

ATLAS OF ALTERATION

A FIELD AND PETROGRAPHIC GUIDE TO
HYDROTHERMAL ALTERATION MINERALS

EDITORS: A.J.B. THOMPSON AND J.F.H. THOMPSON
MDD SERIES EDITOR: K.P.E. DUNNE

MDRU



Geological Association of Canada
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INTRODUCTION

Secondary alteration of rocks and their contained minerals is common in nature. Alteration reflects the interaction of fluid, typically dominated by water, with rock at temperatures that range from warm (< 100°C) to hot (>500°C). For geologists who wish to study the primary mineralogy and chemistry of rocks, alteration is a nuisance to be avoided. Alteration mineralogy, however, documents the post-formation history of the rock, information that has practical implications. In particular, alteration is ubiquitous in and around hydrothermal mineral deposits. The distribution and mineralogy of this alteration relates to the hydrothermal environment, and hence, the type of mineral deposit. More importantly for mineral exploration, hydrothermal alteration around mineral deposits commonly forms halos that provide a target which is much larger than the deposit itself. The mineralogy and in some environments the chemical composition of the alteration provide an indication of the proximity of mineralization, or in the ideal case, a vector towards mineralization. Interpretation of alteration is, therefore, a routine part of exploration for hydrothermal mineral deposits. Similarly, as a product of geothermal activity, the mineralogy of hydrothermal alteration provides information on reservoir and fluid characteristics, and the evolution of the geothermal system. These data are used in conjunction with other information to evaluate potential geothermal resources.

The aim of this book is to provide basic information on hydrothermal alteration, particularly to assist with field and petrographic recognition. It is not intended to be fully comprehensive either in terms of the types of alteration that are covered, or in terms of the processes responsible for alteration. It provides an introduction to the problem through the minerals that are most common, and a general guide to the ore-forming environment. Interpretation in every case is the responsibility of the user, and this book only introduces the

first step in that process. For students, the information in this book gives an alternative view on the origin of minerals that are commonly encountered in nature. We hope it will help to decipher the 'crud' in thin sections that too often is ignored.

Classification of Alteration

A number of approaches have been taken to the classification of hydrothermal alteration. The terminology has been strongly influenced by the environment of formation, and hence, classifications tend to reflect detailed work on individual types of deposit; examples include porphyry deposits (e.g., Meyer and Hemley, 1967; Rose, 1970; Lowell and Guilbert, 1970; Gustafson and Hunt, 1975; Bean and Titley, 1981), skarn deposits (e.g., Burt, 1974; Einaudi et al., 1981; Meinert, 1987; Kwak, 1994), volcanogenic massive sulphide deposits (e.g., Riverin and Hodgson, 1980; Franklin et al., 1981; Urabe et al., 1983; Lydon, 1984), mesothermal vein deposits (e.g., Roberts, 1987; Colvine et al., 1988; Groves and Foster, 1991; Mueller and Groves, 1991; Hodgson, 1993), and epithermal deposits and geothermal systems (e.g., Browne and Ellis, 1970; Buchanan, 1981; Heald et al., 1987; Reyes, 1990; Henley, 1991; Sillitoe, 1993; Arribas, 1995). In each case, the resultant classification can be extremely useful for interpreting the geometry of the ore system and providing guides to mineralization. Although this type of classification may be internally consistent, reliance on an understanding of the environment may cause problems for the inexperienced, particularly for complex or poorly exposed areas. For example, the term 'phyllic', which is used commonly for sericite-rich alteration associated with porphyry or intrusion-related mineral deposits, is used rarely in the literature to describe similar alteration related to volcanogenic massive sulphide deposits. Obviously, having to know

the environment of formation prior to classifying alteration creates problems and imposes unnecessary genetic constraints on observations.

Alternative approaches to classification, which are summarized by Rose and Burt (1979), are based on the identification of the most important alteration mineral, the mineral assemblage, or the chemical changes that have occurred during alteration. Classification by alteration minerals or mineral assemblages involves field and petrographic observations, supported in some cases by other techniques (X-ray diffraction and scanning electron microscope), and provides the simplest non-genetic approach to alteration. When using alteration mineralogy, however, care must be taken to determine the relationship among minerals prior to assigning them to a single assemblage or interpreting their relationship to other types of alteration. Classifying alteration by chemical changes requires some knowledge of the parent rock and an understanding of the processes and reactions involved in alteration. This approach is particularly useful where progressive changes in mineralogy are observed in a single wallrock unit around a vein, structure, or mineralized zone. Under these circumstances, the mineralogy may be used to document graphically the changing conditions in terms of chemical components or the activity ratios of these components (e.g., Hemley and Jones, 1964; Rose, 1970; Rose and Burt, 1979; Barton et al., 1991; Beane, 1994; Burt, 1994). Several methods are also available to further quantify and classify the chemical changes associated with alteration (e.g., Gresens, 1967; Grant, 1986; MacLean and Krandiotis, 1987; MacLean and Barrett, 1993; Stanley and Madeisky, 1994). These methods require detailed knowledge of the parent rock (composition and/or density) and the identification of immobile or conserved elements. Chemical methods of assessing hydrothermal alteration ("lithogeochemistry") have been applied in mineral exploration, particularly around volcanogenic massive sulphide deposits.

Organization of the Atlas

The Atlas aims to cover some of the most common types of hydrothermal alteration found in different geological environments, particularly those associated with mineral deposits. To avoid the confusion and controversy that surround the terminology for hydrothermal alteration, the organization of the Atlas is based on the simplest mineralogical approach. In most cases, the first step in describing hydrothermal alteration during field work or microscopy is the recognition of a secondary mineral. The Atlas assists in this identification by providing some of the criteria by which the mineral products of hydrothermal alteration are distinguished from their primary counterparts. Information on each mineral also assists in defining alteration assemblages and placing these in their likely environment of formation. As much as possible, cross-referencing to different environments and to the commonly used terminology for mineral assemblages is also provided for each mineral (see Table 1). Several minerals in the Atlas appear more than once because the characteristics of these minerals change with the environment of formation. Checking the characteristics of a mineral against the different descriptions provides a first-order assessment of its environment of formation. Although most minerals are assigned to a single environment on the basis of mineral composition, textures, and coexisting mineral assemblages, less common settings do occur for many minerals and care should be exercised when interpreting the environment from limited mineralogical data.

For each mineral, information is presented under several headings. The first heading, **Characteristics**, describes the mineral and the type of alteration with which it is associated, particularly the features that are observed in outcrop, hand specimen, and thin section. **Related Minerals** provides lists of commonly associated minerals and other accessory minerals that may also be present. The reader should check for the presence of these minerals. Evidence of textural equilibrium among

associated minerals helps define alteration assemblages that relate to the environment of formation more directly than does the presence of an individual mineral. The **Discussion** section provides additional background information on the mode of occurrence and formation of the mineral, and possible relationships to mineralization. The **Discussion** and accompanying **References** for each mineral should be used as a means of further pursuing questions regarding the alteration.

The photos (**Figures**) show some of the important mineralogical and textural characteristics for each mineral. Where possible, four photos are provided to show the range of characteristics from outcrop to hand specimen and thin section. In some cases, the mineral is either always extremely fine-grained, occurs in only minor quantities, or exhibits uniform characteristics. For these minerals, only two photos are used, with the emphasis on identification in thin section.

Interpretation of Alteration Mineralogy

There are several reasons to interpret hydrothermal alteration, particularly for use in mineral and geothermal exploration, and for the evaluation of waste repository sites. The study of hydrothermal alteration may also address research questions such as the physical and chemical conditions responsible for alteration, and the evolution of hydrothermal systems, answers to which often have both theoretical and practical significance. Finally, geologists who are interested only in the primary nature of rocks must be able to interpret the effects of secondary hydrothermal alteration. Regardless of the ultimate reason for studying hydrothermal alteration, a series of steps should be followed in order to make realistic interpretations. These are summarized as follows:

1. Determine what minerals are present in the rock, their mineralogical and textural

characteristics, and evidence for their secondary - hydrothermal - origin.

2. Determine the distribution of the minerals on the outcrop, hand specimen and thin section scales. Ask the following questions: (i) Do the minerals occur as the fill to veins or vugs? (ii) Do they replace specific primary minerals, secondary minerals or clasts (*selective alteration*)? (iii) Do they replace the whole rock and contained minerals in restricted areas, such as the envelopes around veins (*selectively pervasive*)? (iv) Do they replace the whole rock at the outcrop scale (*pervasive*)? (v) Do they occur in specific zones around veins or fractures, and if so, what is the relationship to other zones? In some cases, it may be possible to quantify the intensity of alteration in terms of the extent to which the rock is replaced by hydrothermal minerals. This provides an indication of the permeability in the protolith and the fluid rock ratio during alteration.
3. Define the relationship of the main minerals to each other. In particular, search for evidence of textural equilibrium or replacement. If there is evidence for consistent replacement between minerals, it may help to define paragenetic relationships related to, for example, alteration envelopes surrounding cross-cutting veins.
4. Having defined the hydrothermal mineral assemblages and their timing relationships, their distribution at the map scale should be outlined within the limitations of available outcrop. In reality, geologists start with this step during mapping and the accumulation of field observations. However, it is critical that the interpretations be refined several times as more detailed observations are made, during the above steps.

The Atlas of Alteration assists in the preliminary field observations, helps to highlight questions that need to be addressed during petrography, and begins the process of interpretation. Field and petrographic observations, however, do not always define the mineralogy. Several techniques may be necessary to augment these observations, the most commonly used being X-ray diffraction (XRD) analysis. This technique is necessary to determine the mineralogy of fine-grained alteration, particularly when dominated by clays and phyllosilicates. Typical XRD patterns for the minerals in the Atlas are available through publications of the International Centre for Diffraction Data (ICDD). The chemical composition of the rock can also be interpreted in terms of the major minerals present in the sample, an approach that assists lithochemical analyses (e.g., Barrett and MacLean, 1994; Stanley and Madeisky, 1994). Where unidentified minerals are encountered in small amounts (<1% of the rock) during petrography, a scanning electron microscope (SEM) equipped with energy dispersive facilities may provide the most efficient means of determining the chemical constituents in the mineral. Although extremely useful in the assessment of alteration, these techniques provide data that are restricted to specific samples; there are limitations on the number of samples that can be evaluated, and results may not be extrapolated easily to the map scale. Hand-held shortwave infrared spectrometers are rapidly becoming an important tool for the quick identification of fine-grained alteration minerals in outcrop, hand specimen or drill core, hence allowing more complete alteration maps to be made. As with any bulk technique, however, it is important to recognize that the results should be checked on a suite of samples following steps 1 - 3 above, prior to making a final interpretation.

Many variables affect the mineralogy of hydrothermal alteration. The most important are the composition and mineralogy of the rock, the composition of the hydrothermal fluid - including pH and fO_2 , the fluid to rock

ratio - ultimately whether the system is rock-buffered or fluid-buffered, temperature, and pressure. If the aim of studying hydrothermal alteration is to constrain better some or all of these variables, the detailed field and petrographic observations, summarized in steps 1 - 4, should be augmented by other data. For example, the composition of the hydrothermal minerals should be determined quantitatively by electron microprobe in order to compute shifts in mineral-fluid stability boundaries as a function of mineral composition, usually depicted on activity ratio, activity-temperature, or pH- fO_2 diagrams. Similarly, high quality geochemical analyses, generally involving a combination of methods, are required to determine the material transfer involved in alteration. Finally, fluid inclusion and stable isotope data should be acquired in order to assess the composition and origin of the hydrothermal fluid.

During the study of hydrothermal systems, it is important to evaluate the extent of equilibrium in the alteration assemblage. It is common to find in vugs or veins, minerals that are not necessarily in equilibrium with the minerals that formed by reactions between the hydrothermal fluid and minerals in the wallrock. Similarly, different alteration mineral assemblages may occur with distance from veins, thus demonstrating the progress of reactions and modification of the fluid as it moved into the rock away from the vein or fluid pathway. These observations demonstrate the dynamic and complex nature of hydrothermal systems, but they also provide important information which aids in interpreting the physical and chemical history of a hydrothermal system. During research on hydrothermal systems, the careful assessment of field relations, mineralogical and textural observations, and analytical data are critical to forming a rigorous interpretation. The Atlas of Alteration will assist with some of these steps.

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Table 1: Summary of assemblages of alteration minerals, commonly used terminology, and the environment of formation. Most of the key minerals in this table are dealt with individually in the Atlas; some minerals have multiple entries because their characteristics change in different environments.

| Mineral Assemblage (Key minerals are in bold) | Standard Terminology | Environment of Formation |
|---|---|---|
| <i>Intrusion-related</i> | | |
| biotite (phlogopite), K-feldspar (orthoclase), magnetite , quartz, anhydrite, albite-sodic plagioclase, actinolite, rutile, apatite, sericite, chlorite, epidote | potassic (biotite-rich), K-silicate, biotitic | Generally found in the core of porphyry deposits, particularly those hosted by more mafic intrusions (diorite, monzonite, granodiorite), or mafic to intermediate volcanic/volcanoclastic wallrocks. May form a large peripheral alteration zone in wallrocks (without K-feldspar) that zones out to propylitic alteration. |
| K-feldspar (orthoclase or microcline), quartz, albite, muscovite, anhydrite, epidote | potassic, K-silicate | Found in the core of porphyry systems, particularly hosted by felsic intrusions (granodiorite - quartz monzonite, granite, syenite). |
| albite (sodic plagioclase), actinolite , clinopyroxene (diopside), quartz, magnetite, titanite, chlorite, epidote, scapolite | sodic, sodic-calcic | Occurs with minor mineralization in the deeper (peripheral in some cases) parts of some porphyry systems and is a host to mineralization in porphyry deposits associated with alkaline intrusions. |
| sericite (muscovite-illite), quartz, pyrite, chlorite, hematite, anhydrite | phyllic, sericitic | Commonly forms a peripheral halo around the core of porphyry deposits; it may overprint earlier potassic alteration and may host substantial mineralization. |
| sericite (illite-smectite), chlorite , kaolinite (dickite), montmorillonite, calcite, epidote, pyrite | intermediate argillic, sericite-chlorite-clay (SCC), argillic | Generally forms a structurally controlled to widespread overprint on other types of alteration (potassic) in many porphyry systems; precursor textures are usually preserved. Argillic is often used for texturally destructive alteration that has a similar clay-rich mineralogy, and which occurs in and around structures in the upper parts of porphyry systems. |
| pyrophyllite , quartz , sericite, andalusite, diaspore, corundum, alunite, topaz, tourmaline, dumortierite, pyrite, hematite | advanced argillic | Intense alteration, often in the upper part of porphyry systems, but also form envelopes around pyrite-rich veins that cross-cut other alteration types. |

| Mineral Assemblage (Key minerals are in bold) | Standard Terminology | Environment of Formation |
|--|-----------------------------|---|
| topaz, muscovite , quartz, tourmaline | greisen | Localized high-temperature alteration associated with peraluminous granites and related mineralization. |
| garnet, clinopyroxene, wollastonite , actinolite-tremolite, vesuvianite, epidote | calcic skarn | Generally forms replacement zones in wallrocks (exoskarn - typically in limestone or occasionally mafic to intermediate volcanic rocks), or within intrusions (endoskarn). Andradite and diopside occur in oxidized assemblages related to porphyry Cu systems; grossular and hedenbergite are more common in reduced skarns (Au, W, and Sn). |
| forsterite-diopside or serpentinite-talc , calcite, magnetite, tremolite | magnesium skarn | Magnesium skarns are developed as metasomatic replacements of dolomitic limestone. High-temperature magnesium skarns are characterized by forsterite and diopside and low-temperature magnesium skarns contain serpentinite and talc, both of which occur as retrograde minerals after forsterite and clinopyroxene. |
| calcite, chlorite , hematite, illite-smectite, montmorillonite-nontronite, pyrite | retrograde skarn | Commonly replaces earlier skarn alteration but may also affect adjacent wallrock - limestone. |
| chlorite, epidote, albite, calcite , actinolite, sericite, clay, pyrite | propylitic | Commonly forms the outermost alteration zone at intermediate to deep levels in porphyry systems. In some systems, propylitic alteration is mineralogically zoned from inner actinolite-rich to outer epidote-rich alteration. |
| <i>Intrusion-related – High-sulphidation Epithermal</i> | | |
| quartz , rutile, alunite, native sulphur, barite, hematite, pyrite, jarosite | vuggy silica, vuggy quartz | Typically occurs in structural zones or as replacement bodies in permeable lithologies, usually in the core of zones of advanced argillic alteration. This extreme form of leaching can occur in the upper parts of porphyry systems (telescoped) but is more common at higher (epithermal) levels. |

| Mineral Assemblage (Key minerals are in bold) | Standard Terminology | Environment of Formation |
|--|-----------------------------------|--|
| quartz , chalcedony, alunite, barite, pyrite, hematite | silicic | Represents the addition of silica to the rock, resulting in replacement or, more commonly, the fill to vugs created during intense leaching. Silicification is common in high-sulphidation systems at porphyry to epithermal depths. It is sometimes confused with intense quartz stockwork veining at the top of some porphyry deposits. |
| quartz, kaolinite/dickite, alunite , diaspore, pyrophyllite, rutile, zunyite, alumino phosphate-sulphates, native sulphur, pyrite, hematite | advanced argillic - acid sulphate | Forms widespread zones in the upper parts of some porphyry systems (lithocap); also as more restricted alteration halos around high-sulphidation epithermal deposits. |
| kaolinite/dickite, montmorillonite, illite-smectite , quartz, pyrite | argillic, intermediate argillic | May be present as a zone of alteration between advanced argillic and propylitic alteration, particularly in the high-sulphidation epithermal setting. |
| calcite, chlorite, epidote, albite , sericite, clay, pyrite | propylitic | May occur as an outer regionally extensive alteration zone in systems at moderate depths (>500m). |
| <i>Low-sulphidation Epithermal – Geothermal</i> | | |
| quartz, chalcedony, opal , pyrite, hematite | silicic | Pervasive replacement of the rock by silica minerals. Occurs in some epithermal and geothermal systems as wallrock alteration around fractures and veins or within permeable zones, usually at relatively shallow levels. Also forms blanket-like zones of replacement at the water table below steam-heated advanced argillic alteration. Stratiform replacement silicification may be mistaken for sinter. |
| orthoclase (“adularia”) , quartz, sericite-illite, pyrite | “adularia” | Varies from wallrock alteration around veins, fractures and permeable zones to selective replacement of plagioclase in alteration envelopes. Common at shallow to intermediate depths in epithermal or geothermal systems; may be associated with boiling. Pervasive replacement by “adularia” is difficult to distinguish from silicification. |

| Mineral Assemblage (Key minerals are in bold) | Standard Terminology | Environment of Formation |
|---|-----------------------------------|---|
| sericite (muscovite), illite-smectite , montmorillonite, kaolinite, quartz, calcite, dolomite, pyrite | sericitic, argillic | Occurs as wallrock alteration around veins and replacement zones in permeable lithologies. May exhibit progression from sericite to mixed layer clays with increasing distance from mineralized (upflow) zones. Blanket-like carbonate-bearing alteration zones in the upper part of some geothermal/epithermal systems may reflect the condensation of gases (CO ₂) from deeper boiling zones. Carbonate may also be important in some deeper base metal-rich systems. |
| kaolinite , alunite , crystalite (opal, chalcedony), native sulphur, jarosite, pyrite | advanced argillic - acid-sulphate | Forms extensive areas of alteration above the water (paleowater) table related to the condensation and oxidation of gases (H ₂ S). Associated with mud pools, fumaroles and deposits of native sulphur. |
| quartz , calcite | silica-carbonate | Replacement of ultramafic rocks in the shallow parts (low temperature) of geothermal systems. |
| calcite , epidote , wairakite , chlorite, albite, illite-smectite, montmorillonite, pyrite | propylitic, zeolitic alteration | Regionally extensive alteration around epithermal and geothermal systems. Mineralogical changes from zeolite-rich to propylitic assemblages reflect increasing depth and temperature. The concentration of CO ₂ also influences the stability of zeolites and the relative importance of calcite versus epidote. |
| Mesothermal | | |
| calcite , ankerite , dolomite, quartz, muscovite (Cr-/V-rich), chlorite, pyrite, pyrrhotite | carbonate | Wallrock alteration in and around veins or shear zones, and extensive replacement of ultramafic to mafic rocks. Carbonate-rich alteration may be regionally extensive and is not always related to mineralization. |
| chlorite , muscovite, quartz, actinolite, pyrite, pyrrhotite | chloritic | Wallrock alteration in and around veins and shear zones, particularly in mafic volcanic and volcanoclastic sedimentary rocks. |
| biotite , chlorite, quartz, pyrite, pyrrhotite | biotitic | Wallrock alteration in and around veins and shear zones, particularly in sedimentary rocks. |

| Mineral Assemblage (Key minerals are in bold) | Standard Terminology | Environment of Formation |
|--|----------------------|---|
| <i>Sediment-hosted gold</i> | | |
| quartz , pyrite, hematite | jasperoid | Complete replacement of limestone, and occasionally other rock types, by fine-grained quartz; often associated with brecciation. Jasperoids can form as regionally extensive zones, as small bodies related to sediment-hosted Au deposits ('Carlin-type'), and as the upper or outer alteration zones associated with intrusion-related skarn/sulphide replacement bodies. Depth of formation is probably moderate (>2 km - 'mesothermal'), although shallower zones of jasperoid may form; fluids may be metamorphogenic (classic mesothermal), connate, or magmatic. |
| <i>Volcanogenic massive sulphide</i> | | |
| sericite, quartz , pyrite, chlorite, andalusite, chloritoid | sericitic | Pervasive replacement of rocks in the footwall below massive sulphide lenses; concentrated in stockwork feeder zones but may be laterally extensive both deeper in the footwall and extending into the hanging wall in some deposits. Most common in intermediate to felsic volcanic rocks but may also replace the more mafic units in lower temperature systems. Andalusite and chloritoid occur in metamorphosed alteration zones. |
| chlorite , quartz, sericite, pyrite, cordierite, biotite | chloritic | Pervasive replacement of rocks in the footwall below massive sulphide deposits. Fe-rich chlorite occurs in the core of stockwork feeder zones in mafic footwall sequences (e.g. Archean deposits) whereas Mg-rich chlorite has a more erratic distribution, generally around the periphery or upper parts of stockwork zones. Cordierite +/- biotite is common in metamorphosed Mg-Fe-rich alteration zones. |

| Mineral Assemblage (Key minerals are in bold) | Standard Terminology | Environment of Formation |
|--|-----------------------------|---|
| quartz , pyrite, sericite, K-feldspar | silicic | Pervasive replacement of rocks in the footwall below massive sulphide deposits; particularly common in permeable siliceous ash-rich beds, where the silicified rock may be mistaken for cherts (chemical sediments). Also occurs as wallrock alteration in some quartz vein stockwork zones. |
| dolomite , siderite , ankerite, calcite, quartz, sericite, chlorite, pyrite | carbonate | Usually occurs as disseminated alteration in footwall sequences, commonly over extensive lateral and stratigraphic intervals. The composition of carbonates may change with distance from ore zones. |
| <i>Sediment-hosted massive sulphide</i> | | |
| quartz , muscovite, siderite, dolomite, garnet, celsian, pyrrhotite, pyrite, barite | silicic | Pervasive replacement of footwall strata below massive sulphide; also of baritic facies of the sulphide body and less commonly in the hanging wall. Well developed within calcareous strata but more cryptic in siliciclastic strata. Can be mistaken for siliceous shale or chert. Occurs as "garnet quartzite" in high grade metamorphic rocks. |
| tourmaline , muscovite, quartz, pyrrhotite | tourmalinite | Pervasive replacement of footwall strata below massive sulphide. Associated with abundant disseminated sulphide in shallow footwall. Limited to feldspathic strata. |
| ankerite , siderite , calcite , quartz , muscovite, pyrrhotite | carbonate | Disseminated carbonate, often as euhedral crystals, in the shallow footwall below massive sulphide and baritic facies. Disseminated ankerite/siderite can be very extensive within calcareous strata along major structures. |
| sericite , chlorite , quartz , pyrrhotite, pyrite, albite | sericitic | Pervasive replacement of strata in broad halo around massive sulphide deposit; forms discordant bodies in structurally controlled vent areas. Occurs as potassium feldspar in high grade metamorphic rocks. Best developed in feldspathic strata. |
| albite , chlorite , muscovite , biotite | albitic | Pervasive replacement of strata, and massive sulphide; more typically along structures and around mafic intrusions. Limited to feldspathic strata. |

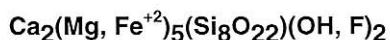
HYDROTHERMAL MINERALS

On the following pages, forty-nine descriptions of common hydrothermal minerals are set out with accompanying photographic figures. Minerals are identified on some of the photographs, using the standard abbreviations of Kretz (1983), *American Mineralogist*, v. 68, p. 277-279.

The following abbreviations are used with reference to Figures for each mineral in the Atlas:

| | |
|-----|--|
| OC | Outcrop |
| HS | Hand specimen |
| DC | Drill core |
| TS | Thin section (includes polished thin sections) |
| PPL | Plane polarized light |
| XPL | Crossed polars |
| RL | Reflected light |
| FOV | Field of view – defined for the long dimension of photomicrographs and some hand specimens |

ACTINOLITE



Environment: *Intrusion-related*

Alteration: *Propylitic, Potassic, Sodic-calcic*

Characteristics

Hydrothermal actinolite occurs in veins and as selective or pervasive replacement, commonly of mafic minerals (phenocrysts in volcanic and intrusive rocks). Actinolite may be altered to chlorite.

Hand Specimen: Actinolite typically occurs as dark green fibrous to columnar crystals, particularly in veins or cavities. Replacement of mafic minerals by fine-grained secondary actinolite is suggested by the green colour and the irregular mottled appearance in the original mineral.

Thin Section: Alteration actinolite is pleochroic, ranging from colourless to very pale yellow to pale green. Crystals show a variety of forms including tabular, columnar, fibrous, bladed and rhombic habits, with the latter exhibiting amphibole cleavage. Alteration textures range from weak partial, sometimes selective, alteration of pre-existing minerals, to pervasive replacement. Partial to total infilling of veins and cavities also occurs.

