in lower ¹⁰Be accumulation and younger exposure ages.

We collected and analyzed 40 samples (boulders, $n = 27$; sediment, $n = 13$). We avoided boulders that were clearly pushed to the surface by freeze and thaw and/or fault activity. Sediment was collected from the surface of five sites. By comparing ¹⁰Be concentrations in boulders and sediment at the same location, we were able to elucidate some of the geomorphic processes operating on these surfaces and evaluate their effects on ¹⁰Be accumulation.

To evaluate the effect of snow cover, we obtained measurements for six stations around the study area (<http://www.ncdc.noaa.gov/oa/climate/stationlocator.html>) (Data Repository item DR2; see footnote 1). For production rate calculations, we chose the station with the longest record and thickest snow cover (Denali National Park Headquarters). Boulder erosion rates were estimated from previous studies in the Arctic zone (1 and 3 mm/k.y.⁻¹; e.g., Briner et al., 2002). Our calculations show that the impact of snow cover and boulder erosion rate on age calculations of Holocene and late Pleistocene samples amounts to <9% (Fig. 2; Data Repository item DR3, see footnote 1). Because the moraines across the Denali and Totschunda faults were derived from small drainage basins (1–5 km²), we assume that cosmogenic nuclide inheritance is low. Therefore, ages were not corrected for possible cosmogenic nuclide inheritance.

RESULTS—AGES OF OFFSET SURFACES

Two lateral moraines, sites DFCR and DFMF, lie along the central Denali fault (Fig. 1). These moraines have broad, flat crests with many exposed boulders (Fig. 2A). At each site, boulders and sediment were collected from both sides of the fault. At site DFCR the boulder samples ($n = 9$) yield an average age of 12.0 ± 1.3 ka, identical to the surface sediments ($n = 2$; 11.9 ± 1.3 ka; Table 1). At site DFMF the boulders ($n = 5$) yield an average age of 14.1 ± 1.5 ka, slightly older than the sediment ($n = 2$; 11.6 ± 1.2 ka; Table 1). Within each site, boulder ages are internally consistent, as are sediment ages (Fig. 2).

The age consistency on each moraine suggests that differential erosion of boulders and predeposition accumulation of ¹⁰Be (inheritance) are not significant. It also testifies to the rapid stabilization of the moraines shortly after ice retreat (Briner et al., 2005). The similarity between boulder and sediment ages suggests only minor erosion of the boulders and minor removal of sediment off the moraines. Differences observed at site DFMF may result from mixing of surface and subsurface sediment by bioturbation and cryoturbation. The consistency of boulder ages within each site and the similarity between boulder and sediment ages provide us confidence in the exposure ages determined at other places along the Denali fault system with fewer sampled boulders or with surface sediment only.

Three offset surfaces were dated on the western Denali fault, west of the 2002 surface rupture (Fig. 1). At site DFSC a surface incised by an abandoned meander and an adjacent moraine were dated. The average age of three boulders from the incised surface is 16.8 ± 1.8 ka. This provides a maximum age of the offset meander, although the relatively straight and continuous slopes connecting the surface and the offset meander suggest that incision occurred rapidly after the surface was formed. The average age of two boulder samples, collected from the moraine crest, one from each side of the Denali fault, is 17.0 ± 1.8 ka. Site DFWC is an offset alluvial fan. The average age of two boulder samples, one from each side of the Denali fault, is 2.4 ± 0.3 ka.

Two offset moraines of different ages were dated at site DFTR on the eastern Denali fault. A boulder sample collected from a high moraine yields an age of 15.7 ± 1.7 ka, similar to the average age of two sediment samples (16.0 ± 1.8 ka) collected from each side of the fault. From a low moraine, two boulder samples, one from each side of the fault, yield an average age of 10.4 ± 1.1 ka, younger than the average age of the sediment samples (13.1 ± 1.4 ka).

