A MICROSTRUCTURAL STUDY OF PIETERSITE FROM NAMIBIA AND CHINA

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Pietersite has been described as a brecciated variety of tiger's-eye. This study examined pietersite specimens from Namibia and China (the main sources) using powder X-ray diffraction, optical microscopy, environmental scanning electron microscopy, and conventional gemological methods. On the basis of the results, quantitative approaches were developed to distinguish pietersite samples from the two localities. It is also proposed that the petrogenesis of this gem material is quite different from that of South African tiger's-eye.

Pietersite is named after its discoverer, Sid Pieters, a well-known gem and mineral dealer who first described it in 1962 from a locality in Namibia (Thomas, 2008). The term is now used generally to describe brecciated varieties of tiger's-eye. Tiger's-eye *sensu stricto* occurs within Precambrian banded iron formations as seams that run parallel to layers of jasper. It is characterized by lustrous "golden" brown bands that exhibit a radiant chatoyancy when polished due to the inclusion of crocidolite fibers within a microcrystalline silica host (Heaney and Fisher, 2003). (Crocidolite is an asbestiform variety of an amphibole called riebeckite.) Although Namibian pietersite exhibits the same mineralogy as tiger's-eye, the chatoyant field is not observed as a continuous band. Rather, pietersite contains angular fragments that are cemented as an irregular patchwork of "bundles," some of which exhibit sheen (Koivula et al., 1992). Thus, pietersite offers a chaotic chatoyancy, with a brecciated texture that has been likened to bold paint strokes that flow in many directions (see, e.g., figure 1).

Pietersite has been found at two main sources: Kuraman, Namibia; and Xichuan, Henan Province, China. Mr. Pieters discovered the Namibian pietersite within round dolostone cobbles while prospecting some farmland in the neighborhood of Outjo, in the Kuraman district. He registered the gem in the mineral records of Great Britain in 1964 and brought it to market in the 1970s (Koivula et al., 1992; Thomas, 2008). In 1996, Zeitner reported that much of the minable stock in Namibia was depleted and that material was becoming scarce. Chinese pietersite was discovered in 1966 while geologists were prospecting for crocidolite. It was mined in the 1970s and 1980s, but it did not come to market until the 1990s (Zhong, 1994). Although it appears that both mining areas are still closed, material from these localities continues to appear in the marketplace.

In this article, we compare the properties of pietersite from Namibia and China, identify their distinguishing characteristics, and propose mechanisms for their formation that account for differences in their appearance and phenomena. A comparison to South African tiger's-eye is also provided.

MATERIALS AND METHODS

The specimens examined included five samples from China and six from Namibia (e.g., figure 2). The Chinese specimens consisted of two flat polished oval slabs from the GIA Collection (no. 32394, donated by the late Hannes Kleynhans) and three cabochons labeled as Chinese and purchased at the 2008 Tucson Gem and Mineral Show. The Namibian specimens consisted of three polished pieces and

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Figure 1. China and Namibia are the only known sources of gem-quality pietersite. Studied for this report, this Chinese sample (left, 39.85 g) displays an overall brownish red color, whereas the polished specimen of Namibian pietersite (right, 80.76 g) is dominated by blue-gray, "golden" yellow, and white hues. Photos by K. Hu.

three flat unpolished slabs from author PJH's personal collection (purchased at the 2008 and 2009 Tucson gem shows). Two of the six Namibian samples contained traces of the original host rock. The specimens ranged from 7 to 85 g.

Standard gemological tests were performed on all samples. RI values were measured from the five Chinese and three Namibian polished specimens with a GIA Duplex refractometer. We obtained hydrostatic SG values using a Scout Pro SP 602 electronic balance. UV fluorescence was observed with standard long-wave (366 nm) and short-wave (254 nm) UV lamps.

Figure 2. These are some of the Namibian pietersite specimens that were investigated for this report (3.3–6.0 cm in maximum dimension). Photo by K. Hu.

