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An estimate of kinematic vorticity from rotated elongate porphyroblasts

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Abstract

Internal fabric in strain shadows around elongate rutile porphyroblasts indicates rotation of porphyroblasts relative to the incremental stretching direction during deformation within a regional-scale shear-zone in south-central Alaska. For porphyroblasts of various aspect ratios and initial orientations, this fabric is used to assess the sense of rotation relative to the direction of maximum incremental stretching, the total rotation, and the vorticity. The total rotation of porphyroblasts relative to the external fabric based on these parameters varies as a function of porphyroblast orientation. All 111 porphyroblasts, regardless of orientation, have rotated in a clockwise sense relative to the external fabric. Comparison of these results with previous models suggests that the deformation which affected the porphyroblasts took place in the field of continuous forward rotation with a maximum ratio of the rate of pure shearing to the rate of simple shearing (s_r) of 0.21 or a kinematic vorticity number $W_k > 0.92$. The model curves showing rotation vs final orientation do not vary significantly over the range of s_r and R that is relevant to this study. The data have significant scatter, yet there is remarkable agreement between the data and the model for a γ of 1.5. These results illustrate how strain shadows around porphyroblasts with large aspect ratios and variable initial orientations provide a more complete assessment of kinematics than inclusion trails within more equant porphyroblasts.

1. Introduction

Spiral inclusion trails, or large differences in orientation between inclusion trails within porphyroblasts (S_i) and the external fabric (S_e), have typically been taken as evidence that porphyroblasts rotate relative to internal reference frames (e.g. the incremental stretching axes or shear plane) during non-coaxial strain (Rosenfeld, 1970; Schoneveld, 1977). Over the last decade, this interpretation has been called into question based on the argument that porphyroblasts in shear zones occupy local domains of coaxial strain where they are fixed relative to external reference frames (Bell, 1985; Bell et al., 1986, 1992c; Hayward, 1992). The porphyroblast debate has largely focused on kinematic interpretations for the difference in orientation between the external fabric and the inclusion trails within porphyroblasts (Bell et al., 1992a, c; Passchier et al., 1992; Wallis, 1992). These interpretations are not always well constrained (Bell et al., 1992c) since small (< 90°) apparent rotations of spherical porphyroblasts can represent coaxial strain with rotation of the external fabric relative to incremental stretching axes (Ramsay, 1962; Kennan, 1971) or noncoaxial strain with rotation of the porphyroblast and fabric relative to incremental stretching axes (Rosenfeld, 1970; Schoneveld, 1977; Williams and Schoneveld, 1981). Even large (> 90°) apparent rotations and truncations of inclusion trails have been attributed to the overgrowth of crenulations (Bell et al., 1986) or transposed foliations (Bell et al., 1992b). This debate is of more than microstructural interest, since, as Bell and Johnson (1989) point out, these structures may be capable of providing key insights into tectonic processes.

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Since the widespread dissemination of the view that porphyroblasts may be unlikely to rotate, work on the topic has continued on several paths. Studies have used the assumption of non-rotation of porphyroblasts to determine the history of foliation development, particularly near plutons (for example Vernon, 1989 and many others reviewed in Paterson et al., 1991). Other used spiral textures to investigate strain rates (Christensen et al., 1989; Barker, 1994). A number of modeling studies have shown how complex textures within and adjacent to porphyroblasts can arise from simple deformation histories (Masuda and Ando, 1988; Bjørnerud, 1989; Masuda and Mochizuki, 1989; Busa and Gray, 1992; Bjørnerud and Zhang, 1994; Gray and Busa, 1994; Zhang and Bjørnerud, 1995; Beam, 1996). Microstructural studies have shown both types of behavior (Vernon et al., 1993; Henderson, 1997; Morgan et al., 1998). Review articles have addressed the ambiguity of some structures, and suggested ways of distinguishing rotation from non-rotation (Johnson, 1993a, b; Johnson and Bell, 1996). Some have addressed non-spherical porphyroblasts in particular (Fisher, 1990; Busa and Gray, 1992; Visser and Mancktelow, 1992). It is this approach that we apply here.

