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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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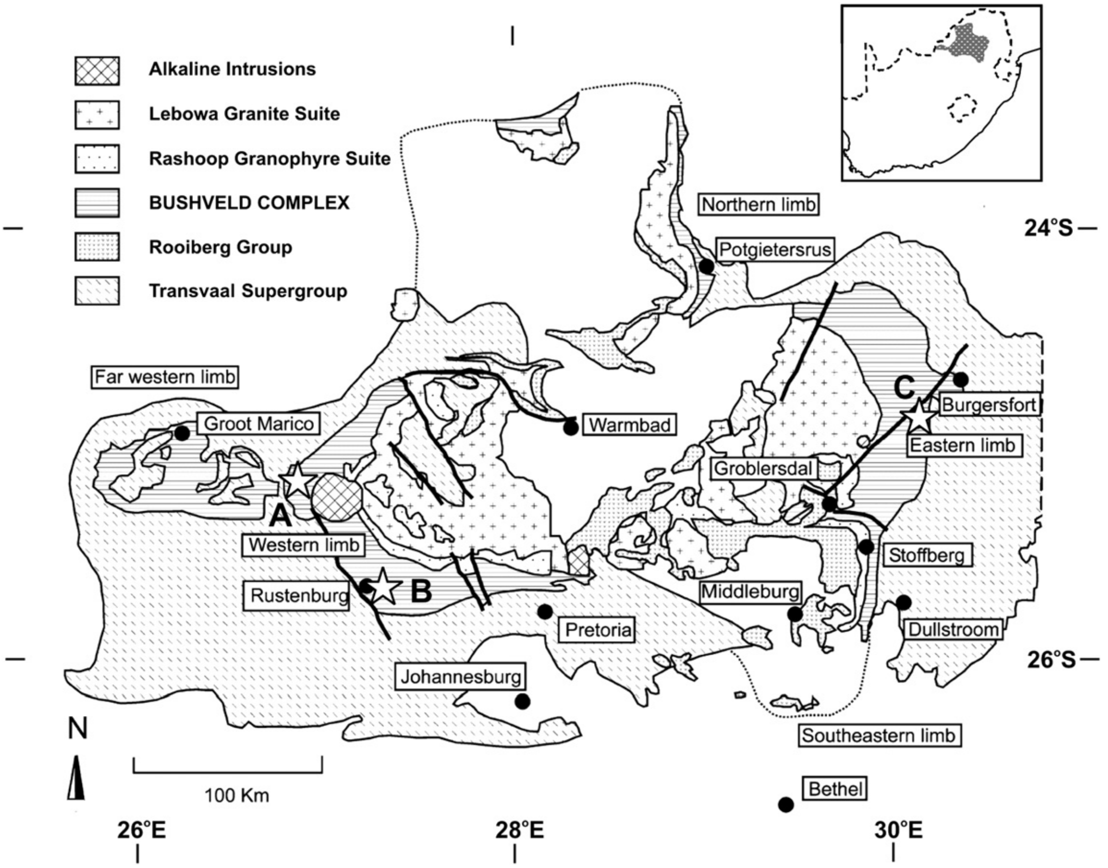

Fig. 1. Geological map of the Bushveld Complex showing the location of the five limbs: eastern, western, far western, northern and southeastern, with the outline of the southeastern and northern limbs interpreted from aeromagnetic and gravity data (after Kinnaird et al., 2005). White stars labelled A, 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

