

Late Holocene slip rate for the North Anatolian fault, Turkey, from cosmogenic ^{36}Cl geochronology: Implications for the constancy of fault loading and strain release rates

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ABSTRACT

Geomorphologic mapping and cosmogenic radionuclide (^{36}Cl) dating of an offset fluvial terrace yield a preferred late Holocene slip rate of 20.5 ± 5.5 mm/yr for the central part of the North Anatolian fault, Turkey; an independent slip rate constrained by ^{14}C ages is 20.5 ± 8.5 mm/yr. These rates are generally similar to, but possibly slightly slower than, the short-term rate of elastic strain storage of 25 ± 1 measured geodetically across this major strike-slip fault (Reilinger et al., 2006), suggesting that loading and strain release on this part of the North Anatolian fault have been relatively constant when averaged over the past $\sim 2\text{--}2.5$ k.y. We attribute this consistency to the relatively simple structure of the Anatolia-Eurasia plate boundary in north-central Turkey, where almost all plate boundary strain is accommodated along the North Anatolian fault. The absence of other moderate to high slip rate faults (and the earthquakes they produce) leads to a relatively simple stress evolution for the fault dominated by steady tectonic loading.

Keywords: North Anatolian fault, geologic slip rate, cosmogenic nuclide dating, tectonic geomorphology.

INTRODUCTION

The degree to which fault loading and strain release rates are constant (or non-constant) in time and space is one of the most fundamental unresolved issues in modern geodynamics. In particular, it is not clear what processes control strain release at time scales longer than one to a few earthquakes. Is strain release relatively continuous, as would be expected if faults are loaded steadily from beneath by plate motions? Or is strain release markedly non-constant, as might occur if fault loading is controlled by temporally transient mechanisms, such as lower crust creep pulses or feedback related to earthquake clustering? Over what time scales do all of these processes operate, and do different plate boundaries store and release strain differently, perhaps as a consequence of relative structural complexity or simplicity? In this paper we document the late Holocene slip rate of the central part of the North Anatolian fault in Turkey. We discuss this result in terms of its implications for understanding the constancy of strain storage and release on this major strike-slip fault, and speculate about the causes of the different behavior of major continental strike-slip faults.

EKSİK STUDY SITE

Our study site is near the village of Eksik, Turkey, along the central part of the North Anatolian fault (Fig. 1; see the Appendix in the GSA Data Repository¹). The North Anatolian fault, which extends across the study site as a narrow (2–10-m-wide), well-defined N65°E trending zone,

is oriented nearly perpendicular to several deeply incised, south-flowing drainages that have been offset by right-lateral slip along the fault (Hubert-Ferrari et al., 2002) (Fig. 1B). Initial incision of these drainages resulted in the development of broad canyons incised into bedrock. These large canyons, which have been consistently offset ~ 200 m along the North Anatolian fault, are thought to have formed ca. 10 ka (Hubert-Ferrari et al., 2002). A set of younger (middle to late Holocene) incised canyons that exhibit smaller offsets is inset into the bases of these offset canyons. Following their incision, these younger inset canyons were filled by fluvial gravels composed of white limestone cobbles and pebbles derived from steep limestone bedrock cliffs 1.0–1.5 km north of the fault. Subsequent incision by active streams into these gravels has isolated several geomorphically well defined, nearly flat fluvial terrace remnants nestled within the much larger, older canyons incised into bedrock.

We mapped in detail the offset of one of these fluvial terraces along Ağılönü Canyon, one of the major incised drainages 2 km west of Eksik (Fig. 2). Two active streams, which in the vicinity of the fault flow southward near the eastern and western edges of Ağılönü Canyon, have incised ~ 20 m into the fluvial terraces. Although this recent incision has isolated the terrace into several distinct remnants, similarities in clast content, surface morphology, elevation, soil development, and age (discussed in the following) indicate that these remnants are all parts of a once-continuous fluvial aggradational fill sequence of Ağılönü Canyon.