Related Minerals

Associated: albite, biotite, calcite, chlorite, dolomite, diopside, epidote, K-feldspar, pyrite, pyrrhotite, quartz, sericite

Accessory: apatite, rutile, titanite

Discussion

Actinolite occurs as an alteration mineral in the core of some porphyry Cu deposits, where it may be associated with potassic alteration and mineralization. It also occurs in sodic-calcic alteration, which may form by the interaction of external fluids with magmatic-hydrothermal systems, and in calcic skarn alteration, particularly endoskarn. In some systems, actinolite occupies an inner (higher temperature) zone of propylitic alteration, succeeded outward by epidote-chlorite-dominated assemblages. In active geothermal systems hosted by intermediate to mafic volcanic rocks, actinolite is present at temperatures >280-300°C and is characteristic of alteration proximal to intrusive bodies.

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Figures

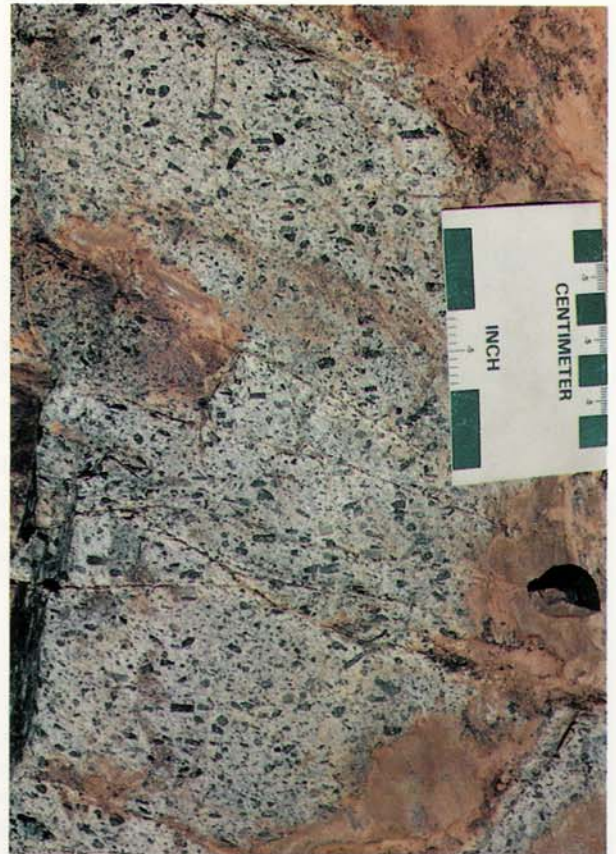
- 1.1 OC. Irregular green actinolite veins and infilled cavities in brecciated monzonite altered to pervasive pink K-feldspar. Mount Polley alkaline porphyry Cu-Au deposit, central British Columbia.
- 1.2 OC. Hornblende-plagioclase porphyry; hornblende replaced by green actinolite, with alteration of plagioclase and matrix to albite, carbonate, and pyrite. Red Mountain Au prospect northwestern British Columbia.
- 1.3. TS (PPL). Cavity infill showing prismatic crystals of actinolite occurring together with chlorite, from a prospect in Indonesia. FOV = 1.1 mm.
- 1.4. TS (XPL). Same as above. FOV = 1.1 mm.

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1.1



1.2



1.3



1.4

ALBITE



Environment: *Intrusion-related*

Alteration: *Propylitic, Sodic, Sodic-Calcic*

Characteristics

Albite alteration is generally distributed along fracture and vein envelopes, typically becoming more pervasive toward the centre of the zone of alteration, where it may form a dense massive rock.

Hand Specimen: Albite alteration varies from white to pink or reddish with increasing fine hematite in the albite. Pale green colours indicate the presence of fine sericite, whereas a chalky white colour suggests secondary clay.

Thin Section: In thin section, secondary albite forms a variety of textures with increasing intensity of alteration ranging from 1) clear tabular crystals (typically An_{10}) that are difficult to distinguish from unaltered plagioclase except by extinction angles, to 2) "patchwork" albite (An_{5-10}), to 3) "checkerboard" or "chessboard" albite (An_{0-10}), to "irregular" albite ($\text{An}_{0-}\text{Ab}_{100} - \text{Ab}_{90-}\text{Or}_{10}$) to untwinned "anoralbite" ($\text{Ab}_{90-}\text{Or}_{10} - \text{Ab}_{70-}\text{Or}_{30}$). After twinning has disappeared at about Or_{30} , the hydrothermal alkali feldspar is virtually indistinguishable from secondary K-feldspar except by macroscopic staining tests.

Related Minerals

Associated: actinolite, calcite, diopside, epidote, quartz, sericite

Accessory: clay, hematite

Discussion

Albite is a common alteration mineral in some porphyry systems, where it may occur in deep or peripheral zones (e.g. Yerington, Nevada), central zones (e.g. Island Copper, British Columbia), or associated with mineralization in alkaline porphyries (e.g. Ajax, British Columbia). The first three stages of alkali feldspar development (clear, patchwork and checkerboard albite) occur as weak to moderate replacements of primary plagioclase in the core of weakly mineralized systems, or at the fringes of more strongly mineralized systems. The fourth stage (irregular albite or "anoralbite") is found as vein envelopes in weakly mineralized systems, but becomes increasingly pervasive toward the centres of deposits, where it may be transitional to true potassic alteration. Typically, An content decreases or Or content increases with increasing intensity of alteration.

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Figures

- 2.1 OC. Fracture-controlled and pervasive albite alteration of diorite in the Ajax West alkaline porphyry deposit, British Columbia. Dark mineral is diopside replacement of mafic minerals. Chalcopyrite fills fractures.
- 2.2 OC. Pervasive albitic alteration (pale, lower left) controlled by fractures. Outcrop in the Ajax West pit, British Columbia.
- 2.3 TS (XPL). Secondary albite surrounding chalcopyrite-filled fracture with intergrown epidote and diopside. Ajax West deposit, British Columbia. FOV = 5 mm.
- 2.4 TS (XPL). Close-up of checkerboard twinning in secondary albite, Mount Polley alkaline porphyry Cu-Au deposit, British Columbia. FOV = 1.25 mm.

Submitted by:

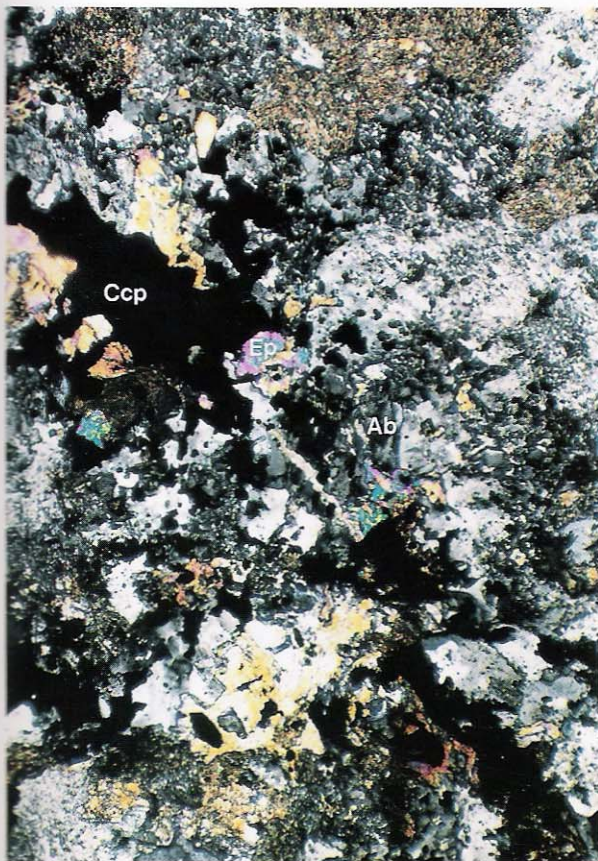
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2.1



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2.4

ALBITE

NaAlSi₃O₈

Environment: *Sediment-hosted massive sulphide*

Alteration: *Albitite*

Characteristics

Albitized outcrops are fine-grained, white to buff in colour, hard, dense and show destruction of texture with increasing intensity of alteration. Albitization may be fracture-controlled, grading to complete replacement of host lithologies. Good examples occur at the Sullivan Pb-Zn sedimentary-exhalative deposit, British Columbia.

Hand Specimen: Mesoscale textures are either laminated (relict primary bedding) to massive, or fractured to brecciated within a chlorite-pyrite matrix. Colour varies from buff to white with increasing intensity. Intense albitization is difficult to distinguish from silicification.

Thin Section: In thin section, albitization is typically texture-destructive, forming a massive replacement of 0.1 to 1 mm subhedral, simply twinned, albite crystals generally with interstitial to fracture-controlled chlorite (clinochlore). Incipient; fracture-controlled, fine (0.05 mm) albite crystals interstitial to detrital quartz are typical of weakly albitized rock.

Related Minerals

Associated: biotite, chlorite, pyrite, titanite

Accessory: allanite, carbonate, quartz, sericite

Discussion

The textures noted with the occurrence of albite in porphyry-related systems are not typically developed with sedimentary hosted deposits. The Sullivan deposit and nearby area, British Columbia, serve as the type example of this alteration. At Sullivan, simple twinned albite with composition near An_{0.5} is typical; the lack of potassium in the alteration fluid may preclude the development of untwinned "irregular albite" or "anoralbite". The timing of albitization is generally earlier than chlorite in albitite, although early chlorite-pyrrhotite occurs at the base of the Sullivan orebody. Association of albitites with sill contacts indicates a close relation to sill emplacement; the relationship to ore-forming processes is not clear.

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Figures

- 3.1 OC. Interbedded albitite (white) and chlorite-pyrite altered argillite (grey-black) in the hanging wall of the Sullivan mine, British Columbia, illustrating bedding-controlled replacement of sandy beds. FOV = 2 m. (Courtesy Cominco Ltd.).
- 3.2 DC. (left) Breccia of albitite fragments (white) in a matrix of dark green chlorite; base of eastern hanging wall albitite zone, Sullivan Mine, British Columbia. (right) Laminated sandstone altered to massive albite, partly obscuring bedding, cut by chlorite-pyrite veinlets.
- 3.3 OC. Albitite cut by a grey network of dolomite-Fe chlorite-pyrite-minor quartz-titanite fractures, Sullivan mine, British Columbia.
- 3.4 TS (PPL). Subhedral 0.1 mm albite and interstitial chlorite, cut by pyrite-chlorite fractures; detrital quartz has been completely replaced. FOV = 1.1 mm.

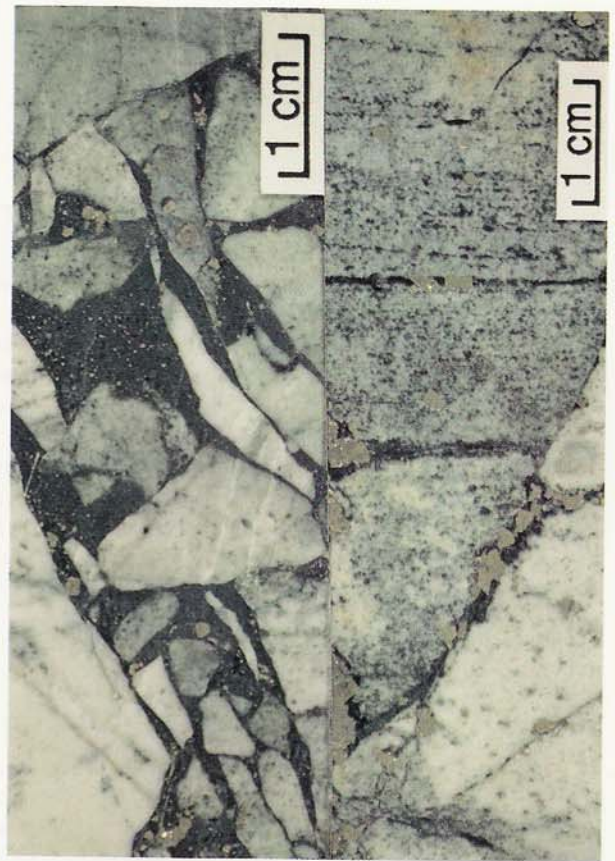
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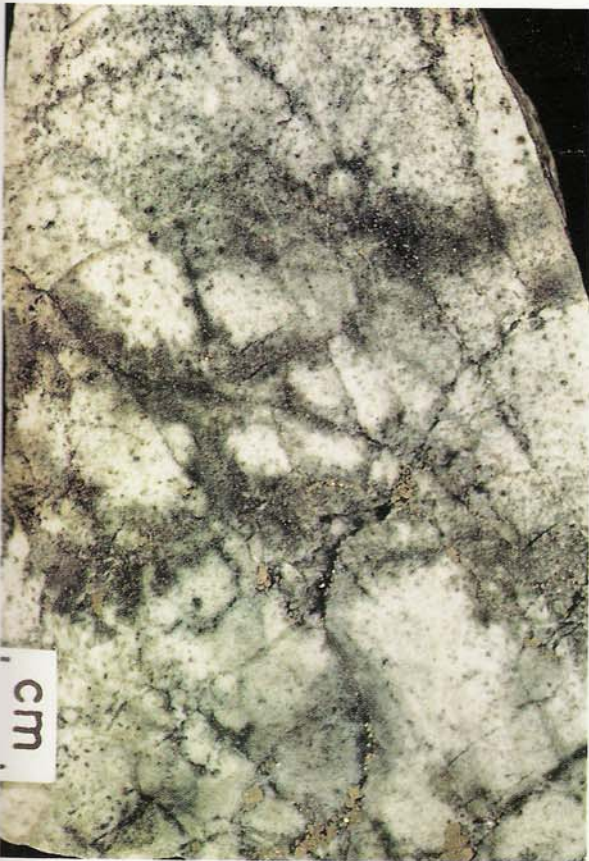
Robert J.W. Turner, Geological Survey of Canada, Vancouver, British Columbia



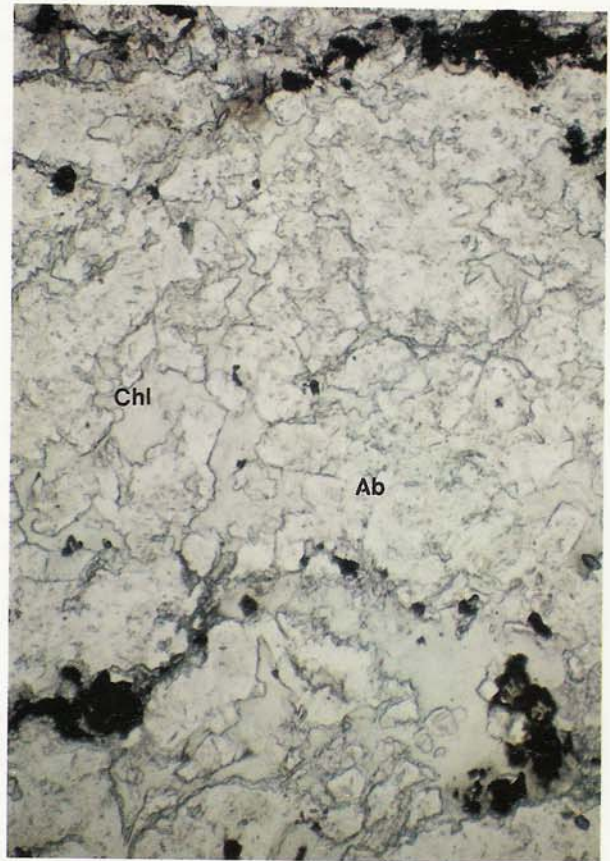
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ALUNITE



Environment: *Intrusion-related, Epithermal*

Alteration: *Advanced Argillic*

Characteristics

Outcrops containing alunite-bearing hypogene alteration are typically pink to tan in colour, due in part to the oxidation of associated pyrite. Hydrothermal breccias are a common feature and silicification, or vuggy silica/quartz, is present either in the outcrop or in adjacent zones.

Hand Specimen: Hypogene alunite may be white, pink, or tan. Disseminated, coarse-grained alunite gives a sparkly appearance to the rock. Frequently, feldspar phenocrysts are replaced by alunite, producing white pseudomorphs. Veins dominated by coarse alunite crystals, up to 2 cm in length, occur in some districts.

Thin Section: Alunite related to magmatic-hydrothermal environments is generally tabular to thin tabular, ranging in length from 10 μm to 200 μm and may be zoned. Birefringence ranges from 0.01 to 0.02, typically exhibiting first order greys, with occasional blue and orange. Natroalunite has similar optical properties to alunite. Textures include replacement of feldspars by alunite and alunite disseminated in microgranular quartz.

Related Minerals

Associated: aluminum phosphate-sulphates, dickite, kaolinite, pyrite, pyrophyllite, quartz

Accessory: andalusite, diaspore, jarosite, native sulphur, rutile, sericite/illite, topaz, tourmaline, zunyite

Discussion

Alunite is a significant mineral in advanced argillic alteration, and is associated with a variety of types of mineralized systems that include porphyry $\text{Cu}\pm\text{Au}\pm\text{Mo}$ and high-sulphidation epithermal precious metal deposits. In this environment, the disproportionation of magmatic SO_2 in the presence of water generates H_2S and H_2SO_4 , which together with HCl react with rocks to form extensive zones of alunite-bearing advanced argillic alteration. High-sulphidation-type gold-silver mineralization is commonly associated directly with zones containing quartz-alunite \pm pyrite \pm enargite, and often occupies relatively small parts of the much larger zones of advanced argillic alteration. Similar alteration dominates the upper parts of many strato-volcanoes and is prevalent in geothermal systems associated with acid-sulphate waters in andesitic volcanic terranes.

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Figures

- 4.1 HS. Alunite is disseminated throughout the sample and is concentrated in patches that replaced feldspars (white). Aldebaran area, Maricunga district, Chile.
- 4.2 HS. Pervasive alunite (replaced feldspars) with minor sulphur in rocks with early porphyry-related quartz veins. Advanced argillic alteration associated with the Marte Au porphyry, Maricunga district, Chile.
- 4.3 TS (XPL). Tabular, zoned alunite crystals partially replaced (rimmed) by supergene jarosite. Esperanza area, Maricunga district, Chile. FOV = 2.1 mm.
- 4.4 TS (XPL). Tabular alunite infilling vug and finer-grained crystals with quartz in the groundmass. Esperanza area, Maricunga district, Chile. FOV = 2.1 mm.

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4.1



4.2



4.3



4.4

ALUNITE



Environment: Epithermal

Alteration: Advanced Argillic

Characteristics

Outcrops of steam-heated alunite-bearing alteration are commonly white to tan in colour, and may be massive to extremely porous. The outcrops occur in zones above the current water or paleowater table, and typically have a blanket shape (parallel to the water table).

Hand Specimen: Steam-heated alunite is generally white, or tan. Rocks containing a high proportion of massive fine-grained alunite have a porcelaneous texture.

Thin Section: Alunite formed in the near-surface environment is typically extremely fine-grained. In section it is commonly <10 μm in size, and may be cryptocrystalline. Intermixed kaolinite may give a dark, mottled appearance to the section. Rare patches of slightly coarser-grained alunite may occur.

Related Minerals

Associated: cristobalite, kaolinite, opal, pyrite, quartz

Accessory: aluminum phosphate-sulphates, jarosite, native sulphur

Discussion

Steam-heated advanced argillic or acid-leach alteration forms in the near-surface above the water table (vadose zone) from the condensation and oxidation of H_2S , and reaction of the resultant H_2SO_4 with rocks. The H_2S is transported in vapour released from boiling hydrothermal fluids below the water table. The zone of advanced argillic alteration commonly forms a blanket characterized by alunite-cristobalite \pm kaolinite \pm native sulphur assemblages. The deep fluids in these hydrothermal systems may be chloride waters near neutral in pH, possibly associated with low-sulphidation precious metal mineralization, or may be low-pH acid-sulphate waters possibly related to high-sulphidation deposits. In either case, steam-heated advanced argillic alteration may descend onto deeper alteration thus resulting in complex overprinting relationships in partly eroded systems.

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Figures

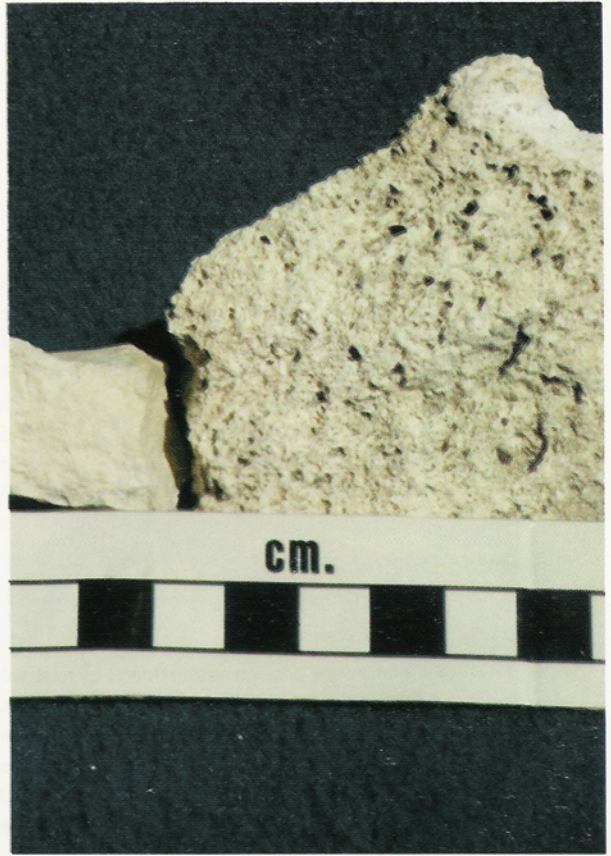
- 5.1 OC. Fine grained mixture of alunite, kaolinite and cristobalite alteration surrounding a recent fumarolic vent in the White Mountain area, southern Utah. Sulphur coats the surface of the rock.
- 5.2 HS. White porous and massive alunite-quartz samples from the NG alunite deposit, Utah. The porous sample is dominated by residual quartz, and contains minor alunite.
- 5.3 TS (XPL). Cryptocrystalline mixture of cristobalite, alunite, and kaolinite from the White Mountain vent zone (same as Figure 5.1). FOV = 1 mm.
- 5.4 TS (XPL). Primary quartz phenocryst set in finer-grained mixture of alunite \pm kaolinite. White Mountain area, southern Utah. FOV = 1 mm.

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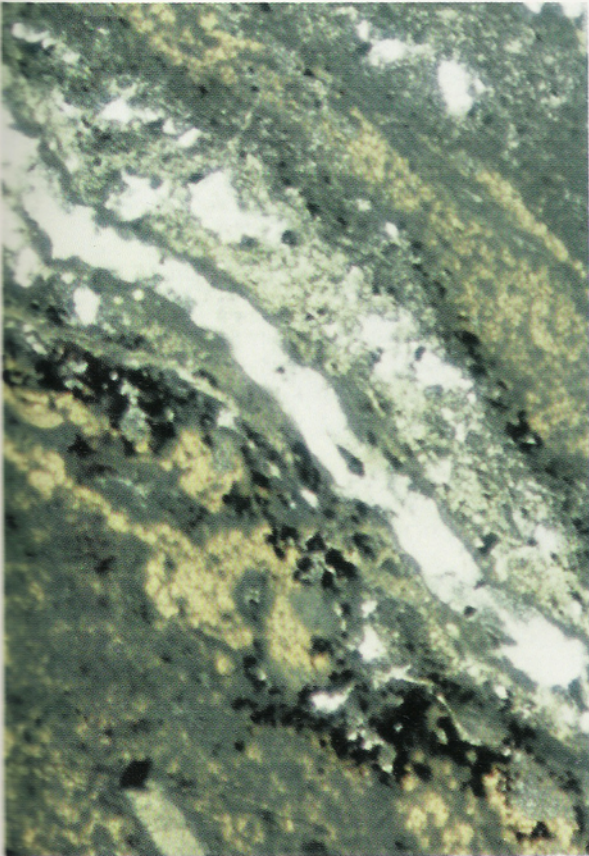
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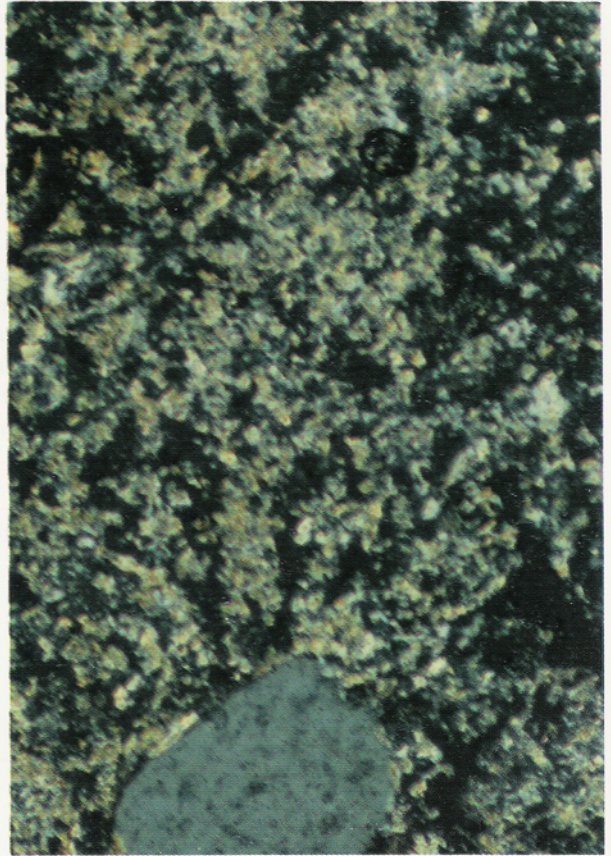
5.1



5.2



5.3



5.4

ANDALUSITE

Al_2SiO_5

Environment: *Intrusion-related*

Alteration: *Advanced Argillic*

Characteristics

Andalusite occurs in some advanced argillic alteration mineral assemblages, typically as replacement of feldspars, but also disseminated in the envelopes around veins.

Hand Specimen: Hydrothermal andalusite is usually fine-grained and is virtually impossible to identify in hand specimen. It may be present in advanced argillic alteration, particularly if there is evidence of high temperature mineral assemblages and moderate grain sizes (sugary textures).

Thin Section: Andalusite forms aggregates after feldspar or occurs disseminated within the groundmass. It is commonly associated with pyrophyllite, but the two minerals are rarely in textural equilibrium. In high temperature assemblages, andalusite may coexist with corundum. In some cases, andalusite occurs with minerals more typical of potassic alteration (sericite, K-feldspar, and biotite).

