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### New interpretation of the origin of tiger's-eye: Comment and Reply : REPLY

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#### Notes

## New interpretation of the origin of tiger's-eye: Comment and Reply

## COMMENT

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Peter J. Heaney and Donald M. Fisher are to be congratulated for their detailed mineralogical characterization of hawk's-eye and tiger's-eye. However, their interpretation of mineral formation based on mineralogical and crystallographic information requires discussion. They conclude that the formation of hawk's-eye involved "cracking of the crocidolite host rock followed by the antitaxial deposition of columnar quartz crystals from silica-saturated fluids" (Heaney and Fisher, 2003, p. 325), implying that crocidolite asbestos and quartz originated during the same geological event. This conclusion is based on textural evidence and the presumption that pseudomorphous hawk's-eye and tiger's-eye after crocidolite should contain chalcedony or quartzine, and not well-crystallized columnar quartz. However, Heaney and Fisher's interpretation ignores the geological setting of tiger's-eye and hawk's-eye.

South African tiger's-eye and hawk's-eye come from an area near Griquatown and Niekerkshoop, Northern Cape Province. They are restricted to a well-defined ancient planation surface that drapes the Asbestos Hills iron formations. This surface corresponds to the late Mesozoic African land surface (Partridge and Maud, 1987) (Fig. 1). Where this planation surface intersects the Asbestos Hills iron formations, it is marked by a 2–4-m-thick zone of massive silicification and goethitization. This altered zone is related to a specific period of silicification whereas goethitization appears to be an ongoing process that locally crosscuts the zone of silicification (Fig. 1).

The association of tiger's-eye and hawk's-eye with surficial silicification is evident in field outcrops, mining-related exposures, and drill core intersections. Tiger's-eye and hawk's-eye occur only where the planation surface cuts bedding-parallel vein systems filled by asbestiform crocidolite (Fig. 1). Crocidolite mineralization in these vein systems is explained by a bedding-parallel crack-seal vein-filling process with fiber growth in minimum stress direction during a period of mild

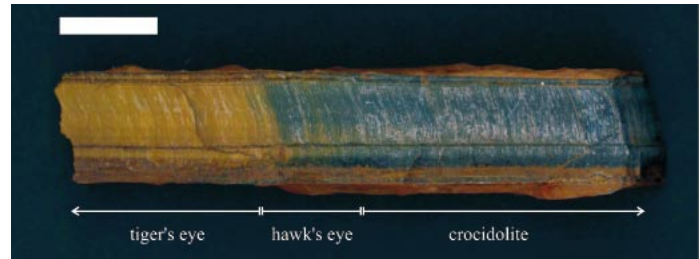
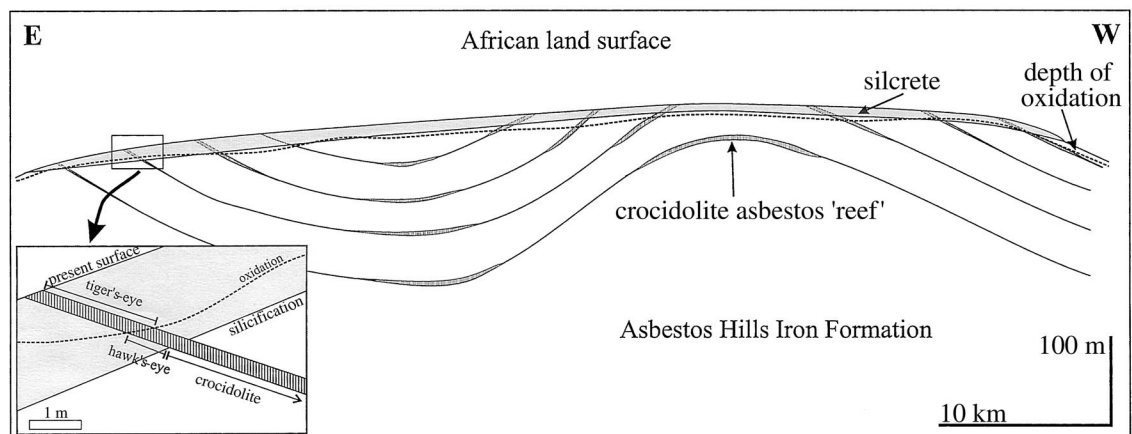


Figure 2. Hand specimen photograph illustrating the transition of tiger's-eye through hawk's-eye into unaltered crocidolite asbestos on a centimeter scale. Scale bar is 2 cm long.

EW- and NS-directed compression (Dreyer and Soehnge, 1992). If the episodic crack-seal vein process and cogenetic formation of quartz and crocidolite proposed in the model by Heaney and Fisher applied, we would expect to see hawk's-eye, i.e., silicified crocidolite developed at depth. However, this has never been observed in any of the extensive underground workings developed to exploit the crocidolite asbestos (Dreyer and Soehnge, 1992). In fact, tiger's-eye and hawk's-eye are restricted to the silicified surficial zone. A rapid but gradual transition of tiger's-eye at surface through hawk's-eye into unaltered crocidolite fibers is observed (Dreyer, 2003, personal commun.); this transition is obvious even on a hand-specimen scale (Fig. 2).

The intimate and systematic relation between hawk's-eye and tiger's-eye provides evidence for the transformation of crocidolite asbestos first into hawk's-eye by silicification and then into tiger's-eye by partial oxidation of the  $Fe^{2+}$  contained in crocidolite to goethite. Depending on the current depth of oxidation relative to past silicification, and the rate of mechanical weathering, tiger's-eye, hawk's-eye, and oxidized but unsilicified crocidolite occur in surface outcrops (Fig. 1). Field evidence thus leads to the conclusion that hawk's-eye and tiger's-eye, whilst not pseudomorphs *sensu strictu*, nevertheless originate as alteration products of pre-existing crocidolite veins in a replacement process that is marked by an exceptional preservation of textural detail.

