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Diurnal and semidiurnal tide-induced lateral movement of Ronne Ice Shelf, Antarctica

Keith Makinson,[1] Matt A. King,[2] Keith W. Nicholls,[1] and G. Hilmar Gudmundsson[1]

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[1] Recent GPS observations from a spatially extensive network across Ronne Ice Shelf show significant daily ice flow variations. At all sites, the almost-synchronous horizontal displacements occur at diurnal and semidiurnal tidal periods. During spring tides, displacements, velocities and strains near the ice front have superimposed oscillations that are ±300% of their mean values and occur over a six-hour period, resulting in regular ice shelf flow reversals. Close to ice stream grounding lines, however, the horizontal diurnal and semidiurnal signals decay and almost vanish. From our analysis, we conclude that ice shelves respond primarily elastically to tidal tilting, thus accounting for the observed diurnal and semidiurnal flow variations, and their amplification toward the ice shelf front. Our findings suggest that detailed modeling of these data could provide improved ice shelf and ice stream models for correctly simulating ice shelf flow and predicting future ice sheet evolution. **Citation:** Makinson, K., M. A. King, K. W. Nicholls, and G. Hilmar Gudmundsson (2012), Diurnal and semidiurnal tide-induced lateral movement of Ronne Ice Shelf, Antarctica, *Geophys. Res. Lett.*, *39*, L10501, doi:10.1029/2012GL051636.

1. Introduction

[2] The majority of Antarctic ice streams and outlet glaciers drain into the floating ice shelves that fringe much of the Antarctic Ice Sheet [*Rignot et al.*, 2008]. Ice shelves are now known to play an important role in the dynamics of the entire ice sheet by regulating the inland ice's coastward flow [*Dupont and Alley*, 2005; *Gagliardini et al.*, 2010]. Ocean tides modify ice shelf back stresses and can significantly affect the large-scale and long-term flow regime of active ice streams [*Gudmundsson*, 2011; *King et al.*, 2011a] and hence their contribution to sea level change. Prior to Global Positioning System (GPS) observations, ice shelves were usually considered only to rise and fall with the tides and to have a uniform horizontal motion with flow determined by viscous processes [e.g., *MacAyeal et al.*, 1996]. Significant diurnal and semidiurnal horizontal ice shelf motions were first reported close to the grounding line of Ekströmisen [*Riedel et al.*, 1999]. Away from the effects of grounding line flexure, similar motions were observed on Brunt Ice Shelf [*Doake et al.*, 2002], Mertz Glacier Tongue [*Legrésy et al.*, 2004], Ross Ice Shelf [*Brunt et al.*, 2010], and Larsen C Ice Shelf [*King et al.*, 2011a]. In addition, Ross and Larsen C ice shelves show amplification of the motions toward the ice shelf front. Analysis of these horizontal motions has considered the effect of basal drag from ocean tidal currents, and the effects of tidal elevation changes modifying how the ice shelf interacts with shear margins, ice rumples and grounding zones. Frequent conclusions have been that basal drag from ocean currents would need to be unphysically large to account for the ice shelf motion and links to interactions at the ice shelf margins have generally been inconclusive. *Thomas* [2007] suggested tidal tilting of ice shelves may be a mechanism responsible for the horizontal motions. *Brunt* [2008] considered tidal elevation changes and basal drag from ocean currents within a viscous ice shelf flow model in an attempt to explain the tidal motion of Ross Ice Shelf; however, the model only captured 4% of the observed daily oscillations. How ocean tides cause smooth sinusoidal diurnal and semidiurnal variations in horizontal flow, amplified toward the ice shelf front, remains unclear.

[3] Here we report on new data collected from an extensive network of GPS receivers deployed across Ronne Ice Shelf (RIS); the first ice shelf survey with up to year-long contemporaneous GPS records at multiple sites from the shelf front, central ice shelf and close to grounding zones. These data, combined with sub-ice shelf current meter data, provide new insights into the mechanical coupling between ocean tides, ice shelves and ice streams, and allow us to determine the principal mechanism driving daily ice shelf motions.