Eight doubly polished petrographic thin sections were prepared from both the Chinese and the Namibian material (four from each), and these were examined with an Olympus SZ-CTV microscope and an Olympus BX40 petrographic microscope. Photomicrographs were obtained with a Nikon DS-5M camera. Powder X-ray diffraction (XRD) patterns were collected using a Rigaku DMAX-Rapid microdiffractometer. Environmental scanning electron microscope (ESEM, in which the sample does not need an electrically conductive coating) analysis of all eight thin sections was performed using an FEI Quanta 200 microscope operating at 20 kV, and chemical analyses were obtained using an Oxford INCA energy-dispersive spectroscopy system. All work was conducted in the Pennsylvania State University Mineralogy Laboratory in the Department of Geosciences, and in the Materials Characterization Laboratory at the Pennsylvania State University Materials Research Institute.

RESULTS

The gemological properties of the samples are described below and summarized in table 1.

Visual Appearance. The Chinese pietersite specimens were intensely brecciated, with individual fields measuring 2–8 mm in diameter. The overall color was a jasper-like brownish red hue, but regions of chatoyant blue and yellow were discernible, with white flecks from calcite. The chatoyant effect was best developed in the yellow regions, but it was noticeably less vibrant than is typically observed in Namibian pietersite.

The color of the Namibian specimens was not as

TABLE 1. Gemological properties of pietersite from China and Namibia.

Property	China	Namibia
Color	Brownish red, "golden" yellow to brown, rarely blue	Blue-gray, "golden" yellow to brown, rarely red
Diaphaneity	Opaque	Semitranslucent to opaque
Refractive index	1.54–1.55	1.54–1.55
Specific gravity	2.67–2.74	2.50–2.58
UV fluorescence		
Long-wave	Inert	Moderate-to-weak light green
Short-wave	White in calcite areas	Moderate-to-strong bright green
XRD analysis	Quartz, minor calcite	Quartz, minor calcite
Textural features observed by optical microscopy and ESEM	Brecciated clasts measuring 2–8 mm in diameter; fibrous crocidolite intensely coated by hematite and chlorite; quartz veins cross-cutting crocidolite; calcite inclusions	Brecciated clasts measuring 5–10 mm in diameter; fibrous crocidolite occasionally coated by goethite and hematite; chalcedony spherulites; inclusions of calcite, dolomite, barite, and pyrite

varied as that of the Chinese material. Blue-gray and "golden" yellow fibrous regions predominated, with rare secondary brownish red fields, and the overall bodycolor of the Namibian specimens was blue-gray. The brecciated clasts ranged from 5 to 10 mm in diameter, but on average they were larger than those seen in the Chinese specimens. Chatoyancy was particularly well developed in the blue fields. Three of the Namibian specimens had ~2-mm-thick veins of colorless translucent chalcedony. Chalcedony was observable in the Chinese specimens only with the aid of light microscopy.

Refractive Index. The RI values, around 1.54, were consistent with quartz for all samples. There was no difference in RI values between the Chinese and Namibian specimens.

Specific Gravity. The SG values of the Chinese specimens ranged from 2.67 to 2.74. The SG values of the Namibian specimens were notably lower, 2.50–2.58. The SG of quartz is 2.65.

UV Fluorescence. Most of the Namibian specimens luminesced a moderate-to-weak light green to long-wave UV radiation and a moderate-to-strong bright green to short-wave UV. This bright green luminescence is most likely explained by the greater chalcedony content in those sectors. Portions of some of the Chinese specimens luminesced white to short-wave but were inert to long-wave UV; these areas corresponded to calcite.

Powder X-ray Diffraction. Our XRD patterns for the Chinese and Namibian specimens were indistinguishable, producing diffraction peaks only for quartz with minor calcite. No evidence of crocidolite was detected. This result is similar to our experience with many tiger's-eye specimens from Griquatown, South Africa, for which crocidolite was detected only by synchrotron X-ray radiation (Heaney and Fisher, 2003). We infer from these results that despite the intense chatoyancy of pietersite, the mass fraction of crocidolite is on the order of a few weight percent or less.