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¹GSA Data Repository item 2007218, Appendix, including Figures DR1–DR9 and Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

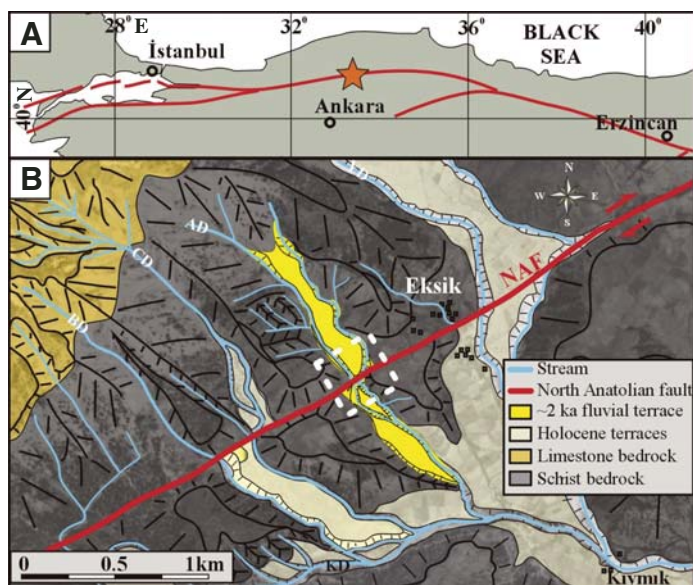


Figure 1. A: Location of Eksik study site (star) along North Anatolian fault (NAF) in north-central Turkey. B: Corona satellite image overlaid with geomorphic interpretation (modified from Hubert-Ferrari et al., 2002). Offset fluvial terrace discussed in text is highlighted in yellow. BD—Beygirçtu Dere; CD—Çatal Dere; AD—Ağılönü Dere; YD—Yatçam Dere; KD—Kuru Dere (“Dere” means “creek” in Turkish).

In general, the inner edges of the fluvial terrace, where the planar upper surface of the terrace gravels abuts the canyon walls, are geomorphically well defined over most of the site. The white limestone-cobble gravels that make up the terrace contrast markedly with the underlying dark grayish-green schist bedrock and bedrock-derived colluvium, greatly facilitating mapping of the limits of the terrace deposits. In addition, the buttress unconformity marking the inner edge of the top of the terrace gravels is exposed in several natural side drainages along the west side of Ağılönü Canyon. Subsequent to abandonment of the terrace, the buttress unconformities at the inner edges of the terrace deposits have been locally covered by bedrock-derived colluvium. In order to determine the exact location of the terrace inner edges as close to the fault as possible, we excavated several 2–5-m-deep fault-parallel trenches and test pits (Fig. 2; Appendix [see footnote 1]).

There are two points relevant to determining the slip rate at Eksik: (1) the geometry of the terrace inner edge where it crosses the fault; and (2) the relationship between the offset of the inner edge and the age of the terrace. Offset of the terrace inner edge along the eastern side of Ağılönü Canyon is not well defined, because the upper part of the terrace (including the inner edge) just south of the fault offset has been eroded by the modern stream. As a result, we concentrated our efforts on the well-exposed western inner edge of the terrace. Our trenches and the natural exposures allowed us to map the western terrace inner edge in detail for hundreds of meters along Ağılönü Canyon, to within a few tens of meters of the fault (burial by colluvium precludes direct examination of the inner edge closer to the fault). North of the fault, the inner edge curves gently downstream, from a several-hundred-meter-long, linear reach that trends S20°E, to a S35°–40°E trend as it approaches the fault. South of the fault, the inner edge exhibits a linear S40°E trend for