2. Observations and Data Analysis

[4] Geodetic-quality GPS receivers were deployed at nine sites on RIS (Figure 1) during the Austral summer of 2007-08; they recorded the three-dimensional ice shelf motion over periods spanning 2.5 to 58 weeks. The station coordinates were determined every five minutes using the GPS processing methods described by *King et al.* [2011b], giving a precision of ~5 mm in the horizontal and ~10 mm in the vertical.

[5] The mean ice shelf velocities are highest near the ice front and central ice shelf (Figure 1) and a map view of the horizontal ice shelf displacement at FR07 over a 2-day period (Figure 2a) clearly shows a rotary motion superimposed on the mean flow, resulting in regular flow reversals. These displacements equate to velocity variations that are around ±300% of the long-term value. Apart from FR03 and FR04 close to grounding lines, similar rotary oscillations and velocity variations (Figure 2b) are observed at all sites on RIS, with similar but smaller amplitude motions also observed on other ice shelves. In this paper we consider band-pass

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[1] British Antarctic Survey, Natural Environment Research Council, Cambridge, UK.

[2] School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK.

Corresponding author: K. Makinson, British Antarctic Survey, Natural Environment Research Council, Cambridge CB3 0ET, UK. (kmak@bas.ac.uk)

filtered (2–36 hour) data, based on a finite impulse response filter, with a 20-day portion of the along-flow displacement shown in Figure 2b for several of the sites. This reveals the strongly semidiurnal variation in along-flow velocity which is almost zero close to the southern ice stream grounding lines (e.g., FR03) and greatest along the ice front region (FR07 and FR10).

[6] To investigate these oscillations more closely we performed a harmonic analysis [*Pawlowicz et al.*, 2002] of the band-passed displacement time series. For all the sites, apart from FR03 and FR04, which are located close to the ice stream grounding lines, this analysis finds that over 96% of the variance of the horizontal displacements within this frequency band occurs at diurnal and semidiurnal tidal frequencies, confirming that the ice shelf motion is dominated by signals of tidal origin. These tidal oscillations are characteristic of those seen on other ice shelves [e.g., *Brunt*, 2008; *King et al.*, 2011a], which are amplified near ice fronts but suppressed close to grounding line regions. Harmonic analysis of current-meter data from directly beneath FR07 and at Site 3, 70 km south of FR05 (Figure 1) also allows the reconstruction of the tidal ocean currents during the GPS campaign (Figure 2c).

3. Results

[7] The near-synchronous horizontal oscillatory response across the whole ice shelf, predominantly at semidiurnal tidal periods (Figure 2b), indicates that RIS acts as a coherent plane responding to the semidiurnal tidal Kelvin waves that rotate around the southern Weddell Sea embayment [*Nicholls et al.*, 2009]. One potential forcing mechanism for the observed oscillations may come from tidal elevation changes along grounding lines, where tidal flexure, for example, could drive ice shelf wide motions. However, the changing character of tidal elevations across RIS (Figure 2d), the significant phase differences around the coast [*Nicholls et al.*, 2009], and the absence of a mechanism to significantly amplify the signal toward the ice front, suggest that this process cannot be the primary driver of the ice shelf wide semidiurnal horizontal oscillations. Tidal currents however, are predominantly semidiurnal, and become stronger nearer the ice front (Figure 2c), while tidal surface slopes tilting the ice shelf are strongly semidiurnal perpendicular and parallel

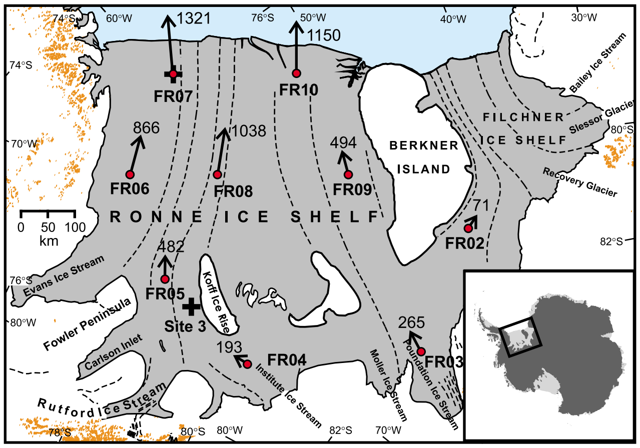

Figure 1. Map of Ronne Ice Shelf (grey shading) showing the GPS sites (red circles) and mean annual ice velocity vectors in m a^{-1}. The black crosses show the position of ocean current meter sites.