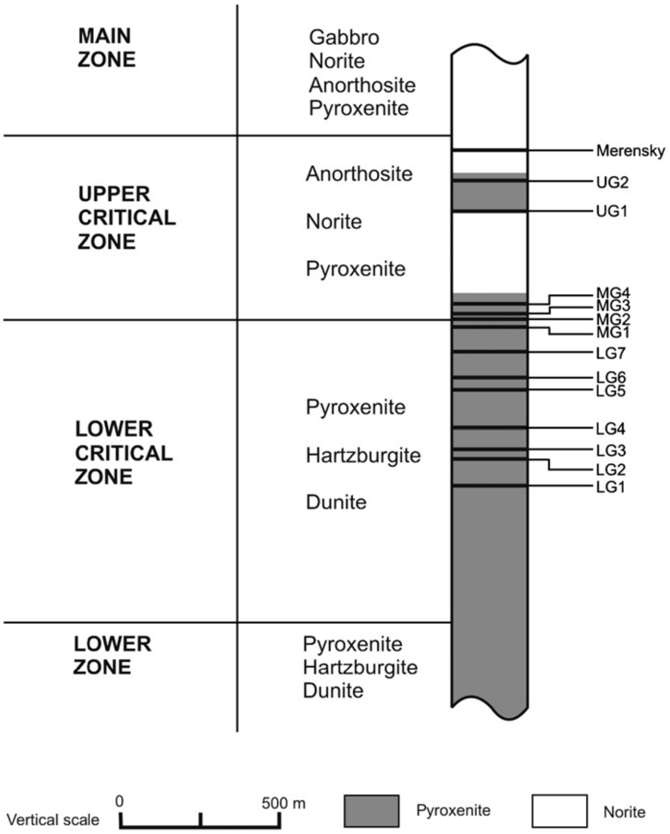

Fig. 2. Simplified vertical section of the Bushveld Complex, showing the position of significant chromitite seams. LG, MG and UG refer to the Lower, Middle and Upper Groups of chromitites (Schürmann et al., 1998).

C is characterised by layering dipping on average at 290/10 (Fig. 5). Underground exposures of the MG1 and UG2 chromitites (Figs. 2 and 4) were investigated at this locality. The MG1 chromitite layer, which is also characterised by pyroxenite hangingwall and footwall, averages 1.8 m in thickness and contains occasional thin, discontinuous, pyroxenite layers and blebs. The UG2 comprises a lower chromitite layer which ranges in thickness from 0.6 m to 1.3 m. This is typically overlain by three thinner chromitite layers with intercalated pyroxenite, although a very thin fourth chromitite layer is occasionally present. The thickness of these layers (called ‘‘leaders’’ or ‘‘triplets’’) is variable; the complete package may be confined to a metre above the main layer, or the uppermost layer can occur 3 m or more above the main layer. The upper and lower contacts of the main layer are often undulating, with amplitudes of up to 0.5 m, while the chromitite layers of the ‘‘triplets’’ tend to be far more planar. The footwall is usually a pegmatoidal feldspathic pyroxenite (Eales et al., 1993; Schürmann et al., 1998).

2.1. Layer-parallel faults

Layer-parallel faults, characterised by polished slip planes, slickenside striations and a combination of calcite, talc and clay infill, are exposed at each site. The faults typically occur along the top and bottom of the chromitite layers, at the chromitite-pyroxenite contacts (Fig. 6). An exception is the main