NEED TO KNOW

- Pietersite, often described as a brecciated variety of tiger's-eye, is known from China and Namibia.
- Pietersite from the two localities has similar RI ranges, but the Namibian material has a lower SG.
- Crocidolite fibers are more densely intergrown (parallel, radial, and disordered textures) in Chinese samples. The fibers in Namibian specimens are generally oriented parallel to one another.
- Namibian pietersite formed under very different geologic conditions from those that produced South African tiger's-eye.

Optical Microscopy. Examination of thin sections of pietersite from both China and Namibia revealed the presence of crocidolite embedded within microcrystalline quartz. The crocidolite could be distinguished on the basis of its moderately high relief, pleochroic grayish blue to greenish blue coloration, and optical extinction of 8–10° in cross-polarized light.

We also noted significant textural differences

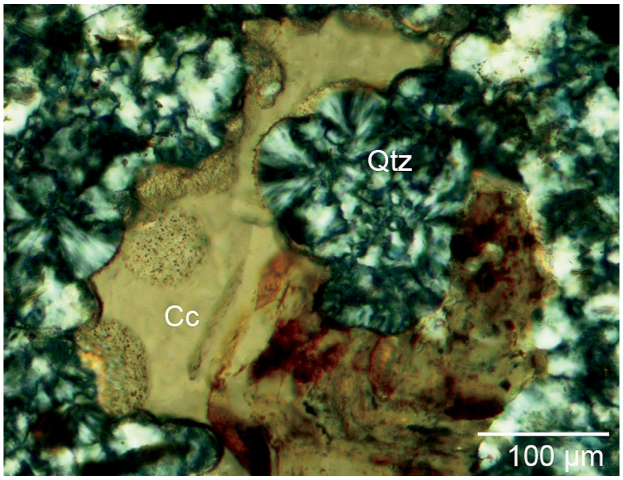

Figure 3. In cross-polarized light, this Namibian pietersite exhibits fibrous chalcedony (Qtz) spherulites that are embaying calcite (Cc) and are surrounded by fine-grained hematite. Photo by K. Hu.

between the Chinese and Namibian specimens. In the Chinese samples, the fibers were more densely intergrown, and they showed a broader variety of fabrics—parallel, radial, and disordered. They ranged from 20 µm to 2 mm long and rarely exceeded 2 µm wide. Both hematite and chlorite coated the fibers of crocidolite. The Chinese pietersite also differed from the Namibian samples in the presence of fibrous chlorite inclusions. The chlorite fibers exhibited strong pleochroism from deep green to yellowish brown.

Unlike the Chinese material, the crocidolite fibers in the Namibian specimens were generally oriented parallel to one another. Fiber lengths were shorter than in the Chinese material, typically 10–50 µm, and they were less than 2 µm wide. The fabric of the microcrystalline quartz also differed significantly; it was commonly fibrous chalcedony and quartzine, whereas in Chinese samples it was uniformly fine-grained and equant, similar to jasper (Heaney and Veblen 1992). Radial spherulites of chalcedony grew within both calcite and hematite in the Namibian pietersite (figure 3).

ESEM Analysis. Consistent with the overall jasper-like red bodycolor of the Chinese pietersite, ESEM imagery showed that the crocidolite fibers were coated with hematite to a much greater degree than in the Namibian specimens (figure 4, right). Both Chinese and Namibian pietersite included calcite as an accessory mineral (figure 4, left), but ESEM revealed that the Namibian pietersite also contained microcrystalline dolomite, barite, and pyrite (figure 5), which we did not observe in the Chinese specimens. In places, these minerals were partly replaced by quartz, with only the edges of crystals visible (figure 6).

Backscattered electron images of the quartz matrix in the Namibian pietersite revealed growth textures that were unusual and instructive. Rims of fine-grained hematite typically enveloped radially fibrous chalcedony spherules, which embayed the precursor dolostone (figure 7, left). The chalcedony spherules displayed concentric, oscillatory spheres of microquartz fibers and open cavities. Crocidolite fibers grew out radially from the hematite-rimmed spherulites into open spaces between them (again, see figure 7, left). In regions marked by a higher degree of overall silicification, the chalcedony spherules appear to have coalesced, and the cores locally contained fibers of crocidolite coated with hematite. In more silicified samples, the crocidolite fibers were seen transecting multiple spherulites (figure 7, right).