Figure 1. Schematic E-W directed cross section illustrating the relationship between regional folding and crocidolite formation in the Griquatown-Niekerkshoop area. Syndeformational crocidolite pre-dates the African planation surface. Tiger's-eye and hawk's-eye are closely related to the Mesozoic planation surface, associated with surficial silicification and oxidation. Note vertical exaggeration; not to scale.



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**REPLY**

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We thank Jens Gutzmer, Nicolas J. Beukes, and Bruce Cairncross for their interest in our study of the formation of tiger's-eye, and we would like to acknowledge their far-reaching contributions in the field of South African geology. Their work continues to serve as a touchstone for us in this and other projects. Nevertheless, we remain unpersuaded by the objections that Gutzmer and colleagues have raised against our model for the origin of tiger's-eye. In particular, we are surprised that the authors chose not to found their argument on the textural evidence that we presented to support our contention that tiger's-eye is the product of crack-seal crystallization.

To summarize that evidence, we noted that: (1) Tiger's-eye forms within banded iron formations as flat planar intergrowths that run parallel to bedding and that rarely exceed 5 cm in thickness. (2) These intergrowths contain columnar quartz crystals measuring  $\sim 0.5 \times 10$  mm that emerge from fine-grained aggregates of equant quartz crystals at the vein walls. (3) The columnar quartz crystals are oriented perpendicular to the vein walls but commonly depart from orthogonality toward the center of the vein. (4) Neighboring length-slow quartz columns share identical crystallographic orientations. (5) Bands or trails of crocidolite microfibers are included within the quartz columns, frequently crosscutting quartz column boundaries at angles up to 30°. (6) Unweathered crocidolite fibers display a strong morphological asymmetry, such that each filament exhibits a smoothly tapered tip at one end and a jagged surface at the other. (7) The jagged ends of crocidolite fibers abut against irregular surfaces that cut across the long axes of the columnar quartz hosts. (8) These irregular boundary surfaces are highly repetitive (100–500  $\mu\text{m}$  spacing), and they are oriented roughly parallel to the vein margins. (9) The tapered tips of the crocidolite fibers always point toward the fine-grained, equant quartz crystals lining the opposite vein wall.

The inference that tiger's-eye formed during crack-seal deformation strikes us as inescapable. The periodic, jagged surfaces that slice across both the columnar quartz crystals and their included crocidolite fibers can be interpreted only as fracture planes. The emergence of length-slow columnar quartz crystals from fine-grained equant quartz at the vein wall is *prima facie* evidence for competitive growth from the vein wall toward the center of the vein. The orientation of the tapered crocidolite tips toward the equant quartz at the opposing vein wall verifies our interpretation that crocidolite and quartz growth were antitaxial. Thus, we maintain that the textures in tiger's-eye provide unambiguous evidence for the mechanism of crack-seal deformation as

described by Ramsay (1980) and Cox (1987). In particular, the morphological asymmetry of the crocidolite inclusions is diagnostic of the crack-seal process and is incompatible with pseudomorphic replacement by quartz.

We were disappointed that in their refutation of our model, Gutzmer and colleagues have made no attempt to provide an alternative explanation for the fabrics that we documented in our original paper. Compounding our perplexity, two of these authors have invoked some of the same textural evidence to validate their interpretation of a crack-seal origin for asbestiform manjiroite and todorokite veins in altered braunite-kutnahorite lutites from the Kalahari manganese field of South Africa (Gutzmer and Beukes, 2000).

In their comment on our article, Gutzmer et al. assert that field relations between tiger's-eye and crocidolite are not compatible with our model. Specifically, they argue that pure crocidolite veins were transformed to tiger's-eye through the formation of silcrete duripans when the crocidolitic rocks were exposed as land surfaces in the late Mesozoic. As a consequence, they contend tiger's-eye occurs only where asbestiform crocidolite veins are cut by this ancient planation surface. The authors do accept a crack-seal origin for the supposedly antecedent crocidolite mineralization. They err, however, in attributing this hypothesis to Dreyer and Söhnge (1992), who explicitly argue against an association of crocidolite seams with dilational veins and favor crocidolite crystallization through diagenesis of a magadiite-like precursor (Dreyer and Söhnge, 1992, p. 97).

We maintain that the textural evidence *against* a pseudomorphic replacement of crocidolite by quartz, and that *for* a crack-seal deformation mechanism, is so strong that interpretations of South African paleosurfaces on the basis of massive silicification of crocidolite should be reconsidered. Certainly, the petrologic relations diagrammed in Figure 1 of the comment are overly schematic. Our field observations of tiger's-eye near Griquatown, South Africa, do not support the model of a simple oxidation boundary between tiger's-eye and hawk's-eye. As mentioned in our original paper, intergrowths of blue hawk's-eye and brown tiger's-eye are complex, and lateral interfingering of hawk's-eye and tiger's-eye are commonly observed within single, flat-lying veins. These observations suggest that oxidizing fluids infiltrated the veins of hawk's-eye along fronts that are spatially variegated.

The gradation reported by Gutzmer et al. of tiger's-eye to hawk's-eye to crocidolite within a single vein is undoubtedly intriguing. Nevertheless, as our model proposes that all of these textures formed by crack-seal deformation, the existence of laterally contiguous hawk's-eye and crocidolite does not invalidate our interpretation. Rather, it demonstrates that the geochemistry of the fluids responsible for hydrofracturing and subsequent mineralization is extremely sensitive to, and in some cases controlled by, local mineralogical environments.

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