ELASTIC BUCKLING OF FRACTURED BASALT: CASE STUDY OF THE COLUMBIA PLATEAU, EARTH, USING AN IMPROVED STRENGTH CRITERION,

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Summary. The continental flood basalts of the Columbia Plateau, Washington State, have been deformed into a series of anticlines termed the Yakima Fold Belt. These periodically spaced folds may be associated with buckling instability of a basaltic layer overlying a sedimentary substrate. Previous calculations of critical stress and dominant wavelength associated with possible buckling of these rocks assumed the strength properties of intact basalt. Those calculations suggested that buckling required very large modulus contrasts. Here we investigate the effect of using a rock-mass strength criterion and a deformation modulus on simple elastic models for buckling of basalts at the Earth's surface. We find that buckling can be predicted for smaller, more plausible values of modulus contrast. Using revised parameters, the buckling model provides a reasonable explanation for periodic folding in these fractured basalts.

Introduction and Results. Folding of sequences of basaltic lava flows on the Columbia Plateau, Washington State, is a plausible mechanism for forming the Yakima ridges [1]. Although thrust faults have nucleated in the cores of these anticlines [2], the regular spacing between ridges is consistent with localization and dominant wavelength of folding due to buckling instability at or near the free surface [3].

In order for previous elastic models to predict the proper ridge spacing on the Plateau (12–28 km), large Young's modulus contrasts (plate vs. substrate) that exceed 500 or 1000 are typically required. This result requires that the critical stress for buckling is less than the shear strength of the basaltic plate. Division of the strong basaltic plate into a number of thinner plates with frictionless contacts is also needed. The requirement of very large modulus contrast has rendered elastic buckling models somewhat limited in their applicability to this problem. As a result, viscous models have been preferred over elastic models for predicting ridge spacing.

Because the strength of the plate is a constraint on elastic buckling models, the choice of strength criterion for the strong basaltic layer is of fundamental importance. Previous work assumed an elastic (basaltic) plate with shear strength limited only by Byerlee's law [4], a single plane of weakness model of static frictional strength [5]. Here we assume instead a rock-mass strength envelope based on the Hoek-Brown criterion [6] and applied to basaltic lava flows by Schultz [7]. Evaluation of the rock-mass strength criterion for the strong plate demonstrates that an elastic buckling model can be applied successfully to the stated problem.

Buckling of the basaltic sequence is modeled by evaluating the deflection of an elastic plate at the free surface due to an in-plane horizontal end load [e.g., 8]. The plate rests on a substrate having finite thickness, which in turn overlies a rigid halfspace.

Using the Hoek-Brown formulation, the critical stress for buckling and dominant wavelength of folding are dependent in part on the modulus of the plate. Because the computed deformation modulus is also related through RMR to the rock-mass strength criterion, the stress and strength criteria are not completely independent. This interplay is depicted in Fig. 1, where lower and upper values of RMR for various basalts from the Columbia Plateau ($45 < \mathrm{RMR} < 75$) are associated with lower and upper values of deformation modulus ($15 < E^* < 45$ GPa). The deformation moduli correspond to modulus contrasts of ≤ 250.

The required contrast in (deformation) moduli between the basaltic plate and substrate is much lower than for previous solutions. However, plate thicknesses, modulus contrasts, and dominant wavelength of folding should all be consistent with the observations for the model to be considered successful. The thickness of the Grande Ronde basalt sequence, which was involved in the folding, is ~2.0–3.5 km. As shown in Fig. 2, modulus contrasts of less than ~250 are sufficient to predict the spacing of ridges on the Columbia Plateau. A plate thickness of 3000–4000 m is implied by the mean ridge spacing of ~20 km, comparable to the observed thickness of basalts.

The use of a simple Byerlee's law criterion to represent the shear strength of the basaltic plate prohibits buckling of relatively thin multilayers for the range of modulus contrasts evaluated. This implies that thinner basalt sequences cannot buckle. However, field observations do not support this prediction. Secondary (or second-order) folds arranged in echelon sets are developed on the flanks of some of the anticlines [1]. Some of these smaller anticlines and synclines appear to be rooted in relatively thick sedimentary interbeds that occur in the upper section of the Columbia River Basalt Group and involve basalt sequences <500 m thick. Folding of these thinner layers is consistent with the buckling model, assuming a rock-mass strength criterion for the basaltic layer.