Two localities were studied along the Totschunda fault (Fig. 1). At site DFNM one boulder and two sediment samples, one from each side of the fault, were collected from an offset moraine. The boulder sample yields an age of 13.3 ± 1.4 ka, slightly older than the average sediment age (11.8 ± 1.3 ka). A single sediment sample collected from an offset inactive rock glacier adjacent to this moraine yields an age of 10.1 ± 1.1 ka. At the DFDP site, four samples, two from each side of the fault, were collected from an offset inactive rock glacier. The average boulder age is 11.1 ± 1.2 ka, within 1σ of the average sedi-

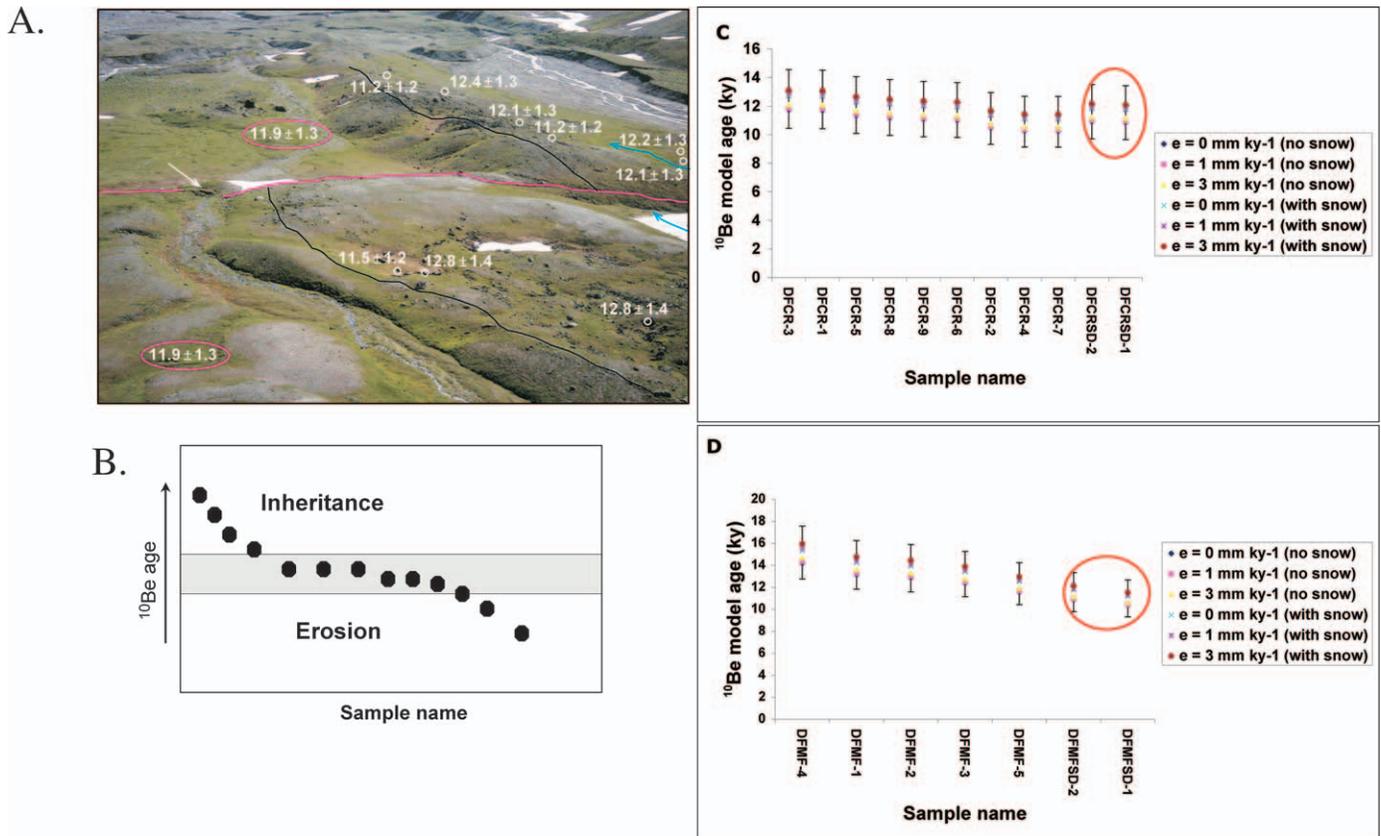


Figure 2. A: Site DFCR—offset moraine along the Denali fault. Boulder and sediment samples were collected from both sides of the fault. White open circles—sample locations, ages in thousands of years; red line—fault trace; black line—offset moraine crest; blue line—offset channel (offset appears foreshortened because of photo perspective). White arrow points at 2002 earthquake offset of ~5 m (Haeussler et al., 2004). Sediment ages are in red ovals beside the moraine. **B:** Expected distribution of hypothetical cosmogenic ages. Upper tail indicates samples with prior exposure (inheritance). Lower tail indicates higher than expected erosion. **C, D:** Cosmogenic ages of boulder and sediment samples collected from offset moraines along the central Denali fault. (**C**, site DFCR; **D**, site DFMF). 1σ error bars span upper age (maximum erosion and snow cover) and lower age (no erosion and no snow cover) limits. Age consistency, within each moraine, suggests that differential erosion and inheritance are not significant (Briner et al., 2001, 2002). At both sites, sediment ages are consistent with boulder ages. Sediment samples are circled.

ment age (13.3 ± 1.4 ka). All of the moraine ages calculated in this study correspond to established glacial periods in the Alaska Range (Hamilton, 1994).

DISCUSSION

