

SHORT COMMUNICATIONS

MINERALOGICAL MAGAZINE, JUNE 1977, VOL. 41, PP. 288-92

Rutile and apatite: Useful prospecting guides for porphyry copper deposits

SUMMARY. The accessory minerals rutile and apatite have been studied in 77 known porphyry copper deposits. Their value as indicators has been well established on the basis of specific chemical and paragenetic variations which they show.

Rutile occurs as the only Ti-mineral in the quartz-sericite zone, is dominant in the biotite-orthoclase zone, and is generally found in the inner fringes of the chlorite-epidote zone. It forms in these zones mainly as a result of the destruction of sphene, but also from biotite and hornblende.

The length:width ratio of rutile crystals is 1.5:1 in the centre of a porphyry system, increasing gradually outward to 2:1. A characteristic red colour displayed in thin section is attributed to a high copper content ranging from 100 to 500 ppm. The ratio of Cr+V:Nb+Ta is also unusually high.

Apatite shows evidence of a complicated history of corrosion and redeposition accompanied by outward migration during the life of the porphyry system. The migration parallels that of copper and typically extends far into the host rocks. The apatite is enriched in chlorine. A plot of *a* versus *c* shows a clear separation of apatites of various genetic types, including tin and molybdenum porphyries.

DURING the past 14 years 77 known porphyry coppers have been studied using approximately 8000 thin sections. The samples studied in thin section were also used for spectrographic and geochemical analysis.

An additional 33 000 samples taken from various prospects, outcrops, and drill cores for which some geological information was available were similarly studied. The information gathered was compiled gradually and eventually two accessory minerals were revealed as consistently reliable prospecting criteria.

Rutile is the major Ti-bearing phase in porphyry copper intrusives and their walls. It starts crystallizing at the beginning of the deuteric stage in the porphyry intrusion, and continues to form outward from it during the metasomatic and hydrothermal stages in the wallrocks. It is frequently seen in even very incompletely developed porphyries as a replacement product (with calcite) of sphene.

In the biotite-orthoclase zone, rutile is virtually the only Ti-accessory with two exceptions: in low-pressure areas (e.g. breccia pipes or veins) it may be substituted by anatase; also, if the host rocks in this zone are calcareous, perovskite may proxy for it.

In the quartz-sericite-pyrite zone rutile is very common and again substituted by anatase only in breccias or open veins. Rutile continues to be stable in the inner portions of the chlorite-epidote zone, eventually disappearing outwardly in favour of the local Ti-bearing accessory in the host rocks.

Along veins, the influence of the porphyry copper intrusive may extend much further than in the encasing wallrocks. Rutile may occur in the selvages of veins over a mile laterally from the typical porphyry copper.

Whereas the mere existence of rutile in a calc-alkaline intrusive or in a chlorite-epidote assemblage should excite curiosity, its presence in the assemblage quartz-sericite-pyrite is commonplace, whatever the origin of the alteration. There are other features about the rutile in porphyry copper systems, however, that render it a unique indicator.

Analysis of a number of porphyry copper rutiles and rutiles from other environments was undertaken by laser probe using analysed standards. Owing to the minuteness of most available

crystals, and the inaccuracies inherent in the analytical method, results are at best semi-quantitative.

Most rutiles of other origins exhibit a high ratio of Nb+Ta to Cr+V. The reverse is true of all porphyry-related samples and, in fact, neither Nb nor Ta was detected in any sample. The most striking discovery, however, was the presence of Cu, which ranged, in all porphyry-related samples studied, between 100 and 500 ppm. No rutile of other origin exceeded 50 ppm.

The copper content appears to be related to another feature common to all porphyry-related rutiles; they are a distinctive reddish colour in thin section. The depth of the colour

