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Is there some commonality between the geological structures in the Bushveld Complex and the Great Dyke?

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The presence of geological structures in igneous complexes such as the Bushveld Complex in South Africa and the Great Dyke in Zimbabwe is to be expected. Understanding such geological structure in relation to the various mining methods used is essential for to safety and productivity. Recently, the presence of flexural slip thrust faults in the Bushveld Complex was described in the scientific literature. These structures have a history of being the root cause of falls of ground during mining operations resulting in fatalities, injuries and losses of production. Fault gouge can be associated with flexural slip thrust faults and, if the bord and pillar mining method is employed and fault gouge is present in the vicinity of the reef, the integrity of the mining operations can be severely compromised and in some cases have been abandoned. Following recent work on the Great Dyke, the authors put forward some evidence that flexural slip thrust faults are also present in the Great Dyke. If this premise is correct then mining methods and support strategies for mining operations on the Great Dyke will be required to be modified to take into account the presence of these geological structures.

Introduction

Geological structure within and around orebodies can have a profound effect on the determination of viable mining methods and can impose limitations on those mining methods that are employed to mine the given orebody. In both the Bushveld Complex and the Great Dyke jointing is present. Joints are fractures or cracks in a rock mass along which no appreciable movement has occurred. Typically the jointing is planar and the jointing can be defined by joint sets, each set containing joints that are of approximately the same orientation. The jointing varies with intensity which can locally effect excavation stability and this can be measured by determining the rock mass rating at a particular site. However, in addition to planar jointing, the presence of non planar structures or curved structures greatly complicates the accommodation of a mining method with stable spans into such a rock mass. Such curved structures have been seen in both the Bushveld Complex and the Great Dyke. The implications for mine design and support are discussed in this paper.

The Bushveld Complex—flexural slip thrust faults

The 2.06 Ga old Bushveld Complex in South Africa is the largest mafic layered intrusion in the world up to 9 km thick and greater than 350 km in diameter, see Figure 1. Whereas planar jointing is ubiquitous, the intensity varies widely. In addition to planar jointing, the presence of other structural features in the Bushveld Complex was recently described in the literature[1] and was identified as flexural slip thrust faults. These features are of considerable economic importance for mining activities because they cause instability of mining excavations with concomitant production loss and safety issues. 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'. These structures represent two particular threats to mining activities in the Bushveld Complex, namely a fall of ground threat and a pillar failure threat.

The fall of ground threat

A flexural slip thrust fault consist of two components, namely a layer-parallel portion of the fault, known as a flat and an inclined non planar surface, known as the ramp portion of the fault. It is the ramp structures that are colloquially referred to as 'domes' and are known to have caused many fall of ground fatalities, particularly where these structures intersect high angle joints, faults and/or veins. Figure 2 is a schematic section illustrating the complexity of flexural slip thrust faults. This Figure shows multiple ramps contained within floor and roof flats. Figures 3 and 4 show an actual fall of ground in a bord and pillar operation where the block that fell consisted of a ramp intersecting a steep joint. Another example is shown in Figure 5 where evidence of an earlier fall of ground can be seen in the hangingwall profile that has exposed the ramp portion of a flexural slip thrust fault.

Where bord and pillar mining is undertaken, the stability of these structures can be controlled by closing bord widths and/or the installation of 4 m long 400 kN cable anchors as support units. Some mines install the cable anchors on a systematic pattern, and a typical pattern would have a spacing of 1.5 m by 1.5 m giving a support resistance in excess of 200 kN/m^2. The visual location of these structures before they fall can be difficult and some mines attempt to locate these structures using ground penetrating radar and borehole cameras and install cable anchors as required.