Related Minerals

Associated: diaspore, pyrite, pyrophyllite, quartz

Accessory: biotite, corundum, K-feldspar, sericite

Discussion

Andalusite is a characteristic mineral of relatively high-temperature advanced argillic alteration in the upper parts of some porphyry and intrusion-related deposits. In some systems, andalusite spans a transition from potassic to advanced argillic alteration, implying formation from fluids moderately low to very low in pH. Andalusite is restricted commonly to veins and vein envelopes associated with a particular (usually late) paragenetic event that may overprint earlier alteration assemblages. At higher levels, andalusite may be part of pervasive advanced argillic alteration, associated with the base of porphyry-related alteration lithocaps.

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Figures

- 6.1 DC. Andalusite bearing samples from the Frieda River porphyry Cu-Au deposit, Papua New Guinea. Porphyritic textures of the fine grained dioritic protolith are poorly preserved.
- 6.2 TS (XPL). Sample shown in Fig. 6.1. Aggregates of andalusite (low birefringence), pyrophyllite (fine-grained, moderate birefringence) and diaspore (high birefringence) in quartz-pyrite matrix. FOV = 1.25 mm.
- 6.3 TS (PPL). Sample shown in Fig. 6.1. Andalusite (centre) occurs as an aggregate after feldspar. FOV = 1.25 mm.
- 6.4 TS (XPL) As above. The sample also contains aggregates of fine pyrophyllite (moderate birefringence), diaspore (high birefringence), quartz and pyrite. FOV = 1.25 mm.

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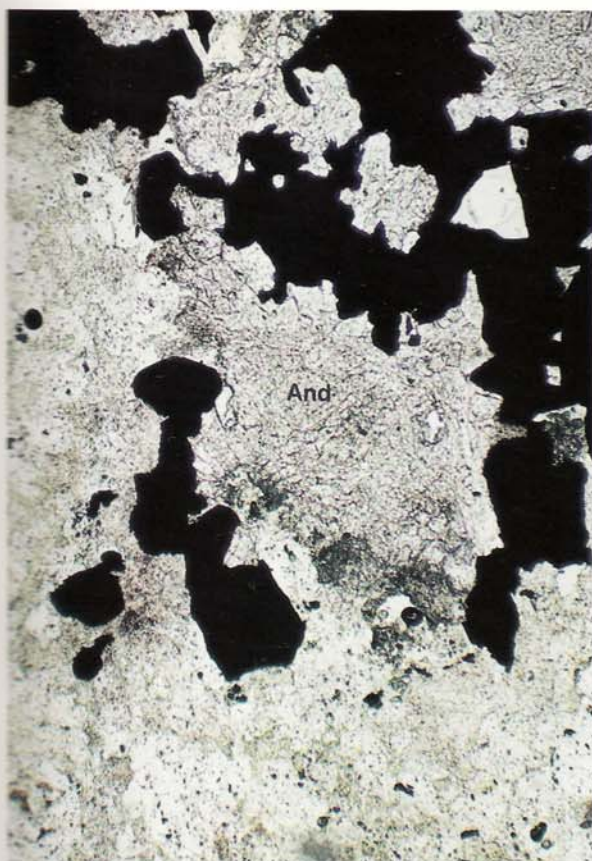
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6.1



6.2



6.3



6.4

ANHYDRITE

CaSO₄

Environment: *Intrusion-related*

Alteration: *Potassic*

Characteristics

Hydrothermal anhydrite typically occurs in veins or vugs, and/or as a replacement mineral in the wallrock. Close to surface, anhydrite is usually replaced by gypsum or may be removed completely, resulting in a highly fractured and friable rock.

Hand Sample: Veins or vugs filled by anhydrite are characterized by fine-grained white aggregates or rarely by transparent, blue or violet crystals. Gypsum is extremely soft, replaces anhydrite and fills late fractures.

Thin Section: In veins or vugs, anhydrite can be identified by two clear (pinacoidal) cleavages and moderate birefringence. In the matrix, care must be taken to distinguish fine-grained anhydrite from sericite. Gypsum typically consists of grey to white and brown fibrous aggregates with low birefringence.

Related Minerals

Associated: biotite, carbonate, K-feldspar, quartz, sericite

Accessory: apatite, bornite, chalcocopyrite, chlorite, garnet, pyrite, rutile

Discussion

Anhydrite is a common alteration mineral in some porphyry copper deposits, particularly those associated with diorite to granodiorite intrusions. It usually occurs in potassic alteration but may also be present in sericitic and advanced argillic alteration. Anhydrite veins may contain mineralization or may be barren. In high-temperature (>300°C) environments, anhydrite precipitates from cooling hydrothermal fluids, but it may also precipitate from heated seawater because of its retrograde solubility. Therefore, anhydrite also occurs in and above some volcanogenic massive sulphide deposits, and in geothermal systems which involve seawater. Hydration of anhydrite to form gypsum, and complete dissolution of gypsum and anhydrite near surface are common.

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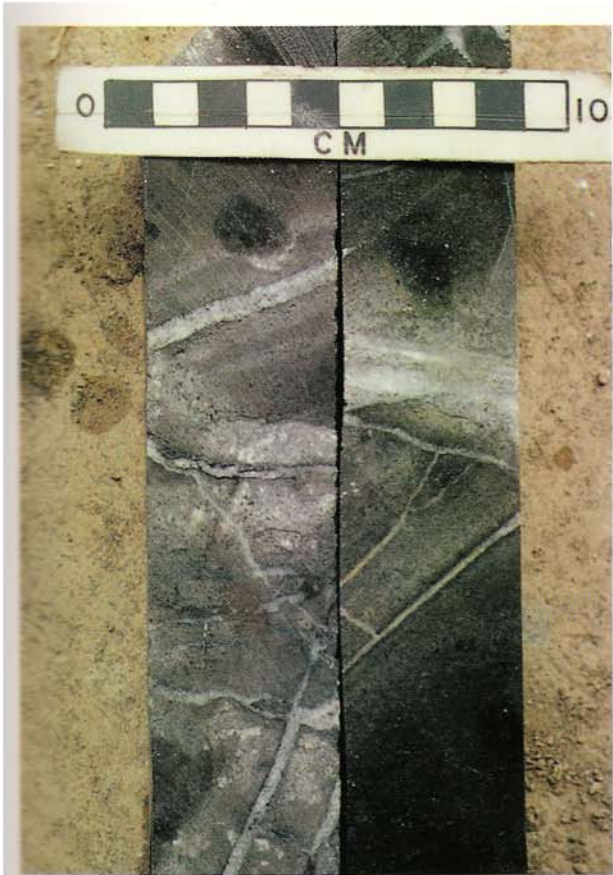
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Figures

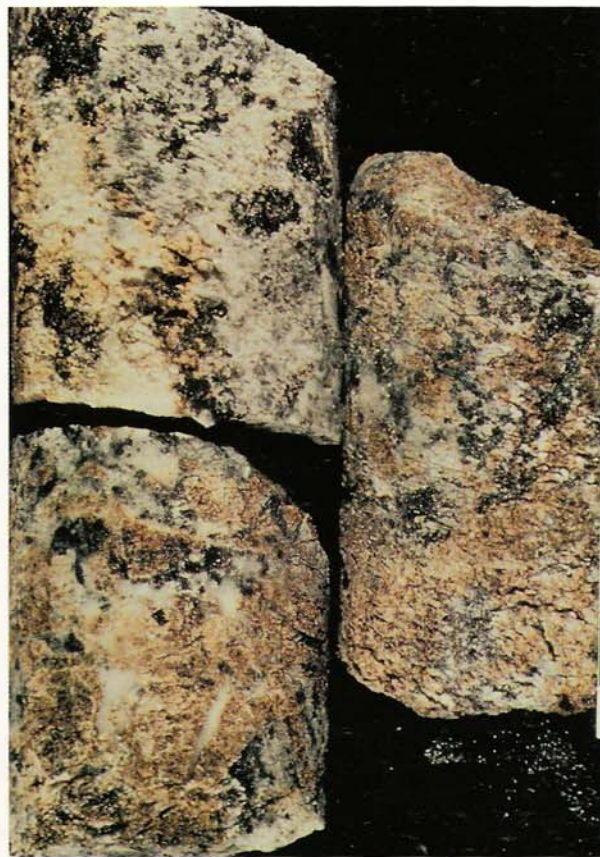
- 7.1 DC. Anhydrite veins in fine-grained monzonite altered to biotite and K-feldspar. Dark biotite envelopes occur around some anhydrite veins. From below the Ladolam gold deposit, Lihir Island, Papua New Guinea.
- 7.2 DC. Anhydrite filling of cavities and veins between coarse garnet and biotite. The anhydrite is partly converted to gypsum, resulting in the fractured and friable texture. Galore Creek, northwestern British Columbia. FOV = 14cm.
- 7.3 TS (XPL). Anhydrite infilling space between well-zoned, weakly anisotropic garnet. Galore Creek, northwestern British Columbia. FOV = 1.25 mm.
- 7.4 TS (XPL). Gypsum vein in K-feldspar altered rock with large primary apatite (centre of photograph). Gypsum also occurs in the matrix and may have crystallized during the conversion of anhydrite to gypsum. Galore Creek, northwestern British Columbia. FOV = 3 mm.

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7.1



7.2



7.3



7.4

APATITE

$\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$

Environment: *Intrusion-related*

Alteration: *Potassic, Magnetite-apatite-actinolite*

Characteristics

Apatite which occurs with magnetite and actinolite (Kiruna-type) occurs as disseminated crystals, veins, and more commonly within magnetite or magnetite-actinolite veins, stringers, pods and breccias. Associated minerals vary with host-rock composition. In porphyry deposits, apatite is visible rarely at the outcrop scale.

Hand Specimen: Apatite forms anhedral to euhedral prismatic crystals, up to several centimetres in diameter. Colours typically range from pink to mauve, but are also grey, red-brown, green and yellow-green.

Thin Section: Apatite is hexagonal in cross-section and is generally colourless to grey (c-axis sections). Irregular fractures and partings are common. Disseminated elongate prismatic crystals commonly occur in pervasively altered rocks. Inclusions of apatite and interstitial apatite are found in magnetite and actinolite veins and pods.

Related Minerals

Associated: actinolite, biotite, diopside, hematite, K-feldspar, magnetite

Accessory: albite, anhydrite, barite, calcite, chalcopyrite, chlorite, epidote, fluorite, hornblende, monazite, pyrite, quartz, rutile, sericite, scapolite, talc, titanite, tremolite, zircon

Discussion

Apatite is a common secondary mineral in high-temperature hydrothermal alteration zones. It occurs in potassic alteration in porphyry systems, particularly in those associated with more mafic or alkaline intrusions. Apatite also occurs as part of zoned alteration systems related to silicic to intermediate intrusive rocks, typically in cratonic or continental-arc environments. Overlapping feldspar (inner), magnetite-apatite-actinolite and sulphide (pyrite-chalcopyrite) (outer) zones occur above intrusive igneous rocks. Magnetite zones may be economic deposits of iron, with associated copper and/or uranium and REE mineralization. Apatite in this environment typically is fluorapatite. Rare earth elements substitute for Ca, typically about 0.5 to 0.8%. Apatite-bearing magnetite lenses have been interpreted as the crystallization products of magmas, but associated hydrothermal alteration suggests that many are hydrothermal in origin. Regardless, stable isotopic analyses and fluid inclusion studies of alteration minerals indicate the importance of magmatic fluids and temperatures in the range of 200-400°C.

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Figures

- 8.1 HS. Apatite in magnetite-actinolite-epidote-albite pod, from Port Radium, Northwest Territories. FOV = 8 cm.
- 8.2 TS (XPL). Coarse-grained apatite intergrown with pyroxene from the El Laco Fe deposit, Chile. Fluid inclusions occur in the pyroxene and apatite. Note spiraling inclusions in the pyroxene. FOV = 1.5 mm.
- 8.3 TS (PPL). Fine secondary apatite needles associated with K-feldspar, magnetite and biotite. Galore Creek, porphyry Cu-Au deposit, northwestern British Columbia. FOV = 1.25 mm.
- 8.4 TS (PPL). Cluster of secondary apatite and fine biotite. The apatite occurs in a zone of K-feldspar adjacent to an anhydrite vein. Galore Creek, northwestern British Columbia. FOV = 0.6 mm.

Submitted by:

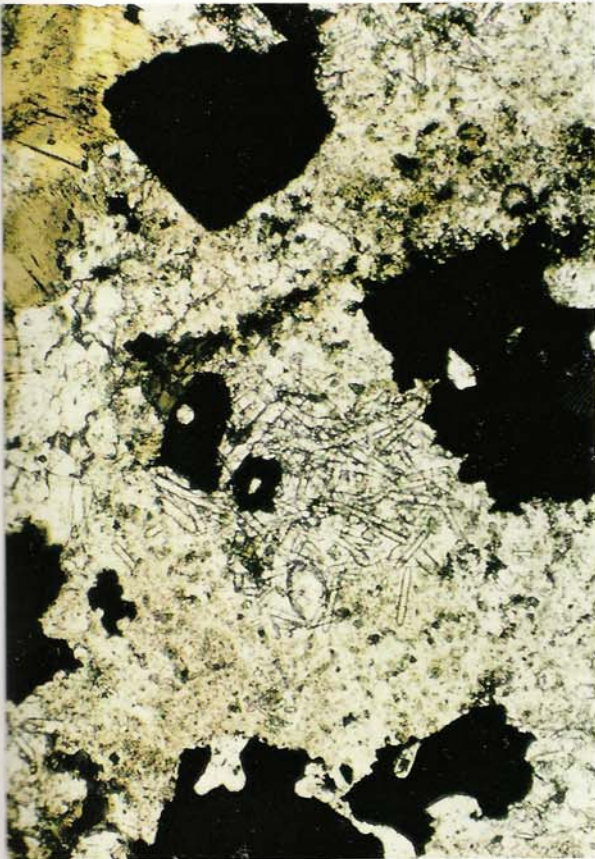
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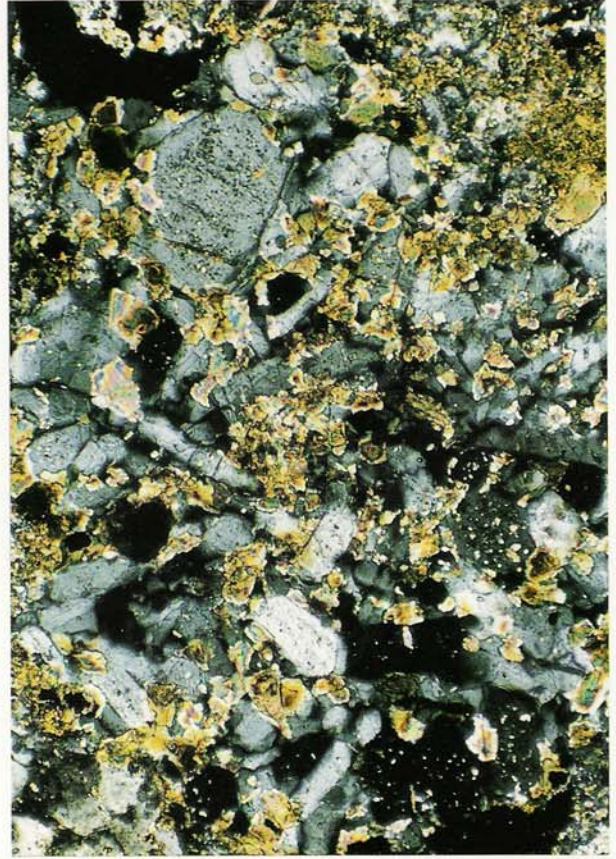
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8.4

BARITE

BaSO₄

Environment: *Intrusion-related, Epithermal, Volcanogenic massive sulphide*

Alteration: *Sericitic, Argillic, Advanced Argillic*

Characteristics

Barite is a common hydrothermal mineral in a variety of hydrothermal environments. It forms a minor late phase in veins, cavities and vugs, and is a major alteration phase in some stratiform deposits. In the latter, it may also occur as beds of massive barite, laminated barite, framboidal barite, or reworked and brecciated barite.

Hand Specimen: Barite is typically white and less commonly yellow, brown, grey, greenish or blue. It occurs as tabular and prismatic crystals.

Thin Section: Barite is usually colourless but may have pale yellow or pale blue tints. It occurs in granular aggregates or in masses of subhedral bladed or tabular crystals in veins and as cavity infill. Cleavage traces occur at right angles on (110) or on (010) and as a single set on (001).

Related Minerals

Associated: aluinite, anhydrite, carbonate, kaolinite, quartz, sericite

Accessory: calcite, celestite, chalcopryrite, dolomite, fluorite, galena, manganite, pyrite, siderite, sphalerite, stibnite

Discussion

Barite precipitates with decreasing temperature from oxidized fluids with moderate salinities over a temperature range up to 300°C. At low salinities, barite becomes more soluble (retrograde solubility) above ~100°C. Late barite fills veins and cavities in epithermal environments and jasperoids, reflecting deposition associated with decreasing temperature and increasing oxidation. In the seafloor environment, barium is transported in saline reduced fluids, but precipitates through interaction with cool seawater containing sulphate. This may happen below the seafloor and/or at the seawater - rock interface, where extensive barite-rich sedimentary beds form.

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Figures

- 9.1 OC. Tabular crystals of barite as infill of a vug in silicified andesites. Dobroyde prospect, New South Wales, a high-sulphidation epithermal precious metal prospect.
- 9.2 DC. Tabular barite intergrown with pyrite in a vein. Dobroyde prospect, New South Wales.
- 9.3 TS (PPL). Vein/cavity infill of coarse-grained pale grey-pink (high relief) barite overgrown on quartz and sulphides (galena overgrown on pale yellow sphalerite). FOV = 2.2 mm
- 9.4 TS (XPL). Large tabular crystal of barite overgrown on sulphides (sphalerite and galena) and in turn overgrown by chalcedonic quartz. Fractures cutting through the barite are infilled by chalcopryrite. Klitik area, southeastern Java, Indonesia. FOV = 2.2 mm.

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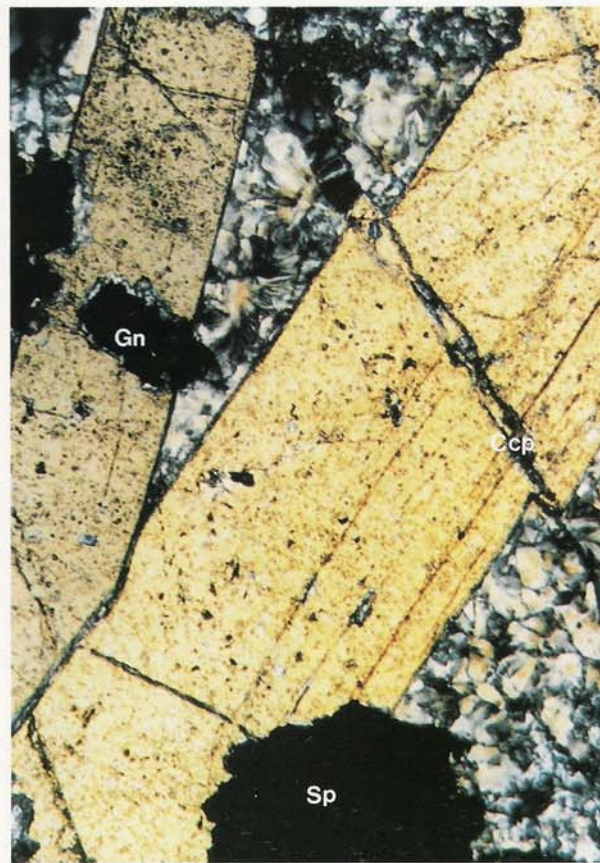
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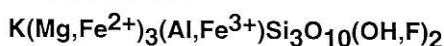


9.3



9.4

BIOTITE



Environment: *Intrusion-related*

Alteration: *Potassic, Biotitic*

Characteristics

Alteration biotite occurs in pervasive, selectively pervasive, and veinlet-controlled styles, and commonly replaces ferromagnesian minerals.

Hand Specimen: Biotite is typically black, brown or green. Grains range from euhedral to shreddy crystal forms. Individual grains or books may occur in a pegmatoidal texture but are more commonly fine-grained to microcrystalline.

Thin Section: Hydrothermal biotite is usually pleochroic in shades of green to brown, whereas igneous biotite is more commonly brown to reddish-brown. In fine-grained occurrences, the higher birefringence of biotite distinguishes it from chlorite. Hydrothermal biotite typically contains rutile and occurs as anhedral, intergrown aggregates of small grains, that replace pyroxene, amphibole and/or biotite, or fill dilatant veins.

Related Minerals

Associated: bornite, chalcopyrite, K-feldspar, magnetite, pyrite, quartz

Accessory: albite, anhydrite, chlorite, rutile, sericite, titanite

Discussion

Biotite is a significant hydrothermal mineral in many ore deposit types and is particularly common in porphyry base and precious metal deposits. Biotite alteration is usually among the earliest hydrothermal events in the formation of a porphyry mineral deposit and may either precede or accompany main-stage alteration and mineralization. Early secondary biotite is susceptible to overprinting by later chloritic alteration, which may obliterate evidence for the former presence of the mica. Compositionally, secondary biotite usually has higher Mg/(Mg+Fe) ratios and lower Ti concentrations than igneous biotite. The lower concentration of Fe and Ti in hydrothermal biotite relative to the precursor mineral commonly results in the formation of secondary titanite, rutile (anatase) and/or magnetite intergrown with or immediately adjacent to alteration biotite. Biotite and K-feldspar commonly occupy similar, early, and temporally and spatially overlapping positions in the high-temperature, cores of porphyry deposits, but biotite is typically more abundant in dioritic host rocks whereas K-feldspar is predominant in felsic host rocks.

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Figures

- 10.1 HS. Envelope of brown secondary biotite developed along a vein of quartz, K-feldspar, molybdenite, chalcopyrite and pyrite. Bingham Canyon, porphyry Cu deposit, Utah. FOV = 10 cm.
- 10.2 TS (PPL). Biotite envelope in Figure 10.1. FOV = 3 mm.
- 10.3 TS (PPL). Green-brown hydrothermal biotite replaces the matrix whereas igneous biotite is recrystallized to aggregates of brown biotite. Yandera, Papua-New Guinea. FOV = 3 mm.
- 10.4 TS (PPL). Fine-grained, reddish-brown hydrothermal biotite replacing the margins of igneous hornblende phenocrysts in granodiorite at Bagdad, Arizona. FOV = 1.5 mm.

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10.1



10.2

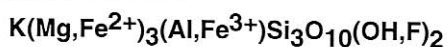


10.3



10.4

BIOTITE



Environment: Mesothermal

Alteration: Potassic, Potassium Silicate

Characteristics

Outcrops affected by biotite alteration are commonly brown with a purple to red hue. Biotite alteration may occur as vein envelopes, pervasively in shear zones, or as part of a mixed alteration zone of varied width (commonly >5 m wide) along veins or shear zones. Biotite is commonly foliated, and may be interlayered with chlorite, muscovite/sericite, amphiboles or carbonates.

Hand Specimen: Biotite is black, brown or green in hand sample and is characterized by its dark colour and micaceous cleavage. Many rocks containing abundant biotite are schistose or phyllitic. Biotite may occur within veins, commonly as radiating or foliated masses.

Thin Section: Biotite is tabular or platy in thin section, and ranges in length from 20 to 400 μm . It is characterized by mottled extinction, brown to green colour, single cleavage and high birefringence. Biotite usually occurs in foliated or shreddy, felted masses, commonly with chlorite, muscovite, amphibole or K-feldspar. Biotite commonly replaces mafic minerals.

Related Minerals

Associated: ankerite, calcite, chlorite, K-feldspar, muscovite/sericite, plagioclase, pyrite, quartz

Accessory: actinolite, chalcopyrite, clinopyroxene, epidote, garnet, hornblende, magnetite, pyrrhotite, tremolite

Discussion

Biotite is a common alteration mineral in shear zone and vein-hosted mesothermal gold deposits that were formed between sub-greenschist and amphibolite-facies conditions. Accessory minerals vary with metamorphic grade, ranging from sericitic muscovite, chlorite, and carbonates in sub-greenschist and greenschist terranes, to amphiboles, pyroxene and garnet at higher metamorphic grades. Biotite-dominant alteration frequently forms an alteration zone adjacent to zones with chlorite, muscovite/sericite and/or carbonates. In many Archean deposits, biotite and related alteration forms at or immediately following peak metamorphic conditions. Biotite commonly defines or is modified by fabrics developed during deformation and alteration.

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Figures

- 11.1 OC. Biotite envelope (black) around a calcite-chlorite-actinolite-pyrite veins in altered greywacke. Twin zone, Snip mine, northwestern British Columbia. FOV = 7 cm.
- 11.2 DC. Biotite envelope around pyrite shear vein, Snip mine. Dark chlorite occurs locally with the biotite. Pervasive biotite-K-feldspar-calcite replaces the surrounding greywacke. FOV = 10 cm.
- 11.3 TS (PPL). Weakly foliated biotite replacement of green clinopyroxene in diorite adjacent to a calcite-biotite-chlorite-pyrite shear vein near the Snip mine. The dark green, high relief mineral is epidote. FOV = 1.3 mm.
- 11.4 TS (XPL). Foliated biotite envelope on a pyrite-quartz vein, Snip mine. Outside the biotite envelope is quartz-biotite altered greywacke. FOV = 1.3 mm.