A kinematic interpretation for porphyroblasts with 'rotated' inclusion trails can be further constrained by examination of the distribution of apparent rotations recorded by porphyroblasts of various aspect ratios and orientations (Fisher, 1990). For a general shear, a spherical rigid inclusion will rotate relative to an internal reference frame at a constant rate equal to one half the internal vorticity, whereas elongate rigid inclusions experience angular accelerations and decelerations, depending on their orientation relative to the kinematic frame (Ghosh and Ramberg, 1976; Simpson and De Paor, 1993). For simple shear, all rigid inclusions rotate in the same sense (Jeffrey, 1923). During combined pure and simple shear elongate rigid inclusions can stabilize with long axes parallel to the shear plane, and there is a range of orientations for which rigid inclusions rotate in an opposite sense as the sense of shear (Ghosh and Ramberg, 1976; Simpson and De Paor, 1993).

Visser and Mancktelow (1992) and Mancktelow and Visser (1993) used this type of reasoning to evaluate the apparent rotations of equant and elongate garnets around a fold. The rotations, as determined by difference between internal and external foliations, fit theoretical predictions both for the rotation of a rigid object, and for fold formation. Disagreement about the timing of garnet growth (Forde and Bell, 1993) may cast some uncertainty on this interpretation, but the overall pattern seems quite consistent with a rotational history.

Syntectonic fabrics in pressure shadows or strain shadows around porphyroblasts are another commonly observed texture that can be used to determine if porphyroblasts rotate relative to internal or kinematic reference frames during noncoaxial deformation (Fisher, 1990). Because fibers grow approximately parallel to the incremental extension direction (Durney and Ramsay, 1973) curved fibers represent rotation of the porphyroblast relative to the principal stretching axis. This feature is particularly useful when combined with analysis of porphyroblasts with a range of aspect ratios and orientations (e.g. Fisher, 1990). In the case of strain shadows addition of quartz can occur parallel to the quadrant on the porphyroblast surface that faces the incremental stretching direction. If the porphyroblast rotates with respect to the external foliation during general shear, the silica-rich strain shadow immediately adjacent to the porphyroblast rotates with the porphyroblast; intrafolial folds in the strain shadow record the minimum rotation of the porphyroblast with respect to the fabric. For porphyroblasts with large aspect ratios, the distribution of these rotations for a range of initial orientations can be used to evaluate the kinematic vorticity.

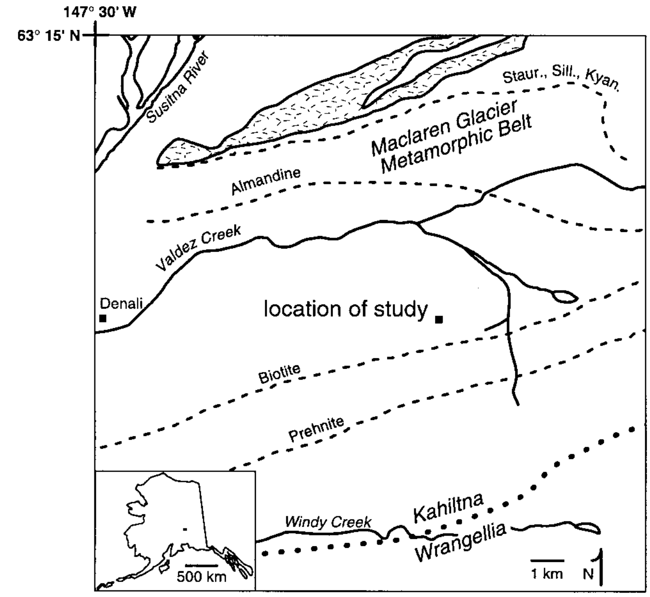

Fig. 1. Geologic map showing the sample locality along the northern boundary of Wrangellia, after Smith (1981). Inset map of Alaska shows location.