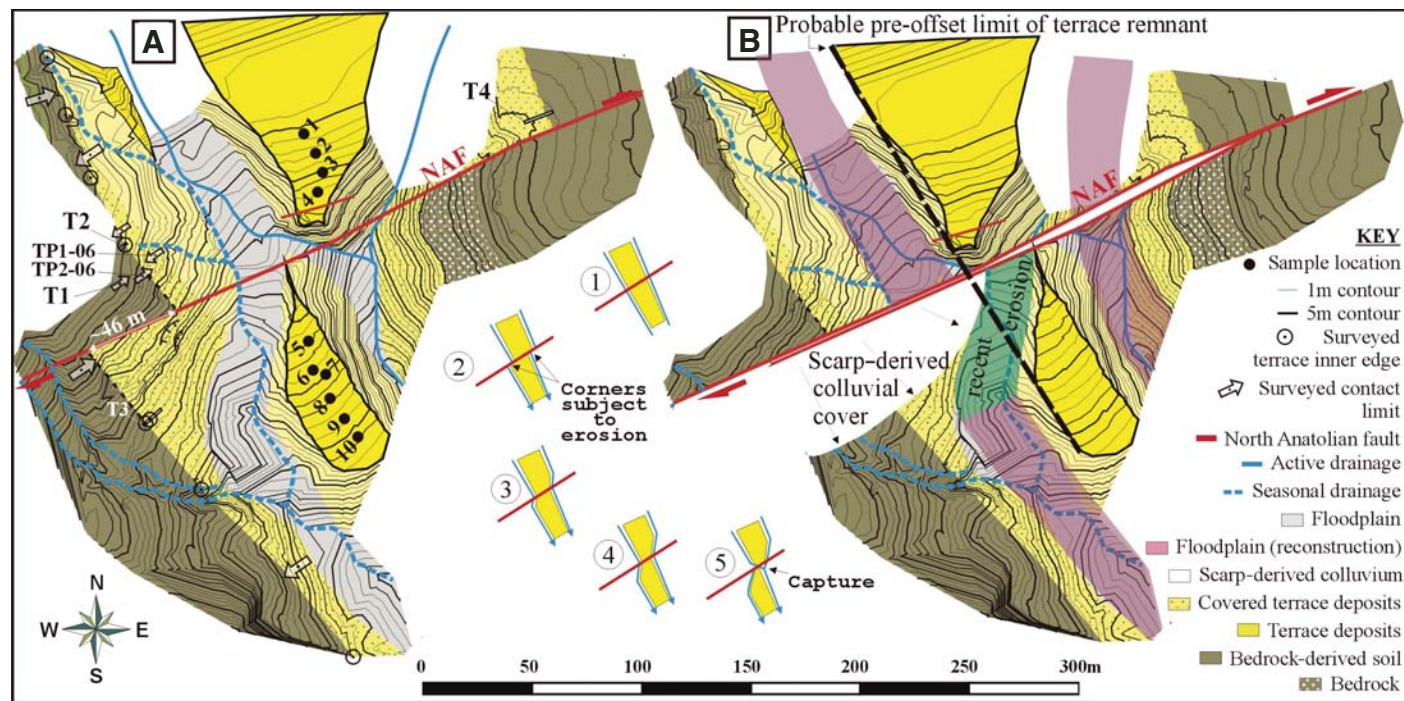


Figure 2. A: Geomorphic map of study area showing the offset fluvial terrace described in text, as well as locations of cosmogenic radio-nuclide samples (numbered black dots) and our trenches (e.g., T1, T2). Topographic base map was surveyed with a laser range-finding total station with electronic compass attachment. Black dashed lines show the inferred inner edge locations projected from the nearest exposures. Circles with dots indicate surveyed locations of exposures of terrace inner edge. Circles with arrows show limiting locations for terrace inner edge. B: Restoration of 46 m of right-lateral slip along North Anatolian fault (NAF) aligns the western terrace inner edge, the active channels that have incised into the terrace deposits, and the western edge of the preserved mid-canyon terrace remnants. The consistent offsets of these different features suggest that incision of terrace deposits occurred soon after stabilization of terrace surface. Heavy black dashed line highlights relatively linear western edges of the two mid-canyon terrace remnants. Inset shows our proposed model for sequential development of these features. Bedrock shown as green with white dots denotes area where terrace inner edge has been eroded.

>200 m downstream. Restoration of 46 ± 10 m of right-lateral displacement yields a best-fit, gently curved original channel morphology (for discussion, see the Appendix in the GSA Data Repository). This restoration also restores the incised channels of the two major active streams that have cut down through the terrace deposits, as well as the linear western edges of the mid-canyon terrace remnants (Fig. 2).