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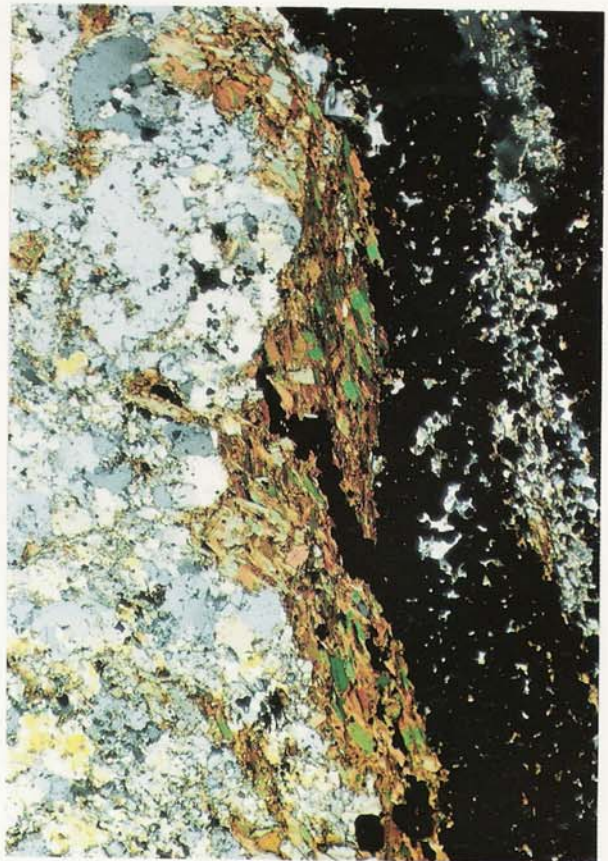
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11.4

CALCITE

CaCO₃

Environment: Epithermal

Alteration: Propylitic, Argillic

Characteristics

Calcite is a common gangue mineral of low-sulphidation epithermal deposits, occurring as replacement of calcium-bearing minerals and volcanic glass, or as open-space fill.

Hand Specimen: Identification, especially as a replacement mineral, is easily determined by using dilute HCl acid. Plates (basal pinacoid), rhombs and scalenohedrons occur as open-space fill. Crystal size is variable, with maximum dimensions up to 50 cm.

Thin Section: Calcite is distinct because of its relief, which changes from very high to very low as the stage is rotated, and very high birefringence, which gives it a light pink colour under crossed nicols. Its cleavage at 120° and uniaxial optical figure distinguishes it from anhydrite.

Related Minerals

Associated: illite, quartz

Accessory: "adularia", chlorite, epidote, pyrite, smectite, wairakite

Discussion

Calcite forms over a wide temperature range, and its stability is mainly sensitive to aqueous CO₂ concentrations. Calcite replaces calcium-bearing minerals (e.g. Ca-plagioclase, zeolites, epidote) and volcanic glass in the presence of CO₂-rich fluids in rocks with low porosity and low permeability. It occurs both proximal and distal to low-sulphidation epithermal mineralization, where it is characteristic of the propylitic assemblage. In open spaces, calcite deposits in response to boiling and exsolution of CO₂. Platy calcite (also known as lattice texture or angel wing) appears diagnostic of this process, but it is commonly completely replaced by quartz. Platy calcite occurrence is intimately associated with epithermal mineralization. Rhombic and scalenohedron forms occur in massive coarse calcite that typically fills late open spaces formed subsequent to metal deposition.

References

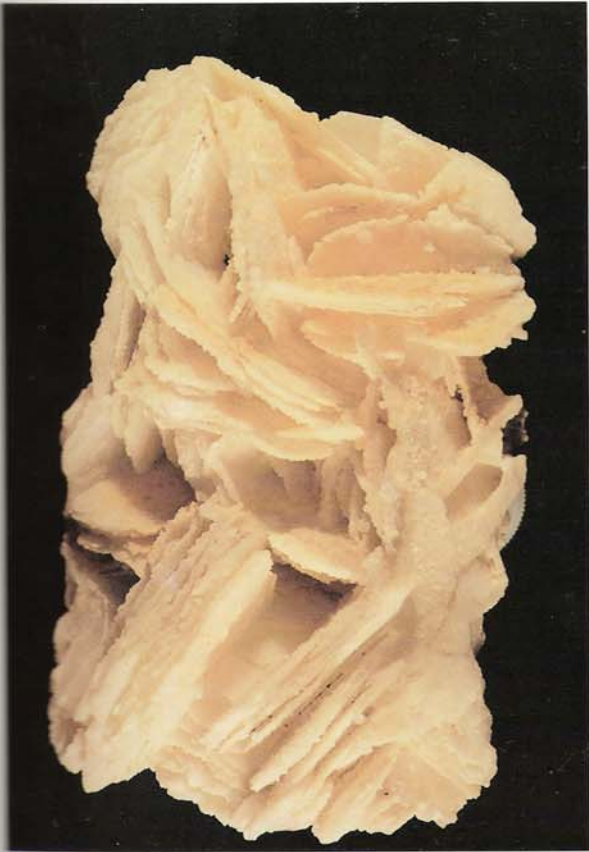
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Figures

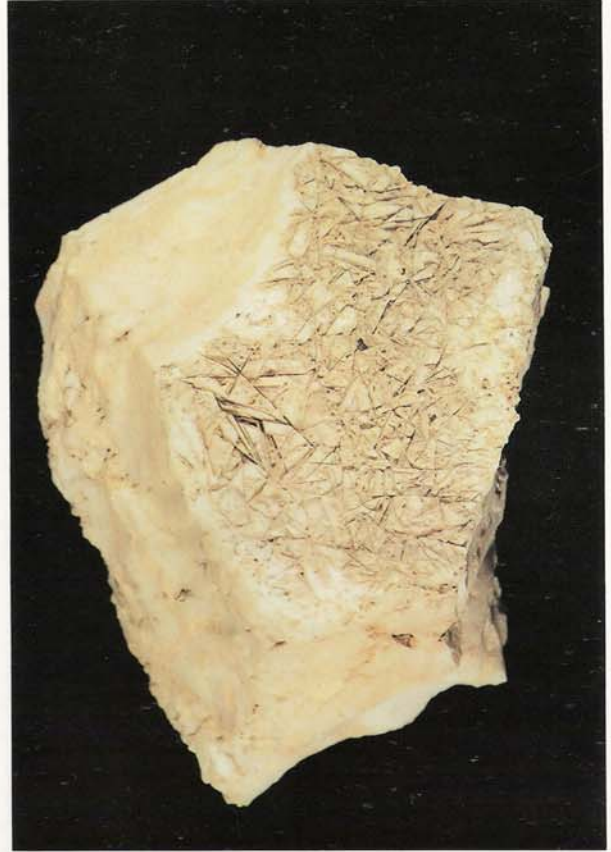
- 12.1 HS. Open-space fill of white lattice-texture calcite from the Martha epithermal Au-Ag mine, Waihi, New Zealand. FOV = 20 cm.
- 12.2 HS. Open-space fill of white microcrystalline quartz showing molds of lattice-texture calcite. Massey reef (epithermal deposit), Coromandel Peninsula, New Zealand. FOV = 9 cm.
- 12.3 TS (PPL). Vug fillings of platy calcite, totally replaced by quartz are visible in the centre. The vugs occur in pervasively quartz, chlorite, illite, and pyrite altered andesite. Sample is from drill core at the Kawerau geothermal system, New Zealand. FOV = 4 mm.
- 12.4 TS (XPL). Rhyolite pumice with most of the glass having been preferentially replaced by calcite (high birefringence). Note the unaltered andesine phenocrysts. Sample is from drill core at the Broadlands-Ohaaki geothermal system, New Zealand. FOV = 1.3 mm.

Submitted by:

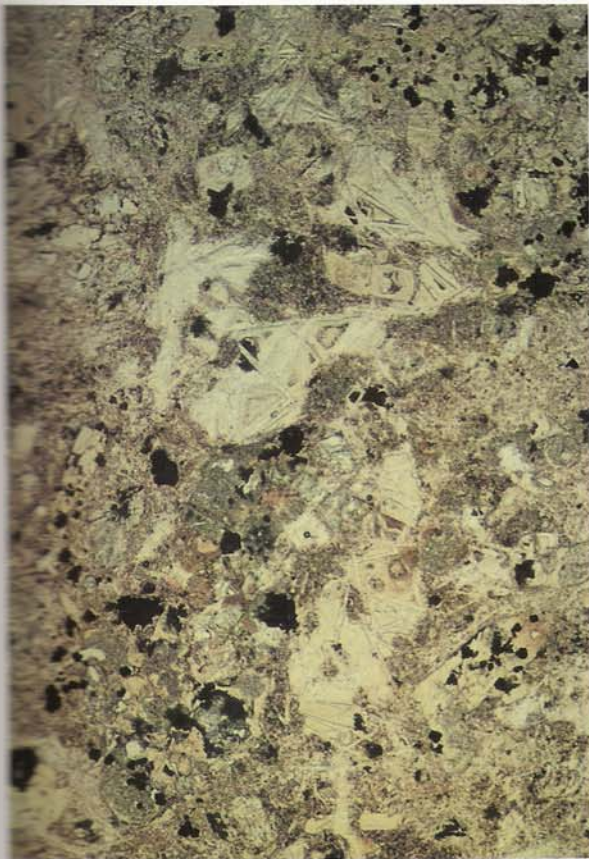
Stuart F. Simmons and Patrick R.L. Browne, University of Auckland, Auckland, New Zealand



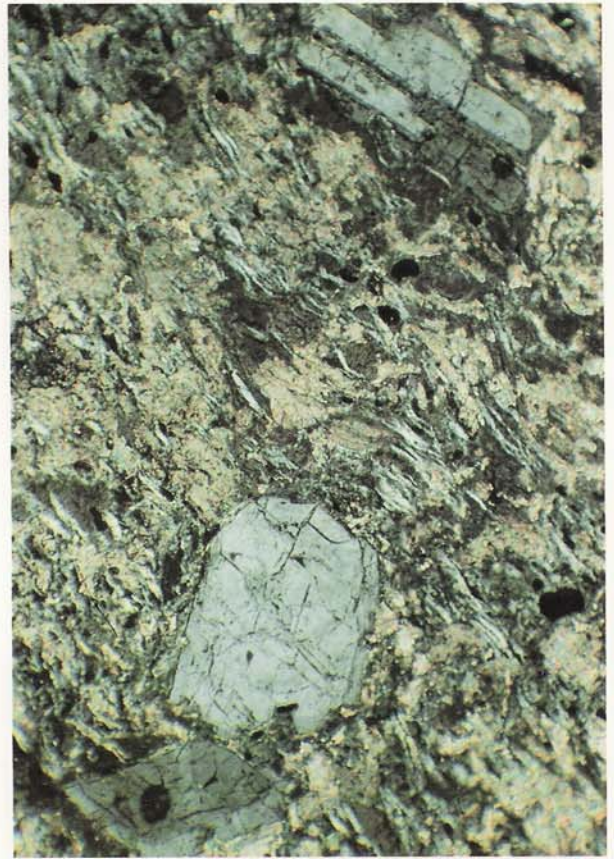
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12.4

CARBONATE

(Ca, Fe, Mg)(CO₃) – Ca(Mg,Fe)(CO₃)₂

Environment: Mesothermal

Alteration: Carbonate

Characteristics

Carbonate alteration is cream, buff or green in colour and weathers to a rusty brown. It commonly forms bleached envelopes to auriferous quartz veins in mafic to ultramafic rocks. Large zones of pervasive carbonate alteration host gold mineralization in some deposits. Dominant carbonate minerals include ankerite, calcite, dolomite and magnesite.

Hand Specimen: Carbonate is massive or foliated and reacts variably with cold dilute HCl. The alteration may be green when it contains chromian muscovite. Sulphide content is generally less than 1%.

Thin Section: Carbonates are characterized by their high birefringence and relief. Deformation lamellae are common, and grain size is highly variable. Spaced, pressure-solution cleavage is common and is defined by laminae phyllosilicates. Carbonates may pseudomorph mafic minerals or feldspar.

Related Minerals

Associated: albite, chlorite, pyrite, quartz, sericite/muscovite

Accessory: arsenopyrite, biotite, magnetite, rutile, scheelite, stibnite, titanite

Discussion

Carbonate alteration is common in mesothermal gold deposits within sub-greenschist and greenschist-facies greenstone belts. Alteration may occur as selvages to quartz and/or carbonate veins that are hosted by shear zones (e.g., Bralorne, B.C. and Sigma, Quebec), or as pervasive, semi-tabular zones of carbonate alteration that host auriferous sheeted or stockwork quartz veins (e.g., Kerr Addison and Aquarius, Ontario). In vein envelopes, carbonate alteration commonly is zoned from proximal Fe-Mg carbonate to more distal calcite. The latter forms early and is progressively replaced by the Fe-Mg carbonates. Greenish, chromiferous, muscovite-carbonate alteration associated with ultramafic rocks is commonly termed listwanite.

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Figures

- 13.1 OC. Ankerite vein with bleached ankerite-dolomite envelopes hosted by metabasalts. Greenstone Nose area, Dome mine, Timmins, Ontario. FOV = 1.25 m.
- 13.2 DC. Pervasive magnesite-dolomite-albite alteration of komatiitic volcanics. Note the relict spinifex textures in both samples. The green colour in the left sample is imparted by chromian muscovite. The coin on the right core is on a coarse carbonate-quartz vein. Aquarius deposit, east of Timmins, Ontario. FOV = 12 cm.
- 13.3 TS (XPL). Massive carbonate alteration, Aquarius deposit east of Timmins, Ontario. FOV = 5 mm.
- 13.4 TS (XPL). Carbonate (magnesite/dolomite) cross-cut by albite vein. Aquarius deposit east of Timmins, Ontario. FOV = 5 mm.

Submitted by:

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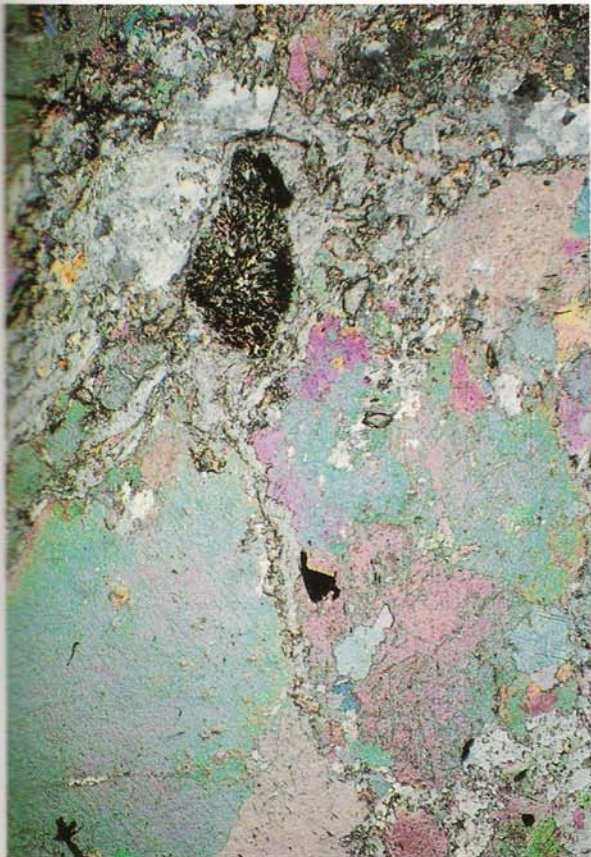
Craig H.B. Leitch, Consultant, Salt Spring Island, British Columbia



13.1



13.2



13.3



13.4

CARBONATE

(Fe,Mg,Ca)(CO₃) - Ca(Mg,Fe)(CO₃)₂

Environment: Volcanogenic massive sulphide

Alteration: Carbonate

Characteristics

Carbonate minerals are locally important in footwall alteration zones to volcanogenic massive sulphide deposits. The carbonate may be widely disseminated, may occur in veins or distinct zones, and may vary in composition.

Hand Specimen: The orange-brown weathering of Fe-rich carbonates is characteristic in hand specimen. Carbonate nodules and euhedral porphyroblasts in recrystallized (metamorphosed) rocks are common and assist in the identification of the carbonate.

Thin Section: High relief, high birefringence, and rhombic cleavage, are diagnostic. The type of carbonate mineral is not easily determined in thin section, and other analytical methods are required for positive identifications.

Related Minerals

Associated: chlorite, pyrite, quartz, sericite

Accessory: andalusite, chloritoid

Discussion

Carbonate is an important alteration mineral in some volcanogenic massive sulphide environments. It may occur in the immediate footwall to deposits, but may also be widespread in semi-conformable alteration zones deeper in the footwall stratigraphy. The type of carbonate varies from siderite to dolomite, probably reflecting the composition of rocks hosting alteration, proximity to Fe-rich feeder zones, and interaction with seawater. Carbonate minerals are usually disseminated, but may form massive or banded zones of either replacement or exhalative origin.

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Figures

- 14.1 DC. Dolomite-quartz-sericite-pyrite alteration in the footwall of the Kutcho Creek volcanogenic massive sulphide deposit, British Columbia. The presence of fine-grained carbonate is indicated by the orange-stained bands. Coarse dolomite also occurs as flattened rhombs and in pressure shadows adjacent to large pyrites. FOV = 20 cm.
- 14.2 DC. Dolomite rhombs visible in a silicified clast from the footwall of the Kutcho Creek deposit. FOV = 10 cm.
- 14.3 TS (XPL). Coarse dolomite (right) in the pressure shadow of a large pyrite grain adjacent to foliated chlorite (dark band) and quartz-sericite alteration. From the footwall of the Kutcho Creek deposit. FOV = 3 mm.
- 14.4 TS (XPL). Intergrowth of dolomite-quartz-pyrite from the footwall alteration zone at Kutcho Creek (dolomite is the highly birefringent mineral). FOV = 3 mm.

Submitted by:

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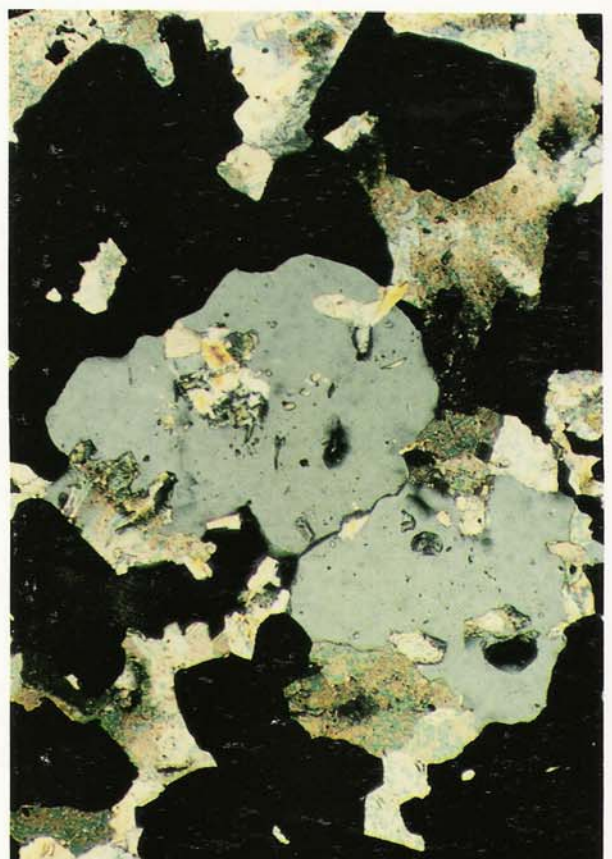
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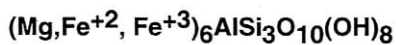


14.3



14.4

CHLORITE



Environment: *Volcanogenic massive sulphide*

Alteration: *Chlorite, Quartz-chlorite*

Characteristics

Chloritic alteration in outcrop is commonly blue-grey to green in colour except where weathered to form hematite, creating a red, pink or brown colour. The textural pattern (including massive, patchy and breccia) and the proportions of chlorite to quartz are influenced by the pre-existing rock and its composition. In deformed areas, chlorite alteration generally has a strong cleavage or schistosity.

Hand Specimen: Mg-rich chlorite is pale to very dark blue-grey in colour, whereas Fe-rich chlorite is pale to very dark green. Rocks with abundant chlorite are soft, and patches are dark and waxy in appearance.

Thin Section: Chlorite has the platy habit of mica, and is pleochroic (green). Grain sizes are generally small, but may range up to 200 μm in rocks of lower greenschist metamorphic grade. Birefringence is dependent on composition, and anomalous blues are generally characteristic of Mg-rich chlorite.

Related Minerals

Associated: Ca-Mg-Fe carbonates, epidote, pyrite, quartz, sericite, talc

Accessory: actinolite, anthophyllite, biotite, cordierite, garnet, hematite, K-feldspar, montmorillonite, rutile, titanite

Discussion

Chlorite is a common hydrothermal alteration mineral in many systems, particularly in peripheral propylitic alteration (e.g., porphyry and epithermal deposits) or retrograde overprinting alteration (e.g., replacement of hydrothermal biotite in porphyry deposits). In volcanogenic massive sulphide deposits, chlorite is a diagnostic mineral commonly concentrated in the footwall zones that also host chalcopyrite-pyrite "stringer" veins. When present, chlorite and quartz-chlorite alteration typically occupies an innermost alteration zone, and passes outward into sericite alteration. In addition to mineralogical zoning, the composition of chlorite may vary from Fe-rich adjacent to massive sulphide mineralization, to Mg-rich on the periphery of mineralized zones. This occurs particularly in Precambrian deposits, whereas younger deposits may be dominated by Mg-rich chlorite. Mg-rich chlorite is considered to result from the interaction of cold seawater with hot hydrothermal fluids.

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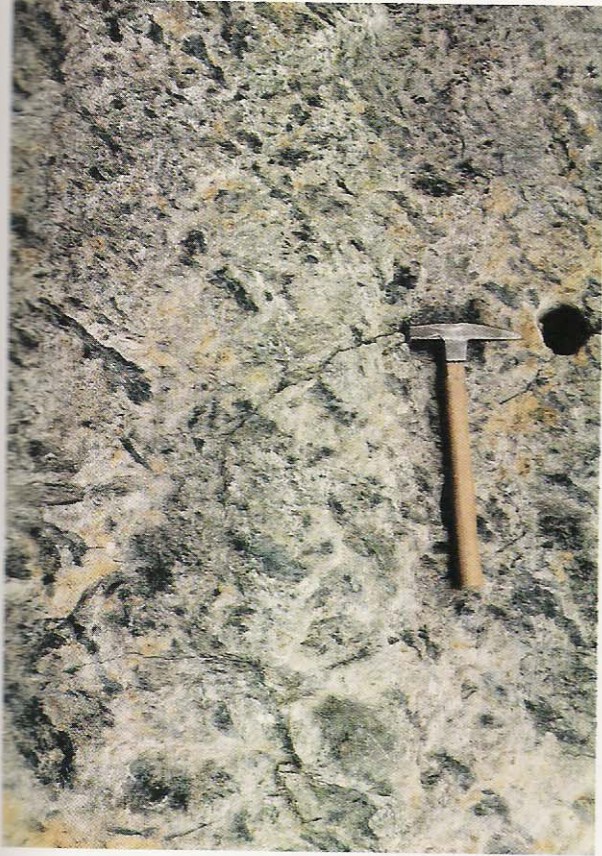
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Figures

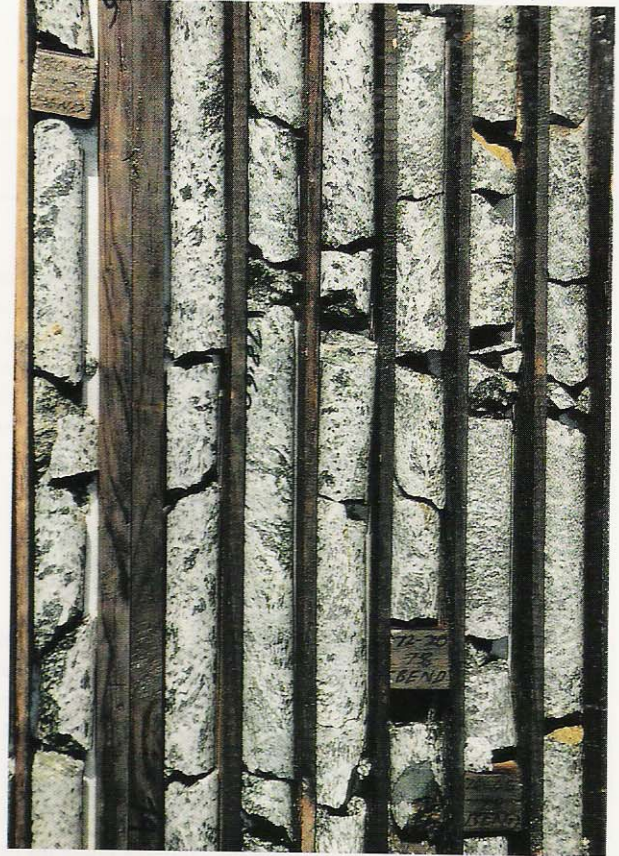
- 15.1 OC. Quartz-chlorite-altered, rhyolitic pyroclastic rock, in the footwall chlorite alteration zone of the Hercules deposit, Tasmania, Australia. Chlorite (dark blue-grey) has replaced sericite and large fiamme of pumice, whereas the original matrix has been replaced by quartz-rich quartz-chlorite alteration (pale grey). FOV = 1 m.
- 15.2 DC. Pseudobreccia texture in the footwall rhyolite lava of the Wilga deposit, Victoria, Australia. The textures reflect early chlorite-quartz (dark grey), followed by quartz-chlorite or quartz (pale grey). FOV = 65 cm.
- 15.3 TS (XPL). Massive fine-grained Mg-rich chlorite with minor quartz and pyrite. From the immediate footwall in the United Verde deposit, Arizona. FOV = 5 mm.
- 15.4 TS (XPL). Amygdule in altered footwall basalt, Tulsequah Chief massive sulphide deposit, British Columbia. The amygdule is filled with patchy brown to green chlorite, muscovite, epidote and pyrite. FOV = 1.25 mm.