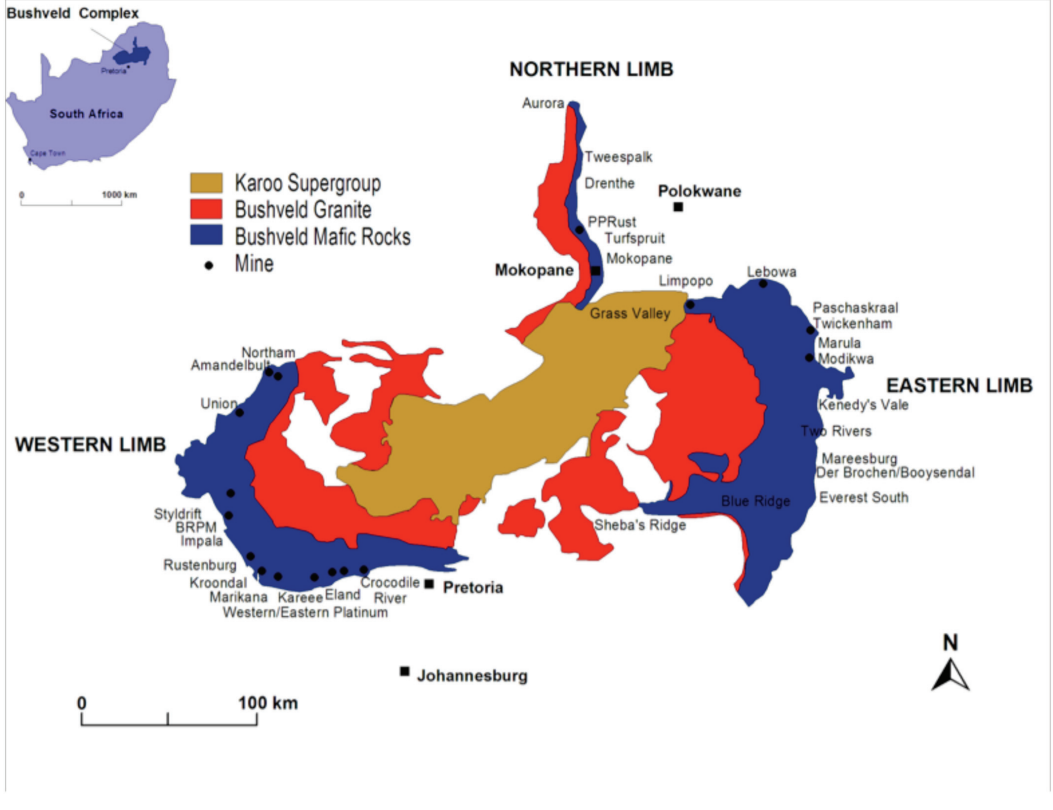

Figure 1. Map showing the locality and mines of the Bushveld[2]

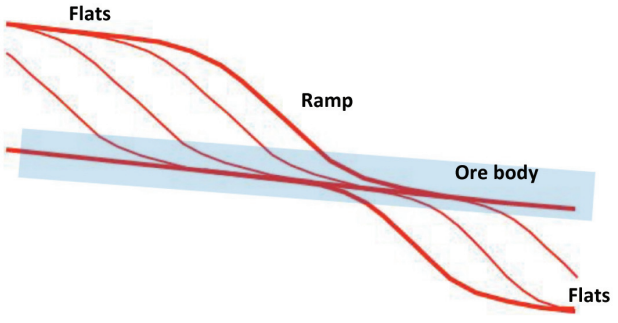

Figure 2. Schematic section showing multiple ramps contained within floor and roof flats

These structures can also affect ground stability where conventional mining is undertaken. Many Bushveld platinum mines that are mined conventionally have grout ranges and are able to construct and install grout packs. These have proved to be an effective support system that can stabilize these structures.

Apart from the obvious fall of ground hazards that these structures present, the spatial understanding of these structures in three dimensions and how they impinge on the mining excavation,s and hence the determination of a preferential mining direction and mining spans, is an important component of managing the hangingwall.

Figure 3. A fall of ground in a bord and pillar operation from a flexural slip thrust fault, author holding a slave lighting device

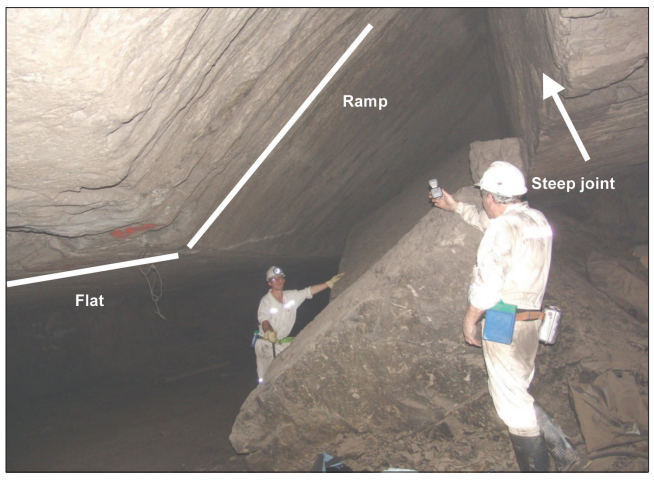

Figure 4. The flat and ramp making up the flexural slip thrust fault

Figure 5. Evidence of an earlier fall of ground in the hangingwall profile that has exposed the ramp portion of a flexural slip thrust fault