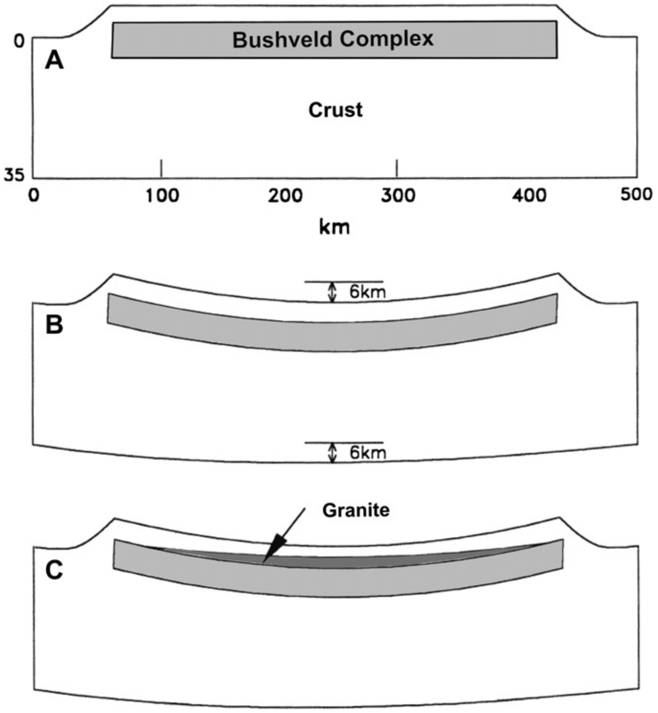

Fig. 3. Evolution of the continental crust in response to the intrusion of the Bushveld Complex (from Cawthorn and Webb, 2001). (A) Intrusion of a 7 km-thick Bushveld Complex at a depth of 3 km. (B) Effect of isostatic readjustment. The 6 km depression of the base of the crust is drawn as a gentle basin but its exact morphology is not well constrained. (C) Emplacement of 2 km-thick Bushveld Granite derived from melting at the base of the crust.

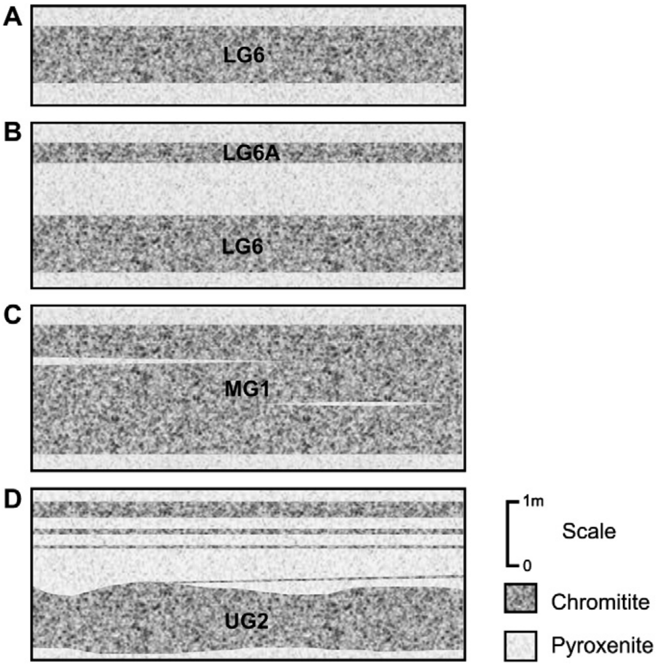

Fig. 4. Schematic diagrams of the (A) LG6 (exposed at Horizon Chrome Mine, locality A), (B) LG6 and LG6A (exposed at Kroondal Chrome Mine, locality B), (C) MG1 (exposed at Helena Chrome Mine, locality C) and (D) UG2 (exposed at Mototolo Platinum Mine, Locality C) Critical Zone chromitite layers.