Submitted by:

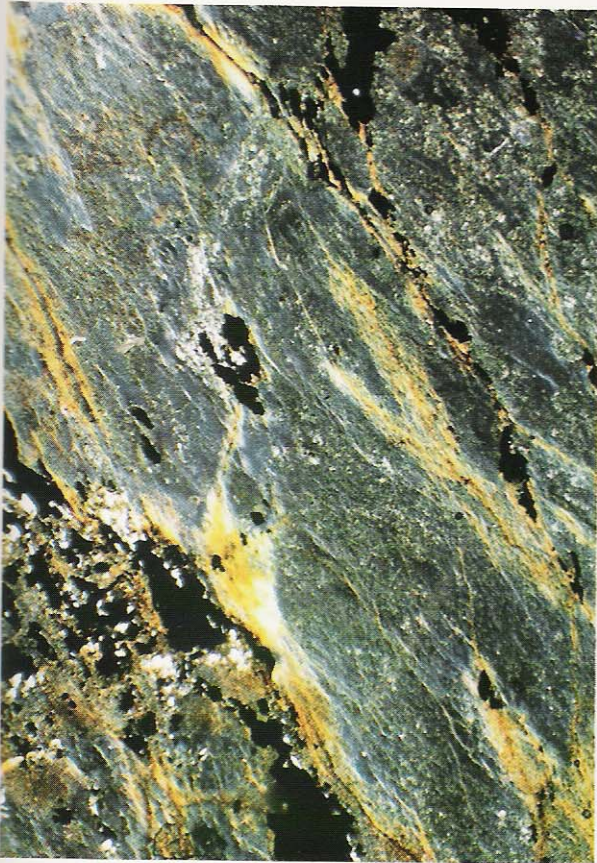
Rodney L. Allen, Consultant, Volcanic Resources Limited, Stavanger, Norway
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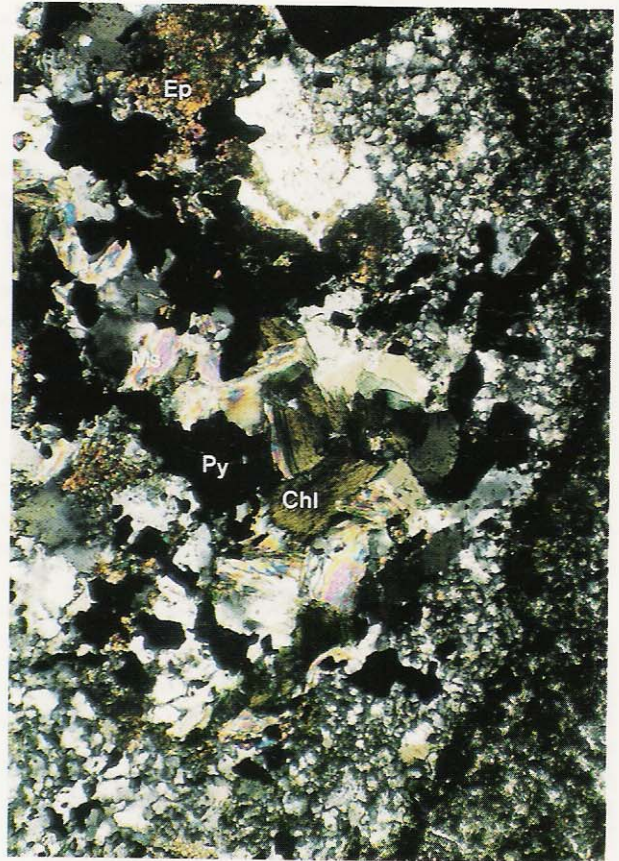
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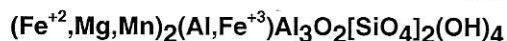


15.3



15.4

CHLORITOID



Environment: Volcanogenic massive sulphide, Mesothermal

Alteration: Sericitic, Aluminous

Characteristics

Chloritoid typically occurs as small randomly oriented porphyroblasts in greenschist-facies metapelites and it may also be present in altered felsic to mafic volcanic rocks, chemical sediments (exhalites), and veins.

Hand Specimen: In hand specimen, chloritoid typically forms millimetre-scale, moderately elongate prisms, dark green to greenish black in colour. Variants include ottrelite and magnesiochloritoid, respectively enriched in Mn and Mg, and the related Fe-Al germanate, carboirite.

Thin Section: Chloritoid is usually pleochroic in pale to medium green to yellow to blue- or grey-green tints. It generally displays cleavage traces and commonly shows lamellar twinning or hourglass zoning.

Related Minerals

Associated: aluminosilicates, biotite, chlorite, garnet, quartz, sericite/muscovite, staurolite

Accessory: calcite, graphite, hornblende, oxides, plagioclase, pyrophyllite, sulphides

Discussion

Chloritoid develops under both prograde and retrograde conditions, and may be replaced by staurolite and garnet. It occurs in regionally metamorphosed greenschist and blueschist rocks, within hornfels in contact aureoles, and in altered volcanic rocks. Chloritoid is found in metamorphosed alteration zones in the footwall to volcanogenic massive sulphide deposits (e.g., Golden Grove, Louvicourt, Onaman, Teutonic Bore), associated with some gold deposits (e.g., Crixas, Casa Berardi, Chetwynd, Hope Brook), and in aluminous metasediments such as in the Witwatersrand. The presence of chloritoid is controlled by protolith composition and metamorphic grade. Chloritoid varies in composition, as do some associated phases such as white micas (muscovite, phengite, paragonite) and feldspars. Inferred protoliths include several of potential economic interest: aluminous footwall alteration below volcanogenic massive sulphide deposits, chemical sediments and aluminous paleosols.

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Figures

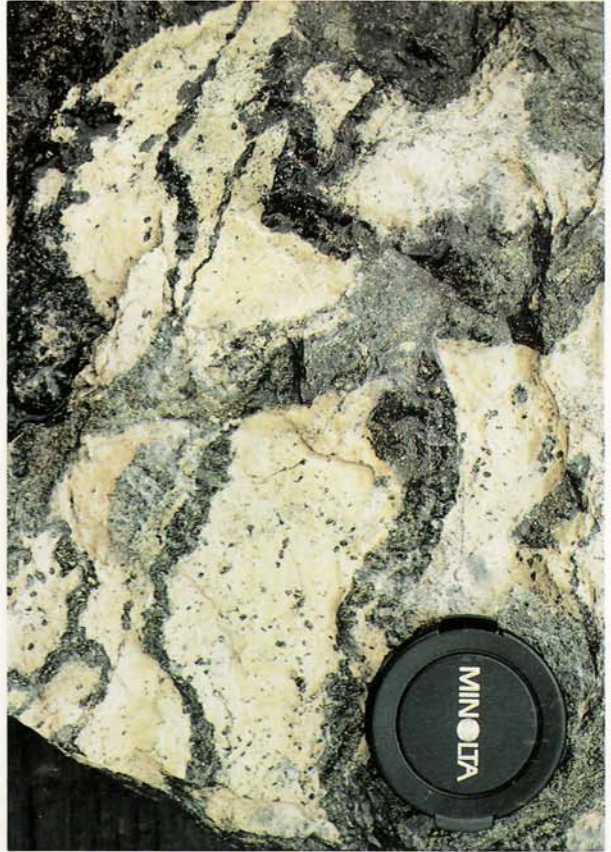
- 16.1 OC. Chloritoid (dark green specks) in sericite-altered pillow basalt, Teutonic Bore volcanogenic massive sulphide deposit, Western Australia. FOV = 19 cm.
- 16.2 OC. Chloritoid in sericite altered basalt cut by chlorite-sulphide veins. Teutonic Bore volcanogenic massive sulphide deposit, Western Australia. FOV = 23 cm.
- 16.3 TS (XPL). Coarse chloritoid porphyroblast displaying cleavage traces, and quartz and Fe-Ti oxide inclusions in syntectonic overgrowth of foliated chloritic groundmass in a staurolite-bearing garnet-chlorite schist, Snow Lake area, Manitoba. FOV = 2.3 mm.
- 16.4 TS (XPL). Radiating chloritoid 'bow tie' with lamellar twinning, in calcite-muscovite-chloritoid schist. From the Grenville province, eastern Ontario. FOV = 1.2 mm.

Submitted by

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16.1



16.2



16.3



16.4

CLINOPYROXENE



Environment: Skarn

Alteration: Calc-silicate

Characteristics

Outcrops of pyroxene skarn alteration are commonly light to dark green in colour. Pale rusty brown or black Mn-oxide coatings may occur where the pyroxene contains Fe or Mn. Pyroxene can overprint both the genetically related intrusion to produce endoskarn, as well as the adjacent country rocks to form exoskarn. Pyroxene occurs as disseminated crystals, irregular masses, veins, stratabound layers, or massive replacements.

Hand Specimen: Skarn pyroxenes are commonly pale to dark green; colour differences can reflect variations in Fe and/or Mn compositions.

Thin Section: Clinopyroxene in cross-section commonly shows near right angle cleavage. Grains range from euhedral, prismatic crystals to anhedral, granular masses. In plane-polarized light, clinopyroxene is commonly colourless to pale green. In skarns, pyroxene grains often occur as small inclusions in garnet.

Related Minerals

Associated: *Prograde*- biotite, calcite, garnet, quartz, wollastonite, olivine (Mg skarn);
Retrograde- amphibole, calcite, chlorite, epidote, K-feldspar, and serpentine (Mg skarn)

Accessory: chondrodite, prehnite, sulphides, scapolite, vesuvianite

Discussion

Clinopyroxene is a characteristic alteration mineral in skarns, but it also occurs with some porphyry deposits and in rocks overprinted by contact or regional metamorphism. Skarn pyroxenes exhibit systematic compositional variations (Fe, Mg and Mn contents) that can reflect their associated skarn deposit class and their environment of formation. Although pyroxenes in most skarns are diopside-hedenbergite (Mg-Fe) solid solutions, an increased johannsenite component (Mn) is present in some Zn and W skarns, and more rarely in some Fe skarns. Fe-rich hedenbergitic pyroxene characterizes many Au, Fe, Zn and W skarns and, in some instances, it reflects a reduced environment relative to skarns dominated by diopside.

References

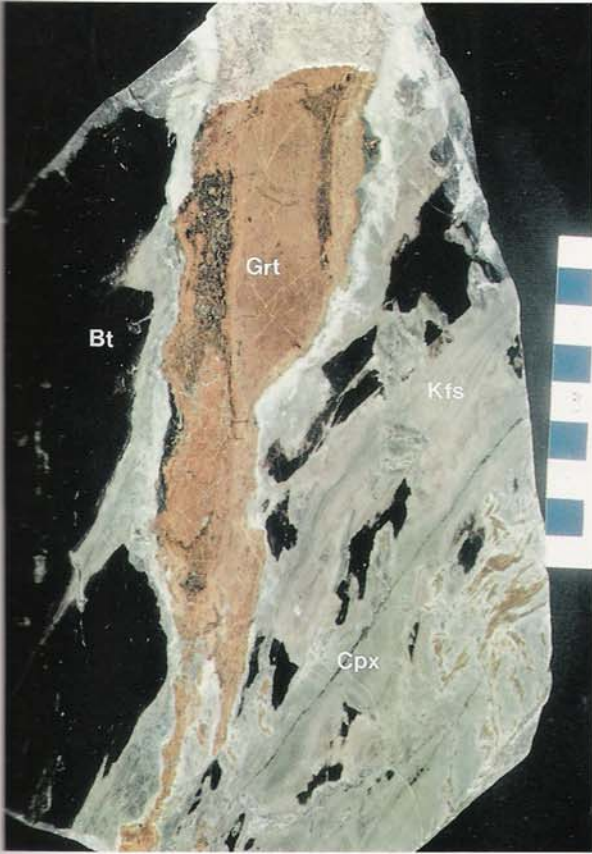
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Figures

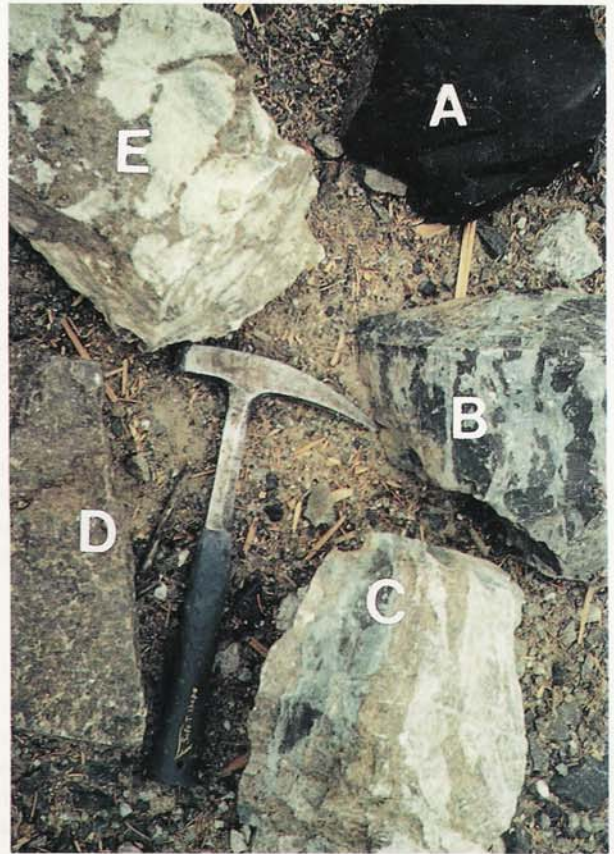
- 17.1 HS. Pyroxene exoskarn (light green) which replaced biotite-rich alteration (black) and is crosscut by a garnet vein (brown). Replacement of biotite results in reaction zones of K-feldspar (light pink). French Au skarn deposit, Hedley district, British Columbia. FOV = 30 cm.
- 17.2 HS. Five samples illustrating varieties of exoskarn alteration in a skarn deposit. A: massive biotite alteration; B: biotite alteration partly replaced by veins of light green clinopyroxene; C: clinopyroxene, marble and biotite partly replaced by brown garnet; D: massive garnet skarn; E: garnet skarn overprinting the original muddy matrix of a sedimentary limestone breccia (remnant clasts are now white marble). French Au skarn deposit, Hedley district, British Columbia. FOV = 80 cm.
- 17.3 TS (PPL). Inclusions of subhedral diopside within massive grossular garnet. Dead Goat W skarn, near Cassiar, northern British Columbia. FOV = 3 mm.
- 17.4 TS (XPL). Same sample as in Figure 17.3; strongly birefringent pyroxene crystals within weakly birefringent garnet. Dead Goat W skarn, Cassiar, northern British Columbia. FOV = 3 mm.

Submitted by:

Gerald E. Ray, Geological Survey of British Columbia, Victoria, British Columbia



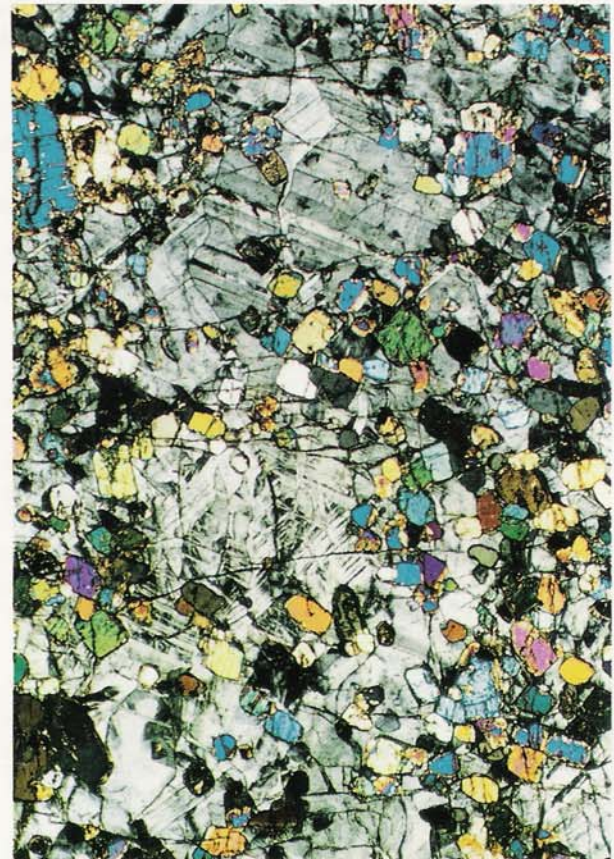
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17.4

CORDIERITE

$Mg_2Al_4SiO_5O_{18}$

Environment: *Volcanogenic massive sulphide*

Alteration: *Mg-Fe metasomatism, Dalmatianite*

Characteristics

Cordierite is characteristic of metapelites, but it also occurs as a diagnostic mineral in some metamorphosed alteration zones.

Hand Specimen: Cordierite is greyish blue, lilac-blue, dark blue or grey in colour and has a glassy appearance with a conchoidal fracture. Often translucent, cordierite becomes turbid when altered to mica and chlorite and may take on a greenish colour. In alteration zones, it typically occurs as irregular round grains or aggregates, but may form stubby prismatic crystals.

Thin Section: Cordierite resembles quartz in thin section. Some cordierite may exhibit strong pleochroism, from violet-blue to pale grey, particularly in thick sections. It typically forms poikiloblastic grains up to 3 mm in size. Cordierite occurring in well-developed crystals is commonly twinned, i.e., lamellar, cyclic, or pseudo-hexagonal. Cordierite may be replaced by fine-grained sericite and chlorite due to retrograde alteration.

Related Minerals

Associated: anthophyllite, biotite, garnet, plagioclase, sillimanite, staurolite

Accessory: chlorite, cummingtonite, gedrite, magnetite, quartz, sericite/muscovite

Discussion

Cordierite may occur around metamorphosed massive sulphide deposits, where it is associated with hydrothermally altered rocks that have undergone strong Mg-Fe enrichment and Na-Ca-K depletion. A spotted hornfels texture, termed dalmatianite in the Noranda area, Quebec, develops in chlorite-rich footwall alteration pipes below massive sulphide deposits in regionally metamorphosed areas or in the contact metamorphic aureole surrounding post-volcanic intrusions. The spotted texture results from the formation of cordierite during prograde metamorphism. Chlorite, formed during retrograde metamorphism, replaced most of the cordierite. In some areas, e.g., the Geco region, Northwestern Ontario, gneissic rocks containing anthophyllite-cordierite (\pm biotite) occur in both the footwall and hanging wall of massive sulphide orebodies. These zones have been interpreted as the high-grade metamorphosed equivalents of chloritic alteration.

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Figures

- 18.1 OC. Cordierite spots (dalmatianite) in altered mafic volcanic rocks at the Amulet 'A' deposit, Noranda, Quebec. Footwall alteration zone to the massive sulphide mineralization. FOV = 42 cm.
- 18.2 OC. Cordierite spots in altered and locally mineralized sedimentary rocks from the hanging wall of the main Hidden Creek volcanogenic massive sulphide deposits, Anyox, British Columbia. FOV = 60 cm.
- 18.3 TS (XPL). Cordierite porphyroblast in sericite-rich matrix. The alteration occurs in fragmental felsic volcanic rocks which host the Tulsequah Chief massive sulphide deposit, British Columbia. FOV = 5 mm.
- 18.4 TS (XPL). Same porphyroblast as above showing distinctive star twinning. Quartz and pyrite inclusions also occur within the porphyroblast. FOV = 2.5 mm.

Submitted by

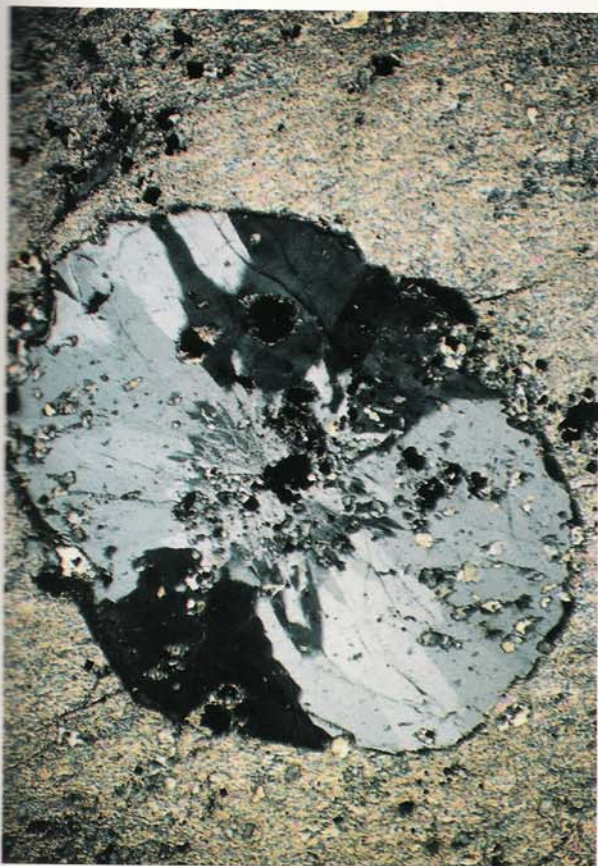
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C. Sebert, MDRU, University of British Columbia, British Columbia
Isobel Wolfson, Noranda Mining and Exploration, Geco Division, Manitouwadge, Ontario



18.1



18.2



18.3



18.4

DIASPORE

AIO(OH)

Environment: Intrusion-related, Epithermal

Alteration: Advanced Argillic

Characteristics

Diaspore is a minor, but important mineral in advanced argillic alteration. It is rarely visible in outcrop but may be expected in pyrophyllite-rich alteration. Identification requires thin section petrography, or if present in sufficient amounts, X-ray diffraction analysis.

Hand Specimen: Diaspore occurs as a fine-grained mineral in pale white to tan pyrophyllite-rich advanced argillic alteration. Grey aggregates of diaspore may be observed.

Thin Section: Diaspore forms aggregates and rare needles, usually within a pyrophyllite-rich matrix. High relief and moderately high birefringence are diagnostic. Quartz is often present in the same sample but shows an antithetic relationship with diaspore.

Related Minerals

Associated: pyrite, pyrophyllite

Accessory: aluminum phosphates, alunite, andalusite, corundum, kaolinite, quartz, rutile, sericite

Discussion

Diaspore is a characteristic mineral of advanced argillic alteration that results from the reaction of low-pH fluids with rocks. It forms at intermediate temperatures in association with pyrophyllite, but overlaps with the stability of kaolinite and andalusite. Diaspore should not occur in equilibrium with quartz, but both minerals are usually present at the sample or outcrop scale. Diaspore is common in geothermal systems dominated by acid-sulphate waters, high-sulphidation epithermal deposits, the upper parts of some porphyry systems, and some gold deposits associated with deformed advanced argillic alteration (e.g., the deposits in the Carolina Slate belt). Diaspore may also occur in metamorphic rocks, whose protolith may represent earlier alteration (high-sulphidation or surficial acid-leach zones above boiling geothermal systems) or weathered regoliths (bauxite).

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Figure

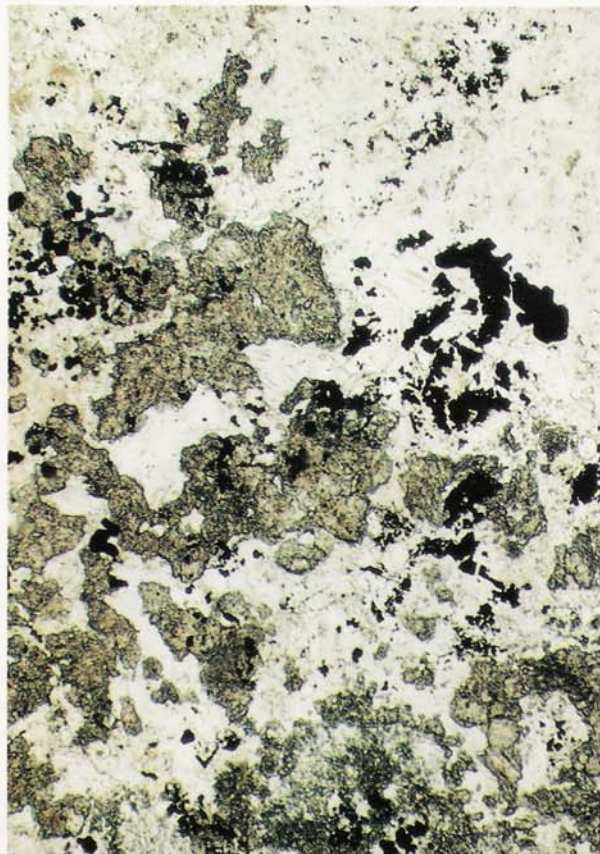
- 19.1 HS. Advanced argillic alteration dominated by pyrophyllite and quartz; the quartz-rich portions have a slightly vuggy texture. Diaspore is not visible but occurs in the white pyrophyllite-rich areas of the sample. Taseko porphyry Cu prospect, British Columbia.
- 19.2 TS (PPL). Diaspore in a pyrophyllite-pyrite matrix; the high relief and irregular aggregates are characteristic of diaspore. Frieda River porphyry Cu-Au deposit, Papua New Guinea. FOV = 2.5 mm.
- 19.3 TS (PPL). Diaspore prisms in a pyrophyllite-rich zone. Same sample as Figure 19.1. FOV = 2.5 mm.
- 19.4 TS (XPL). Same as above, showing the characteristic birefringence of diaspore. The pyrophyllite-rich zone passes into quartz-pyrophyllite, but no quartz occurs with the diaspore. FOV = 2.5 mm.

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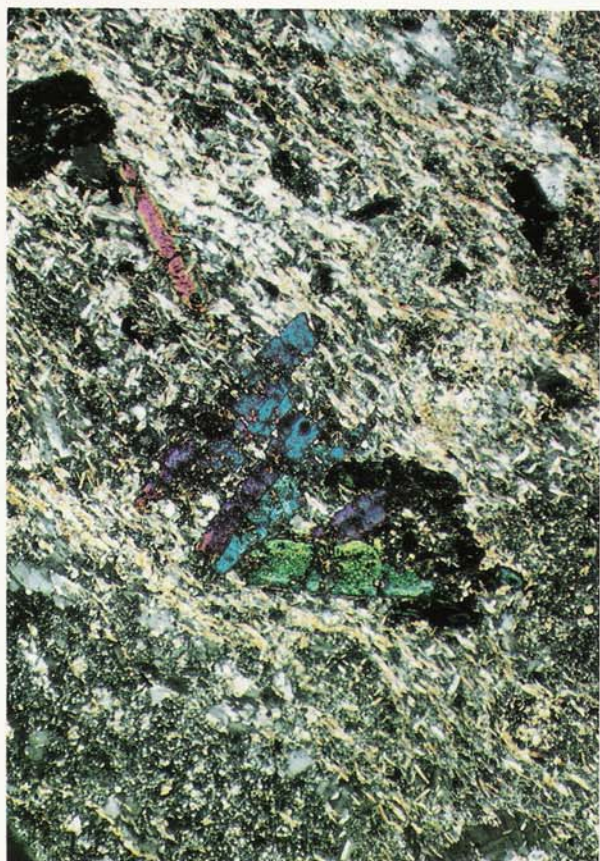
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19.4

DUMORTIERITE



Environment: *Intrusion-related*

Alteration: *Advanced argillic*

Characteristics

Dumortierite occurs in pervasive patches, in alteration envelopes around veins, and in vein fill. Outcrops containing dumortierite commonly are pink or blue.

Hand Specimen: Dumortierite-bearing rock may be mottled pinkish to intensely blue in hand specimen. The intensity of the colour varies with the proportion of dumortierite.

