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Flexural-slip structures in the Bushveld Complex, South Africa?

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Abstract

This paper investigates structures in the layered Critical Zone of the Bushveld Complex in South Africa that have detrimentally affected mining operations. The common structures are layer-parallel faults with reverse dip-slip and ramp faults with curved slip planes and prominent striations. Geometric variations include duplex ramps contained within floor and roof layer-parallel faults and linking ramps connecting separate layer-parallel faults hidden in the footwall and hangingwall. The orientations, geometries, displacements and shear senses of the layer-parallel faults and ramp faults are interpreted to be flexural-slip structures formed during bending of the originally horizontal Bushveld Complex into a basin-fold geometry during crustal loading.

Keywords: Flexural-slip folding; Layer-parallel faulting; Ramps; Duplexes; Bushveld Complex

1. Introduction

The 2.06 Ga old (Walraven et al., 1990) Bushveld Complex[1] in South Africa (Fig. 1) is the largest mafic layered intrusion on Earth (ca. 65,000 km^2; Willemse, 1969). The Bushveld Complex was intruded at the boundary between the overlying Rooiberg Group and the underlying Transvaal Supergroup and basement rocks of the Kaapvaal Craton, resulting in the formation of a mafic-layered sequence up to 9 km thick and greater than 350 km in diameter, excluding the far western limb of ca. 100 km (Kruger, 2005). It is part of the Bushveld Magmatic Province (Kruger, 2005) which, as a whole, comprises five major magmatic suites: the bimodal Rooiberg Volcanic Suite (Twist, 1985; Buchanan et al., 2002); the mafic layered rocks of the Bushveld Complex per se (Kruger, 2005); a suite of marginal pre- and syn-Bushveld sills and intrusions (Willemse, 1969; Cawthorn et al., 1981); the Rashoop Granophyre Suite (Walraven, 1985); and the Lebowa Granite Suite (Walraven and Hattingh, 1993).

The Bushveld Complex is informally subdivided into Marginal, Lower, Critical, Main and Upper Zones, on the basis of changes in lithology. The Critical Zone, which includes the most important mining horizons in the Bushveld Complex, forms the focus of this investigation (Fig. 2). The mining activities exploit tabular ore bodies containing platinum-group metals, nickel and chrome. The Critical Zone is characterised by the presence of very well developed layering as a result of abundant chromitite seams and repeated cyclic units comprising a lowermost pyroxenite layer grading upwards through melanorite and leuconorite into anorthosites (Eales et al., 1993; Schürmann et al., 1998).

The layering of the Bushveld Complex rocks dips centripetally at between 10° and 20°, and a combination of stratigraphic, geochemical and geophysical evidence suggests lateral continuity beneath the cover between the different exposed "limbs" (Fig. 1) (Cawthorn and Webb, 2001; Kruger, 2005). Palaeomagnetic evidence (summarised by Eales et al., 1993) indicates that the layers were originally emplaced horizontally (Fig. 3A) and the presently observed centripetal dips are attributed to the effect of crustal flexure in response to the load of the Bushveld Complex and associated granites (Fig. 3B,C) (Cawthorn and Webb, 2001). The present geometry of the Bushveld Complex can therefore be considered as a single, gentle, non-cylindrical basin fold (i.e. a synform

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[1] The term "Bushveld Complex" is commonly used for the mafic-layered rocks of the Bushveld Magmatic Province in preference to Rustenburg Layered Suite (RLS) (Kruger, 2005).