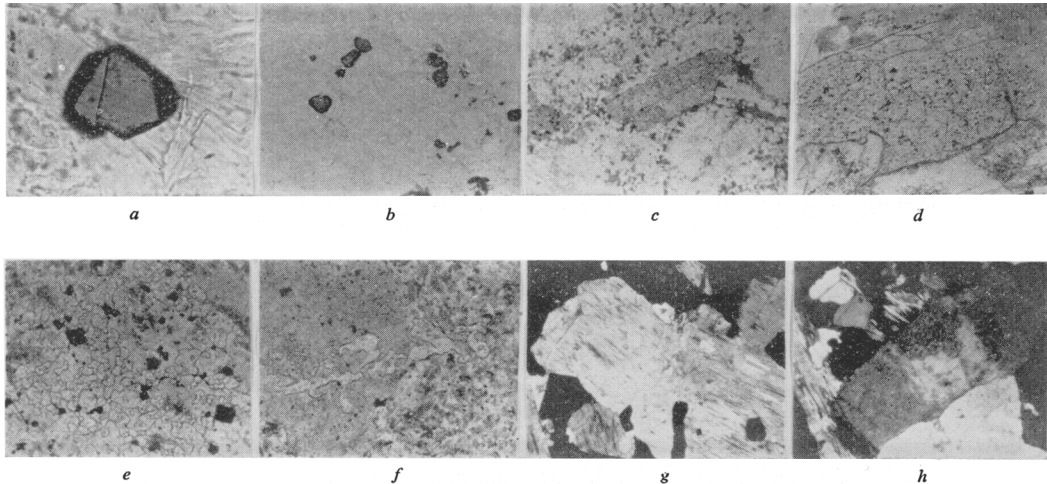


FIG. 1. *a*: Twinned rutile crystal in sericite. *b*: Typical rutile crystals set in quartz and sericite. *c*: Apatite showing corrosion at both terminations. *d*: Slightly corroded apatite. *e*: Abundant new amoeboid apatite in andesitic wallrock. *f*: Apatite growing along incipient veinlet. *g*: Remnants of chlorapatite in fluorapatite; opaque is bornite. *h*: Corroded core of chlorapatite; most is younger fluorapatite.

appears to relate to the copper content and, in general, fades out with increasing distance from the centre of the porphyry copper system. All dark red crystals studied showed a broad and diffuse absorption band in the green.

Also peculiar to porphyry-related rutile is its crystal habit. The length:width ratio of crystals is about 1.5:1 in the centre of a porphyry system increasing to about 2:1 in the outer edges of the quartz-sericite-pyrite zone. In addition, {110} and {111} dominate in the inner zones but share equal importance with {100} and {101} in the outermost zones. The habit change is quite gradual and accords with observations by Kostov (1966) very well. In contrast with his cassiterite, however, rutile habit changes little, and complex, highly modified crystals of rutile belong only to other, non-porphyry environments. Typical crystals are shown in fig. 1a, b.

Most rutile in porphyries forms by replacement of sphene¹ but some also derives from mafites and particularly from primary biotite. Any later (secondary) biotite is notably Ti-poor, and coexists with the earlier rutile. The rutile is typically disseminated, outlining former mafite or sphene sites in only a vague way. Sulphides may be spatially associated, since they also prefer mafite sites for crystallization.

Rutile seems to migrate reluctantly, but is occasionally observed in veins. It is often seen in late magmatic granular quartz-orthoclase veins with molybdenite and chalcopyrite. It also

¹ Analysis of one sphene partially replaced by cuprian rutile showed no detectable copper.

occurs, however, in alpine veins in the porphyry or its immediate walls with their characteristic assemblage as well as bornite and chalcopyrite.

Apatite. The other unique mineralogic characteristic of porphyry coppers is apatite. This mineral begins to migrate early in the life of the hydrothermal system. It is not found in veins of late magmatic age, but begins to mobilize during the deuteritic stages of the porphyry and thereafter until the peak of pro-grade zoning has passed. Its migration can be noted in veins and within the wallrocks. After migration has ceased, a characteristic zoning similar to liesegang rings but vastly larger in scale can be observed.

The nature of these 'liesegang rings' has been based largely on modal analyses of numerous deep drillhole samples at Cananea, Sonora, and at Dos Pobres, Arizona.

The core of the porphyry, c. 5000–7000 feet below its mineralized top, may carry only its primary apatite content ($\pm 0.5\%$ by volume). Surrounding this is a zone of leaching with a small drop in apatite content, followed successively by a zone of modest enrichment. Another zone of leaching is then encountered, followed by a zone of enrichment. The zones culminate with an enrichment zone that coincides roughly with the top of the intrusive but does not follow its walls; rather it is of broad parabolic outline, convex upward, leading out into the wall rocks with depth. Within the major zone of enrichment, the apatite content (by volume) typically attains 2%, occasionally as high as 5%. Further zones beyond this die out again in amplitude, with a final weak zone of enrichment in the chlorite-epidote zone.

The final enrichment zone can often be detected 2000–3000 feet laterally away from the intrusive. In veins, however, where the apatite is usually 'frozen' in some stage of transport, enrichment can be detected a mile or more from the porphyry.

