

*Abraded pyrite crystals from the Witwatersrand  
gold mines.*

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[Taken as read 24 January 1957.]

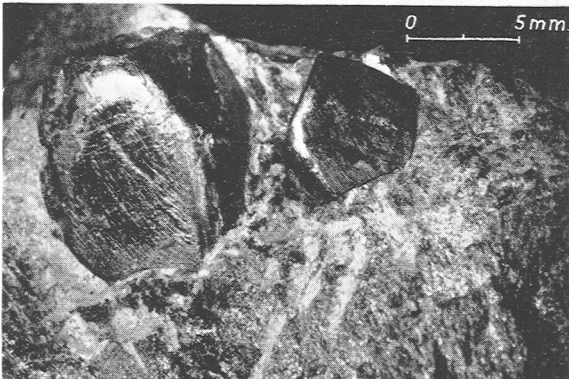
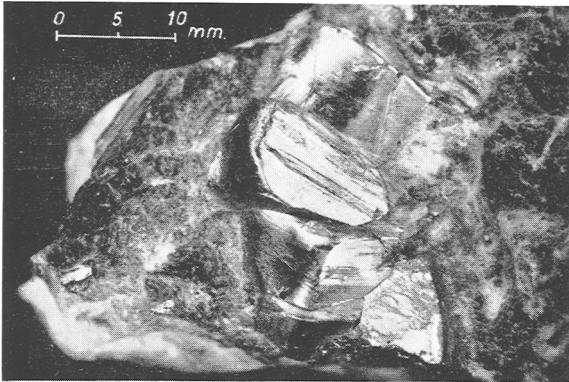
*Summary.* Metamorphosed dyke rocks in Witwatersrand gold mines carry pyrite crystals of unusual appearance. These crystals, particularly along the dyke margins, show curved and scratched surfaces that cut across crystal faces. The abrasion of the crystals is due to movement of dyke material under pressure. There is some suggestion of surface flow on the abraded surfaces. No deformation or granulation was obtained in laboratory experiments on pyrite crystals. Pressure shadows around the pyrite are described.

**P**YRITE crystals are frequently observed underground in dyke intrusions in the Witwatersrand gold mines. Fine examples set in the associated rock from a number of the mines were collected for me by mining students of the Witwatersrand Technical College several years ago.

Many of the dykes have been metamorphosed and the original constituents are replaced by quartz or by a chlorite and quartz. Contacts between dyke and sediment may also be post-intrusion fault planes; movement along these faults has further intensified the schistosity of the marginal portions of the dykes which are now dark green chloritic schist with much slickenside.

The pyrite crystals, scattered at random in the body of the intrusions, are more concentrated along the marginal zones (*cf.* Young, 1917, p. 91). They are generally associated with silicification and there are few that are not partly mantled by a thin layer of quartz. The dyke margins are heavily charged with narrow veins and irregular masses of quartz parallel to the contacts. The crystals are not always completely or perfectly developed. Individuals range in size from about 1 mm. across to 5 cm. along the cube edge; crystal aggregates have a similar size range. The striated cube is the dominant form, pyritohedra are less common, while combinations of these, the octahedron, and other forms occur to a minor extent. The curved faces produced by the oscillatory combination of the cube and pyritohedron show remarkably well on the larger specimens. Apart from these observations there is little to warrant

further description of the crystals occurring in the body of the intrusions. Crystals in the marginal zones, on the other hand, often have an unusual appearance. Examples of such pyrite porphyroblasts in dark green



FIGS. 1 AND 2.

FIG. 1 (*top*). Cluster of abraded pyrite crystals, City Deep mine. Abraded surfaces were cut on the left-hand side of the crystals. Although the crystals lie in different orientations, the general scratch direction is the same. Note the fractures and the appearance of a 'burr' on the central crystal.

FIG. 2 (*bottom*). Abraded surfaces on pyrite crystals, City Deep mine. The scratches have the same general direction. The 'protected' portions of the crystals face the top, while the schist is considered to have moved over the crystals from the bottom of the photograph.

schistose rock from two localities on the City Deep mine were considered worthy of closer examination.

The dykes were observed to cut obliquely through the conglomerates, quartzites, and chloritic schists. The pyrite crystals lie either entirely within the dark green schistose dyke or at the contact between vein quartz layers and sediment or dyke. In the latter type of occurrence the crystals have grown on the vein quartz and project into the softer rock.