Thin Section: Dumortierite generally consists of radially oriented acicular crystals or fibrous sheaves. It is characterized by a distinct pleochroic scheme (X pink to purple, Y=Z colourless), parallel extinction in the longitudinal section, and a negative elongation, which distinguishes it from fibrous sillimanite. Dumortierite may be intergrown with quartz, andalusite or rutile, which appear as alternating bands in metamorphic schists.

Related Minerals

Associated: andalusite, pyrophyllite, quartz

Accessory: apatite, epidote, kyanite, rutile, sericite, tourmaline, zircon

Discussion

Dumortierite is associated with advanced argillic alteration (peraluminous mineral assemblages). It may contain small amounts of Mg, Ti, Fe and P. Formation of dumortierite relative to tourmaline is favoured where concentrations of Fe, Mg, Ca and Na are low, possibly due to leaching prior to the addition of boron. In some cases, dumortierite may replace tourmaline. The presence of dumortierite may be a mineralogical expression of acid metasomatism associated with precious metal and base metal mineralization. Examples of deposits with significant dumortierite include the Island Copper porphyry Cu-Mo-Au deposit, Vancouver Island, British Columbia, the Chetwynd Au deposit in Newfoundland, and the Big Bell Au deposit in Western Australia.

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Figures

- 20.1 OC. Variable purple to pink alteration reflecting the abundance of dumortierite. From Louvicourt, Quebec. FOV = 135 cm.
- 20.2 HS. Dark blue dumortierite in dominantly quartz-pyrophyllite-bearing rock. Island Copper porphyry Cu-Au-Mo deposit, Vancouver Island, British Columbia.
- 20.3 TS (XPL). Typical sheaf of radially oriented euhedral crystals of dumortierite, which developed as an overgrowth on andalusite grains. Sample from Louvicourt, Quebec. FOV = 1.7 mm.
- 20.4 TS (XPL). Typical radially oriented and fibrous dumortierite crystals, showing anomalous interference colours. Reddish brown, almost opaque grains are rutile. Sample as in Figure 21.2. FOV = 0.65 mm.

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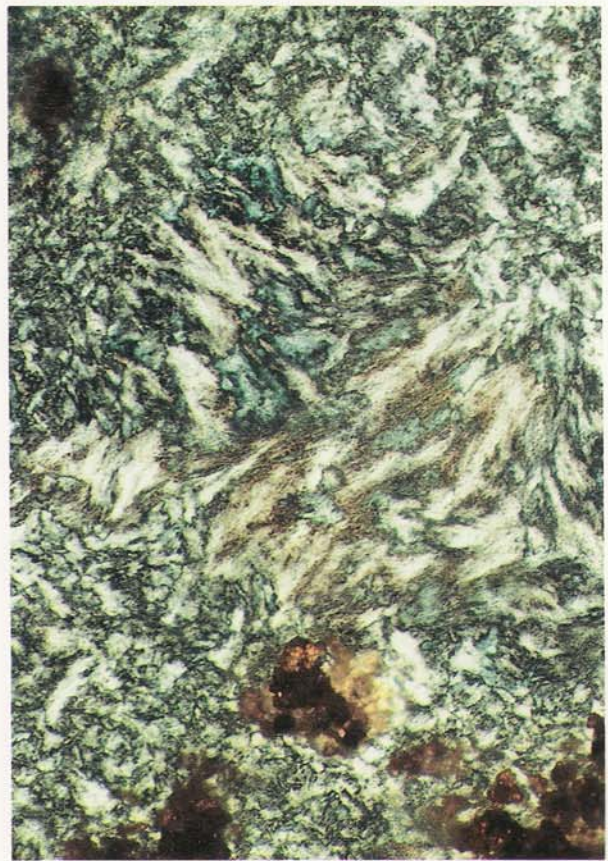
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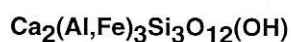


20.3



20.4

EPIDOTE



Environment: *Intrusion-related, Epithermal*

Alteration: *Propylitic*

Characteristics

Epidote usually has a distinctive pistachio-green colour, and occurs as a replacement mineral in altered volcanic rocks or as open-space fill in veins.

Hand Specimen: Epidote is hard (~7) and its crystals may be up to a few millimetres long, in which case the green colour makes it easy to identify the mineral.

Thin Section: Epidote is colourless to pale yellow, green, and greenish brown, with weak to moderately strong pleochroism. Epidote forms clusters of anhedral to euhedral columnar crystals, and occurs with other calcium bearing minerals such as calcite and wairakite, typically replacing calcic-plagioclase or ferromagnesian minerals. The high relief and birefringence are distinctive.

Related Minerals

Associated: calcite, chlorite, wairakite

Accessory: "adularia", albite, clinozoisite, illite, K-feldspar, quartz

Discussion

Epidote occurs in altered volcanic rocks, where hydrothermal temperatures exceeded about 230°C; hence, epidote is common both proximal and distal to mineralization in deep epithermal and porphyry environments. Epidote is susceptible to replacement by calcite in the presence of CO₂-rich fluids. Crystals increase in size and appear more prismatic with increasing temperature. Epidote also occurs with K-feldspar in some potassic alteration zones in mafic rocks, and as part of retrograde alteration assemblages in skarns.

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Figures

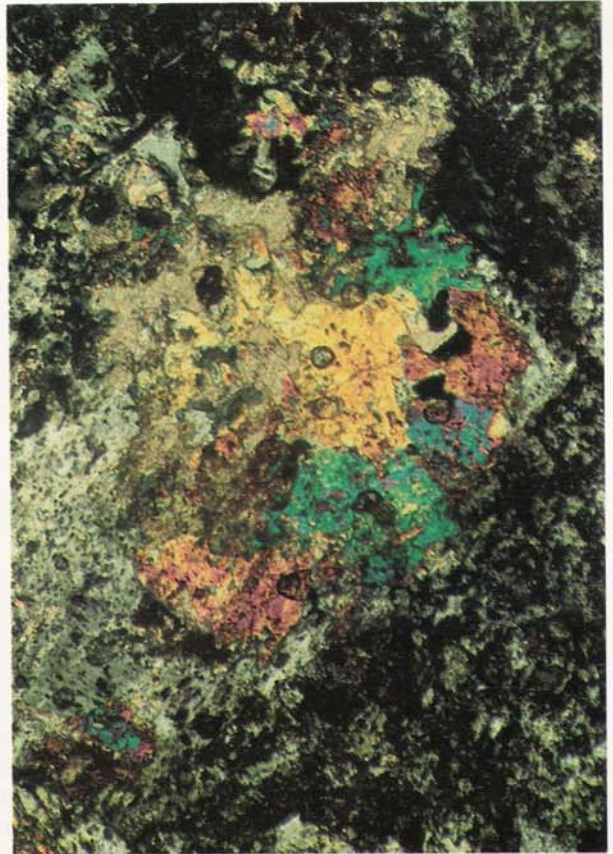
- 21.1 DC. Intensely altered rhyolite ignimbrite containing epidote, wairakite, illite and quartz. Aggregates of green epidote crystals are visible; the white mineral is wairakite. Sample is from drill core at the Broadlands-Ohaaki geothermal system, New Zealand. FOV = 7 mm.
- 21.2 TS (XPL). Intensely altered andesite containing epidote, calcite, chlorite, pyrite and minor quartz. The plagioclase phenocryst is completely replaced by epidote, calcite and minor chlorite. Sample is from drill core at the Broadlands-Ohaaki geothermal system, New Zealand. FOV = 2 mm.
- 21.3 TS (PPL). Altered andesite with a plagioclase phenocryst completely replaced by albite, epidote (greenish brown with high relief), plus minor chlorite and illite. Mt. Muro epithermal deposit, Central Kalimantan, Indonesia. FOV = 0.8 mm.
- 21.4 TS (XPL). Same as Figure 21.3.

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21.1



21.2

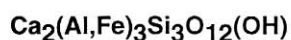


21.3



21.4

EPIDOTE



Environment: *Volcanogenic massive sulphide*

Alteration: *Epidote-quartz*

Characteristics

Epidote-quartz alteration in volcanogenic massive sulphide environments is common in volcanic and intrusive rocks of mafic composition, but is rare in felsic igneous rocks. Altered rocks have a distinct greenish white colour. This alteration forms round to irregular amoeboidal spots or patches (< 1 cm to several metres) with sharp to diffuse borders, fills fractures and vesicles, and occurs as halos around amygdules and fractures.

Hand Specimen: In hand specimen, epidote-quartz alteration gives a greenish white colour to the rock depending on the amount of epidote versus quartz.

Thin Section: Epidote-quartz alteration is characterized by the assemblage of epidote (clinozoisite) and quartz in ratios of 0.5:1 to 2:1. Primary volcanic textures are commonly obliterated by granular aggregates of fine-grained (<0.1 mm) epidote and quartz. Amygdules are filled by massive granular and fibrous prismatic epidote crystals (up to 5 mm long).

Related Minerals

Associated: quartz

Accessory: actinolite, calcite, chlorite, opaque minerals, sericite

Discussion

Epidote-quartz alteration is a semi-conformable (or stratabound), synvolcanic style of alteration present within the footwall and hanging wall stratigraphy of volcanogenic massive sulphide deposits (VMS). Zones of alteration are commonly extensive; they may be tens of kilometres in strike length and hundreds of metres thick. Distribution of alteration is controlled by the primary permeability of the rocks, as indicated by an increase in the density of alteration spots adjacent to VMS deposits, synvolcanic intrusions and faults, flow contacts, and around concentrated zones of amygdules.

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Figures

- 22.1 OC. Greenish white epidote-quartz alteration patch in massive silicified andesite. Note the concentration of amygdules in the patch compared to the surrounding rock. Waite Andesite formation, Upper Member; Central Noranda Volcanic Complex, Quebec. FOV = 40 cm.
- 22.2 OC. Rhyolite hyaloclastite with fractures filled by epidote-quartz. Waite Rhyolite formation; Central Noranda Volcanic Complex, Quebec. FOV = 80 cm.
- 22.3 OC. Epidote-quartz alteration halos mantling amygdules which are filled by acicular epidote and calcite. Waite Andesite formation, Upper Member; Central Noranda Volcanic Complex, Quebec. FOV = 25 cm.
- 22.4 TS (XPL). Epidote-quartz altered andesite; the primary interstitial texture and the primary minerals have been obliterated, leaving a granular assemblage of epidote and quartz. The amygdule (top) is filled by coarse-grained epidote. Rusty Ridge formation, Central Noranda Volcanic Complex, Quebec. FOV = 7 mm.

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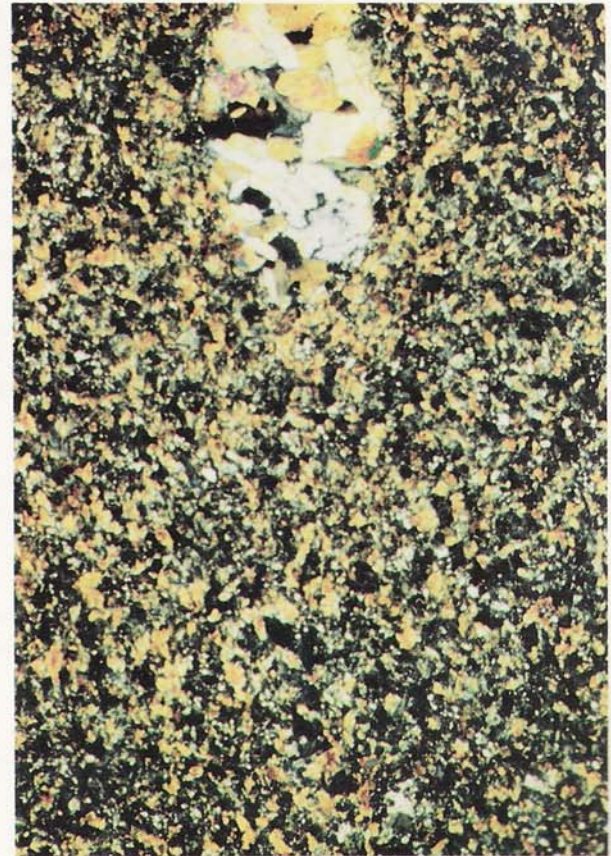
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22.4

FLUORITE

CaF₂

Environment: *Intrusion-related*

Alteration: *Fluorite*

Characteristics

Fluorite often occurs infilling veins and open spaces. It may also form the matrix to hydrothermal breccias, imparting an overall purple colour to the rock.

Hand Specimen: Fluorite occurs as cubes, or less often as octahedra. Twinning on (111) is common, and cleavage, also on (111), is perfect. Fluorite is colourless and transparent when pure, but purple, blue, blue-green and green colours are common; yellow, red and pink are less common. The colour may change from green to purple on exposure to sunlight. Colour zones parallel to the crystal faces are common. Most fluorite fluoresces strongly in ultraviolet light.

Thin Section: Fluorite is colourless to pale purple, with purple being less common. It is isotropic, but may show zones of weak anomalous birefringence. The relief is high and the perfect octahedral cleavage is distinctive.

Related Minerals

Associated: barite, calcite, dolomite, quartz, sericite/muscovite

Accessory: anhydrite, celestite, gypsum, sulphur

Discussion

Fluorite forms under a wide variety of geological conditions and therefore occurs in a broad range of mineralizing environments. Fluorite is an important mineral in alkalic epithermal deposits, occurring in veins, as replacement of wallrock, and in the matrix to breccias. It also occurs in mesothermal veins and pipes, both as the principal constituent, and as a gangue mineral with lead and silver ores. Tin-tungsten and REE-enriched granites and pegmatites are often characterized by the presence of fluorite as a late accessory mineral. Variations in the trace-element composition of fluorite, in particular the frequent substitution of Y and Ce for Ca, may be useful in exploration.

References

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Figures

- 23.1 HS. Pervasive, fine-grained fluorite occurs throughout the matrix of a hydrothermal breccia. Zortman-Landusky Au deposit, Montana.
- 23.2 TS (PPL). Sample as above; showing pervasive fluorite throughout the matrix (fine-grained, purple, high relief). FOV = 5 mm.
- 23.3 TS (PPL). Large fluorite grain, showing good cleavage and small secondary fluid inclusions, overgrown on quartz, muscovite and minor chlorite. Kidston Au deposit, Queensland, Australia. FOV = 2.2 mm.
- 23.4 TS (XPL). Same as above, showing isotropism of the fluorite, and well defined, birefringent laths of muscovite. FOV = 2.2 mm.

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23.1



23.2



23.3



23.4

GARNET

(Ca,Mn,Fe,Mg)₃(Al,Fe,Mn,Cr,Ti)₂(SiO₄)₃

Environment: Skarn

Alteration: Calc-silicate

Characteristics

Outcrops containing abundant garnet skarn alteration are commonly brown in colour and tend to be resistant to weathering. Garnet can overprint the genetically related intrusion to produce endoskarn, as well as the adjacent country rocks to form exoskarn. Skarn garnet can occur either as disseminated crystals, irregular masses, veins, stratabound layers or massive replacements.

Hand Specimen: Skarn garnets are commonly pale pink to brown, but yellow, green, red and black crystals do occur. Individual crystals are commonly <1 cm in diameter and can exhibit rhythmic colour zoning.

Thin Section: Skarn garnets range from euhedral to anhedral, and from weakly birefringent to isotropic. Crystals lack cleavages, but partings parallel to {110} and irregular fractures are common. Optical and compositional zoning are common; crystals are colourless to pale pink or pale brown in PPL.

Related Minerals

Associated: *Prograde* - biotite, calcite, pyroxene, quartz, wollastonite, (olivine in Mg skarns)

Retrograde - amphibole, calcite, chlorite, epidote, K-feldspar, (serpentine in Mg skarns)

Accessory: chondrodite, magnetite, prehnite, scapolite, sulphides, vesuvianite

Discussion

Garnet is a characteristic alteration mineral in many skarns, but also occurs with some porphyry deposits, and in zones of regional and contact metamorphism. Skarn garnets exhibit systematic chemical variations (notably in their Fe, Ca, Mn, Al and Mg contents) that can reflect their associated skarn deposit class and their environment of formation. Most skarn garnets are grossularite-andradite (grandite) solid solutions, although spessartine-almandine garnets are more common in W and Sn skarn deposits, and the garnets in these deposits can also be enriched in F and Sn. Pyrope is generally only a minor component in skarn garnets (less than 1.5 mol % pyrope). In many skarns, garnets display spatially and/or temporally-controlled chemical, textural and optical zoning patterns. Garnets developed proximal to the source intrusions tend to be coarser grained, darker coloured and more abundant than those formed distally. Knowledge of these patterns, at the deposit or single crystal scale, can assist mineral exploration and reveal details on the history of the hydrothermal system.

References

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Figures

- 24.1 OC. Massive brown garnet exoskarn with zones of pyroxene-amphibole alteration (dark green) and veins containing quartz, carbonate, chalcopyrite and magnetite. Queen Victoria Cu skarn deposit, British Columbia. FOV = 1 m.
- 24.2 HS. Layered garnet (light brown), pyroxene (pale green) and biotite (dark brown) skarn developed in thinly bedded limestones and calcareous argillites. Contact Pb-Zn skarn deposit, near Cassiar, British Columbia.
- 24.3 TS (PPL). Euhedral garnet crystals intergrown with carbonate. Lawrence Pb-Zn skarn occurrence, northwestern British Columbia. FOV = 3 mm.
- 24.4 TS (XPL). Same sample as in Figure 24.3; garnets with isotropic cores and birefringent margins. FOV = 3 mm.

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24.1



24.2



24.3



24.4

HEMATITE

Fe₂O₃

Environment: Intrusion-related, Epithermal

Alteration: Potassic, Sericitic, Vuggy quartz, Jasperoid

Characteristics

Hematite is present in a variety of styles of alteration as bladed specular hematite in veins, vugs or matrix, as a replacement of magnetite, or as fine-grained hematite giving a red stain to altered rocks.

Hand Sample: Coarse specular hematite is distinguished by its distinctive habit, lustre and red streak. When coarse, blades of hematite may be intergrown with other minerals in veins. The presence of fine-grained hematite is indicated by the blood-red colour in the rock, and coating fractures.

Thin Section: Hematite is recognized in thin section by dark red colours in transmitted light, and by strong anisotropism and internal reflections in reflected light. Intergrowths with magnetite, and secondary replacement of magnetite around the edges of grains and on fractures (martitization), are common.

Related Minerals

Associated: biotite, chlorite, magnetite, quartz, sericite

Accessory: calcite, chalcopyrite, ilmenite, pyrite, rutile

Discussion

Hematite is a common alteration mineral in many intrusion-related systems. In porphyry copper deposits related to diorite or granodiorite intrusions, hematite may occur in veins (\pm magnetite and sulphides) associated with potassic alteration, and more commonly at higher levels in sericite-chlorite alteration. Hematite is a major mineral in the breccias at the Olympic Dam Cu-U-Au deposit and is typical of similar deposits associated with intrusions, breccias and shallow hydrothermal activity. In the epithermal environment, hematite may be important in vuggy quartz in high-sulphidation systems and also occurs in some base metal-rich low-sulphidation epithermal veins, usually associated with chlorite-rich alteration. Low-temperature alteration of magnetite (primary or secondary) typically results in replacement (martitization) by hematite around grain boundaries and along fractures.

References

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Figures

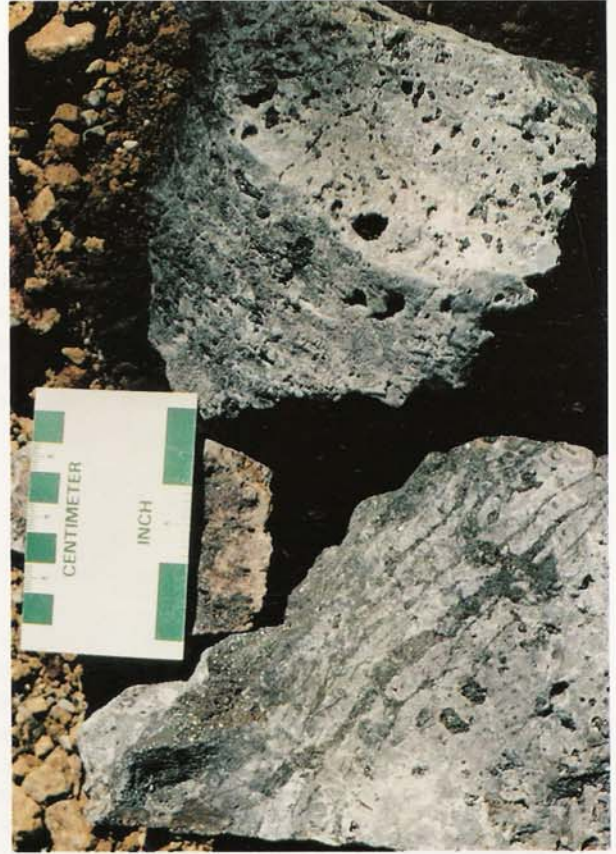
- 25.1 OC. Fine-grained specular hematite (centre of photo) replacing a clast in intermediate volcanic rocks. Equity Silver high-sulphidation Ag-Au-Cu deposit, British Columbia.
- 25.2 HS. Vuggy quartz with vugs and cross-cutting veins filled by coarse specular hematite. Red Dog porphyry - high-sulphidation prospect, northern Vancouver Island, British Columbia.
- 25.3 TS (RL). Intergrowth of hematite, magnetite, bornite and chalcopyrite. Hematite is bladed and silvery grey; magnetite has brownish tints. Galore Creek porphyry Cu-Au deposit, northern British Columbia. FOV = 2.5 mm.
- 25.4 TS (RL). Finely disseminated hematite associated with sericite-carbonate alteration between quartz-carbonate veins. Red Chris porphyry Cu-Au deposit, northern British Columbia. FOV = 5 mm.

Submitted by

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25.1



25.2

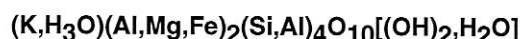


25.3



25.4

ILLITE



Environment: *Intrusion-related, Epithermal*

Alteration: *Illitic, Argillic*

Characteristics

Illite refers to a group of mica-clay minerals which are usually white or cream and typically occur as replacement in volcanic rocks or less commonly as open-space fill. Intense alteration may destroy original textures.

Hand Specimen: Pervasive illite gives a bleached appearance to the rock, and the rock is easily scratched.

Thin Section: Illite tends to be flaky and fine-grained (<1 mm) except where prolonged thermal activity at higher temperatures promotes formation of larger grains with a higher degree of structural order. Crystals show parallel extinction.

Related Minerals

Associated: calcite, chlorite, quartz

Accessory: "adularia", albite, chalcedony, illite/smectite, kaolinite, pyrite, smectite, wairakite

Discussion

Illite is a general term for mica-clay minerals, in which the bulk composition has more silica and less potassium than muscovite. Since its temperature stability ranges from about 200° to 300°C, it can be used as a geothermometer of prograde thermal effects. Above about 300°C, muscovite is produced. At less than about 200°C, interlayered illite/smectite or discrete smectite prevails and may overprint pre-existing illite. Illite forms in the presence of weakly acid (CO₂-rich) fluids. It occurs both proximal and distal to epithermal mineralization and in the peripheral upper parts of some intrusion-related systems. X-ray diffraction analysis is used to confirm the presence of illite and to determine its crystallinity.

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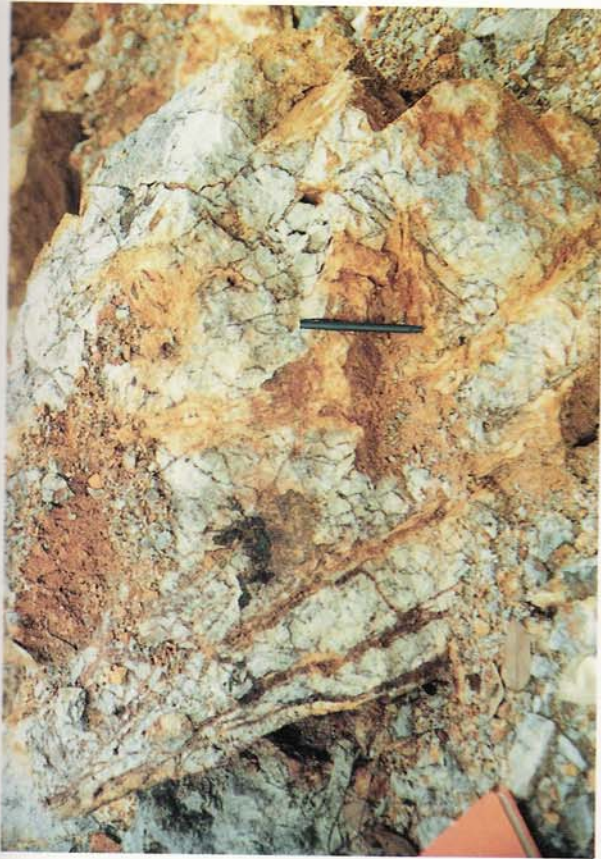
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Figures

- 26.1 OC. Altered andesite composed of illite, quartz and pyrite (mostly oxidized) cross-cut by quartz-filled veins. Volcanic textures are mostly destroyed. Mt. Muro epithermal deposit, central Kalimantan, Indonesia. FOV = 1 m.
- 26.2 DC. Strongly altered rhyolite. Primary feldspars (bleached appearance) and ferromagnesian minerals are completely altered to fine-grained illite and quartz. Broadlands-Ohaaki geothermal system, New Zealand. FOV = 7 cm.
- 26.3 TS (XPL). Strongly altered dacite. Primary feldspars and ferromagnesian minerals are altered to illite (fine-grained, birefringent) and pyrite (opaque) with minor quartz, "adularia" and calcite. Drill core from the Broadlands-Ohaaki geothermal system, New Zealand. FOV = 0.4 mm.
- 26.4 TS (XPL). Plagioclase phenocryst from strongly altered andesite flow that has been completely converted to illite and subsequently cross-cut by a fracture filled with quartz and "adularia". Where quartz veinlets cut plagioclase, the plagioclase is altered to "adularia". Mt. Muro epithermal deposit, central Kalimantan, Indonesia. FOV = 5 mm.