Conclusions. We demonstrate that an elastic buckling model, in combination with a rock-mass strength criterion, can satisfactorily predict the spacing and occurrence of folds in near-surface basaltic rocks on the Columbia Plateau. The presence of very large modulus contrasts between basalt and substrate, required in previous elastic models, may no longer be necessary when rock-mass strength is used instead of simple discontinuity strength.

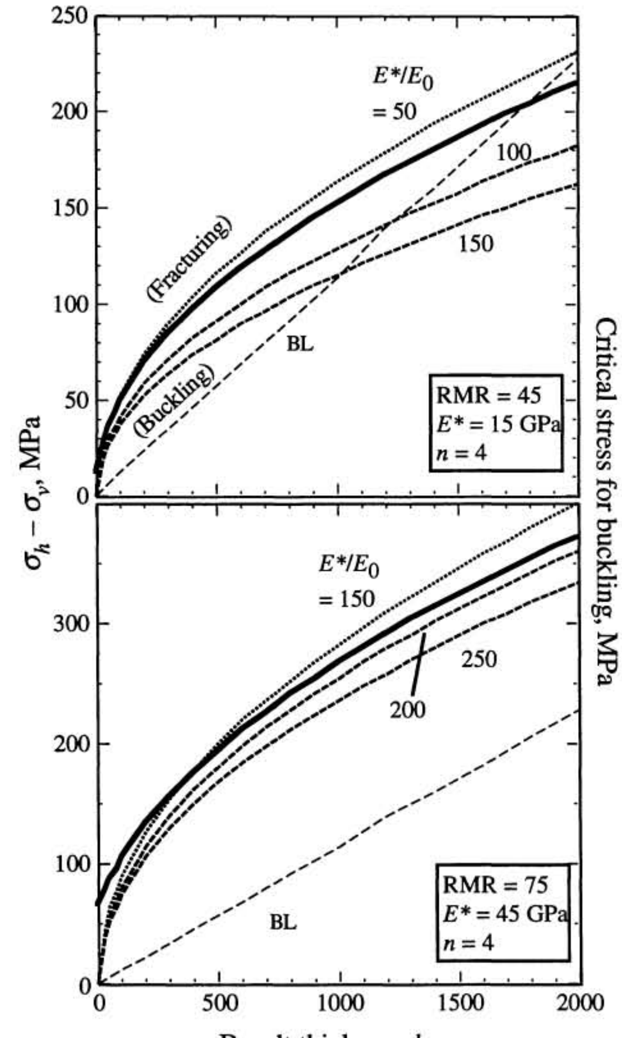

Figure 1. Critical stress for buckling (dashed, dotted curves) vs. thickness of basaltic plate for plausible values of RMR. Plate divided into $n = 4$ layers. BL, Byerlee's law.

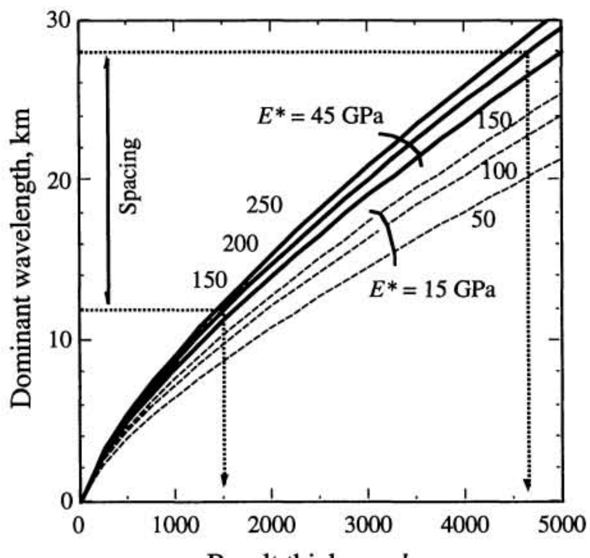

Figure 2. Determination of plate thickness consistent with observed ridge spacing for indicated modulus contrasts.

References. [1] Reidel et al., *GSA SP* **239**, 247–264, 1989. [2] Reidel, *Am. J. Sci.* **284**, 942–978, 1984. [3] Watters, *GSA SP* **239**, 283–292, 1989. [4] Byerlee, *Pure Appl. Geophys.* **116**, 615–626, 1978. [5] Priest, *Discontinuity Analysis for Rock Engineering*, Chapman & Hall, 1993. [6] Hoek and Brown, *J. Geotech. Eng. Div. ASCE* **106**, 1013–1035, 1980. [7] Schultz, *JGR* **98**, 10,883–10,895, 1993. [8] McAdoo and Sandwell, *JGR* **90**, 8563–8569, 1985.