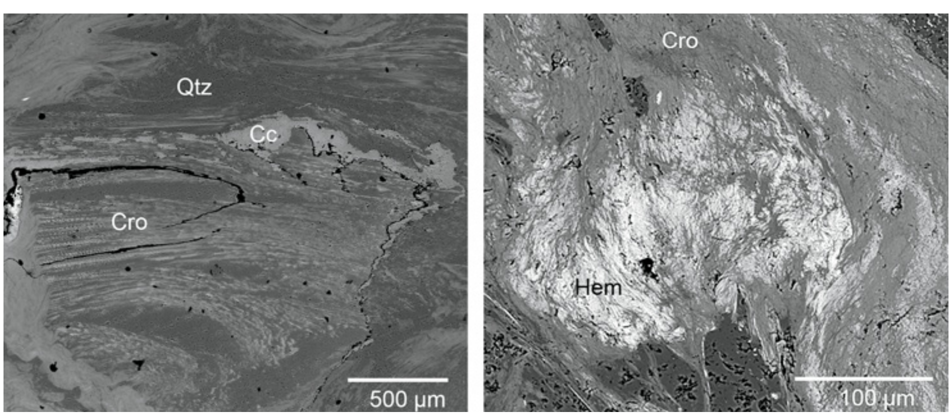

Figure 4. Parallel aggregates of crocidolite (Cro) and intergrowths of calcite (Cc) are evident in the backscattered electron (BSE) image of Chinese pietersite on the left. On the right, the BSE image of a Chinese specimen shows the coating of some crocidolite fibers (dark gray) by hematite (Hem; light gray). Micrographs by K. Hu.

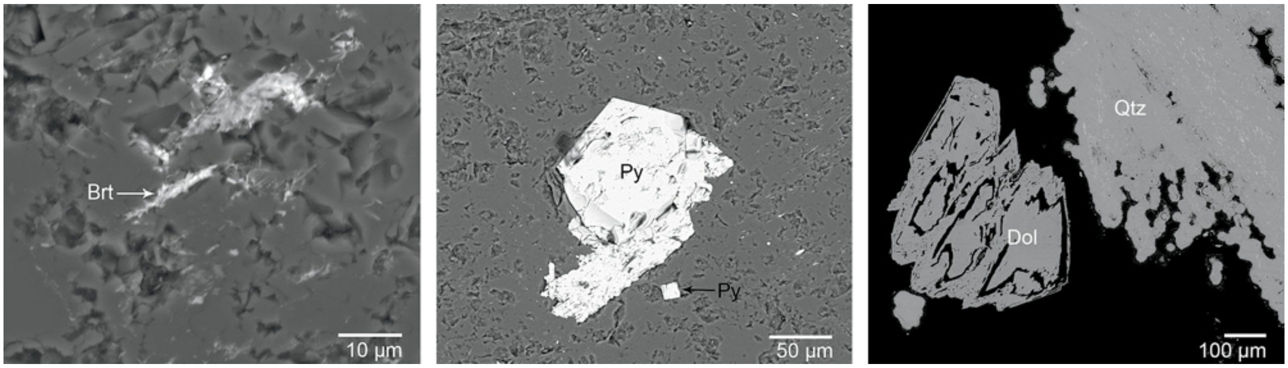

Figure 5. As revealed in BSE images (and identified by energy-dispersive spectroscopy), Namibian pietersite included barite (Brt; left), pyrite (Py; center), and dolomite (Dol; right). Micrographs by K. Hu.

Consistent with a previous report (Leake et al., 1992), energy-dispersive spectroscopy revealed that the crocidolite in both Chinese and Namibian material contains variable amounts of Mg in solid solution with Fe and should be classified as magnesioriebeckite.