In this paper, we describe the evolution of porphyroblasts from a regional-scale shear zone in south-central Alaska. For porphyroblasts of various aspect ratios and initial orientations, the curvature of fabric in strain shadows is used to assess the sense of rotation relative to the direction of maximum incremental stretching, the total rotation (i.e. the total curvature), and the rate of rotation (i.e. the radius of curvature).

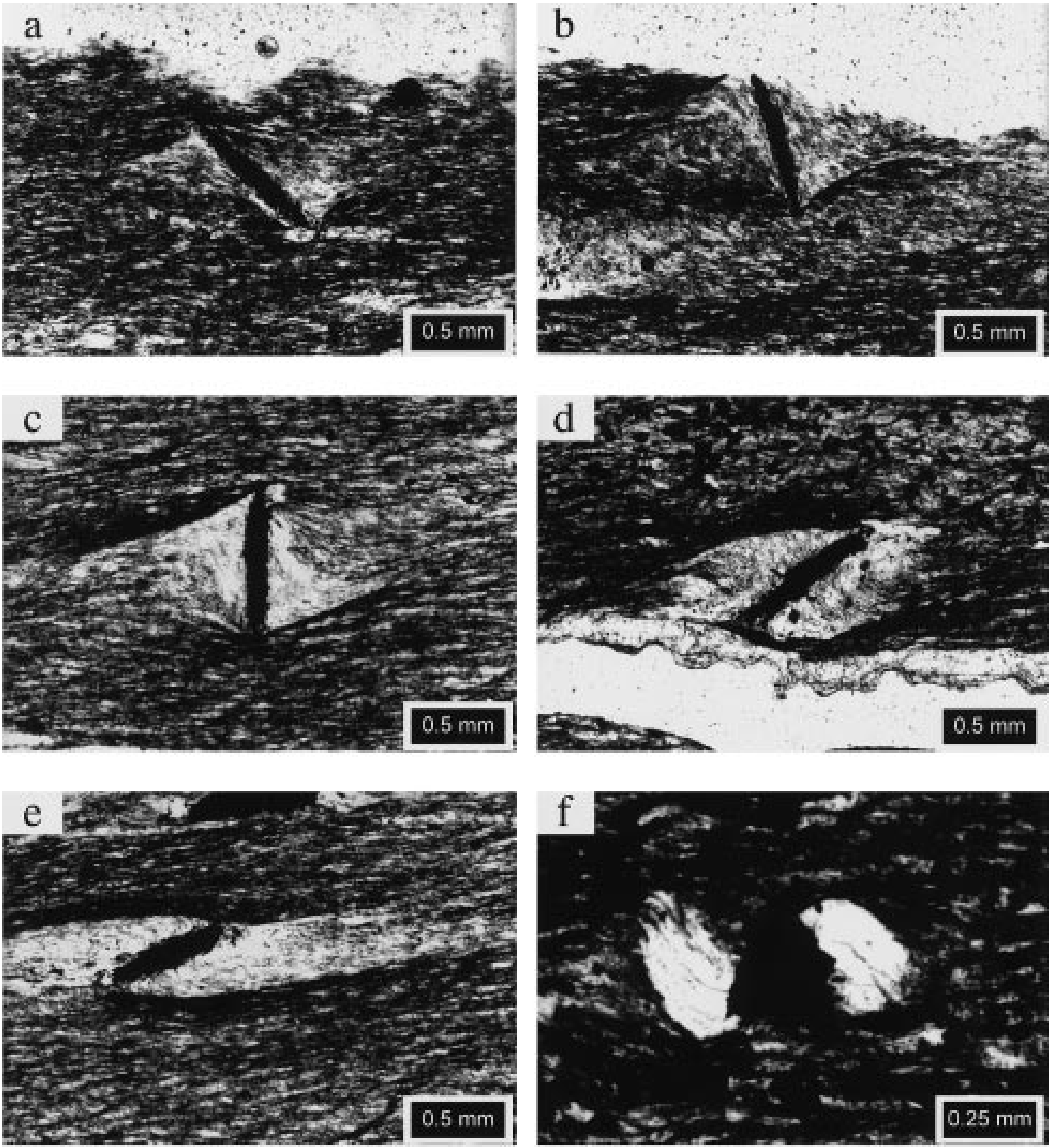

Fig. 2. Photomicrographs of typical strain shadows around rutile porphyroblasts (a–e) and pressure shadow around pyrite (f). All are plane polarized light.

These results allow us to assess whether the amount of rotation for porphyroblasts of various initial orientations is consistent with models for non-coaxial viscous flow around rigid ellipsoidal inclusions (Jeffrey, 1923; Ghosh and Ramberg, 1976).

2. Geologic setting

Samples for this study were taken from a Jurassic–Cretaceous flysch basin (i.e. the Kahiltna terrane) that lies between the Maclaren Metamorphic belt (to the north) and Wrangellia (to the south), and marks the suture between the Talkeetna superterrane and North America in the Clearwater mountains, Alaska (Fig. 1). We recognize three phases of deformation in the flysch: (1) D_A—development of numerous duplexes with small scale (10–30 cm thick) thrust slices that record footwall collapse along south-dipping (after tilting related to subsequent events is removed) frontal ramps that connect bedding-parallel detachments, (2) D_B—development of a regional scale shear zone and associated fabric, and (3) D_C—development of north-vergent folds with a fold wavelength of 100–2000 m (Smith, 1981). D_C folds both earlier events, leaving their mutual timing unclear.