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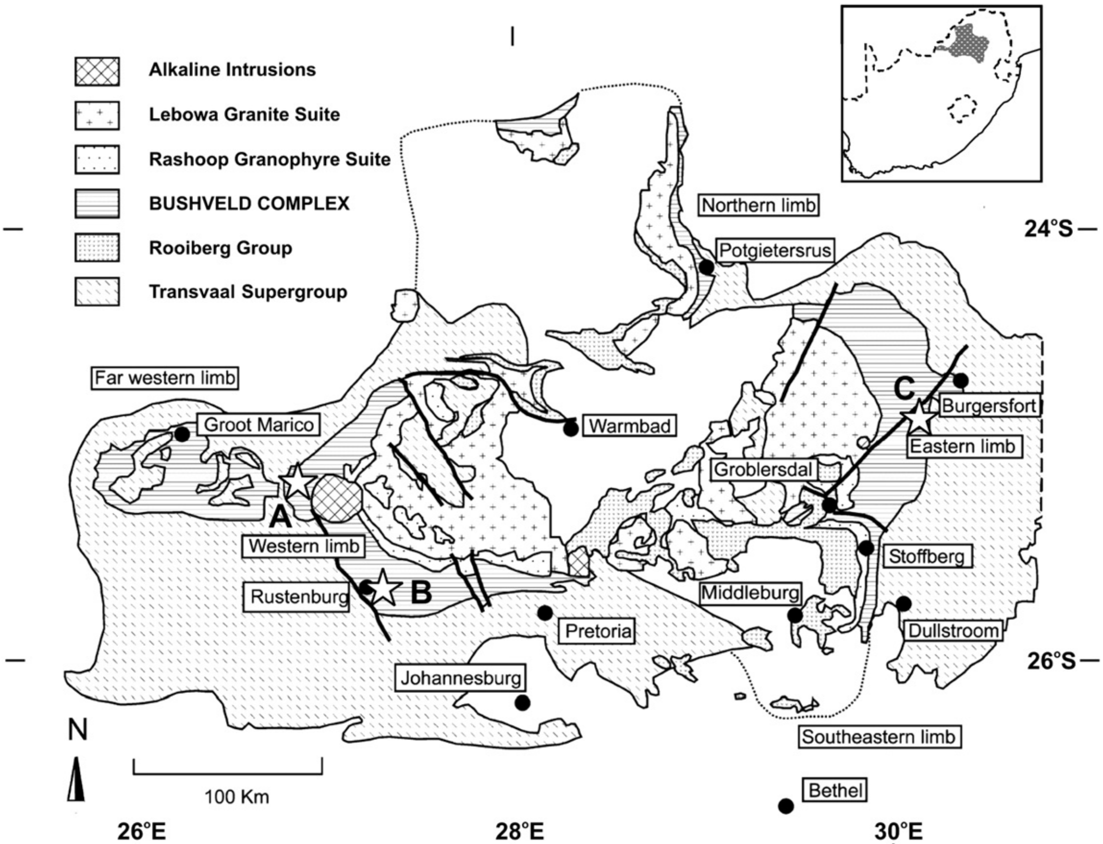

Fig. 1. Geological map of the Bushveld Complex showing the location of the five limbs: eastern, western, far western, northern and southeastern, with the outline of the southeastern and northern limbs interpreted from aeromagnetic and gravity data (after Kinnaird et al., 2005). White stars labelled A, B, C indicate localities investigated in this study (A, Horizon Chrome Mine; B, Kroondal Chrome Mine; C, Helena Chrome Mine and Mototolo Platinum Mine). Inset: Location of the Bushveld Complex in South Africa.

with hinge line depression), with limb lengths of approximately 180 km.

This paper reports on a suite of structures exposed within the Critical Zone of the Bushveld Complex. Their formation is considered to be a direct result of the accommodation of this reorientation through a flexural-slip mechanism. This structural suite is of considerable economic importance with respect to mining activities because it causes instability of mining excavations. The negative consequences of encountering these structures are well known by the miners and they are colloquially referred to as ‘‘curved joints’’ and ‘‘cooling domes’’.

Flexural-slip is often identified as the dominant mechanism for accommodating upper crustal folding in sequences of layered rocks that display large competence contrasts (e.g. Ramsay, 1967, 1974; Chapple and Spang, 1974; Behzadi and Dubey, 1980; Tanner, 1989; Becker et al., 1995; Gross et al., 1997). Slip typically occurs along layer boundaries or within more ductile strata and increases in magnitude from zero at the fold hinge to a maximum along the limbs (Suppe, 1985; Gross et al., 1997). Whereas flexural-slip is widely reported for buckle folds in contractional settings, this mechanism may also operate during the bending of layers in response to vertical movements of the underlying basement (Price and Cosgrove, 1990; Gross et al., 1997).

2. Observations from underground exposures in the Bushveld Complex

Underground exposures of the Critical Zone were investigated in three regions of the Bushveld Complex: the western part of the western limb (locality A, Horizon Chrome Mine); the southern part of the western limb (locality B, Kroondal Chrome Mine); and the central part of the eastern limb (locality C, Helena Chrome Mine and Mototolo Platinum Mine) (Fig. 1). The exposures were all accessed through underground mining operations belonging to Xstrata Alloys. The bord and pillar mining method employed at all locations is particularly amenable to good exposure of the rock in and around the ore body. The exposure investigated at locality A consists of LG6 chromitite (Figs. 2 and 4) with a pyroxenite hangingwall and footwall. The LG6 layer averages 0.8 m in thickness and dips 080/10 (Fig. 5). The LG6 is laterally persistent and is characterised by highly planar upper and lower contacts with the pyroxenite. The LG6 chromitite layer is also exposed at locality B, but here it is overlain by the 0.3 m thick LG6A, with a 0.7 m thick pyroxenite layer separating the two chromitite layers (Fig. 4). The layering at locality B dips 010/08 (Fig. 5) and, similarly to locality A, the LG6 chromitites are characterised by highly planar upper and lower contacts with the pyroxenites. Locality