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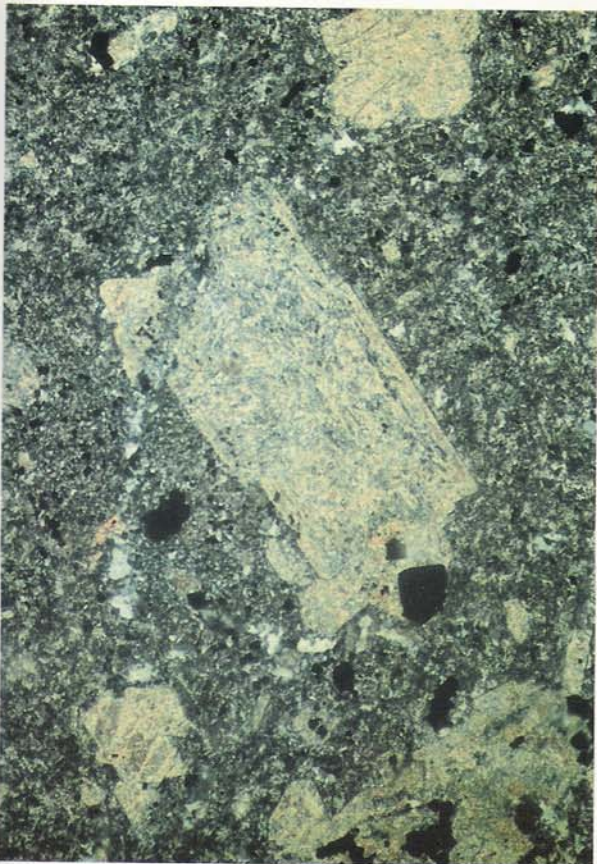
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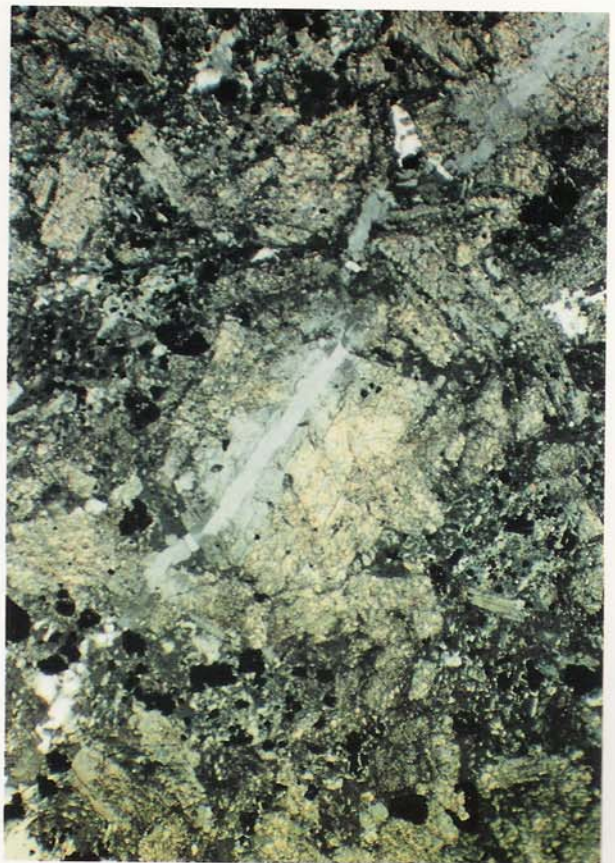
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KAOLINITE/DICKITE



Environment: *Intrusion-related, Epithermal*

Alteration: *Argillic, Advanced Argillic*

Characteristics

Outcrops altered to kaolinite/dickite are typically white to tan in colour and may have a brown to orange oxidized outer surface due to the weathering of pyrite. Outcrops are generally soft, though intermixed quartz may make the rock harder than expected.

Hand Specimen: Although commonly white, kaolinite may show moderate to strong shades of blue to blue green. It typically occurs as pervasive replacement of the rock, as selective replacement of feldspars, or as infill in veins and cavities. Kaolinite is characterized by its softness ($H = 2.5$) and is sticky to the tongue. Dickite is not distinguishable in hand specimen.

Thin Section: Kaolinite and dickite, which are polymorphs, occur in replacement masses and as vein infill. Kaolinite forms colourless to pale yellow crystals, which rarely are pleochroic. Kaolinite is typically fine-grained and occurs as anhedral crystals, platy flakes, and rarely as crystals with hexagonal or triangular outlines. Dickite is colourless to very pale yellow. It occurs as anhedral crystals, as hexagonal tablets, or as parallel or radial fan-like aggregates. Kaolinite replaces minerals, particularly feldspar. It may occur with carbonates such as dolomite and calcite, and may be replaced by sericite and quartz.

Related minerals

Associated: illite-smectite, pyrite, quartz, smectite

Accessory: alunite, carbonate, diaspore, halloysite, illite, marcasite, pyrophyllite, sericite

Discussion

Kaolinite/dickite formed during hydrothermal alteration occur in pervasive and selectively pervasive styles within the marginal argillic zone of high-sulphidation systems; the minerals are indicative of formation at a pH of around 3-4. Kaolinite forms under low-temperature conditions ($<150\text{-}200^\circ\text{C}$), whereas dickite forms at higher temperatures ($<200\text{-}250^\circ\text{C}$) transitional to those for pyrophyllite formation. Kaolinite also forms in the near-surface, steam-heated environment above the water table, and occasionally as zones of massive argillic alteration in low-sulphidation epithermal environments, e.g., Amethyst Vein, Creede, Colorado. Kaolinite may form during supergene weathering, but dickite is restricted to hydrothermal environments.

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Figures

- 27.1 OC. Pervasive kaolinite-alunite alteration at the margin of a vuggy quartz alteration zone. From the Kasuga high-sulphidation epithermal Au-Ag deposit, Japan. FOV = 60 cm.
- 27.2 DC. Quartz-muscovite replacement of feldspars in the envelopes of veins (on left) grading into white quartz-kaolinite alteration (core on right). Valley porphyry Cu deposit, British Columbia. FOV = 15 cm.
- 27.3 TS (PPL). Phenocryst altered to kaolinite and illite cut by veinlets of clear quartz + kaolinite + sulphides. Wafi Prospect, Papua New Guinea. FOV = 2.2 mm.
- 27.4 TS (XPL). Large interlocking dickite with diaspore. Miwah prospect, Indonesia. FOV = 0.54 mm.

Submitted by:

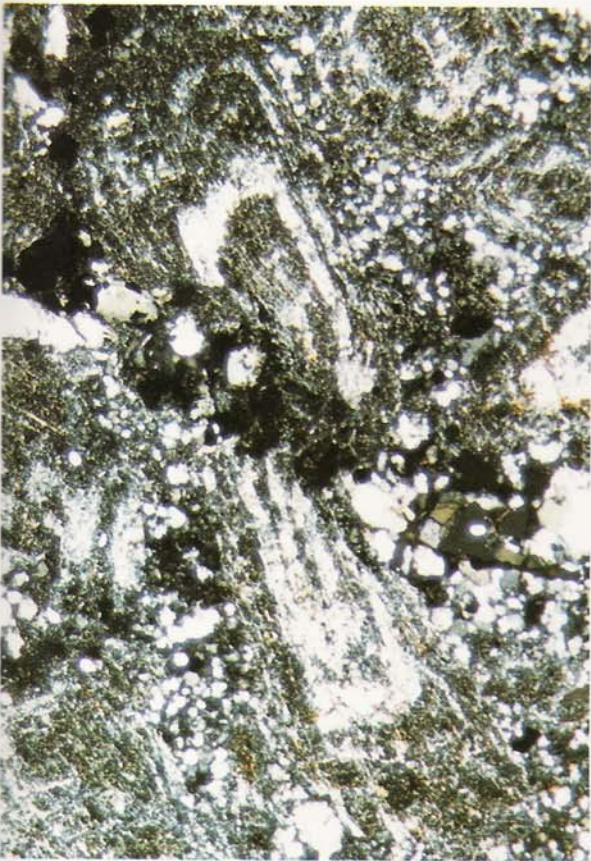
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MAGNETITE

Fe₃O₄

Environment: *Intrusion-related*

Alteration: *Potassic, Calc-silicate*

Characteristics

Magnetite is associated with several environments of hydrothermal mineralization, and in most cases it can be observed in outcrop or detected with a magnet. Magnetite occurs as a constituent of veins and as widespread replacement or disseminations in pervasive alteration.

Hand Specimen: Magnetite is black with a blue iridescence and occurs as octahedrons, dodecahedrons or in granular masses. Magnetite is strongly magnetic and has a black streak.

Thin Section: Magnetite is opaque and commonly has an octahedral crystal outline. In reflected light, magnetite is grey, isotropic and does not have internal reflections.

Related Minerals

Associated: actinolite, apatite, biotite, calcite, chalcopyrite, chlorite, epidote, garnet, hematite, K-feldspar, pyrite

Accessory: bornite, chromite, pyrrhotite, quartz, sphalerite, spinel-group minerals

Discussion

Magnetite is a widespread hydrothermal mineral and is associated with many ore-deposit environments, including: porphyry base-metal, skarn, volcanogenic massive sulphide, and iron formations. Magnetite is a major constituent of iron and tin skarn deposits, and is a significant to minor component of copper, zinc-lead, tungsten, molybdenum and gold skarn deposits. It may occur in massive replacement bodies adjacent to the sediment-intrusive contact, as thin distal bedded replacement horizons, and as disseminated grains within late hydrothermal breccias. Magnetite occurs as disseminations or vein-fills within early quartz-amphibole alteration in some porphyry deposits (eg., Island Copper, British Columbia) and is a common constituent of biotite-rich potassic alteration in many porphyry deposits. High concentrations of magnetite are particularly common in gold-rich porphyry deposits.

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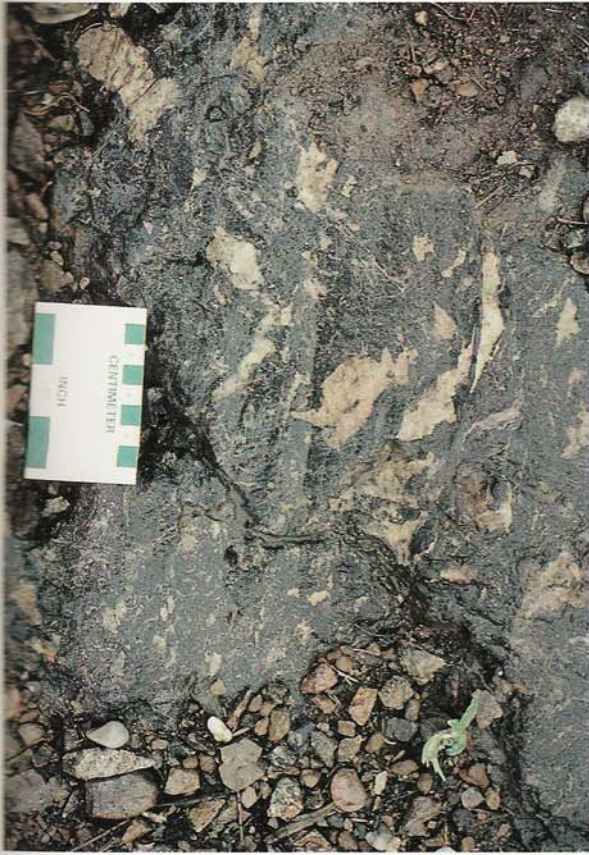
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Figures

- 28.1 OC. Massive magnetite with irregular patches of garnet; zone of magnetite skarn adjacent to porphyry Cu-Au mineralization at the Mt Polley alkaline porphyry deposit, British Columbia.
- 28.2 OC. Fracture-controlled and pervasive magnetite associated with quartz, albite and amphibole in brecciated porphyry. From the core of the Island Copper porphyry Cu-Au-Mo deposit, British Columbia.
- 28.3 TS (PPL). Secondary magnetite intergrown with hydrothermal biotite from the Galore Creek porphyry deposit, British Columbia. The matrix is dominated by secondary K-feldspar (pinkish) and apatite. FOV = 3 mm.
- 28.4 TS (RL). Subhedral to euhedral magnetite crystals (extensively replaced by hematite) intergrown with calcite gangue, adjacent to a coarse euhedral quartz crystal. From the quartz-calcite-chlorite-potassic feldspar matrix of the intrusive Homestake breccia, New World Cu-Au-Ag deposit, Montana. FOV = 480 µm.

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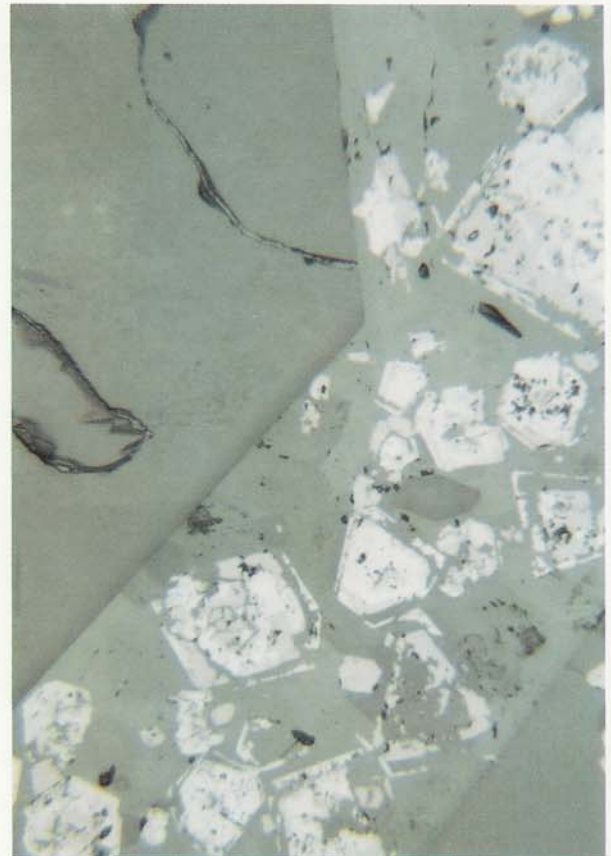
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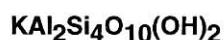


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MUSCOVITE



Environment: *Intrusion-related*

Alteration: *Potassic to Phyllic*

Characteristics

Coarse-grained muscovite occurs in several hydrothermal environments as selvages to veins and as selective to pervasive alteration in wallrocks.

Hand Specimen: Coarse-grained, flaky muscovite is visible with the naked eye and hand lens in the selvages of quartz veins and in the alteration envelopes to veins, where it may selectively replace feldspars.

Thin Section: Muscovite occurs as coarse grains (up to 0.5 mm) that form distinctive layers of grains radiating either from the wallrock or from fragments within veins. In the wallrock, muscovite is generally finer grained and replaces feldspars and the groundmass, or occurs in fractures.

Related Minerals

Associated: quartz

Accessory: biotite, illite, kaolinite, K-feldspar, pyrite

Discussion

Coarse muscovite ($2M_1$) occurs as a major alteration phase in several intrusion-related mineral deposits and is particularly important in some Sn-W systems, associated with greisen alteration. The formation of muscovite during hydrothermal alteration requires a lower ratio of $a(\text{K}^+)/a(\text{H}^+)$ than for K-feldspar-rich (potassic) alteration. Muscovite (sericite) is therefore commonly regarded as a diagnostic mineral of phyllic alteration. However, muscovite also occurs in potassic alteration assemblages, particularly the coarse 'flaky' $2M_1$ variety (e.g., the Highland Valley porphyry deposits, British Columbia). At Highland Valley, coarse muscovite occurs with quartz, K-feldspar, and locally biotite, in pervasive vein envelopes that grade outwards to argillic alteration assemblages. The transition from potassic to argillic alteration indicates decreasing $a(\text{K}^+)/a(\text{H}^+)$ in the hydrothermal fluid during hydrothermal reactions that alter feldspar in the granodiorite wallrock.

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Figures

- 29.1** HS. Quartz-K-feldspar fills fractures and is associated with muscovite-biotite-K-feldspar alteration. Unaltered to slightly recrystallized igneous biotite is visible throughout the sample. Granodiorite of the Bethsaida phase of the Guichon batholith, Valley porphyry deposit, Highland Valley, British Columbia. FOV = 9 cm.
- 29.2** HS. Prominent quartz-bornite vein with the alteration envelope dominated by coarse 'flaky' muscovite. The muscovite passes outward to argillic alteration (kaolinite - mixed-layer clays), which has a pinkish colour, and has partly destroyed primary textures. Valley deposit, British Columbia. FOV = 8 cm.
- 29.3** TS (XPL). Muscovite (bright birefringent mineral) with quartz in veins surrounding igneous quartz and K-feldspar. Valley deposit, British Columbia. FOV = 2.5 mm
- 29.4** TS (XPL). Muscovite-quartz replacement of plagioclase interstitial to quartz and K-feldspar. Valley deposit, British Columbia. FOV = 1.25 mm.

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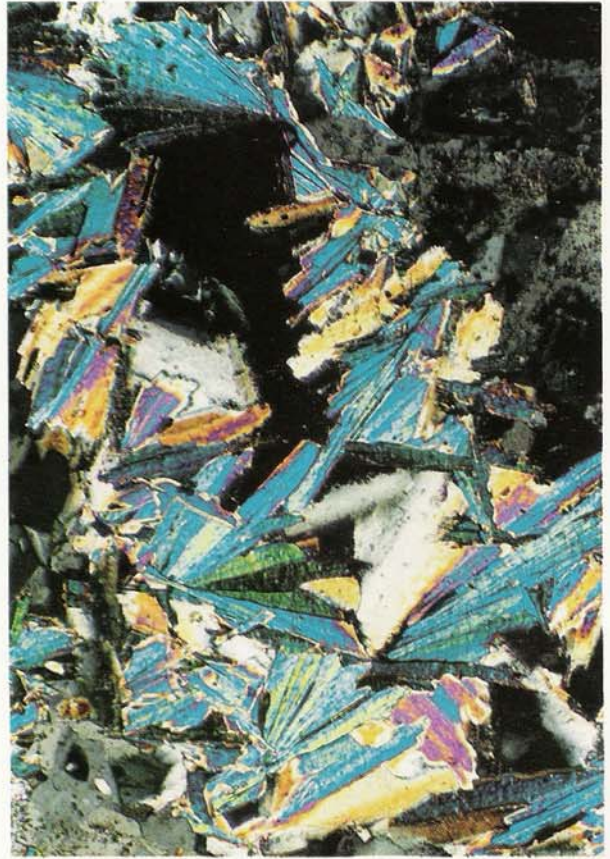
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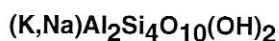


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MUSCOVITE (Sericite)



Environment: Intrusion-related

Alteration: Sericitic, Phyllic

Characteristics

Alteration sericite occurs in pervasive, selectively pervasive and veinlet-controlled styles. Pervasively altered outcrops are commonly white to grey, and primary textures are often absent.

Hand Specimen: Sericite is typically fine-grained but may be visible as white, pale yellow-brown or pale pink flakes. Where alteration is pervasive, the rock varies from soft (sericite-dominant) to hard (quartz-dominant).

Thin Section: Sericite is typically colourless but may be pale yellow to pale green colours. It is fine-grained and occurs as anhedral-euhedral crystals in aggregates. Textures range from selective incipient development in primary phenocrysts to total replacement of pre-existing crystals, deposition in veins, and cavity infill.

Related Minerals

Associated: andalusite, carbonate, chlorite, dickite, K-feldspar, pyrite, pyrophyllite, quartz

Accessory: anhydrite, apatite, hematite, rutile

Discussion

Sericite is a general term for a fine-grained member of the mica group, usually muscovite, but may include paragonite or illite. Sericite forms under slightly acid condition (pH 4-6) and coexists with the kaolin-group minerals at pH 4-5. The crystallinity of sericite increases with increasing temperatures and can be assessed by X-ray diffraction analyses on the peak width of the (001) reflection. Well-formed, fine-grained sericite occurs at >200-250°C with very coarse-grained sericite forming at > 250-300°C. Sericite is a characteristic alteration mineral in porphyry Cu±Au±Mo, where it is the dominant mineral in sericitic or phyllic alteration zones; this style of alteration may overprint other alteration types associated with structures and fractures, or may form a broad halo around the potassic core of the system. Sericite also forms in lode gold and epithermal precious metal environments, where it is contemporaneous with or immediately follows ore formation, and commonly occupies an inner or intermediate alteration zone between the core and outer margin of the altered region.

References

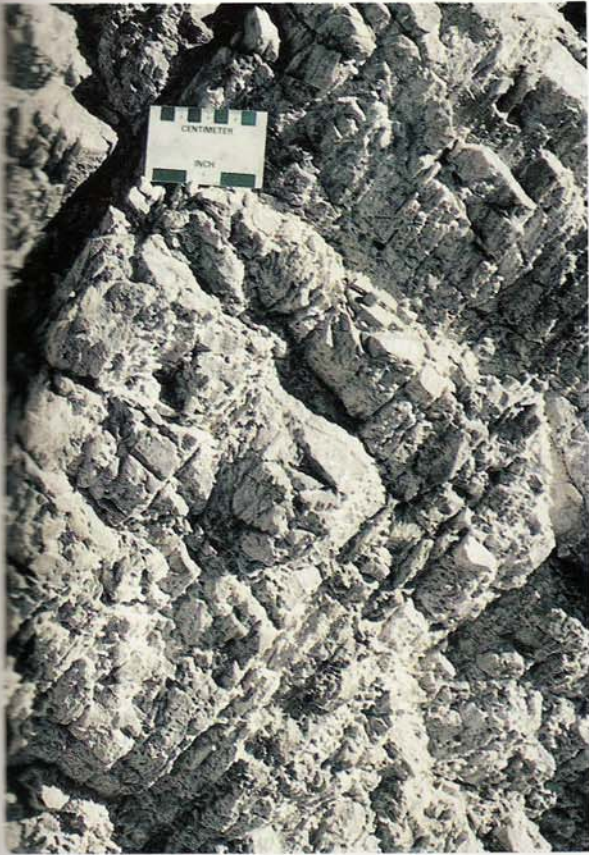
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Figures

- 30.1 OC. Pervasive sericite-quartz-pyrite alteration developed in Precambrian schists adjacent to Cu-Au porphyry mineralization. Lavender pit, Bisbee, Arizona.
- 30.2 DC. Strong sheeted to stockwork quartz veins in quartz monzonite porphyry altered to pervasive sericite-quartz-pyrite. Kemess South porphyry Cu-Au deposit, British Columbia. FOV = 35 cm.
- 30.3 TS (XPL). Plagioclase crystal in porphyritic andesite altered to fine-grained sericite. Menawan prospect, Aceh, Indonesia. FOV = 2.2 mm.
- 30.4 TS (XPL). Plagioclase altered to coarse-grained sheaves of sericite cut by later veinlets of interlocking quartz crystals that displace some of the sheaves of sericite. The quartz has in turn been cut through by fine-grained sericite. Menawan prospect, Aceh, Indonesia. FOV = 2.2 mm.

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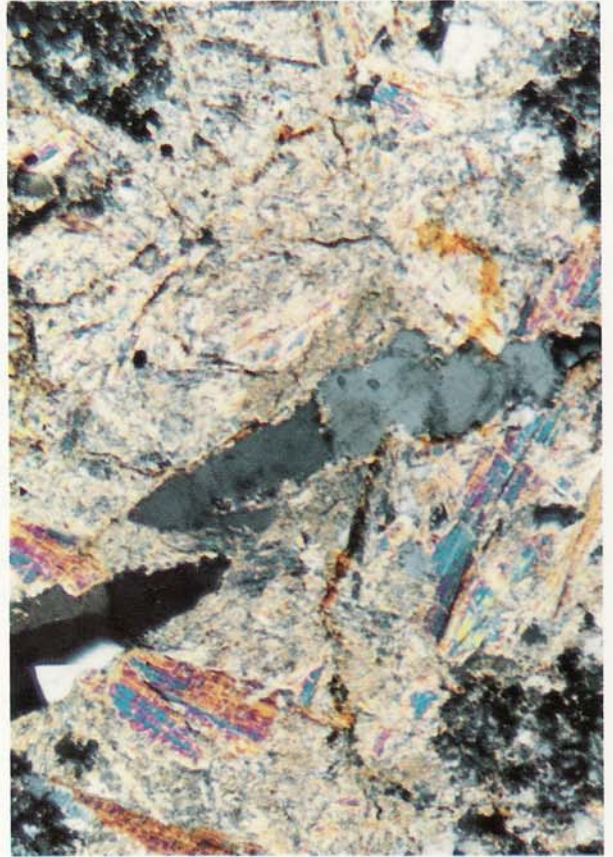
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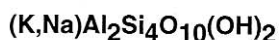


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MUSCOVITE (Sericite)



Environment: *Volcanogenic massive sulphide*

Alteration: *Sericite, Quartz-sericite*

Characteristics

Rocks with sericite or quartz-sericite alteration typically have a bleached appearance compared to unaltered rocks. Quartz is generally intimately associated with the sericite, and occurs in variable amounts. Textures are influenced by those of the pre-existing rock and include massive, uniform, banded and breccia textures. A strong cleavage or schistosity occurs in deformed areas.

Hand Specimen: Sericite-altered rocks are cream, yellow, pale grey, or dark yellow-green, depending on the amount of other associated minerals. Rocks with abundant sericite are soft, and patches are commonly dark and waxy in appearance.

Thin Section: Sericite occurs as aggregates of small white mica plates. In rocks of sub- to lower greenschist metamorphic grade, grain size is typically <50 μm . Textures include replacement of feldspars, micas and other aluminosilicate minerals, and replacement of the groundmass in volcanic rocks, especially primary glass.

Related Minerals

Associated: andalusite, Ca-Mg-Mn-Fe carbonates, chlorite, illite, montmorillonite, pyrite, quartz

Accessory: apatite, corundum, Ti-oxides, topaz

Discussion

Sericite, quartz-sericite or quartz-sericite-pyrite alteration is characteristic of volcanogenic massive sulphide deposits. This alteration occurs mainly in the footwall of the ore deposits, either as the dominant footwall alteration, or as an inner alteration zone enveloping a core zone of silicification (e.g., Kuroko deposits, Japan) or a core zone of chlorite alteration (many Paleozoic and Precambrian deposits). Distribution, composition and intensity of sericite alteration, and spatial relationships to other alteration types, can be good exploration guides to volcanogenic massive sulphide ores.