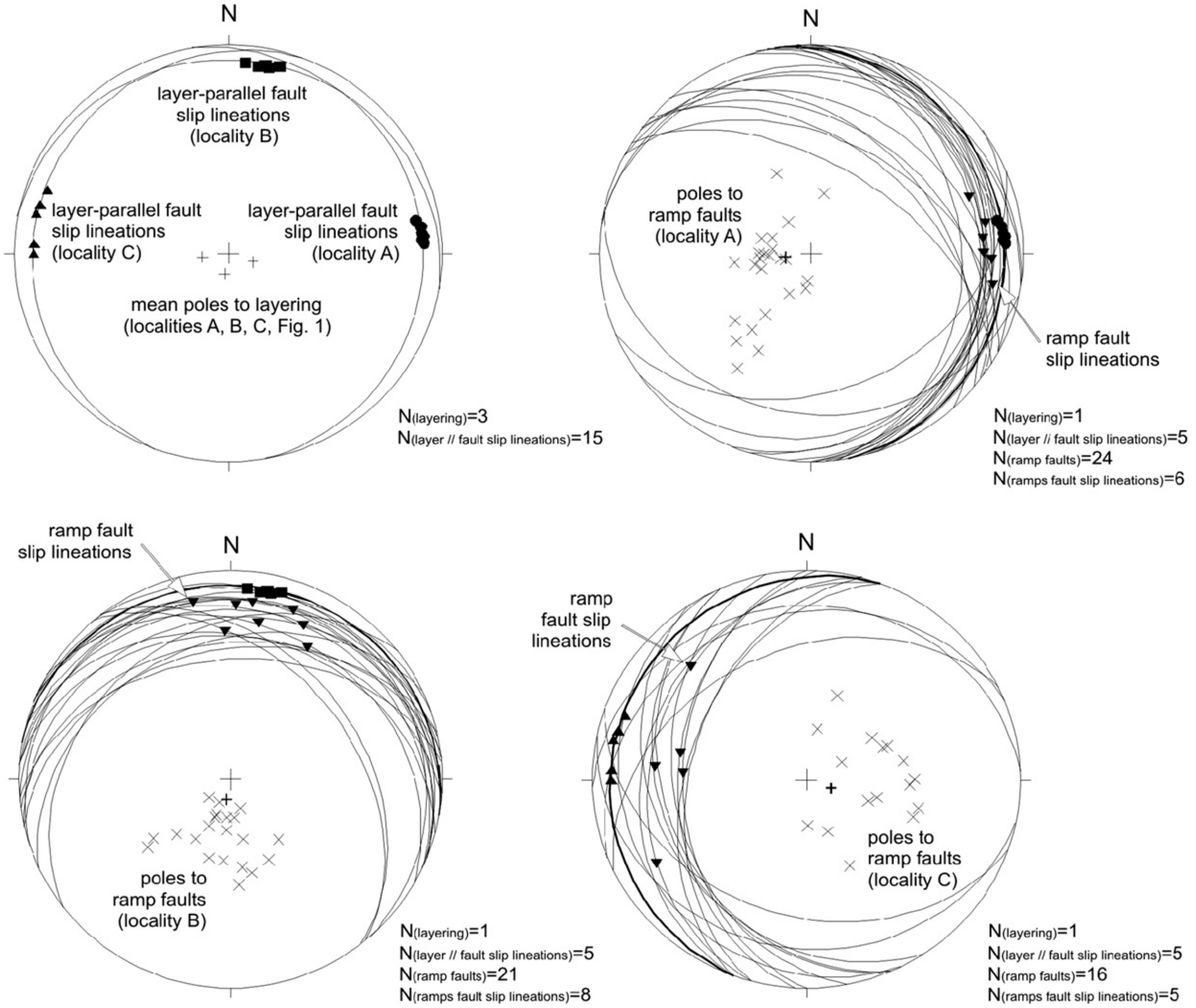

Fig. 5. Lower hemisphere, equal-angle stereographic projections of the layering, layer-parallel faults and ramp faults at localities A, B and C.

chromitite layer of the UG2 where the undulating nature of the upper and lower contacts of this layer results in a surface unsuitable for the accommodation of layer-parallel faulting. Occasionally, layer-parallel faults also occur within the chromitite layers, notably along intercalated pyroxenite layers within the MG1. The slickenside striations on these fault surfaces are typically formed by calcite mineral fibres. A preferred growth direction of these mineral fibres has resulted in the development of distinct ‘‘steps’’ on the movement surfaces. The orientation of the mineral fibres and the slickenside ‘‘steps’’ indicate that reverse dip-slip displacement occurred along the layer-parallel faults at all localities (Fig. 7). Offset pegmatite veins and pre-existing faults indicate displacement amounts of the order of <1 cm to 30 cm. The layer-parallel faults vary in extent as some are continuous across multiple mining panels and can extend along strike for over 50 m, whereas others are discontinuous and either die out or link to frontal or lateral ramps.