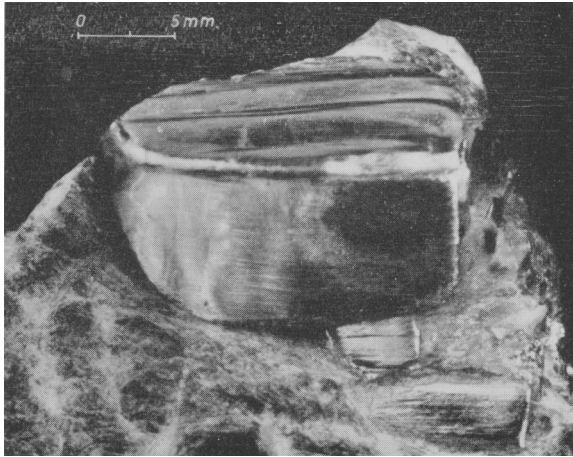


FIG. 3. Curved and finely scratched surface cut on pyrite crystal, City Deep mine.

Small crystals are also found in the vein quartz, grit, or chloritic schist immediately adjacent to the dyke.

When the enclosing dyke material is carefully removed, two types of surface are observed on the crystals: dull, stained faces that are easily recognized as cubic or pyritohedral, and bright polished surfaces that cannot be referred to simple crystal forms. These bright surfaces are strikingly curved, scratched, and finely pitted (figs. 1 and 2). Close inspection shows that they are not the normal curved faces common in pyrite, but surfaces that cut across original crystal faces (fig. 3). The fine scratches cut across the natural striae and have a common orientation on each surface, although some surfaces may have other sets of scratches superimposed upon those of the dominant direction (fig. 4). Fractures have also developed at right angles to the scratches. It is clear that these curved and scratched surfaces are due to abrasion of the pyrite crystals from which amounts up to several millimetres thick have been removed (fig. 5).

Conspicuous coarse grooves and scratches on the contact surfaces of

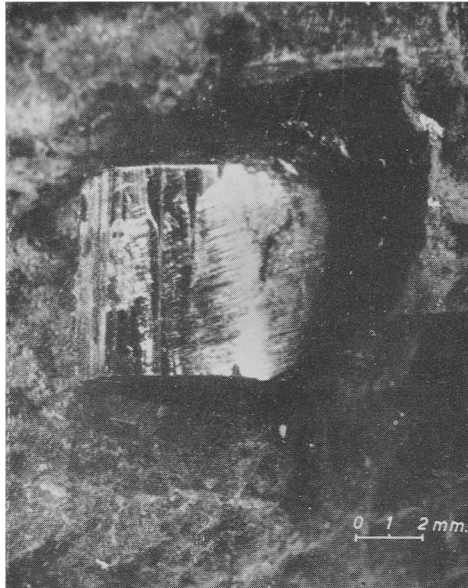


FIG. 4. Scratches cutting across natural striae of the cube face, pyrite crystal, City Deep mine.

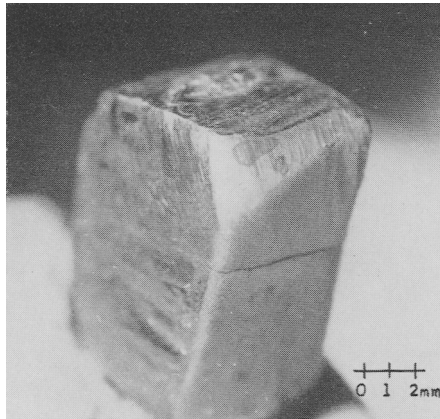


FIG. 5. Abraded coign, pyrite crystal, City Deep mine.

the schistose dyke and vein quartz follow the same general direction as the scratches on the abraded crystals. This direction is slightly modified on crystal aggregates where adjacent faces of individuals form V-shaped

or angular depressions. The amount of abrasion seems to be determined by the orientation of the crystals in the rock (fig. 1). Scattered crystals that have grown in random orientation in both vein quartz and schistose dyke show clearly that abrasion has been effected in one general direction only.

During faulting or metasomatic-metamorphic changes, therefore, only those parts of the crystals presented to the moving dyke material were abraded. The other, or 'protected' parts of the crystals are not modified as a rule and retain original crystal faces. Curved surfaces at both ends of some crystals are due perhaps to a reversal of direction of movement of the rock material. The abrasion of crystals projecting from rigid vein quartz into the softer (plastic) dyke rock may be compared with that of the stoss side of the roches moutonnées of glacial origin.