Consideration of the similar offsets of the terrace inner edge and the canyons that have been incised into the terrace gravels suggests an answer to the second point. As with all fill terraces, the terrace gravels could have been deposited into a partially preexisting offset of the canyon, yielding an incorrect overestimate of the offset measurement and slip rate. However, in that case the offset of the incised channels of the active streams, which must have been cut after emplacement and abandonment of the fluvial terrace, would have to be less than the offset of the buttress unconformities at the terrace inner edge. The observed concordance between the two offsets indicates that all, or nearly all, of the inner edge offset accumulated subsequent to abandonment of the terrace surface. This implies that the modern streams began incising soon after initial stabilization of the fluvial terrace surface, a likely occurrence given the very steep gradients of these high-energy mountain streams. We have used the inner edge offset rather than channel offset to determine the fault slip rate because it is a more precisely determinable quantity.

AGE CONTROL

We used ^{36}Cl cosmogenic surface exposure dating to determine the age of the offset Ağılönü Canyon terrace. We collected a north-south, fault-perpendicular transect of ten limestone cobbles for cosmogenic dating from the surface of the two largest and geomorphically best defined terrace remnants (Fig. 2). The transect extends for 50 m north of the fault (four samples) and 75 m south of the fault (six samples). The sampled terrace surfaces are quite planar, suggesting little to no erosion. These surfaces have <10 cm of local relief, except near the fault offset, where the northern terrace surface locally exhibits as much as 35 cm of relief. The terrace surface is characterized by a large-pebble and cobble pavement, through which a thin (2–10 cm), weak A-C surface soil has developed. We were careful to sample only cobbles that appeared to be stable within the interlocking pavement surface and that did not exhibit any evidence of having been moved. Specifically, all of the sampled cobbles had a well-defined upper slightly weathered surface that contrasted markedly with a soil-stained, smoother lower surface.

Ages were calculated using the program CHLOE (chlorine-36 exposure age; Phillips and Plummer, 1996), using two different estimates of cosmogenic radionuclide production rates. Of the ten ^{36}Cl surface samples, nine yielded remarkably clustered ages for the terrace surface, ranging between 2.1 and 2.9 ka for the production rates of Stone et al. (1996, for Ca) and Evans et al. (1997, for K), and between 1.6 ka and 2.2 ka for the production rates of Phillips et al. (1996) (Table 1; Fig. DR7 [see footnote 1]). One sample (7) yielded an anomalously young age of 0.9 or 1.2 ka. We interpret this sample as an outlier, the young age probably reflecting displacement from its actual exposure site or from physical alteration of the cobble during its exposure history.

There are actually two age peaks within the main cluster of nine ^{36}Cl ages; a younger subcluster of six samples, and an older set of three samples. We suspect that the older subcluster reflects minor inheritance in these three samples on the order of a few hundred years, consistent with the short transport distance from the source of the cobbles to the terrace. If true, this would suggest that the six tightly clustered ages represent more accurately the age of terrace stabilization. These preferred age ranges are 2.1–2.4 ka for the production rates of Stone et al. (1996) and Evans et al. (1997), and 1.6–1.8 ka for the production rates of Phillips et al. (1996).

In addition to the ^{36}Cl exposure dates from the terrace surface, radiocarbon dates from four charcoal samples collected from above and below

TABLE 1. COSMOGENIC (^{36}Cl) AND RADIOCARBON (^{14}C) AGES

Cosmogenic radionuclide sample ages (^{36}Cl)		
Sample number	Phillips et al. (1996) production rates (ka)	Stone et al. (1996) and Evans et al. (1997) production rates (ka)
^{36}Cl -1	2.06 ± 0.05	2.74 ± 0.05
^{36}Cl -2	1.82 ± 0.06	2.41 ± 0.06
^{36}Cl -3	2.09 ± 0.07	2.76 ± 0.07
^{36}Cl -4	1.63 ± 0.05	2.17 ± 0.05
^{36}Cl -5	2.21 ± 0.07	2.93 ± 0.09
^{36}Cl -6	1.84 ± 0.08	2.43 ± 0.11
^{36}Cl -7	0.90 ± 0.03	1.20 ± 0.03
^{36}Cl -8	1.61 ± 0.05	2.14 ± 0.07
^{36}Cl -9	1.64 ± 0.05	2.17 ± 0.07
^{36}Cl -10	1.74 ± 0.05	2.32 ± 0.07
Radiocarbon sample ages (^{14}C)		
Sample number	^{14}C ages (yr B.P.)	Calibrated calendar ages
EX-4-5	2020 ± 30	110–60 B.C.
EX-4-4	2590 ± 80	910–410 B.C.
EX-4-1	2695 ± 35	910–800 B.C.
EX-4-3	2865 ± 45	1210–910 B.C.