2.2. Ramp faults

The ramp faults are characterised by curved surfaces with well-developed striations/corrugations, and occasional thin layers of calcite, talc and clay infill. Structures interpreted to be frontal ramps invariably have a reverse sense of movement. At some sites, these frontal ramps connect directly into layer-parallel faults either as part of duplexes or as linking ramps connecting separate layer-parallel fault horizons (Fig. 6). More commonly, the ramp structures are only partially exposed on the underground mining faces or pillar faces, and it is not always possible to differentiate between duplex ramps contained within floor and roof layer-parallel faults and linking ramps connecting separate layer-parallel faults hidden in the footwall and hangingwall. Structures interpreted to be lateral ramps intersect the layer-parallel faults sub-parallel to the movement direction lineations on both structures and the shear sense is the same. Occasionally, frontal and lateral ramps combine to form large dome-like fault structures.

The ramp faults are often only exposed in cross-section, but a few are revealed dramatically in three-dimensions in the hangingwall as a result of large falls-of-ground (Fig. 6B,F). These three-dimensional exposures show that the ramps tend to be pod-shaped, with their longest dimension parallel to the strike of the layering. Where possible, displacement amounts on the ramp faults were determined from offset

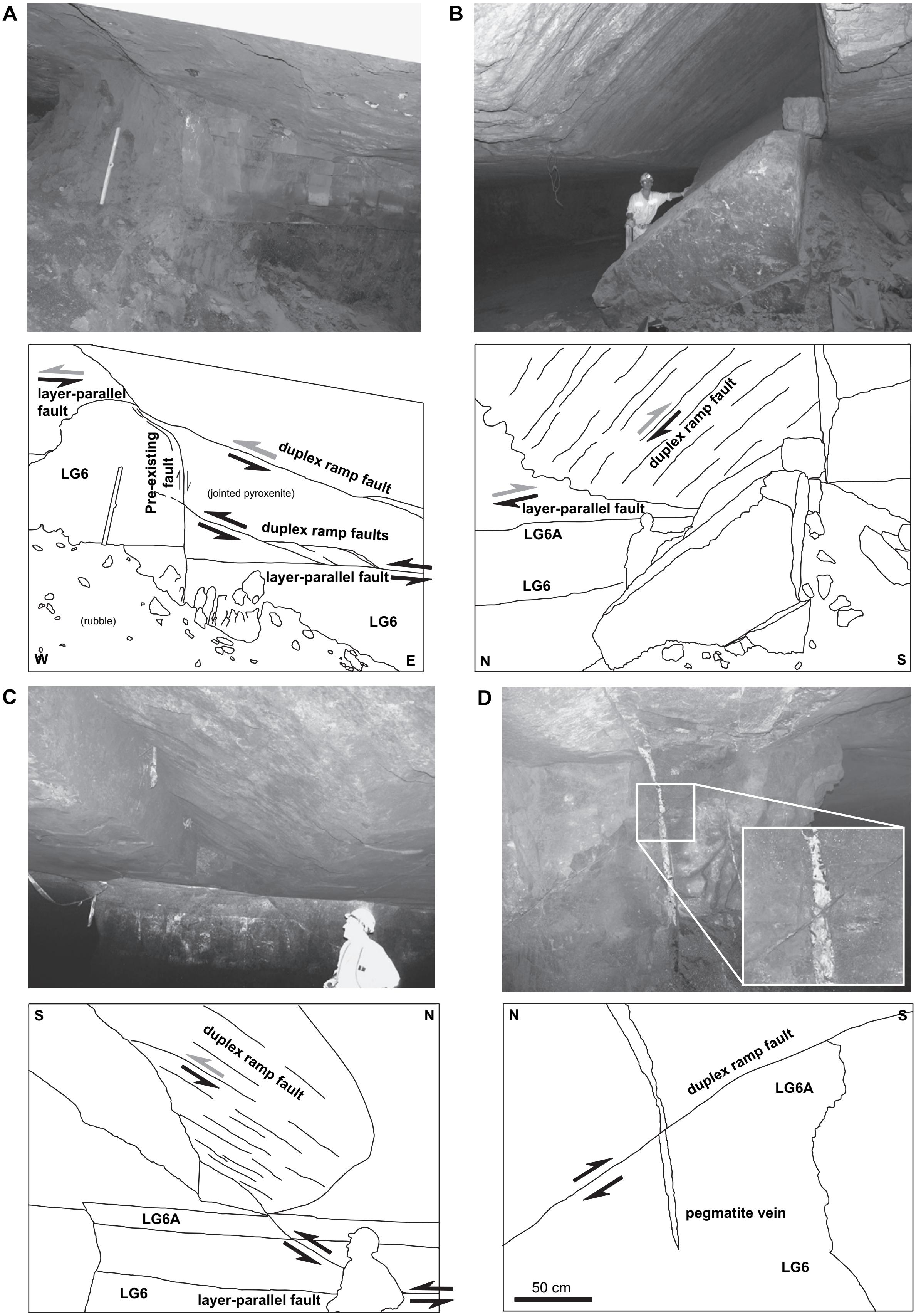

Fig. 6. (A–F) Photographs and interpretive sketches of underground exposures of the Critical Zone in the Bushveld Complex, showing layer-parallel faults and ramp faults developed in the LG6, LG6A and MG1 chromitite layers (A from Horizon Chrome Mine, locality A; B–D from Kroondal Chrome Mine, locality B; E from Helena Chrome Mine, locality C).

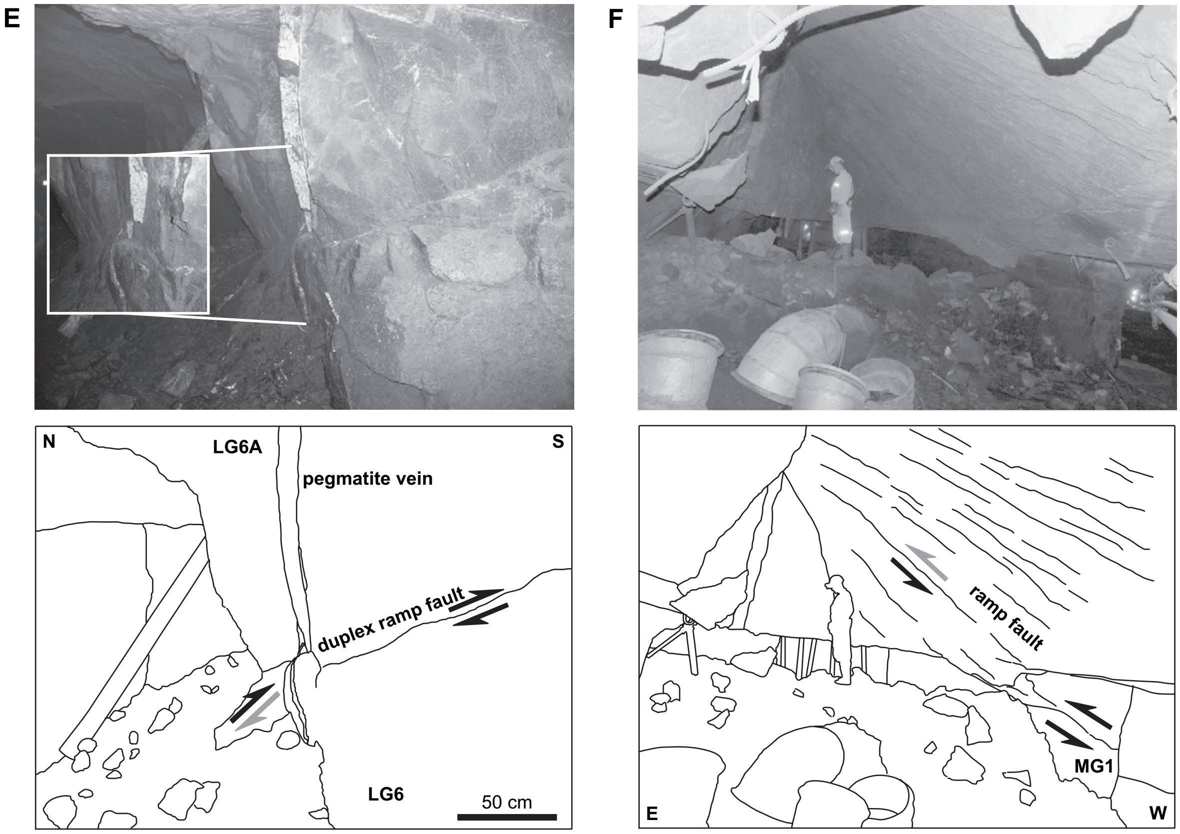

Fig. 6 (*continued*)