Thin and polished sections of dyke-quartz and dyke-sediment contact zones were cut both parallel to and across the schistosity. Under the microscope the dyke shows a fine-grained association of angular quartz, albite, and flaky chlorite with magnetite cubes, patches of leucocene (?), and secondary sphene. The chlorite shows pale green pleochroic tints and is probably a pennine; some flakes have a pink to blue pleochroic scheme. Diffuse oblique illumination reveals faint outlines of original feldspar laths in the matrix. The thin sections also show clearly that schistosity becomes more marked towards the dyke margins where the rock is a fine-grained true chloritic schist. Scattered quartz laths are conspicuous in the well-defined schistose arrangement; between crossed nicols many give a twin-like extinction, which indicates that they are a replacement of original twinned feldspar phenocrysts in a chilled margin. It is well known that underground, metamorphosed dyke rock is similar in appearance to the chloritic schists of sedimentary origin. Metamorphosed dykes, cutting across bedding planes at low angles, and more particularly sills, may be mistaken for altered sediment. The presence of scattered feldspar palimpsests (apart from the fine-grained albite), revealed in thin section, should establish the original igneous nature of the schist.

In thin section granulated and detached fragments of pyrite are seen scattered in the rock near those crystals that have curved and abraded surfaces. This feature was recorded earlier by Harker in 1889. Almost all the porphyroblasts are mantled by a fibrous quartz layer of variable thickness. Polished sections show no development of anisotropism nor any other evidence of deformation of the crystals. Etch tests reveal no zone of surface flow, which if it exists may be of sub-microscopic thick-

ness only. Irregular patches of chalcopyrite lie in the schist between pyrite crystals and marginal vein quartz; between crossed nicols the lamellar twinning makes the anisotropy of the chalcopyrite conspicuous.

Other specimens of similar metamorphosed dyke rock containing abraded and scratched pyrite crystals were collected on the Government Gold Areas and the East Rand Proprietary mines. Pyrite-bearing dyke rock of somewhat different appearance came from the Consolidated Main Reef mine; here the very fine-grained soft dyke rock has a biscuit or dark cream colour and looks rather like unglazed porcelain. Specimens from the body of the dyke are heavily charged with pyrite, which has crystallized as the cube, pyritohedron, and less frequently as combinations of pyritohedron and octahedron. The crystals range from 1 to 10 mm. in size and where they have developed close to one another show little distortion or abrasion. Larger crystals, up to  $4 \times 3 \times 2$  cm., rather more scattered, have grown in the marginal portions of the dyke. Irregularly curved surfaces are dull rather than brightly polished and are only partially scratched. Thin sections show that the fine ground-mass of this rock is completely sericitized, with scattered fine granules of quartz, a little chlorite, and some secondary sphene. The X-ray powder photograph and diffractometer trace<sup>1</sup> of the dyke material indicate that the dominant mineral is a muscovite rather than sericite. There is no marked schistosity except in the contact zone of the dyke, where scattered silicified and sericitized phenocrysts of presumed feldspar are also to be seen.

Fringes or mantles of muscovite flakes around the pyrite crystals are similar to those of fibrous quartz associated with pyrite in the City Deep specimens. These structures, called 'pressure shadows', have been described previously by Harker (1889), Pabst (1931), and many other authors. The width of the shadows is more or less uniform around the pyrite crystals in the central portions of all the intrusions (fig. 6). In the marginal zones, however, the pressure shadows extend in the direction of schistosity and they are therefore frequently wedge-shaped with a thickness varying from 0.1 to 2 mm. They are not always completely formed around the pyrite crystals (Young, 1917, p. 42; pl. XI, fig. 4). Pabst's observation, that the shape of the shadows is largely dependent upon the orientation of the pyrite porphyroblasts with respect to the schistosity, is confirmed.