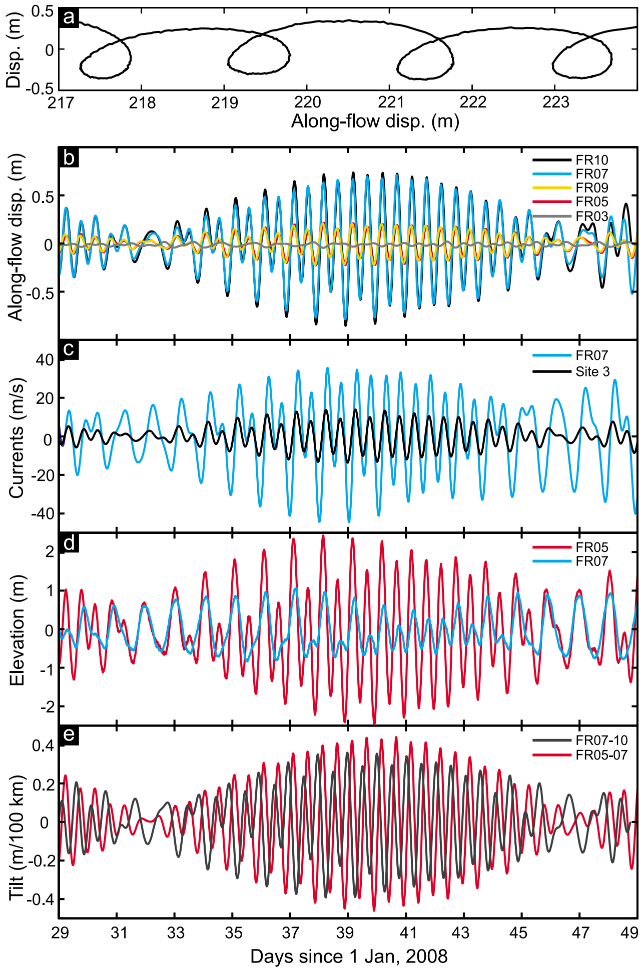

Figure 2. (a) Map view of the horizontal ice shelf displacement at FR07 for days 39 to 41. (b) Along-flow displacement band-pass filtered (11-30 hours) for GPS sites across RIS. (c) Predicted ocean tidal currents at mooring sites oriented in the direction of FR05 to FR07. (d) Elevations from FR05, FR07 and (e) tilt perpendicular (FR05-07) and parallel (FR07-10) to the ice front.

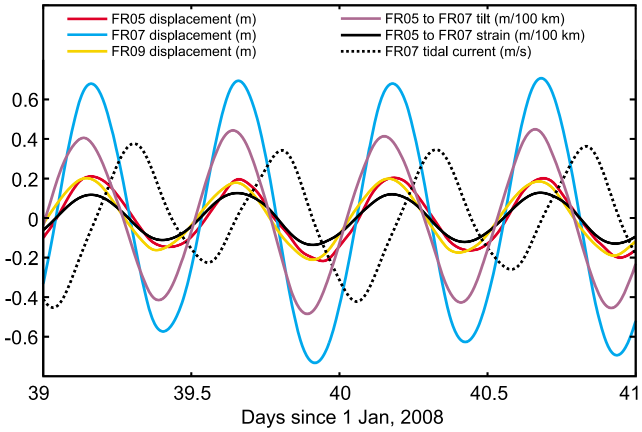

Figure 3. Time series of displacement, tilt, strain and tidal current in the direction of FR05 to FR07.