Our study focuses on spotted slates along the northern margin of the Kahiltna terrane in the southernmost portion of the D_B shear zone. In this area, the slates represent the structurally lowest unit in a north-dipping inverted sequence of pelites that ranges from prehnite–pumpellyite in the south up to amphibolite facies in the north (Smith, 1981). It is believed that the shear zone formed at a depth of approximately 20 km during the collision between Wrangellia and North America (Davidson, 1991; Davidson et al., 1992). Spiral garnets in the upper part of the zone have been attributed to top-to-the-south shear within the shear zone (Davidson et al., 1992). Our own field work shows *S–C* fabrics, asymmetric boudins, pressure shadows with curved fibers which support this sense of shear.

In the spotted slates, elongate porphyroblasts display D_B strain shadows with a curved fabric composed of quartz and chlorite (Fig. 2). Energy dispersive spectra analysis on an electron microprobe shows these porphyroblasts to be composed of TiO_2. Rutile can persist in chlorite zone metamorphic rocks, while prograde growth of rutile occurs at kyanite grade and above (Force, 1980). Extremely thin sections show straight inclusion trails, indicating that this earlier metamorphic episode was not accompanied by deformation. Most porphyroblasts have axial ratios varying from 3 to 7 with an average of 5.02. Pyrite grains in these rocks also host pressure shadows that are primarily composed of quartz.

3. Analyses of porphyroblasts and strain shadows

The porphyroblasts are surrounded by light-colored strain shadows, consisting of curved quartz and chlorite grains. Close to the porphyroblasts, the shape fabric defined by these elongate grains is approximately perpendicular to the porphyroblast boundary. At the distal end, the fabric is parallel to the matrix foliation. We interpret the curvature of this fabric as a record of quartz and chlorite growth during the rotation of the porphyroblasts; thus its curvature records the finite differential rotation of the porphyroblast and the external fabric.