DISCUSSION

Pietersite has been described as a "breccia aggregate made up largely of hawk's-eye and tiger's-eye" (Schumann, 2009, p. 320) and as a "disoriented pseudo-crocidolite mass with limonite" (Manutchehr-Danai, 2008, p. 368). Our analyses indicate that pietersite specimens from Namibia and China do share many hallmarks of tiger's-eye. Mineralogically, both tiger's-eye and pietersite contain asbestiform fibers of crocidolite embedded within a fine-grained quartz host, and the included crocidolite is responsible for the chatoyancy of the material. Chatoyancy is degraded where the crocidolite has altered to iron (hydr)oxides. For example, much of the Chinese material that we examined contained nonphenomenal areas in which a jasper-like dullness superseded the original chatoyancy because of this alteration reaction. Finally, like tiger's-eye, the pietersite samples revealed no evidence for pseudomorphism of quartz after crocidolite, despite popular assumptions to the contrary.

Nevertheless, our analyses suggest that the petrogenesis of pietersite is quite different from that of the tiger's-eye found in Griquatown, South Africa. Heaney and Fisher (2003) proposed that South African tiger's-eye formed through a "crack-seal" process: The hydrofracture of banded-iron formations generated flat seams parallel to the jasper bedding planes, and these cracks were sealed by quartz and crocidolite as an antitaxial infilling (i.e., growth from opposing crack walls toward the center of the vein). The quartz crystals in tiger's-eye exhibit a

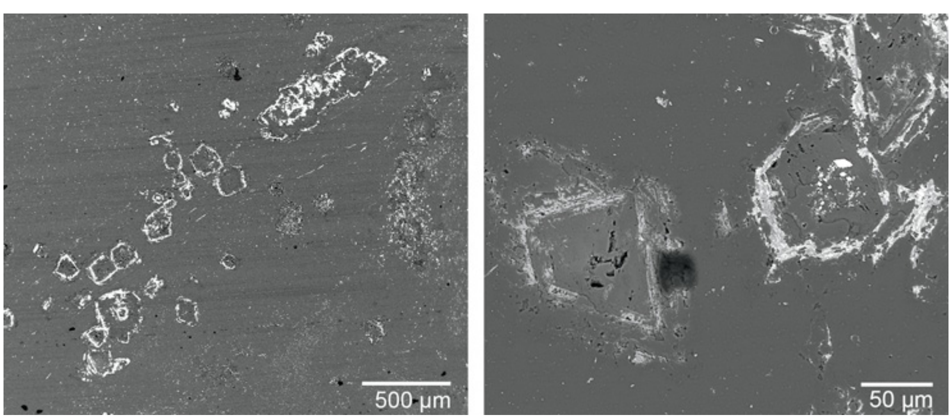

Figure 6. These BSE images of Namibian pietersite show the replacement of barite by quartz, leaving only the outer rims of the crystals. Micrographs by K. Hu.

characteristic columnar habit with an elongation parallel to the c-axis. The crocidolite fibers asymmetrically cross-cut the quartz boundaries, and the ends facing the vein wall are jagged while those facing the vein interior are tapered.

The textures in Namibian pietersite rule out a crack-seal origin. Many lines of reasoning suggest instead that the Namibian (and perhaps the Chinese) pietersites are solution breccias. (Solution breccias form when soluble minerals are partly or wholly removed by circulating groundwater, creating cavities into which overlying rock collapses and fragments. Often, the fragmented material is subsequently welded into a breccia by precipitation of a silica or calcite cement from the groundwater.) Namibian pietersite is developed within dolostone cobbles that underwent fragmentary dissolution and were silicified. During this process, silica-rich fluids partially dissolved the original dolomite and deposited chalcedony spherulites. The presence of hematite crystals at the centers of the spherulites suggests that hematite served as nucleation centers for silica. The growth of chalcedony fibers radially outward from these nuclei "bulldozed" residual hematite to form exterior rims of hematite.