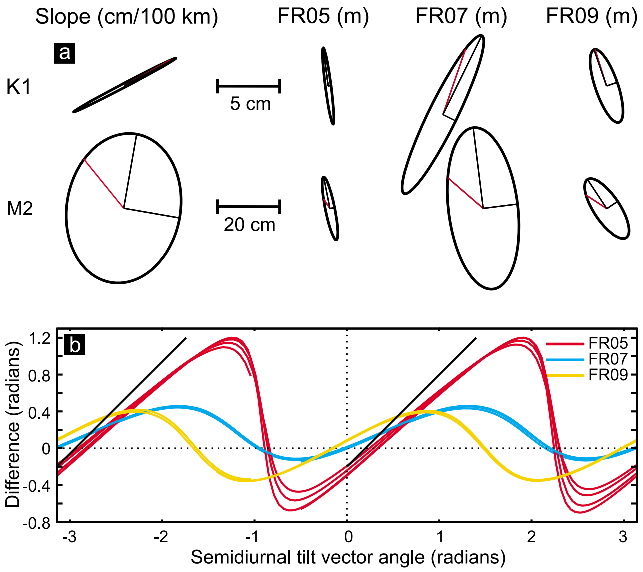

Figure 4. (a) The principal diurnal (K_1) and semidiurnal (M_2) tidal ellipses for the horizontal displacement at the GPS sites and the tilt between FR05, FR07 and FR09. The coordinates are oriented in the direction of FR05 to FR07, the black lines show the ellipse axes and the red line the phase. (b) The semidiurnal tilt vector angle verses the angular difference between the tilt and displacement vectors for FR05, FR07 and FR09 over a 2-day period or 4 tidal cycles. The zero angle is oriented in the direction of FR05 to FR07, positive rotation is clockwise, and the black line indicates the line of no angular change for the displacement vector.

to the ice front (Figure 2e), suggesting two candidate mechanisms for the ice shelf motions.

[8] To investigate tidal currents and tidal tilting as potential forcing mechanisms, we consider FR07 and FR05, which have near continuous year-long GPS records. In Figure 3 we focus on a 2-day time series of predicted ocean currents oriented in the direction of FR05-07 and ice shelf tilt, together with the FR05 and FR07 displacements and strain between them, highlighting the phasing of the potential forcing mechanisms and ice shelf response. Although the tidal currents and the ice shelf response are similar in character (Figure 2), the phasing is significantly different. In contrast, the surface tilt between the two sites matches closely the ice shelf displacement in both the relative amplitude and phase, suggesting that tidal tilt rather than tidal currents is the primary driver of the horizontal movements and the strain between sites (Figure 3). Since ice at −20°C is expected to be almost purely elastic at diurnal and semidiurnal periods [*Gudmundsson*, 2007], the cold ice of RIS behaves predominantly as an elastic sheet at tidal time scales. Anchored at its southern grounding lines, the ice shelf responds to twice daily changes in tilt, causing large variations in both velocity and strain, as well as amplifying the horizontal motions towards the ice front. These large spatial variations in amplitude highlight the fundamental requirement for observations to span the whole ice shelf from grounding line to ice front.

[9] Closer inspection of the RIS displacement response in the direction of FR05-07 reveals differences in phase of up to one hour between sites (Figure 3) and in other orientations these differences can be even greater. Simply considering the displacement oscillations in one orientation, e.g., between the southern grounding lines and the ice front, therefore overlooks the two-dimensional response of the ice shelf (Figure 2a).

[10] Using elevation data from FR05, FR07 and FR09, we are able to define a tilt vector for the bulk of RIS. We then use harmonic analysis to find an ellipse for each tidal constituent of the tilt signal within this region, with the ellipse representing the path traced by the constituent vector's tip. Figure 4a shows the main diurnal (K_1) and semidiurnal (M_2) constituents' ellipses, for the tilt and the displacement signal at each site.

[11] The tilt ellipses show that the forcing between tidal bands is very different as a result of the differing tidal wave fields [*Nicholls et al.*, 2009], with semidiurnal constituents being almost circular, while diurnal constituents are much closer to rectilinear. Although subject to the same diurnal and semidiurnal forcing, the displacement response varies significantly between sites (Figure 4a) because the elastic response perpendicular to coastlines is restricted. Considering only the dominant semidiurnal band, Figure 4b shows the angular difference between the displacements and tilt vector over the 2-day period or almost four tidal cycles, highlighting how this response varies in time and between sites. As the almost circular semidiurnal tilt vector rotates, the local coastline appears to keep the displacement vectors approximately aligned with the direction of flow parallel to the coast, leading to a near linear increase in the angular difference. If the displacement vector remained stationary, the angular difference would follow the black lines in Figure 4b. Once the tilt vector approaches and then passes a line approximately perpendicular to the local coast, the displacement vector rapidly changes direction, catching up with or passing the tilt vector and the process repeats. At FR05 for example, Korff Ice Rise and Fowler Peninsula dictate the primary direction of the horizontal tidal oscillations; likewise at the other sites, the nearest coastline has a similar influence, which becomes less pronounced with distance from the coast. Consequently, the coastal geometry appears to control the magnitude, direction and phase response of the ice shelf.