The inferred rotation of porphyroblasts based on an assumption of syntectonic growth of the fabric in the strain shadows is consistent with the sense of shear that was determined from other kinematic indicators observed by us and by others (Davidson, 1991; Davidson et al., 1992). Antitaxial pyrite pressure shadows from these samples also record non-coaxial strain histories consistent with the sense of shear from fabric curvature adjacent to porphyroblasts. Strain shadows are significantly richer in quartz and chlorite than the surrounding matrix, which indicates either enrichment in silica or less removal of silica than in the surrounding matrix. Dark matrix seams adjacent to porphyroblasts and strain shadows suggest that both were more competent than the surrounding matrix. Thus, the porphyroblast and fibers behaved as a single rigid object, and curvature within strain shadows represents progressive rotation of the porphyroblast–strain shadow complex relative to the incremental extension direction.

It is possible that the textures here were formed by reorientation of an existing cleavage around a fixed porphyroblast, as discussed in Passchier and Speck (1994). The wide variety of porphyroblast orientations and the range of curvature preserved in the fibers make that less likely in this case. In addition the strong agreement of the rotational measurements with theoretical prediction (discussed below) supports a rotational interpretation.

Strain shadows were observed in sections cut parallel and perpendicular to cleavage and parallel to a down-dip mineral lineation (viewed to the east). In cleavage-parallel sections, fibers in pyrite pressure shadows and linear fabric within porphyroblast strain shadows are parallel to the mineral lineation and are relatively straight, whereas fibers and strain shadow fabric are curved in cleavage-perpendicular sections. Thus, all the axes of porphyroblast rotation are normal to the cleavage-perpendicular sections and the deformation can be characterized as plane strain.

4. Results

The total rotation of porphyroblasts relative to the external fabric based on curvature of fabric in the strain shadows is shown in Fig. 3 for porphyroblasts of various orientations relative to cleavage. The most important result of this study is that all porphyroblasts, regardless of orientation, have rotated in a clockwise sense relative to the external fabric. Data fall into two groups. In the first, porphyroblasts have long axes oriented counterclockwise relative to cleavage.

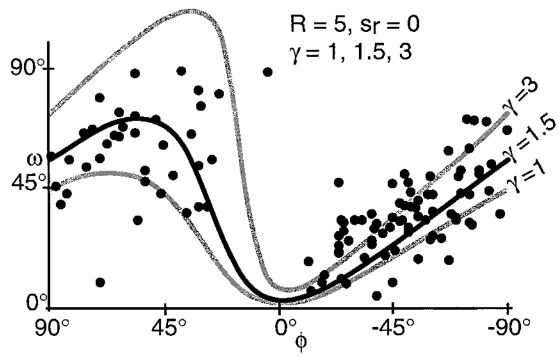

Fig. 3. Total rotation of individual porphyroblasts (ω) plotted as a function of orientation of the long axis relative to D_B cleavage. The cleavage plane is at 0°. Positive numbers are counterclockwise from this orientation, negative are clockwise. Ghosh and Ramberg (1976) model curves are also shown for $R = 5$, $s_r = 0$, and $\gamma = 1$, 1.5, and 3.

These porphyroblasts have a large scatter in rotations, with most being between 30 and 90°. In the second group, porphyroblasts have long axes oriented clockwise relative to cleavage. In this group the amount of rotation increases smoothly from $<10°$ for those close to the cleavage to $\approx 70°$ for those at a high angle to the cleavage. The initial orientation of each porphyroblast relative to this cleavage can be reconstructed by restoring the total rotation. The initial orientations cover a wide range of orientations but there is a normal distribution for the population with a mean of 20° counterclockwise from the cleavage.