Previous estimates of late Pleistocene slip rates range from 8.7 to 11.6 mm/yr^{-1} along the Denali fault and from 10 to 20 mm/yr^{-1} along the Totschunda fault (Plafker et al., 1994, and references therein). These estimated slip rates were based on measured offsets and assumed ages of glacial features and large river valleys.

Our results show that the highest average slip rate is 12.1 ± 1.7 mm/yr^{-1} at sites on the central Denali fault. This rate decreases along the Denali fault both east (8.4 ± 2.2 mm/yr^{-1}) and west (9.4 ± 1.6 mm/yr^{-1}). On the east, a slip rate of 6.0 ± 1.2 mm/yr^{-1} was calculated for the Totschunda fault, which splays from the Denali fault 65 km east of site DFMF (Fig. 1). The combined mean slip rate of the eastern Denali and Totschunda faults, which expresses the total slip along the eastern part of the fault system, is 14.4 ± 2.5 mm/yr^{-1} , similar to the slip rate of the central Denali fault. However, this difference of >2 mm/yr^{-1} might indicate a real decrease of slip along the Denali fault system from east to west. To the west, the mean slip rate decreases by ~ 3 mm/yr^{-1} , to 9.4 ± 1.6 mm/yr^{-1} , between the central Denali fault and the western Denali fault. The general westward decrease in mean slip rate from 14.4 ± 2.5 to 9.4 ± 1.6 mm/yr^{-1} may have resulted from curvature of the central and western Denali fault segments and the concomitant increase in shortening across the fault, as expressed by the broad zone of folding and thrusting of the northern foothills (Be-

mis, 2004), and by partitioning of slip onto structures such as the active McGinnis Glacier fault (Fig. 1). About 60 km west of site DFSC, an exposure dating a constrained slip rate of 6.6 ± 1.7 mm/yr^{-1} was reported from an offset moraine (Meriaux et al., 2004). This value suggests a possible additional decrease in the Denali fault slip rate westward as the fault extends into the eastern part of the Mount McKinley segment, where convergence is accommodated by thrust faults (Plafker et al., 1992; Fletcher, 2002; Haeussler, 2005).