pegmatite veins. The observed displacements were generally small, often less than 1 cm, and not exceeding 10 cm. Convenient displacement markers such as pegmatite veins are not always present, so slip magnitude may only be locally determined. The strongly developed grooves on the surfaces of some larger ramp faults (e.g. Fig. 6B,F) in the hangingwall pyroxenites above the LG6 and MG1 chromitites suggests that displacements greater than a few centimetres may have occurred. The displacement direction lineations on the ramp faults vary from parallel to oblique relative to the layer-parallel fault lineations (Fig. 5).

2.3. Layer-normal fractures and pegmatite veins

Layer-normal joints and pegmatite veins, orientated parallel to the strike of the layering and offset by the layer-parallel and ramp faults, are common. Falls-of-ground that occur beneath the ramp faults are often juxtaposed against these structures (e.g. high-angle joint faces visible in Fig. 6B,C,F). The joints tend to be intra-layer features that occur more frequently in the pyroxenites than the chromitites. The pegmatite veins are typically inter-layer features that often extend through both the pyroxenites and chromitites, but may pinch-out vertically on entering a thick chromitite layer (e.g. in Fig. 6D the pegmatite vein extends through the thinner LG6A chromitite but pinches out on entering the thicker LG6 chromitite layer). Both the joints and the veins are often laterally extensive features and may be continuous along strike for over 90 m.

3. Interpretation and discussion

Structures associated with flexural-slip are well documented, notably the occurrence of layer-parallel faulting and fault duplexes (e.g. Chapple and Spang, 1974; Ramsay and Huber, 1987; Tanner, 1989, 1992a,b; Fowler and Winsor, 1997). Studies have also reported how separate flexural-slip layer-parallel faults can be linked by lateral and frontal ramps, sometimes forming lens-shaped dome faults (e.g. Horne and Culshaw, 2001; termed “wedge faults” by Faill, 1973). Typically, these structures are reported for flexural-slip folds that developed in anisotropic sedimentary sequences during buckling. Less frequently, flexural-slip, and the associated suite of structures, is reported in sequences that folded during bending (Price and Cosgrove, 1990; Gross et al., 1997). It is proposed that the Bushveld Complex, with its well developed layering characterised by lithologies with marked competency contrasts (e.g. chromitite and pyroxenite), layer-parallel faulting, duplexes and ramps, underwent flexural-slip deformation during the crustal flexure that resulted in the development of its basin-fold geometry.

The layer-parallel and ramp faults invariably exhibit a reverse shear sense, which changes radially around the periphery of the dish-like Bushveld Complex, maintaining a consistent