The evidence for apatite migration is easily seen in thin section, no matter where, or in what 'liesegang' zone the apatite is found. In zones of leaching, corrosion features are readily seen (fig. 1c, d), with etch pits deepening preferentially around the girdle of the prisms near their basal terminations. In zones of enrichment, newly arrived apatite deposits on the older or primary crystals, resulting in a characteristic amoeba-like growth (fig. 1e, f). The new apatite is invariably anhedral (fig. 1d) and clouded with cavities and inclusions. Gas cavities are numerous and often partly filled with Cl-rich liquid plus tiny grains of calcite or anhydrite or both.

In terms of the factors influencing zoning, the behaviour of apatite may be modified. In incompletely developed systems, where hydrothermal alteration is slight or non-existent, the tendency for apatite to corrode and migrate is also slight. In general, it can be observed in porphyries likely to carry only more than c. 0.1% Cu. Apatite in porphyries carrying only traces of copper sulphides as an 'accessory' mineral will usually show no corrosion at all.

In high sulphur systems, the 'liesegang' zones are broader and more diffuse but unchanged in over-all geometry. Indeed, apatite is leached in other high-sulphur hydrothermal systems but it is only in porphyry-related ones that the 'liesegang' zoning appears. The mobility of apatite is also high in porphyry copper systems with low total sulphur content, but bands of enrichment and corrosion are thin, and are sharply defined.

In systems that have degassed, apatite is very mobile and may be abundant in degassing structures. In breccia pipes or major veins it may occur as large crystals (up to five inches long on [0001]). Similar but smaller crystals are common in alpine vein assemblages as well.

Chemical and X-ray study of the apatites of porphyry coppers has been accomplished on a number of samples. Only a few similar studies have been done, to my knowledge, particularly one by Sotnikov *et al.* (1971). A few comments are provided on the apatite from Granisle by Carson and Jambor (1974). A recent paper by Banks (1976) assumes only magmatic processes to be responsible for the Cl-F variations in apatite at Ray, Arizona.

The early formed apatites are relatively Cl-rich hydroxy-fluorapatites. The amount of Cl in samples analysed ranged from 0.7% to 2.5%.¹ The OH content is also higher than normal in porphyry-copper apatites, ranging from 0.61% to 0.99%. The balance of anions occupying this site is fluorine, which ranged from 1.4% to 2.7%. The porphyry-copper apatites thus have a higher Cl-apatite component than deemed possible by some authors (Taborsky, 1972).

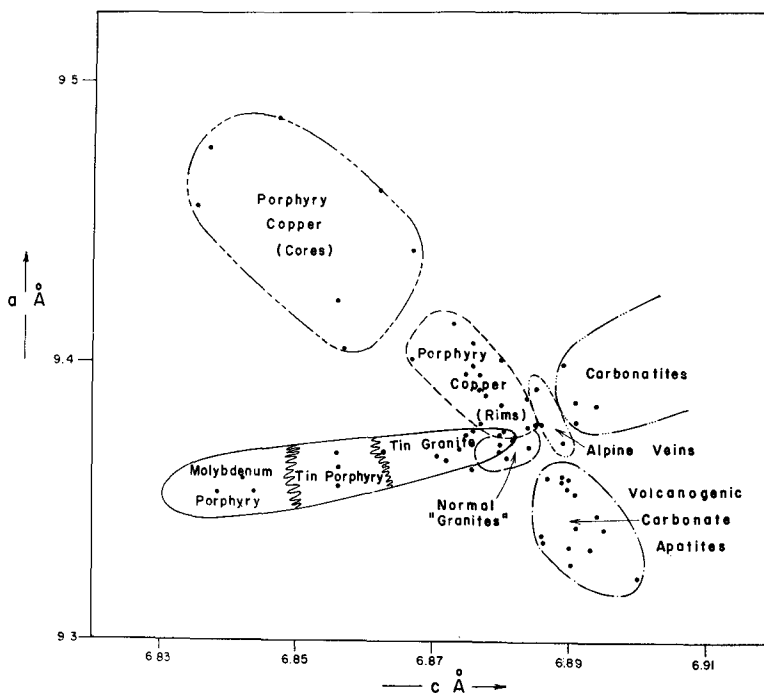


FIG. 2. Plot of a vs. c for apatites from various parageneses.