The late Pleistocene–Holocene slip rates presented here place constraints on the duration and uniformity of offset along the Denali fault and raise the fundamental question about the constancy of slip rates over time and space. This is especially important for seismic hazard analysis, in which slip rates are a primary consideration for calculating earthquake recurrence. Reed and Lanphere (1974) mapped and dated a 38 Ma pluton offset 38 km along the Denali fault near Mount McKinley. Exhumation, and likely uplift, of Mount McKinley began ca. 6 Ma (Fitzgerald et al., 1995) and appear to be linked to the activity along the Denali fault system (Plafker et al., 1992). Therefore, if activity along the Denali fault initiated at ca. 6 Ma, the slip rate calculated from the offset of this pluton is similar to that calculated by Meriaux et al. (2004) for the Mount McKinley part of the fault. We calculated slip rates for intervals as long as 17 ka to as short as 2.4 ka on the Denali fault, and for each interval the rate is essentially constant (Table 1). A short-term (several hundreds of years) geologic slip rate derived from paleoseismic studies is also similar (Schwartz et al., 2003). In contrast, our slip rates on the primary strands of the Denali fault (9.4 ± 1.6 – 12.1 ± 1.7 mm/yr^{-1}) for the past 2.4–17 k.y. are twice the rate

determined by GPS geodesy ($\sim 5 \text{ mm/yr}^{-1}$) before the 2002 earthquake (Fletcher, 2002). It is possible that the GPS-determined slip rate underestimates the long-term rate owing to strain transients (Pollitz et al., 2003) associated with the M 9.2 1964 earthquake, or because of the short (5 yr) observation period of the campaign GPS data. This issue is germane to other major strike slip faults such as the Karakorum fault, Tibet, and the Altyn Tagh fault, China, where geodetic short-term and long-term geologic slip rates differ by a factor of 2–3 (e.g., Chevalier et al., 2005).

The transfer of deformation in continental collision zones onto major strike-slip faults (escape tectonics) is observed on several continents (e.g., McClusky et al., 2000; Chevalier et al., 2005). In modern settings the ratio of the collisional plate velocity to velocity on strike-slip systems is variable. The North Anatolian fault has a slip rate nearly equal to the velocity of the Arabian-Eurasian convergence rate (McClusky et al., 2000; DeMetz et al., 1994). About one-third to one-half of the India-Eurasia velocity is accommodated on strike-slip faults related to extrusion of eastern Asia (Ryerson et al., 1997; van der Woerd et al., 2000; Chevalier et al., 2005). The Denali fault plays a similar, although smaller, role in that it accommodates about one-fifth of the Yakutat terrane convergence velocity as lateral slip, with the remainder of the motion going into shortening in the collision zone between the Yakutat terrane and the North American plate (Pavlis et al., 2004). This difference might be related to the fact that the crust of the Yakutat terrane has oceanic affinities (Plafker, 1987), which likely results in lower buoyancy, less coupling, and less effective transfer of stresses into the continental interior.

CONCLUSIONS

Analysis of cosmogenic ^{10}Be concentrations in samples collected from surfaces offset by the Denali and Totschunda faults indicates late Pleistocene–Holocene average slip rates of 9.4 ± 1.6 , 12.0 ± 1.7 , and $8.4 \pm 2.2 \text{ mm/yr}^{-1}$ along the western, central, and eastern sections of the Denali fault, respectively, and $6.0 \pm 1.2 \text{ mm/yr}^{-1}$ along the Totschunda fault. These results show that the combined eastern Denali and Totschunda fault slip rate of $14.4 \pm 2.5 \text{ mm/yr}^{-1}$ decreases westward to $9.4 \pm 1.6 \text{ mm/yr}^{-1}$ on the western Denali fault. The $\sim 5 \text{ mm/yr}^{-1}$ westward decrease appears to result from the transpressive curvature of the Denali fault system and the resulting increase in shortening across it.

The results of this study have implications for the development of moraines in the Alaska Range and the surface processes that operate on them. The consistent ages of boulders at each of our sites suggest that the predeposition exposure history was short and that differential erosion of boulders was limited. The similarity between boulder and sediment exposure ages indicates only minor erosion of the boulders and minor removal of sediment off the moraines, and testifies to the rapid stabilization of the moraines shortly after ice retreat.

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