4. Discussion

[12] Of the potential mechanisms driving diurnal and semidiurnal horizontal ice shelf displacements, it appears that tilting of RIS by tidal sea surface slopes dominates, with the ice shelf responding mainly elastically over these tidal periods. Although complex processes in grounding line regions may dominate locally, it is doubtful that they can drive a significant unified tidal motion across the whole ice shelf that is amplified towards the ice front.

[13] Tidal currents causing drag on the ice shelf base have generally been dismissed as being too weak or the basal drag coefficient too small, to produce the relatively large ice shelf response [*Brunt*, 2008; *Doake et al.*, 2002; *King et al.*, 2011a]. In addition, and in agreement with Kelvin wave theory, our data show that tidal currents are in quadrature with the ice shelf tilt, confirming that currents cannot be the primary driver of the horizontal motions even if basal friction phase-advances the current velocity vector at the ice shelf base by up to 1 hour [*Werner et al.*, 2003]. However, although not the

primary driver of horizontal ice shelf motion, tidal currents, which can reach 1 m s^{-1} along the Ronne Ice Front region [*Makinson and Nicholls*, 1999], will presumably have some minor effect on the ice shelf response.

[14] In the southern Weddell Sea and around Antarctica, tidal Kelvin waves propagate along coasts from east to west, where the amplitude is greatest at the coast, and the steepest gradient is approximately perpendicular to the regional coastline. Assuming a purely elastic ice shelf, the tilt perpendicular to the coast will be at a maximum at high tide, with the ice shelf displacement, strain and stress at a maximum and the oscillatory velocity zero, whereas the peak seaward velocity will occur on the rising tide when the height, tilt and extension are all zero. At low and falling tide, the reverse will occur, completing the oscillatory cycle. The strain between sites FR05-FR07 (Figure 3) also highlights the elastic response of the ice shelf, which accounts for the amplification of the ice motion between grounding zone and ice front. Differences in the phase response to tilting are likely the result of nearby coastlines, with minor contributions from tidal currents and possibly local grounding line processes. For smaller ice shelves or sites near coasts, grounding line processes may play a more prominent role.

[15] On Ross Ice Shelf, flow oscillations occur on diurnal times scales, with strong amplification toward the ice front [*Brunt et al.*, 2010]. *Brunt* [2008] noted that periods of high tide were consistently associated with the maximum northwards displacement toward the ice front, while low tides were consistently associated with the minimum northward displacement, which is consistent with our observations from RIS. On Brunt Ice Shelf, tilting of the ice shelf appears to account for much of the unexplained oscillatory motion reported by *Doake et al.* [2002]. Similarly, observations from both Mertz Glacier Tongue [*Legrésy et al.*, 2004] and Larsen C Ice Shelf [*King et al.*, 2011a] show, with the mean flow removed, near zero along-flow velocity at high and low tide, which coincides with the maximum and minimum displacements respectively. Also, the maximum velocity occurs on a rising tide and the minimum velocity on a falling tide, all characteristics of tilt-driven ice shelf motion.

