Reply to discussion by

M.J. Bovis

of **'Limits to common toppling'**

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by

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"The limits to common toppling" used Goodman and Bray's (1976) assumptions to extend the limits of toppling to plagioclinal and underdip cataclinal slopes, slopes at more than 20° to the dip direction of the bedding or schistosity in the rock mass and slopes less steep than but in the same direction as the dip of the penetrative discontinuity. I am grateful to Bovis for his support of the first of these extensions though his proposal of the term "plagioclinal toppling" to describe the process on plagioclinal slopes may be unnecessary. Common toppling on plagioclinal slopes is mechanically identical to toppling on anaclinal slopes.

We agree about block toppling on underdip slopes. Figure 5 in the Note is similar to Bovis' Figure 2. The Note commented (p.739), " . . . if the column in Figure 5 is to topple as a block, . . . forces . . . need to assist the process and rotate the column through the vertical till it may fall under its own weight".

Savage et al. (1985) have demonstrated that the maximum principal stress is parallel to the slope in the central portions of long, steep, gravity-stressed slopes in elastic continua. When a block rotates away from the slope, it is no longer part of the elastic continuum forming the slope and the stress field in the column changes from that assumed in Goodman and Bray's analysis. It is possible, however, for toppling to take place without separation of columns from the elastic continuum. The columns may fold in flexure-toppling or small blocks forming the columns may rotate or slide slightly with respect to one another in block-flexural toppling. Because the blocks are still in contact at numerous points and there is no substantial change in the slope profile, the stress distribution in the slope can still correspond to that in an elastic continuum. Under these circumstances, Bovis' interesting objections to toppling on underdip slopes do not apply. The principal stresses induced by gravity within the slope remain essentially parallel (and perpendicular) to the slope. Rotations of blocks downslope under these reoriented gravitational stresses do not appear to require any additional energy.

Over what range of slope angles and rotations maximum principal stresses remain parallel to slopes awaits further analysis. My suggestion that underdip cataclinal slopes should be steeper than friction angles on the penetrative discontinuities was intended to be conservative. Further examples of toppling on underdip slopes (Zischinsky, 1966, Stearn, 1935, Riemer, et al., 1988) suggest it is so.

While the Note was concerned only with the consequences of Goodman and Bray's (1976) assumptions, there is another kinematic threshold in toppling on underdip slopes which may be significant. In Figure 1, the block has toppled by sliding on two surfaces, 0A and 0B. The criterion for sliding on 0B is Goodman and Bray's which, as Bovis has pointed out, is not stringent. The condition for sliding on 0A with the largest principal stress again parallel to the slope (and much larger than the other principal stresses) is

$$\tan(\psi - \beta) > \tan\phi$$

Writing this condition as

$$\psi > \phi + \beta$$

allows it to be used to identify discontinuity orientations on slopes where topples may occur. Further examination of natural underdip cataclinal topples may then resolve Bovis' questions. His emphasis on these problems with the analysis of a puzzling natural phenomenon underscores the need for more work on it.

References

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List of Figures

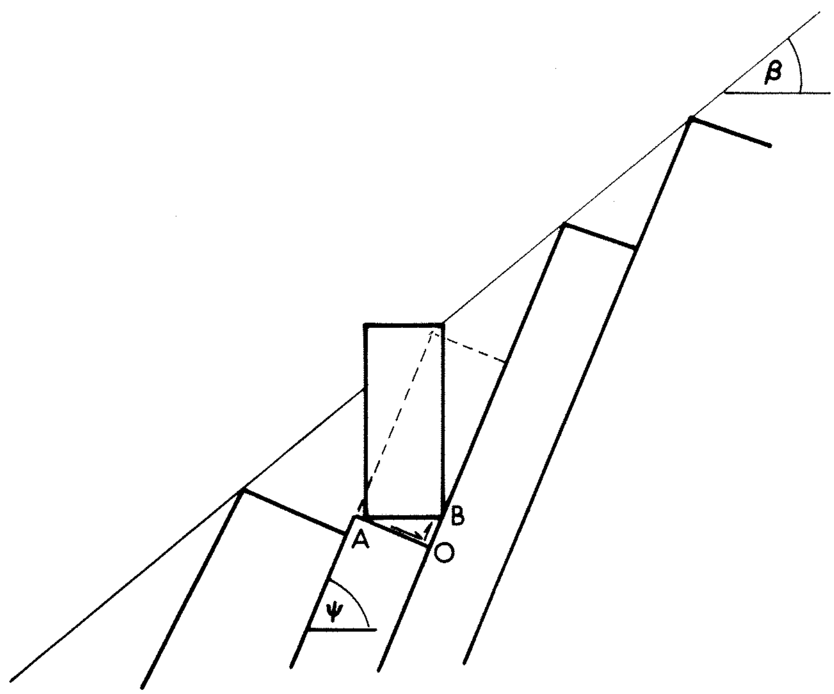

Figure 1. Toppling by sliding on 2 surfaces