Note: ^{36}Cl ages are reported for the different ^{36}Cl production rates of Phillips et al. (1996) and of Stone et al. (1996) and Evans et al. (1997). Errors on radionuclide ages reflect only 1σ analytical uncertainties in the accelerator mass spectrometry measurements. Consideration of all sources of uncertainty would probably result in 10%–15% standard deviation (Phillips et al., 1996). Radiocarbon ages reported as 95.4% confidence limits from OxCal version 3.10 (Bronk Ramsey, 1995, 2001; using atmospheric data from Reimer et al., 2004). See Figure DR8 in the Data Repository (see footnote 1) for locations of ^{14}C samples collected from trench T4.

the youngest terrace gravels exposed at the terrace inner edge in trench T4 along the east edge of Ağılönü Canyon provide an independent constraint on the age of the terrace surface and on the general validity of the ^{36}Cl production rates used in the cosmogenic age calculations. A charcoal sample collected from colluvium 10 cm above the top of the terrace gravels yielded a calibrated calendar age of 1.95–2.12 ka (all calibrations were done using OxCal v.3.10 [Bronk Ramsey, 1995, 2001; using atmospheric data from Reimer et al., 2004]) (Fig. DR7). Three charcoal samples recovered from colluvium beneath the terrace gravels in trench T4 yielded calibrated calendar ages of 2.92–3.22 ka, 2.81–2.92 ka, and 2.42–2.92 ka, in correct stratigraphic order. These four radiocarbon ages thus bracket the age of the easternmost, youngest terrace gravels to be between 1.95 and 2.92 ka. The age range matches closely the 2.1–2.4 ka age range of the subcluster of six ^{36}Cl dates determined with the production rates of Stone et al. (1996) and Evans et al. (1997) (Fig. DR7). We therefore use the Stone et al. (1996) and Evans et al. (1997) production rates in our preferred slip rate calculations.

DISCUSSION AND CONCLUSIONS

We use the ^{36}Cl ages from the offset fluvial terrace to calculate two estimates of the late Holocene slip rate for the North Anatolian fault at Eksik. The ^{36}Cl ages are not normally distributed, probably because a subset of the cobbles underwent a few hundred years of exposure prior to being incorporated into the sampled terrace (Fig. DR7). However, in order to obtain a conservative slip rate estimate, we used all our data except the single obvious young outlier; and instead of using the mean and standard deviation to calculate the uncertainty on our measured slip rate, we use the range. Combining our 46 ± 10 m offset of the terrace inner edge with the 2.1–2.9 ka age range determined for the nine ^{36}Cl samples on the basis of the radionuclide production rates of Stone et al. (1996) and Evans et al. (1997) yields a slip rate of 19 ± 7 mm/yr. The rate calculated using the 1.6–2.2 ka terrace age based on the production rates of Phillips et al. (1996) yields a slip rate of 25.5 ± 9.5 mm/yr. If we assume that the very tight subcluster of six ^{36}Cl ages reflects most accurately the age of terrace

stabilization, the ages approach a normal distribution and we can use the standard deviation to estimate the uncertainty in the ages; then, propagating the uncertainties, our preferred rates are 20.5 ± 5.5 and 27 ± 7 mm/yr, respectively. The radiocarbon dates bracket the youngest terrace gravels and provide an independent slip rate of 20.5 ± 8.5 mm/yr. Alternatively, using only the calibrated, calendar ^{14}C age of the underlying charcoal sample yields a robust minimum rate of $\geq 18 \pm 4$ mm/yr (Table 1). All of these rates are statistically indistinguishable from the short-term, 25 ± 1 mm/yr rate of elastic strain accumulation across this part of the North Anatolian fault measured by geodetic data (Reilinger et al., 2006). The general consistency of these rates suggests that strain storage and release on this part of the North Anatolian fault have been relatively constant when averaged over the past ~2000–2500 yr.