All newly formed apatite seen in porphyry copper systems falls within the analytical ranges reported above with two exceptions: very large apatite crystals are occasionally encountered in veins or pods of pegmatitic aspect, usually within the intrusive. These pods typically consist of coarse quartz, orthoclase, and biotite. The chemistry of apatites in this environment is as described above except that the crystals often (usually, in fact) show overgrowths (referred to as rims in fig. 2) that are more fluorine-rich (see fig. 1g and h). Analysis of such apatites showed the following ranges: Cl = 0.40 to 0.78%, F = 2.70 to 3.06%. Values for OH remain the same as above. A second exception is the apatite of supergene origin that is so common in porphyry copper oxide zones. This is invariably a monoclinic, OH-rich carbonate apatite.

Spectrographic study of all analysed apatites was also undertaken. In the cores of large apatite crystals, or in the smaller unzoned ones (all shown as 'cores' in fig. 2), Ce, Yt, and Mn appear to be enriched markedly, Cu to a minor extent. In the rims of large crystals Cu is highly enriched, and values for Ce and Yt remain high.

Unfortunately the optics of apatite are highly insensitive to their chemistry. The best thin-section evidence is certainly textural and only occasionally is one alerted by subtle variations in birefringence in apatite single crystals (usually ones showing overgrowths).

¹ By contrast, apatites from tin porphyries and molybdenum porphyries ranged from < 0.02% to 0.21% Cl, a range more typical of normal igneous apatites.

Plotting a vs. c for a large number of apatites showed a surprising separation of genetic types. This plot is shown in fig. 2 and its use is recommended as a test to substantiate suspicions of 'interesting' apatite from thin section study. The fields for other hydrothermal systems in which apatite plays an indicator role are included for interest.

All apatites studied were examined in the UV and, without exception, all fluoresced a bright orange. The reaction is brighter in short wavelength but clearly visible at long wavelength. Further experimentation showed an increase in intensity of the excited radiation linked with increasing degree of development of the porphyry system. The reaction is faint in low-grade, immature porphyries but the colour is still distinctive.

Many apatites of other origin were examined but none showed the characteristic orange fluorescence.¹ Apatites from other occurrences gave varied reactions, mostly negative. At this writing, the nature of the activator in porphyry copper apatites is unknown.

Acknowledgements. Marjorie Duggan and Lance Talley assisted enormously with their chemical analyses. Several geologists of Phelps Dodge Corporation have encouraged and aided in this research, particularly R. W. Ludden, Jr. who has given silent support for many years.

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¹ All apatites from tin and molybdenum porphyries examined fluoresced in a pale buttery yellow colour.

REFERENCES

- Banks (N. G.), 1976. Halogen contents of igneous minerals as indicators of magmatic evolution of rocks associated with the Ray Porphyry Copper deposit, Arizona. *J. Res. U.S. Geol. Surv.* **4**, 91-117.
- Carson (D. J. T.) and Jambor (J. L.), 1974. Mineralogy, zonal relationships and economic significance of hydrothermal alteration at porphyry copper deposits, Babine Lake Area, British Columbia. *Can. Inst. Min. Metall. Bull.*, Feb. 1-24.
- Sotnikov (V. I.), Nikitina (Y. I.), Lavrent'ev (Y. G.), and Semenov (V. I.), 1971. Some characteristics of accessory apatite from the explosion-breccia zone of the Zhirekenskoye deposit, eastern Transbaikal. *Dokl. akad. nauk. SSSR*, **200**, 193-6.
- Taborsky (F. K.), 1972. Chemismus und Optik der Apatite. *Neues Jahrb. Mineral., Monatsh.* 79-91.

[Manuscript received 21 June 1976, revised 4 November 1976]

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MINERALOGICAL MAGAZINE, JUNE 1977, VOL. 41, PP. 292-4

Petrogenesis of migmatites in the Huntly-Portsoy area, north-east Scotland—a discussion

IN a recent paper on the migmatites of the Huntly-Portsoy area, Ashworth (1976) has advocated an anatectic origin for all the migmatite types found, i.e. at relatively low grades veined 'trondhjemitoid' and 'muscovite-granitoid' migmatites, and at higher grades 'cordierite-granitoid' and 'noritoid' types. However, the results presented from the trondhjemitoid and muscovite-granitoid migmatites appear to be incompatible with the anatectic model, and to indicate an origin by metamorphic segregation via an aqueous fluid phase.

Both metamorphic segregation and anatexis fulfill the requirement that migmatization took