The pillar failure threat

A number of conditions are required for pillar failure to occur. Firstly, a bord and pillar mining method must be employed, and this mining method is becoming quite common in both platinum and chrome mines. Secondly, a large exposure of the flat portion of a flexural slip thrust fault must be present and approximately parallel to the reef. A third requirement is that the thrust fault has a considerable amount of fault gouge present, see Figure 6. Figure 7 shows an existing pillar with the gouge material above the reef.

There are three examples in the Bushveld where mines were lost or large portions of a mine were lost due to the presence of thrust fault gouge in the vicinity of the reef.

The first was a chrome mine in the Western Bushveld using a bord and pillar mining method. In this case the fault gouge material was in the same plane as the reef and parallel to the reef. As the gouge material in the pillars was compressed, it deformed failing, the pillars in tension effectively pulling the pillars apart.

The second case was a platinum mine in the Eastern Bushveld also using a bord and pillar mining method. In this case the gouge material lay on top of the reef. As in the previous case, the gouge material in the pillars was compressed and it failed the pillars in tension.

The third case wasa platinum mine in the Eastern portion of the Western Bushveld also using a bord and pillar mining method where gouge between of 20 cm and 30 cm was present at the top contact or within the pillars in different areas on the mine. Compression of the gouge contributed to the widespread pillar failure, by the same mechanism described above, that ultimately resulted in mine closure. See Figures 8 and 9. These show the failure of the pillars at some of these mines. Once pillar failure has become extensive then hangingwall failure initiates and differential movement of the hangingwall becomes widespread. Figure 10 is illustrative of this, note the paint line that is interrupted as differential movement has occurred on either side of the joint subsequent to the placement of the paint line.The hangingwall depicted subsequently collapsed.

It is this sequence of events, pillar failure followed by widespread differential hangingwall movement then the collapse of the hangingwall, that leads to the loss of a mine or portion of a mine.

The pillar failure mechanism can be explained in more detail. It occurs where deformation of a weak material (the gouge material) fails the rest of the pillar in tension. The principal author has seen this failure mechanism on a coal mine where a bord and pillar mining method was employed. In this case a weak shale floor deformed and pulled the coal pillars apart in tension. This has also been seen in the Witwatersrand gold mines where a carbon layer on top of the reef destroyed pillars in the same manner.

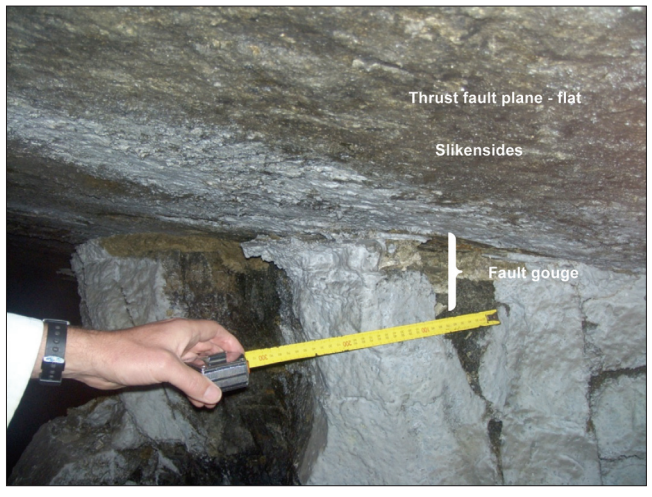

Figure 6. Flexural slip thrust fault and fault gouge sub parallel to the reef

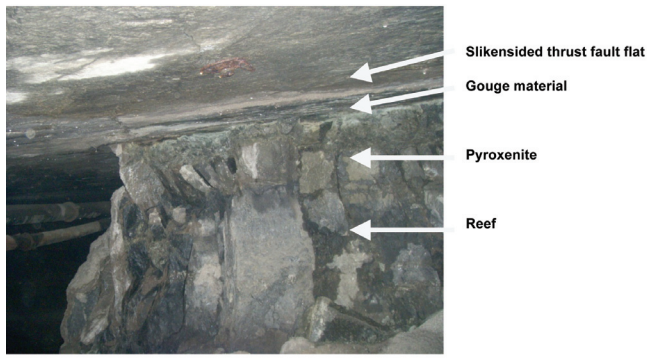

Figure 7. Structures and rock types making up a pillar in a bord and pillar operation