We propose that a later episode of fluid infiltration resulted in the formation of crocidolite (a sodic amphibole) from reactions between chalcedony and hematite in the presence of aqueous Na^+. The formation of crocidolite during the coalescence of chalcedony spherulites generated regions in which the crocidolite fibers grew as parallel thatches. These sheaves of crocidolite are responsible for the spectacular chatoyancy observed in the highest-quality pietersite specimens. As is typical of dissolution breccias, however, the replacement of dolostone by silica was localized, and resulted in distinct patches of crocidolite with differing fiber orientations. This produced the chaotic chatoyancy that differentiates pietersite from South African tiger's-eye. The optical homogeneity that is characteristic of the latter probably can be attributed to the large-scale tectonic forces that exerted a broad control over crack-seal fiber growth. Chemical dissolution, by contrast, is not correlated over long spatial scales.

As is also typical of many South African tiger's-eye specimens, the last stage of pietersite formation involved a back-reaction of crocidolite to hematite and/or goethite. These microcrystalline iron (hydr)oxides initially coated the crocidolite fibers; then, in some instances, they completely replaced the fibers pseudomorphically. This final alteration reaction may have occurred at low temperatures much more recently than the crocidolite reaction, which presumably required low-grade metamorphism (Miyano and Klein, 1983). The breakdown of the crocidolite to iron (hydr)oxides proceeded to a greater extent in the Chinese than in the Namibian material, and it greatly diminished the capacity for chatoyancy.

CONCLUSION

Despite similarities in color, appearance, and mineralogy, we believe pietersite crystallized under very different geologic conditions from those that produced South African tiger's-eye. Whereas South African tiger's-eye probably can be attributed to crack-seal events related to tectonic stress fields, Namibian pietersite (e.g., figure 8) is a brecciated gem material created by fragmentary dissolution of precursor dolomite and replacement by silica. Subsequent reactions between silica and hematite in the presence of aqueous Na^+ formed crocidolite.

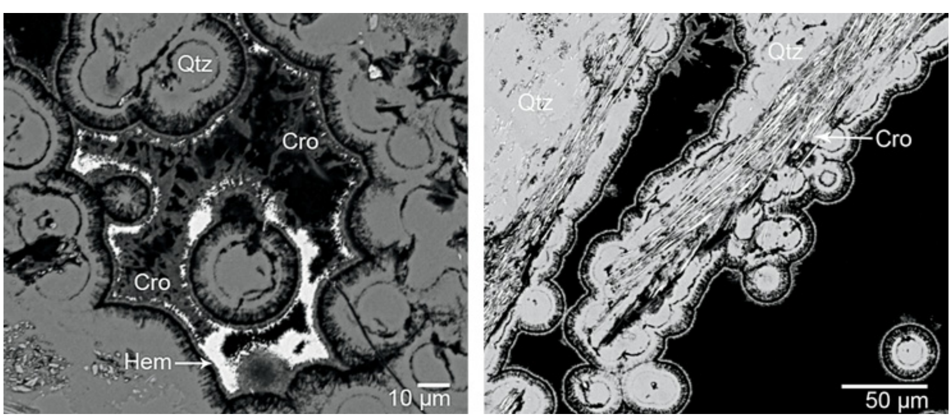

Figure 7. On the left, BSE imaging reveals radially fibrous chalcedony (Qtz) surrounded by white-appearing rims of hematite (Hem). Dark gray fibers of crocidolite (Cro) are present between the chalcedony spherulites. The black areas are empty cavities. The BSE image on the right shows crocidolite fibers transecting chalcedony spherulites in Namibian pietersite. Micrographs by K. Hu.

Figure 8. This slab of pietersite (12 cm across) shows the colorful appearance and brecciated texture that are typical of fine Namibian material. Photo by John Passaneau.

With little published information on the geologic setting of the Chinese pietersite, assigning the same petrogenetic model to the material from Xichuan is less certain. Despite their geographic separation, the microscopic textures of the Namibian and Chinese materials are strikingly similar. Nevertheless, our investigations have revealed that Namibian pietersite can be distinguished from its Chinese counterpart in several ways. Careful microscopic examination along with specific gravity and UV fluorescence characteristics can readily discriminate gems from these different localities.

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