We attribute this approximately continuous loading and release to the relative structural simplicity of this part of the Anatolia-Eurasia plate boundary. Almost all (>90%) plate boundary motion in north-central Turkey is accommodated by slip on the North Anatolian fault (Hubert-Ferrari et al., 2002; Reilinger et al., 2006). Thus, there are few other moderate to high slip rate faults in this part of the plate boundary. Specifically, in the region near Eksik, only the poorly known contractional structures responsible for uplift of the Pontide Mountains might have slip rates of more than a few millimeters per year (see data in Hubert-Ferrari et al., 2002; Reilinger et al., 2006). In such simple settings, where plate boundary motion is dominated by slip on a single fault, the stress evolution on the master fault is likely to be much simpler than in structurally complicated settings characterized by numerous moderate to high slip rate faults (e.g., southern California). Not only will each of these faults generate earthquakes of their own, complicating the stress evolution of the master fault, but if more than one fault is oriented such that both can accommodate significant plate boundary motion, then they may alternate in terms of relative importance such that their loading rates vary through time (e.g., Dolan et al., 2007). In contrast, in simple, single-fault-dominated settings such as the plate boundary in northern Turkey, we suggest that storage of elastic strain will be dominated by quasi-continuous tectonic loading, and in general, the only earthquakes that will complicate the stress evolution of the master fault will be those produced by rupture of other parts of the master fault. However, the ^{36}Cl terrace age based on the Stone et al. (1996) and Evans et al. (1997) production rates leaves open the possibility that the average late Holocene slip rate for the North Anatolian fault is slightly slower than the short-term rate of elastic strain accumulation measured by geodesy (Reilinger et al., 2006), possibly as a result of time-dependent changes in fault-zone loading in response to the occurrence of the A.D. 1939–1999 earthquake sequence.

Displacement on the Eksik reach of the North Anatolian fault was 4–4.5 m during the 1943 M_w 7.7 Tosya earthquake (Barka, 1996). The slip rate data described here, however, in combination with paleoseismologic data from a nearby trench site (Sugai et al., 1998), indicate that these relatively small displacements probably are not characteristic of earthquakes on this reach of the North Anatolian fault. Sugai et al. (1998) observed evidence for only 5 surface ruptures during the past 2 k.y. at their trench site in Aliç (~15 km west of Eksik; Fig. DR1 [see footnote 1]). Although it is possible that events may be missing from the paleoseismologic record, the Sugai et al. (1998) trench was both carefully situated and characterized by markedly continuous sediment accumulation in a marshy, peat-rich, active alluvial fan environment, making this unlikely. Similarly, a paleoseismologic site 160 km to the east of Eksik also reveals only five surface ruptures since 2 ka (Hartleb et al., 2003). If all of the 46 ± 10 m offset of the terrace inner edge measured at Eksik accumulated in earthquakes that exhibited characteristic slip (Schwartz and Coppersmith, 1984) of

4–4.5 m/earthquake, then 8–14 surface ruptures would have had to occur since abandonment of the terrace surface ca. 2.1–2.4 ka. Thus, either displacements in the 1943 earthquake were much smaller than is typical for this reach of the North Anatolian fault, or a cluster of 3–8 earthquakes must have occurred during the 100–400 yr preceding the paleoseismologic record of Sugai et al. (1998) at the nearby Aliç trench site.

ACKNOWLEDGMENTS

We are grateful for helpful discussions with Serdar Akyüz, Aurelia Hubert-Ferrari, Geoff King, Fred Phillips, and the late Aykut Barka. We thank Terry Thomas for help with ^{36}Cl sample preparation. Ziyadin Çakır, Kurt Frankel, and Metin Gürkan provided assistance in the field. We would like to thank Carol Prentice, Mike Oskin, and the anonymous reviewer for helpful reviews. This research was funded by National Science Foundation grants EAR-0409767, EAR-0633489, and EAR-9980564 with additional support from U.S. Department of Energy (University of California, Lawrence Livermore National Laboratory) contract W-7405-Eng-48.

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Manuscript received 11 July 2006

Revised manuscript received 6 April 2007

Manuscript accepted 20 April 2007

Printed in USA

Geology

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Geology 2007;35:867-870
doi: 10.1130/G23187A.1

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