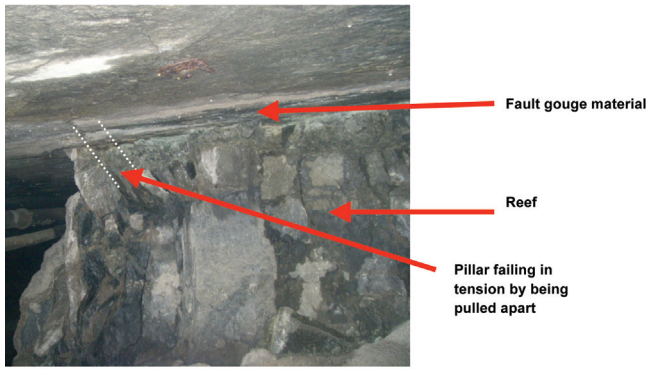

Figure 8. Pillar being destroyed by deformation of fault gouge material

Figure 9. Pillar being destroyed by deformation of fault gouge material

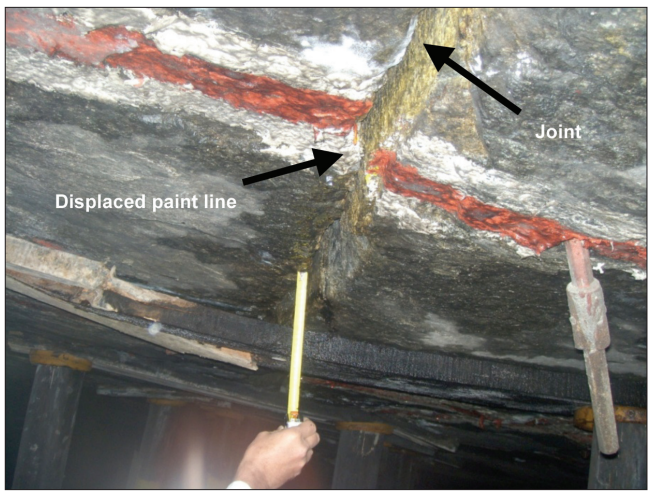

Figure 10. Differential hangingwall movement resulting in widespread hangingwall failure

Because of this failure mechanism, the common way of determining the factor of safety (SF) for pillar systems no longer applies. Normally $SF = \sigma_c/PS$ where σ_c is the expected pillar strength in MPa and PS is the pillar stress in MPa. Because σ_c is unknown, the factor of safety for the pillar system is no longer known.

Of great concern to the authors is the belief that a gouge layer associated with a flexural slip thrust fault can be washed out during exploration drilling and it would manifest in the core only as a 20 or 30 cm core loss. Geotechnical logging could easily miss the fact that such a structure was present and it would be seen only for what it was once mining intersected the reef. A recent discussion with a colleague confirmed that this scenario did indeed happen.

The Great Dyke—planar jointing and non planar structures

The Great Dyke is a 2.59 Ga old, linear shaped layered intrusion, striking over 550 km NNE, with widths varying from 4 to a maximum of ~11 km. At the present levels of erosion the Great Dyke comprises a slightly curved, locally faulted line of 5 layered ultramafic to mafic complexes (see Figure 11). The intrusion cuts Archaean granites and greenstone belts of the Zimbabwe craton. Parallel to the intrusion are a number of satellite dykes comprising gabbro and quartz-gabbro[3].

The geophysical and mass-balance models[4,5] indicate that the dyke is trumpet-shaped in cross section, with the layers shallowly plunging towards the centre (Figure 12). The lower portion of the Great Dyke consists of ultramafic rocks (dunites, harzburgites, olivine bronzitites and pyroxenites) and contains narrow layers of chromitite. The upper Mafic Sequence consists of plagioclase-rich rocks such as norites, gabbro-norites and olivine-gabbros[6,7].

In the 1960s and 70s the Main Sulphide Zone was the subject on intensive exploration for both platinum group metals and nickel, and although trial mining took place at Wedza (1969–71), Selous (1971–72) and at Mimosa (1974–78), ground stability problems and marginal grades acted as disincentives to further exploitation at the time[8,9].