5. Discussion

The pattern of apparent rotations from strain shadow fabrics is most easily explained in the context of a general shear model. Ghosh and Ramberg (1976) defined three fields of behavior for rotating elongate porphyroblasts that are dependent on the ratio of the rates of simultaneous pure shearing to simple shearing (s_r), and the axial ratio of the porphyroblast. In the first field, a porphyroblast may rotate in either direction (in the same or opposite sense as the bulk sense of shear) until it reaches a stable orientation. In the second field, rotation will always be in the same sense as the simple shear, and rotation will be continuous. In the third, the porphyroblast will rotate in the same sense as the simple shear until it reaches a stable orientation. Of 111 porphyroblasts measured, all have rotated forwards. Also, there is no clustering of porphyroblasts around a particular final orientation. From this, we conclude that the deformation which affected the porphyroblasts took place in the field of continuous forward rotation defined by Ghosh and Ramberg (1976). This implies that:

$$R < \frac{1+\sqrt{1+4s_r^2}}{2s_r} \tag{1}$$

where R is the aspect ratio of the porphyroblast. Using the mean axial ratio for the population of 5.02 and solving for s_r obtains a maximum s_r of 0.21 or a minimum kinematic vorticity number W_k of 0.92.

Ghosh and Ramberg's (1976) equation (12) for finite rotation involves one dependent and four independent variables in the form:

$$\phi = f(\gamma, s_r, R, \phi_0) \tag{2}$$

where ϕ_0 is the initial orientation measured clockwise from the normal to the shear plane and γ is the shear strain in the shear direction. This equation can be rearranged into the form:

$$\omega = \phi - \phi_0 \tag{3}$$

where ω is the total porphyroblast rotation relative to the kinematic frame and ϕ is the final orientation. Thus

$$\omega = f(\gamma, s_r, R). \tag{4}$$

For this example, we have constrained $s_r<0.21$ and measured the axial ratios of the porphyroblasts, so the only unknown in this equation is γ. The orientation of the shear plane is not well constrained, but we assume that the cleavage is near parallel to the boundaries of the shear zone. This is based on the large amount of displacement within the shear zone and the near-constant orientation of both the slaty cleavage in these rocks and the mylonitic foliations in the higher grade overlying rocks. The model curves showing rotation vs final orientation do not vary significantly over the range of s_r and R that is relevant to this study. Because the amount of finite simple shear strain γ is the most important factor in determining the nature of the distribution, R and s_r were fixed at a value of $R = 5$ and $s_r = 0$. This corresponds to the condition where only simple shear strain affects the porphyroblasts.

There is remarkable agreement between the data and the model. Much of the scatter may be due to factors such as (1) variability in porphyroblast shape in the third dimension, (2) deformation of strain shadows, and (3) change in shape of the porphyroblast–strain shadow complex as the strain shadow gets larger (Johnson, 1990; Bell et al., 1992a; Passchier et al., 1992). Using a routine that varies γ to minimize the square of the difference between observed and predicted values we find a best fit for the observed data occurs at $\gamma = 1.5$ (Fig. 3). Two thirds of the data fall between a lower bound of 1 and upper bound of 3. Though there is considerably more scatter in the data between 0 and 90° than in the 90–180° interval, it should be noted that the expected ϕ vs ω curves are much more sensitive to γ in this range. For simple shear, the model of Ghosh and Ramberg (1976) predicts that rotating porphyroblasts decelerate relative to the kinematic frame when their long axis is within the quadrant of infinitesimal extension and accelerate when their long axis is within the quadrant of infinitesimal shortening. This could explain the larger number and tighter clustering of rotation for porphyroblasts within the 90–180° interval.

6. Conclusions

1. Syntectonic strain shadows around elongate rutile porphyroblasts indicate clockwise rotation relative to the incremental external fabric of all porphyroblasts, regardless of initial orientation. Some porphyroblasts have rotated through the shear plane. These conditions are consistent with progressive shearing with a ratio of pure shear to simple shear s_r<0.21 (Ghosh and Ramberg, 1976), or a kinematic vorticity number $W_k > 0.92$ (Bobyarchick, 1986).
2. The amount of rotation of elongate porphyroblasts relative to an internal reference frame varies as a function of the orientation of porphyroblast long axes and is consistent with model predictions (Jeffrey, 1923; Ghosh and Ramberg, 1976) for $\gamma = 1.5$.

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