In the City Deep specimens the shadows consist of 'feather' quartz

<sup>1</sup> Kindly taken by the National Physical Laboratory, Pretoria.

with some interspersed chlorite flakes, and the elongated quartz grains are normal to the crystal faces and some of the abraded surfaces. Many of the abraded surfaces are, however, devoid of quartz fringes, although the 'protected' portions of the crystals have a well-developed shadow; a few shadows are distorted. These observations suggest that the pressure shadows were formed over an extended period that commenced

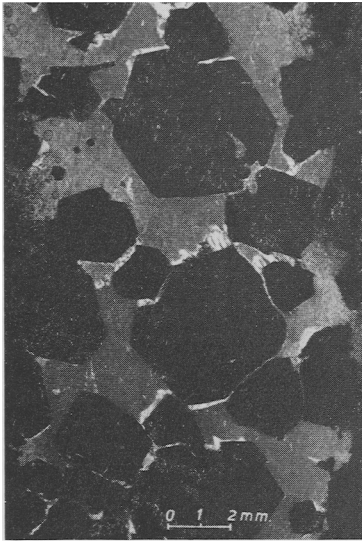


FIG. 6.

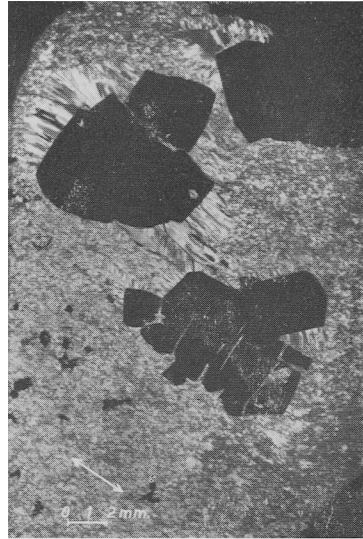


FIG. 7.

FIG. 6 (*left*). Muscovite pressure shadows around pyrite crystals, Consolidated Main Reef mine. Crossed nicols.

FIG. 7 (*right*). Pyrite crystals in schist, City Deep mine. Fractures in the pyrite crystals are normal to the direction of relative tension (indicated by arrows). The quartz pressure shadows have developed along this direction.

before 'flowage' of the dyke had ceased, and continued, perhaps as a succession of intermittent growths, until well after the abrasion of the pyrite was complete. The relationship between the elongation and the crystallographic directions of the fibrous quartz was investigated on the universal stage according to the method described by Pabst. The results when plotted gave an irregular pattern characteristic of unorientated material and thus support Pabst's conclusion that there is no tendency for any crystallographic direction in the quartz to be parallel to the grain orientation. Cracks in the pyrite are at right angles to the direction of 'stretching' and a perfect example of this relationship is shown in fig. 7.

These cracks are frequently filled with fibrous quartz, which is in continuity with that of the pressure fringes.

The pressure shadows in the Consolidated Main Reef specimens are made up of sericite or muscovite plates with fewer flakes of chlorite and some fibrous quartz grains. Smaller and thinner sericite flakes in the fringes appear to be in haphazard association with the fine quartz particles, but tend to have the greater dimensions normal to the pyrite face. Where the plates of muscovite are larger, and the fringes thicker, the basal plane is parallel to the pyrite face.

Particularly in the City Deep material the high polish on abraded surfaces and what appears to be a burr at the edges of fractures transverse to the scratch directions suggest that there has been some surface flow of the pyrite. As noted above, no deformation was observed in polished section study and it was concluded that if flow had taken place, the layer involved is probably of sub-microscopic thickness.

In general, soft sulphides deform with ease, but the harder minerals are brittle and tend to fracture. Pyrite is regarded as a brittle mineral and it has not been observed to deform as other softer sulphides do. In many deformed rocks pyrite crystals are granulated, 'rounded', or sheared into thin plates. In the examples of abraded crystals here described, however, none of the crystals show shattering or more than slight granulation, though a few small fractures have developed in some crystals, and a little granulated pyrite does occur in the rock near the abraded crystals. The abrasion of the pyrite must have been effected under considerable shearing stress, which might have caused some surface flow.

Dr. Raal kindly took both Laue and oscillation X-ray photographs of some of the abraded and polished surfaces both before and after they had been etched. The Laue reflections before etching are in general seen as multiple spots. After the abraded surfaces had been lightly etched, this multiplicity had largely disappeared. These observations suggest that some surface deformation has taken place. The problem of surface flow and possibly greater deformation of pyrite crystals is worthy of a more intensive X-ray study.