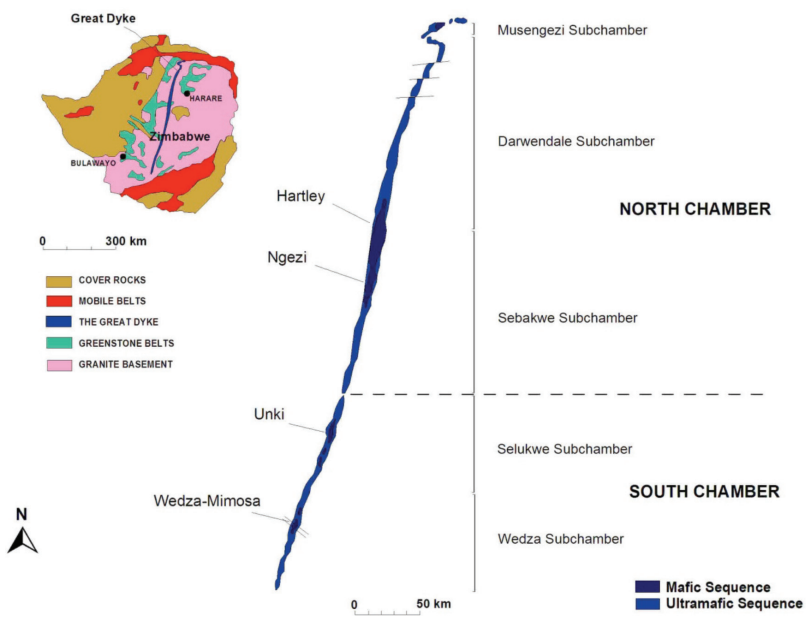

Figure 11. Map showing the locality and mines of the Great Dyke of Zimbabwe[5]

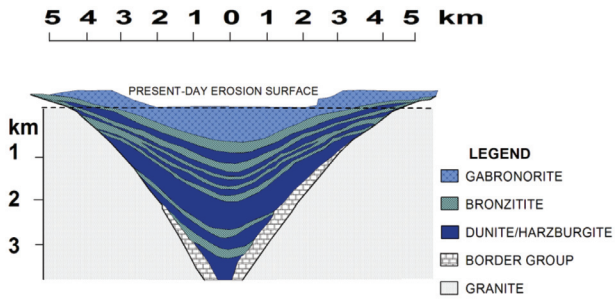

Figure 12. Transverse section of the Darwendale subchamber showing the synclinal structure of the layering[5]. Note the thinning of the layers away from the geometric axis and their greater proximity to the floor/wallrocks near the margins of the intrusion

Trial mining was also carried out at Unki in the late 1960s and early 1970s. Interest was revived in the late '80s culminating in the opening up of the Hartley Platinum Mine (1994), Mimosa Platinum Mine (1995) and continuing exploration and/or trial mining in the Selukwe (Unki), Sebakwe (Ngezi, Mhondoro and Selous) and Musengezi (Snakes Head) subchambers.

Some faulting is close to and sub parallel to the Great Dyke[10] namely the NNE sinistral Popoteke faults and the dextral WNW trending Mtshingwe set. In spite of its great age the Great Dyke is, however, relatively undeformed. As with the Bushveld Complex, planar jointing is ubiquitous but the intensity also varies widely. However, non planar structures have been identified and are described in the next section.

The fall of ground threat

In some areas on the Great Dyke mining conditions are excellent. Where the bord and pillar mining method is practised it is not uncommon to see 15 m bord spans minimally supported, see Figure 13. Other parts of the Great Dyke mining is more onerous where joint intensity is much higher, leading to significant reductions in the bord widths to maintain stability, see Figure 14.

Mining in the presence of planar jointing, irrespective of its intensity, is done routinely all over the world, with changing rock mass ratings dictating what stable span can be mined. However, non planar structures have been identified in the economic horizons of the Great Dyke with one such example shown in Figure 15.

The fact that these structures are curved makes them suspiciously like the ramps of flexural slip thrust faults. Figure 16 shows a similar structure to that depicted in Figure 15 but with slikensides visible. Figure 17 shows a fall of ground where the rock detached from a non planar structure. These non planar structures are tentatively being identified as flexural slip thrust faults. They are not present everywhere on the Great Dyke, however, when they are present, mining conditions deteriorate and it appears that these structures will pose a fall of ground hazard similar to that described earlier.

The pillar failure threat

No fault gouge has been seen to be associated with the curved structures depicted in Figures 15, 16 and 17. However. vigilance by geologists and rock engineers will be required particularly if there is a danger of any fault gouge being washed out of the core during exploration drilling.