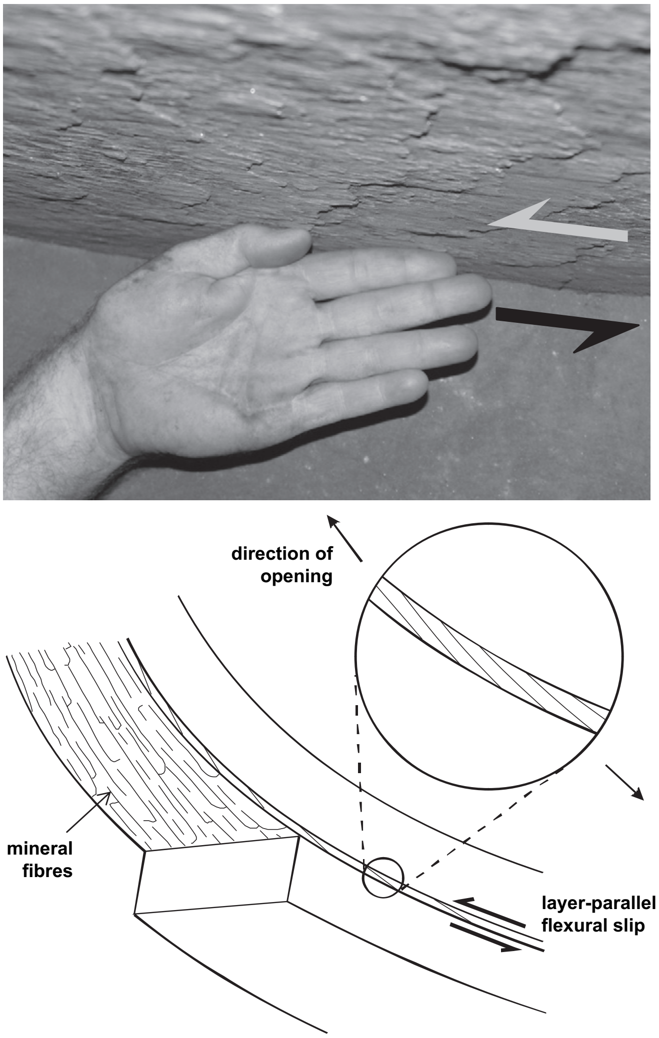

Fig. 7. Photograph and schematic interpretation (after Price and Cosgrove, 1990) of slickenside "steps" on the hangingwall surface of a layer-parallel fault with reverse dip-slip located along the top contact of the LG6 chromitite exposed at Horizon Chrome Mine, locality A. These slickenside "steps" are a typical feature of the layer-parallel fault surfaces.

dip-slip orientation. It is therefore unlikely that these structures developed prior to the folding as a result of a regional compressive event, which would have instead resulted in a single displacement direction across the entire Bushveld Complex. The shear sense is instead compatible with that required by flexural-slip folding.

Another feature associated with layer-parallel slip in flexural folds is the occurrence of regional systematic layer-normal fractures parallel to the flexure hinge (e.g. Billi and Salvini, 2003). These fractures develop in the fold limbs early during deformation if extensional fibre stresses in the flexure flanks exceed the tensile strength of the flexed rock (Billi and Salvini, 2003). Possibly, the layer-normal joints and pegmatite veins that consistently strike parallel to the flexure hinge of the Bushveld Complex have this origin.

The effects of the flexure of the Bushveld Complex are possibly not confined to the layered igneous sequence only. Evidence of eastward- to southeastward-directed bedding-parallel thrust faulting has been documented in and around the gold reefs of the Sabie-Pilgrim's Rest goldfield, situated on the westerly-dipping rim of the Transvaal Basin, adjacent to the Eastern Limb of the Bushveld Complex (e.g. Visser and Verwoed, 1960; Harley and Charlesworth, 1992, 1994, 1996). This bedding-parallel faulting is assumed to be syn-Bushveld in age (e.g. Boer et al., 1993; Harley and Charlesworth, 1996). A possible explanation for their origin could be synchronous flexural-slip during layer reorientation in concert with the formation of the Bushveld basin.

4. Conclusions

1. Layer-parallel faulting is common along the top and bottom contacts of many of the chromitite layers in the Critical Zone of the Bushveld Complex.
2. The displacement direction of the layer-parallel faulting varies radially around the periphery of the centripetally dipping Bushveld Complex, maintaining a consistent reverse dip-slip orientation.
3. The layer-parallel faults connect to frontal and lateral ramp faults as part of duplexes and as linking ramps joining stratigraphically separate layer-parallel fault horizons.
4. The orientations, geometries, displacements and shear senses exhibited by the layer-parallel faults and ramp faults are consistent with a flexural-slip origin.
5. It is proposed that these flexural-slip structures formed as a result of bending of the originally horizontal Bushveld Complex into a basin-fold geometry, in response to crustal loading.
6. A further finding that ramp faults tend to be pod-shaped, with their longest dimension parallel to the strike of the layering has important implications with respect to a preferential mining direction where the bord and pillar mining method is employed. In this case, panels mining updip or downdip would be inherently more stable than those mining in the strike direction.

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