[16] On the larger ice shelves, such as Ronne, Ross and Larsen C, the periodic elastic elongation and compression are sufficiently large to cause flow reversals of the ice shelf during the tidal cycle, particularly at spring tides. On RIS, which experiences the largest tidal range around Antarctica of up to 7 m, the oscillations in velocity and strain are much larger than on smaller ice shelves. The oscillating ice shelf stresses, which will be zero at the ice front and greatest toward grounding lines, will influence the horizontal force balance of the inflowing ice streams and the phase relationship between ice stream flow and the tidal forcing, particularly ice streams with low-friction beds [e.g., *Anandakrishnan et al.*, 2003; *Bindschadler et al.*, 2003; *Thomas*, 2007]. For parts of RIS where its length exceeds 600 km and the thickness ranges from 300 m at the ice front, to over 1200 m at the grounding lines, the horizontal elastic stresses could exceed ±20 kPa, which is approaching the stress perturbations caused by the tidally varying height of the water column. The long-term flow of ice streams and therefore the mass balance of ice shelves is already known to be modified by oceanic tides, generating fortnightly variations in flow speed of up to 20% and increasing mean speeds by 5% [*Gudmundsson*, 2011] to 12% [*King et al.*, 2011a], depending on the basal shear stress of particular ice streams. While visco-elastic model predictions replicate quite well the observed Rutford Ice Stream flow, the lowest speed is not at high tide, as would be assumed if water pressure was the main driver [*Gudmundsson*, 2011]. This suggests that the similarly sized additional stress from tidal tilting, which is absent in current models, may contribute to both enhanced ice stream flow and the complicated phase relationship that arises from the non-linear visco-elastic rheology of ice. Since models are optimized to fit observations, some or all of the horizontal stress from tilt will be integrated into their parameterizations making the significance and the proportion of motion attributable to tilt unclear, particularly if processes are operating in opposition rather than in unison. Consequently, the effects of additional cyclical diurnal and semidiurnal horizontal stresses from tilt may play a significant role in the flow of ice streams and ice shelves, and while there is currently no compelling evidence that tides are responsible for the rifting, calving and breakup of ice shelves, these are mechanisms that may have contributed to the instability of Arctic ice shelves and the generation of Heinrich events during the last glacial period [*Arbic et al.*, 2004].

5. Conclusions

[17] We have used GPS observations from across RIS to determine the primary mechanism through which the ocean tides force near synchronous horizontal ice-shelf displacements at diurnal and semidiurnal-diurnal tidal periods. Our results clearly demonstrate that tidal tilting of RIS drives horizontal displacement and velocity oscillations of up to ±300% of their long-term mean values, with strains exhibiting similar fluctuations. With RIS anchored to the grounded ice sheet at its southern margins, any changes in surface tilt, particularly in the seaward direction, results in horizontal diurnal and semidiurnal-diurnal motions that are amplified toward the ice front, as the ice shelf either compresses or elongates.

[18] Near coastlines the phase of the ice shelf's response is modified from that expected for a pure tilt forcing. The geometry of the coastlines also determines the primary orientation of motion. In regions with small tidal amplitudes and on smaller ice shelves, the horizontal oscillations will be greatly reduced. Inspection of observations from several other ice shelves, both large and small, indicates, however, that tidal tilting remains the dominant driver of diurnal and semidiurnal horizontal ice shelf motions. This represents a newly-observed ice shelf forcing and response that can also generate significant cyclical horizontal stresses at grounding lines. The complicated non-linear response of ice streams to tidal forcing, which includes stresses from ice shelf tilt, show that if we are to fully understand these systems it is important to identify key processes, their interactions, and develop specific parameterizations, rather than combining multiple and potentially opposing effects into a single parameterizations. Since long-term ice-shelf/ice-stream flow is also modified by oceanic tides [*Gudmundsson*, 2011; *King et al.*, 2011a], studying the effects of tidal tilting will enable the validation of more comprehensive non-linear visco-elastic ice shelf / ice stream models.

[19] Understanding the dynamics of ice shelves and how they respond to the full range of natural forcing frequencies such as ocean tides is fundamental to understanding their

coupling to continental ice streams, ice sheet mass balance, and its response to future change. Furthermore, *Arbic et al.* [2004] suggested that tidal stresses may be required to explain paleo-iceberg calving events, while the sensitivity of tidal amplitude to water column thickness and hence changes in both ice shelf thickness and relative sea level could amplify the effects of tidal tilting beyond that shown here when considering paleo megatides [*Griffiths and Peltier*, 2009]. Our observations from RIS and those from other ice shelves show that when tilted by tidal slopes, ice shelves respond primarily elastically to daily tidal forcing and transmit stresses upstream from the ice front toward the grounding lines of inflowing ice streams. These perturbations in stresses at the grounding line due to tidally induced variations in ice-shelf slope can be expected to impact ice-stream flow while the possibility that some of the observed modulation in ice shelf flow is driven by ice-streams cannot be discounted. Quantifying this mutual interaction between ice-streams and ice-shelves requires further modeling efforts.

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