Managing flexural slip thrust faults

Managing flexural slip thrust faults on both Bushveld mines and Great Dyke mines would require the following technical interventions:

- Geologists will be required to identify the presence or absence of flexural slip thrust faults within the orebody.

Figure 13. Excellent mining conditions on the Great Dyke

Figure 14. Challenging mining conditions on the Great Dyke

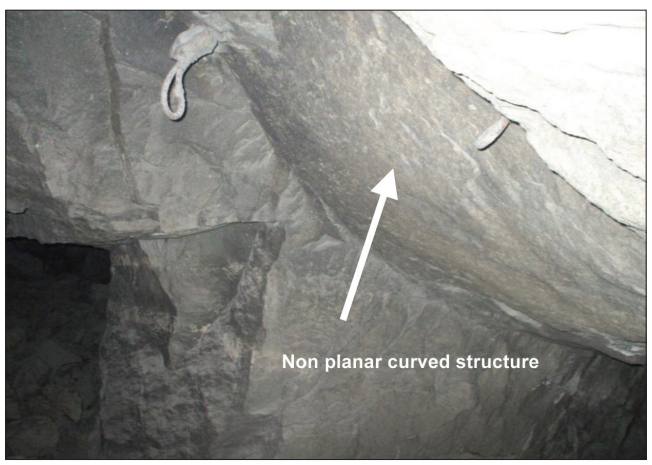

Figure 15. Non planar curved structure in the Great Dyk

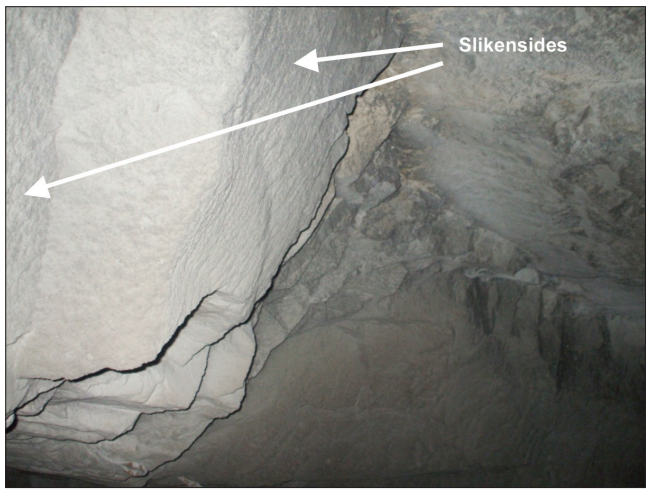

Figure 16. Slikensides on non planar structures on the Great Dyk

Figure 17. A fall of ground with the upper surface a suspected flexural slip thrust fault

- Areas where the structures are absent will be defined as a particular geotechnical area, and areas where the structures are present will be defined as a different geotechnical area.
- It is highly probable that the two geotechnical areas will require different layout geometry and different support requirements.
- The responsible mining engineer and the responsible rock engineer must then satisfy themselves that the mine's codes of practice, layout and support systems are appropriate to safely mine the orebody for both of the defined geotechnical areas.
- Because the two geotechnical areas might require different layout geometry and different support requirements, the mining costs are likely to be different. The mining engineer is encouraged to cost these geotechnical areas separately.

Some mines have been carrying out technical interventions as described above. It is encouraging that on some mines ground penetrating radar is able to locate these structures. Cable anchors have proved to be a particularly effective support system in stabilizing these structures.

Conclusions

Sound technical management of flexural slip thrust faults during the mining process must be a high priority for mine management. The high risk of suffering human or economic loss must be managed using management strategies that will allow safe and productive mining in spite of the presence of flexural slip thrust faults.

A worrying issue is that research leading to further understanding of flexural slip thrust faults appears to have ceased. This could prove to be unwise in future in view of the considerable number of fatalities that instability of these structures has caused in the past.

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Dr Michael Roberts has more than thirty years of rock engineering experience including a number of years as the rock engineering manager on a large South African mine as well as programme manager of the CSIR's Mining Technology rock engineering programme. He has extensive experience on the Bushveld platinum and chrome mines with respect to mine design, mining sequence and the support of excavations which was the subject of his PhD. He actively seeks practical solutions to rock engineering issues that can be easily implemented by mining personnel. He has written extensively and is author or co-author of fifty technical papers