Experimental work on deformation of pyrite was carried out by Adams (1910) and later by Newhouse and Flaherty (1930). Adams embedded pyrite crystals in alum in cylindrical copper tubes, which were subjected to pressures up to 43,000 lb. per sq. in. (see also Buerger, 1928). Newhouse and Flaherty used a modification of Adams's method whereby prepared cylinders of chalcopyrite ore containing pyrite were



fitted tightly into copper tubes. In Adams's experiment on pyrite, the crystal was crushed owing to an unsatisfactory performance of the apparatus. In the later work the pyrite was sheared into thin plates arranged *en echelon* by the movement of the chalcopyrite and the broken fragments had a linear distribution.

As Adams's original experiment was really not satisfactory, it was felt that some further work according to his methods should be done. A number of tests were made using copper tubes having the dimensions given by Adams, in a suitable press in the Department of Mechanical Engineering, Natal University, but the tubes bulged before high pressures could be reached. A further set of experiments, in which tubes of  $\frac{1}{8}$  in. wall thickness were used, was then carried out, and pressures of 36 tons per sq. in. were reached. Perfect crystals of simple form, either cube or octahedron, were used. After the experiments, no visible change was observed in the appearance of the faces, nor did measurement show any change of shape or size. Except for a small fracture (which may have been there originally) in one crystal, none of the cubes showed any disintegration after being subjected to pressures reaching 36 tons per sq. in. in successive runs. One octahedron taken to 35 tons per sq. in. developed a clean fracture along a plane parallel to the octahedral face. These experiments show that pyrite does not granulate or shear as a rule, over the range of pressure so far investigated by this method.

There might also be some relationship between temperature and the development of surface flow; the possibility of pyrite yielding under shearing stress at elevated temperatures created during abrasion might be considered.

The events that produced the features of the dykes and the pyrite crystals described in this paper were probably as follows:

Dynamic metamorphism attendant upon folding of the Witwatersrand sediments affected the early minor hypabyssal intrusions. Basic dykes such as those in the City Deep mine, and others intermediate to acidic in composition of which the Consolidated Main Reef occurrence may be representative, were altered to chlorite-quartz-albite or sericite-chlorite-quartz schists. Silica introduced along the dyke contacts and into marginal fractures formed irregular masses and thin vein-like bodies of quartz. Silicification then continued over a long period and may well have been intermittent. Sulphide entered and crystallized as pyrite throughout the body of the intrusions and particularly along the dyke-sediment contacts, which were now highly charged with quartz. The pyrite crystals clearly transect the schistosity; their perfect crystal-

lization obscures the nature of any mineral they may have replaced and they are therefore typical automorphic replacements. Continued slow movement pulled schist from the sides of the pyrite crystals and the openings thus developed filled up with quartz or silicates as pressure shadows.

This movement along dyke contacts, which had now become fault planes, produced intense slickensides on the quartz layers. The pyrite porphyroblasts, formed partly in schist and partly in quartz, were held firmly by the latter, and abraded probably by quartz granules in the schist, which under intense shearing stress flowed over and around them. Those portions of the crystals projecting into the schist were ground down with removal of coigns and crystal edges and the development of highly polished, curved, and scratched surfaces. There is no pressure shadow around most of the abraded surfaces, although a shadow is still present on 'protected' portions of the crystals. The presence of pressure shadows around some curved surfaces indicates that shadow growth continued after abrasion of the pyrite. Aggregates of pyrite crystals in the marginal schist, but not anchored in vein quartz, are surrounded by distorted pressure shadows. Clearly there was movement of the matrix during the period of formation of these shadows.

Towards the end of the period with which we are concerned, small amounts of later pyrite and chalcopyrite replaced quartz along the contact of schist and sediment. The twinning of the chalcopyrite suggests that pressure effects had not yet ceased.

Careful search should bring to light many more occurrences of abraded pyrite similar to those described in this paper in the mines of the Witwatersrand and adjacent areas.

*Acknowledgements.* I am grateful to Prof. F. J. Turner for supplying a specimen of the Calaveras pyrite-bearing slate described by Pabst. I am indebted to Dr. J. N. van Niekerk of the National Physical Laboratory, Pretoria, and to Dr. J. F. H. Custers and Dr. Raal of the Diamond Research Laboratory, Johannesburg, for the X-ray data quoted in the paper. Thanks are due to my colleague, Mr. P. J. Kramer of the Mechanical Engineering Department, for assistance in the pressure experiments and to Mr. P. J. Newman of the Department of Architecture who took the photographs for figs. 1 and 3.

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