References

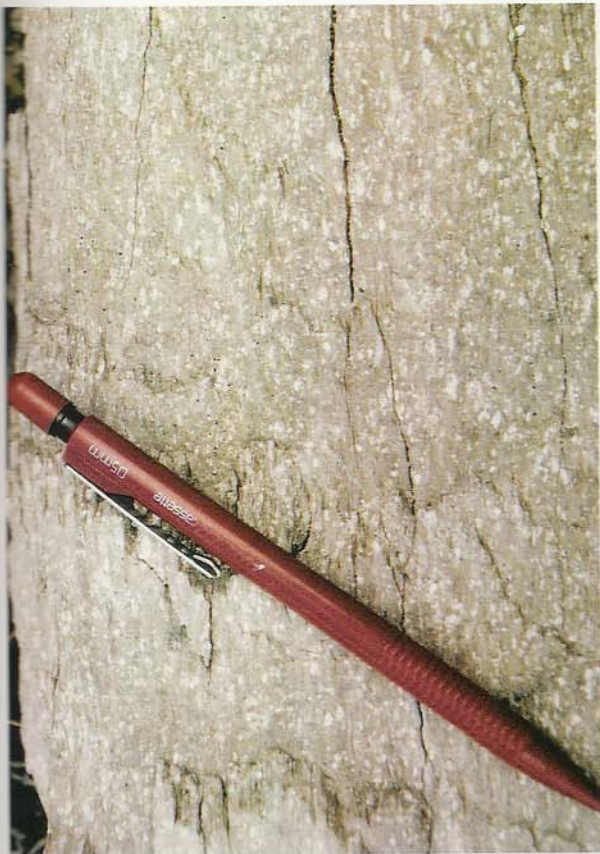
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Figure

- 31.1 OC. Moderately, pervasively sericite-altered, feldspar-phyric (white spots), rhyolitic pumiceous pyroclastic rock in the footwall of the Rosebery massive sulphide deposit (Cambrian age), Tasmania, Australia. FOV = 18 cm.
- 31.2 DC. Quartz-sericite-altered intrusive rhyolite dome in the footwall of the Petiknäs Norra massive sulphide deposit (Early Proterozoic age), Sweden. Left core shows pervasive weak to moderate quartz-sericite alteration. Right three cores show pseudobreccia alteration texture comprising strong sericite alteration (dark yellow-green) overprinted by quartz-sericite (pale yellow-grey). FOV = 20 cm.
- 31.3 TS (PPL). Rhyolitic pumice fiamme (far left) and glass shards (centre and right) replaced by sericite, Hercules massive sulphide deposit (Cambrian), Tasmania, Australia. The sericite is yellow-brown and extremely fine-grained. FOV = 2.1 mm.
- 31.4 TS (XPL). Fine-grained sericite-quartz alteration in vesicular basaltic andesite; vesicles are marked by concentrations of opaque pyrite. From the Hellyer volcanogenic massive sulphide deposit, Tasmania, Australia. FOV = 2.5 mm.

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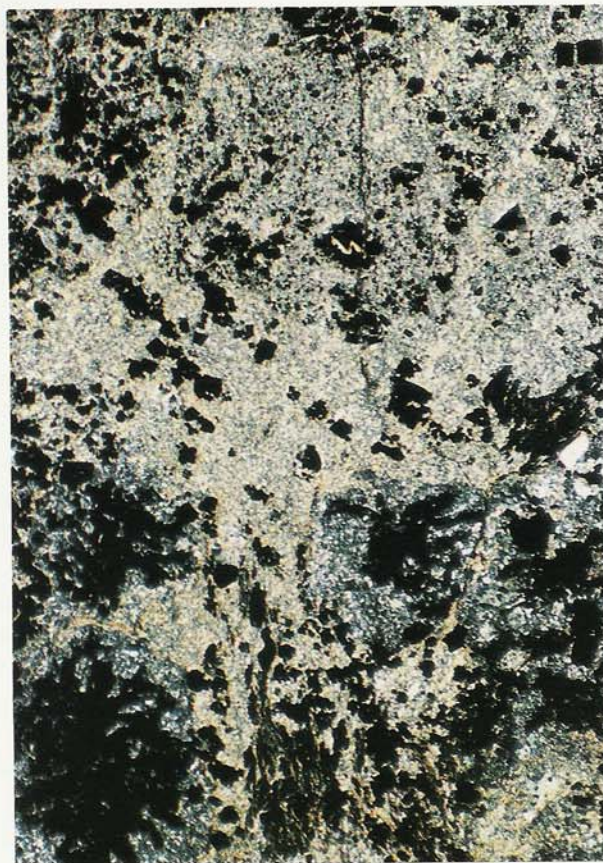
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ORTHOCLASE (“Adularia”)

KAlSi_3O_8

Environment: Epithermal

Alteration: Potassic, “Adularia”

Characteristics

“Adularia” is a variety of orthoclase showing a form that, ideally, is rhombic in cross-section. It is commonly found in, and associated with low temperature, low-sulphidation epithermal ore deposits. “Adularia” is commonly intergrown with quartz and lattice calcite in open-space fillings. It and quartz can also replace host-rock minerals, typically along vein margins or in permeable rock units, wherein primary textures are preserved in most cases.

Hand Specimen: “Adularia” is seldom megascopically visible, except in late vugs or in quartz veins, where it has a coarser grain size. It is translucent, colourless to white, seldom tan or pink (due to hematite inclusions) and is best identified by its rhombic form. It may be confused with carbonates. Pervasive “adularia” forms a hard, resistant rock similar to silicification.

Thin Section: “Adularia” occurs as anhedral to euhedral rhombic crystals (5-50 μm long), typically in close association with quartz and illite, in hydrothermal quartz veins, replacing aluminosilicates, or filling voids. Crystals can show complex zonations of optical structures (monoclinic and triclinic) with some grains showing pairs of alternating oriented sectors. “Adularia” is replaced commonly by illite.

Related Minerals

Associated: albite, calcite, chlorite, illite, quartz, sericite

Accessory: fluorite, pyrite, rhodochrosite, wairakite

Discussion

“Adularia” is a characteristic mineral associated with low-sulphidation epithermal mineralization. Vein “adularia” may form as a result of boiling and exsolution of CO_2 , which increases solution pH and promotes stability of “adularia” over illite. Its widespread occurrence indicates zones of high permeability. Selective replacement of plagioclase is usually restricted to the immediate envelopes of epithermal quartz veins.

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Figures

- 32.1 OC. Adularized sediments, which host Au-rich epithermal quartz veins, at the Manzanita mine, Sulphur Creek district, northern California. The pervasive alteration preserves original sedimentary textures. FOV = 40 cm.
- 32.2 HS. Vug-filling “adularia” (note rhombic forms) coated by jarosite from the Simberi deposit, Papua New Guinea. FOV = 5 mm.
- 32.3 TS (XPL). Clustered euhedral (diamond-shape) “adularia” crystals surrounded by quartz vein fill. Sample is from the Mt. Muro epithermal deposit, Central Kalimantan, Indonesia. FOV = 4.2 mm.
- 32.4 TS (PPL). “Adularia” rhombs in a quartz vein, from the McLaughlin mine, northern California. FOV = 0.26 mm.

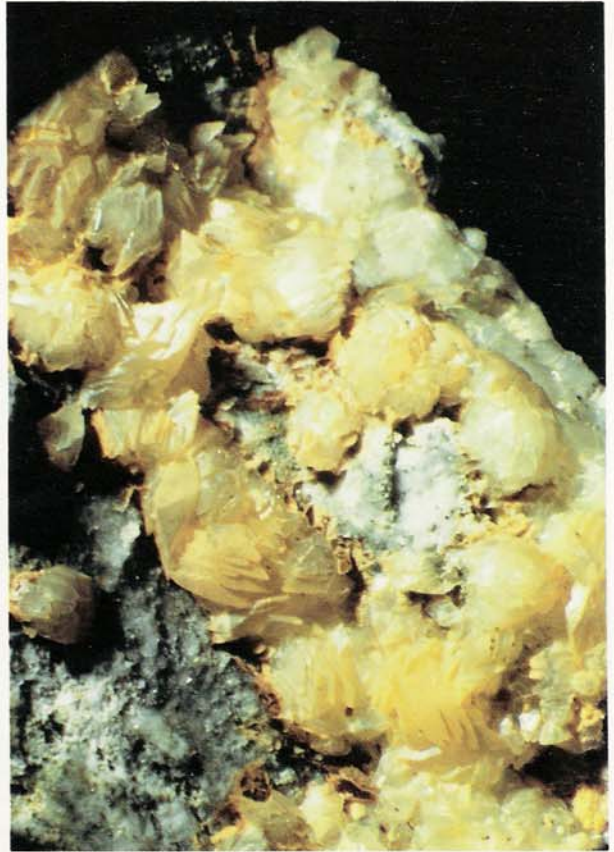
Submitted by:

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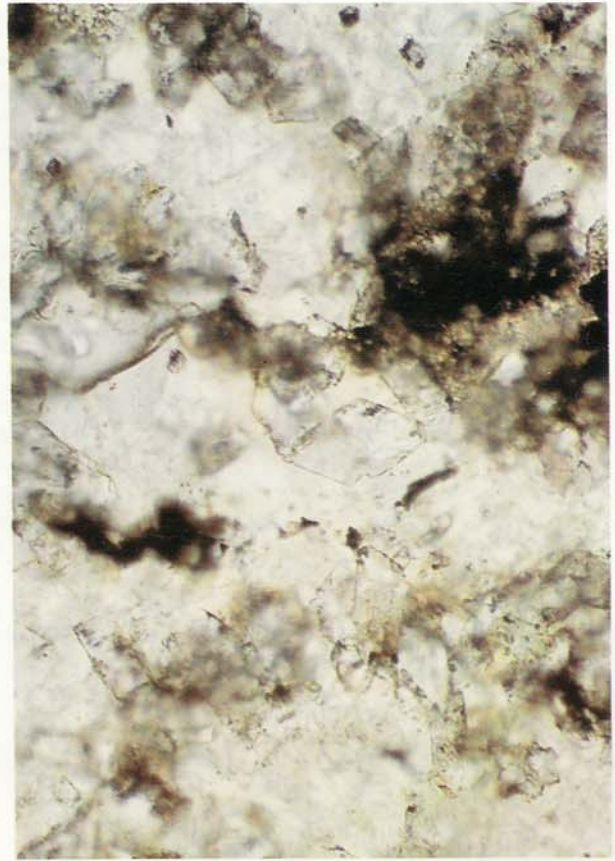
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POTASSIUM FELDSPAR

KAlSi_3O_8

Environment: Intrusion-related

Alteration: Potassic; K-Feldspathatization; Fenitization

Characteristics

Potassium feldspar (K-feldspar) occurs in pervasive, selectively pervasive and veinlet-controlled alteration styles, as well as in alteration envelopes which may coalesce around veins.

Hand Specimen: K-feldspar may be white, pink, red or tan. The colour is usually due to the presence of iron in the crystal structure, or to finely disseminated solid inclusions of iron oxide. When hydrothermal K-feldspar is fine-grained, identification and estimation of its abundance are aided by staining with sodium cobaltinitrite.

Thin Section: Secondary K-feldspar grains range from submicrometre to several centimetres in size. The most common habit is as massive, intergrown, equant grains. Alteration may be totally pervasive, but is more commonly manifested as selective replacement of pre-existing feldspars, or as fill in dilatant veins. K-feldspar commonly contains abundant fluid inclusions with rectangular forms. The typically cloudy, turbid appearance of hydrothermal K-feldspar commonly distinguishes it from igneous K-feldspar.

Related Minerals

Associated: biotite, bornite, chalcopyrite, magnetite, molybdenite, quartz

Accessory: albite, anhydrite, pyrite, rutile, sericite

Discussion

K-feldspar is a major alteration phase in many ore-deposit types, but it is most common and most abundantly developed in porphyry base and precious metal deposits. K-feldspar alteration usually forms early in the hydrothermal history of a mineral deposit, and may either precede or form in company with main-stage alteration and mineralization. In porphyry deposits, K-feldspar tends to be developed better in felsic than in mafic host rocks. In high-temperature alteration, K-feldspar is usually orthoclase, whereas at lower temperatures microcline may form. Early hydrothermal K-feldspar is very susceptible to replacement by sericitic alteration, and evidence for its former presence may be locally obliterated.

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Figures

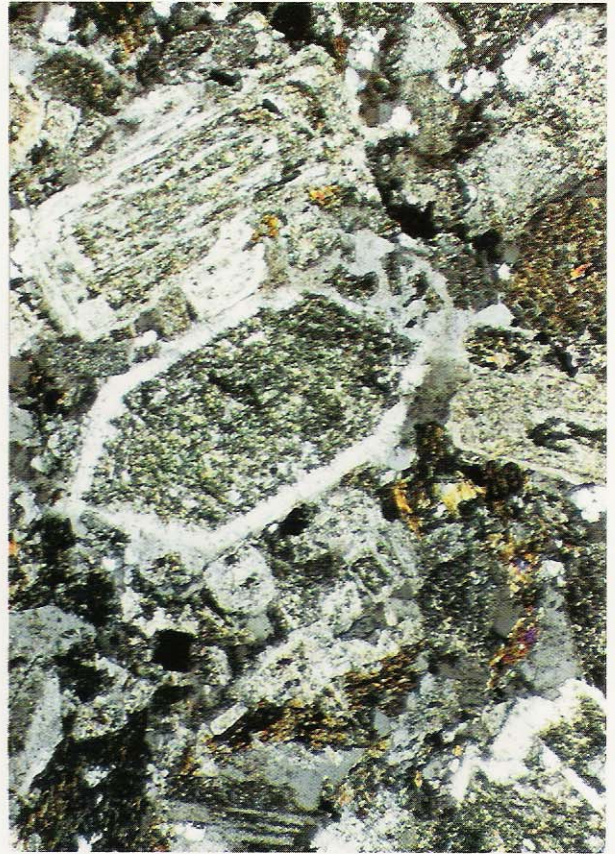
- 33.1 HS. Unstained (top) and stained (bottom) samples of pervasively K-feldspar altered Pothook diorite phase of the Iron Mask batholith, British Columbia. FOV = 13 cm.
- 33.2 TS (XPL). Secondary K-feldspar rims igneous plagioclase phenocrysts. The K-feldspar is accompanied by secondary biotite, and the cores of the plagioclase were subsequently altered to sericite. Dos Pobres porphyry Cu deposit, Arizona. FOV = 3 mm.
- 33.3 TS (PPL). Brown turbid area in the lower part of the photo illustrates a sharply bounded, strongly pervasive K-feldspar alteration front. Beyond the front, original plagioclase phenocrysts are affected by brown, selectively pervasive K-feldspar alteration, whereas clear, igneous groundmass orthoclase is unaffected by hydrothermal fluids. Copper Mountain porphyry district, British Columbia. FOV = 3 mm.
- 33.4 TS (XPL). Same view as Figure 33.3. Note the characteristic patchy appearance of K-feldspar altered plagioclase phenocrysts. FOV = 3 mm.

Submitted by:

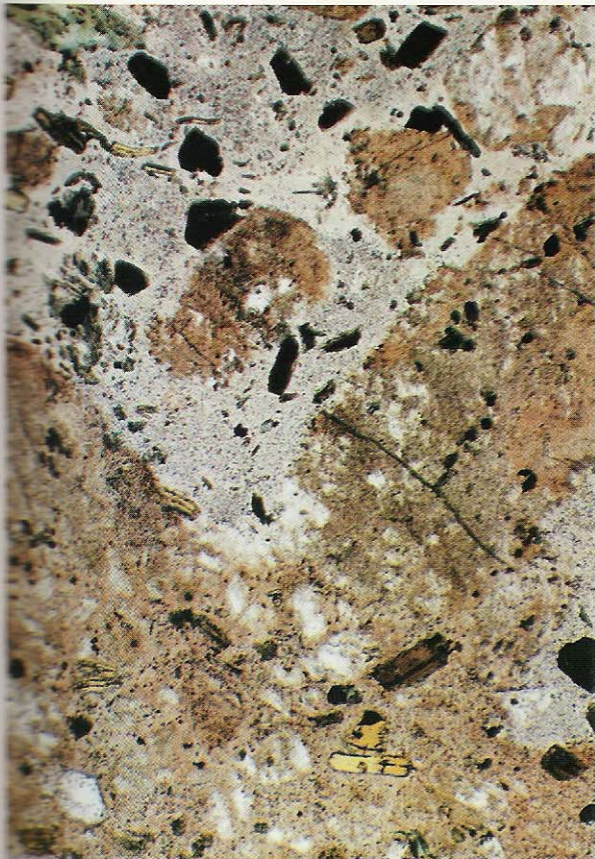
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33.1



33.2



33.3



33.4

PYRITE / PYRRHOTITE (after magnetite)

FeS₂/Fe_{1-x}S

Environment: Mesothermal

Alteration: Sulphidation

Characteristics

Sulphide (dominantly pyrite and pyrrhotite) in banded iron formation is often constrained to particular mesobands in the host rock, resulting in a “bedded” appearance. Quartz veins and zones of structural complexity in the iron formation are in common spatial association with zones of sulphide.

Hand Specimen: Bands of sulphide commonly occur as envelopes distributed bilaterally about quartz-carbonate veins or pervasively in areas of quartz veining. The bands of sulphide and quartz-carbonate veins cut finely laminated magnetite-jasperoid bands.

Thin Section: In reflected light, sulphide and oxide iron-bearing minerals may occupy separate bands and are rarely in contact. Pyrite or pyrrhotite mantles or replacement of magnetite may be present.

Related Minerals

Associated: arsenopyrite, carbonate, chlorite, hematite, hornblende, magnetite, quartz

Accessory: biotite, grunerite, hedenbergite

Discussion

Banded iron formations (BIF) are host to significant gold deposits, mainly in Precambrian rocks. Principal components of the host rocks include variable proportions of interbedded layers of oxide (magnetite, hematite), silica (chert, jasperoid), carbonate (ferroan dolomite), amphiboles (grunerite, hornblende), and sedimentary rock (argillaceous to arenaceous units). Common features of this style of mineralization and alteration include: [1] auriferous pyrite, pyrrhotite and arsenopyrite envelopes surround individual veins; [2] gold-bearing veins and veinlets occur in the mineralized zone; [3] bedding-controlled pyrite and arsenopyrite pass laterally away from auriferous veins into magnetite, carbonate or amphibole layers that are typical components of unmineralized BIF; [4] gold grains show an intimate association with sulphide grains, either affixed to grain margins or in fractures cutting sulphide grains; [5] gold may also, rarely, be present within the vein material. These observations are consistent with the interpretation that the mineralizing process has involved the exchange of oxygen for sulphur (sulphidation) in the host rock due to the influx of a sulphur-bearing species, such as H₂S.

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Figures

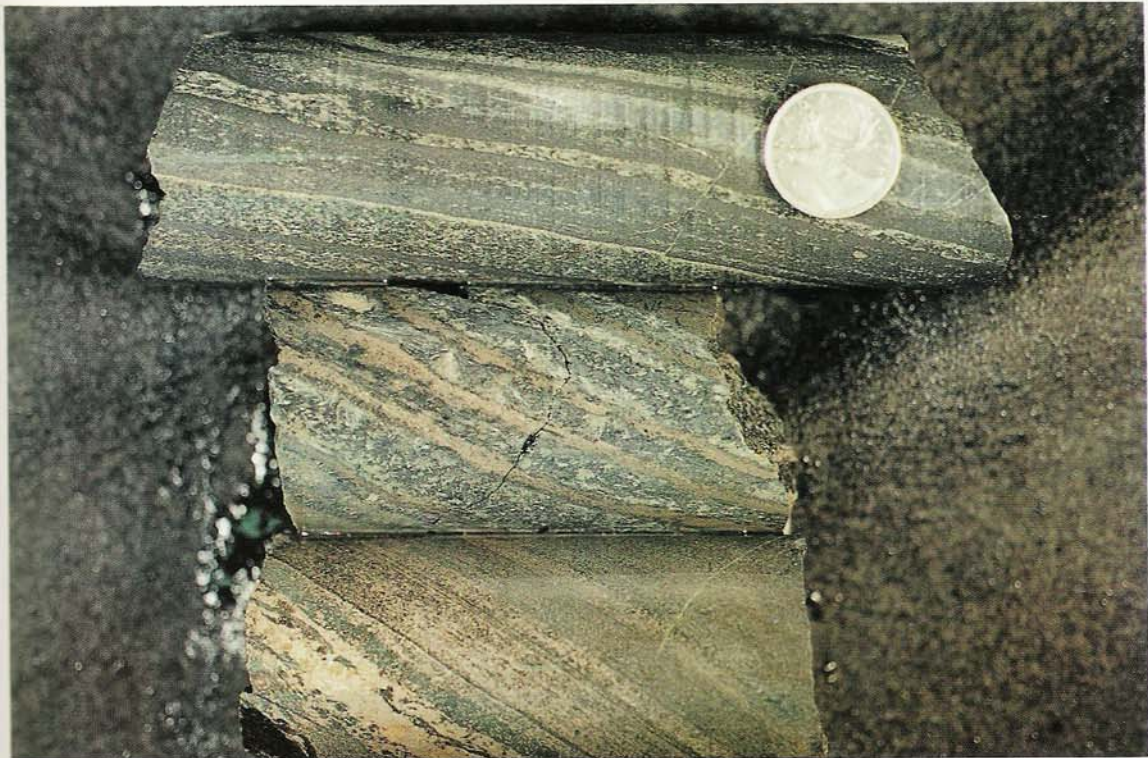
- 34.1 HS. Slab of finely laminated magnetite-jasperoid (red chert) iron formation from the Solomon's Pillar deposit, Geraldton greenstone belt, Ontario. Iron formation is cut by a quartz-carbonate vein with a gold-bearing pyritiferous halo developed around the vein.
- 34.2 DC. Three examples of drill core from the Lupin deposit Northwest Territories. Core shows the progression from pyrrhotite-rich mineralized iron formation (bottom) to magnetite-rich unmineralized iron formation (top). FOV = 15 cm.

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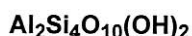


34.1



34.2

PYROPHYLLITE



Environment: *Intrusion-related, Epithermal*

Alteration: *Advanced Argillic*

Characteristics

Where pyrophyllite is the dominant mineral, the rock will be soft, waxy, massive and textureless. More typically, pyrophyllite occurs with quartz and other minerals, and the rock may retain primary textures. Pyrophyllite-rich alteration shows a strong foliation in deformed zones.

Hand Specimen: Pyrophyllite is usually white to tan and can be detected by the soapy feel on fractures. Where dominant, pyrophyllite may form the matrix to breccias, or pervasive alteration envelopes around veins.

Thin Section: Pyrophyllite resembles sericite in thin section and they may be difficult to distinguish. In the absence of X-ray diffraction analyses, the association with other advanced argillic minerals, particularly diasporite, is diagnostic. Pyrophyllite selectively replaces feldspars, forms pervasive envelopes around veins or fractures, occurs in clots, or may be disseminated in the matrix.

Related Minerals

Associated: diasporite, kaolinite, pyrite, quartz

Accessory: aluminum phosphates, alunite, andalusite, corundum, dumortierite, sericite

Discussion

Pyrophyllite is a characteristic mineral of advanced argillic alteration that typically results from the reaction of low-pH fluids with rocks. The mineral forms at temperatures intermediate between kaolinite and andalusite (~200-350°C) and is therefore important in the deeper parts of some high-sulphidation epithermal deposits and the upper parts of some porphyry systems. Pyrophyllite also occurs in some gold deposits associated with strong deformation, though the timing of pyrophyllite crystallization is uncertain. Pyrophyllite forms through the metamorphism of aluminous rocks, which may represent earlier alteration (high-sulphidation or surficial acid-leach zones above boiling geothermal systems), weathered regoliths, or some aluminum-rich sedimentary rocks.

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Figures

- 35.1 OC. Quartz-pyrophyllite breccia with minor dumortierite (blue mineral) from the Island Copper porphyry Cu-Au-Mo deposit, British Columbia. The matrix to the breccia is dominated by pyrophyllite.
- 35.2 DC. Volcanic breccia largely replaced by quartz and pyrophyllite. Frieda River porphyry Cu-Au deposit and related high-sulphidation alteration system, Papua New Guinea.
- 35.3 TS (XPL). Pyrophyllite selective replacement of feldspar phenocrysts in a quartz-rich matrix. The highly birefringent mineral is diasporite. Sample as in Figure 35.2. FOV = 2.5 mm.
- 35.4 TS (XPL). Coarse aggregate and fine matrix pyrophyllite showing characteristic birefringence. Pyrophyllite is intergrown with quartz. From the advanced argillic alteration zone in the Taseko porphyry system, British Columbia. FOV = 1.25 mm.

Submitted by:

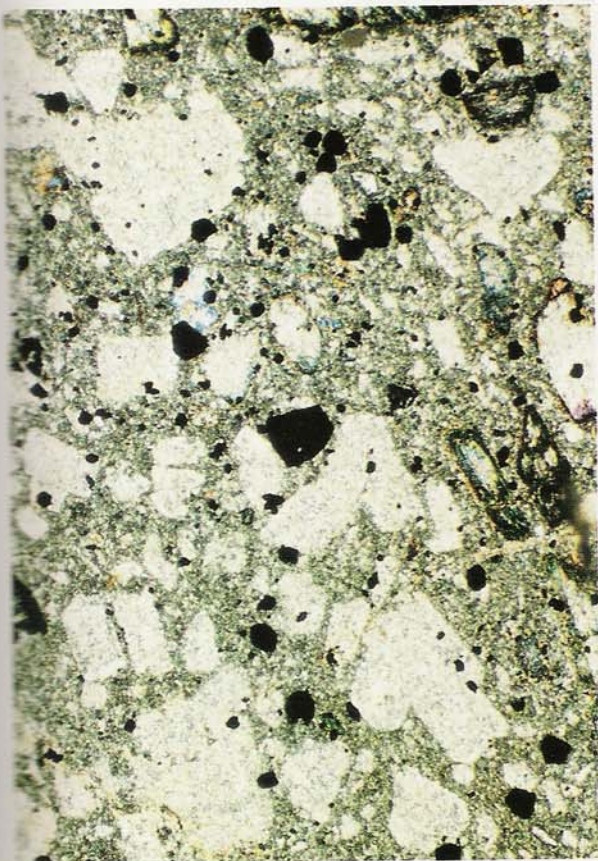
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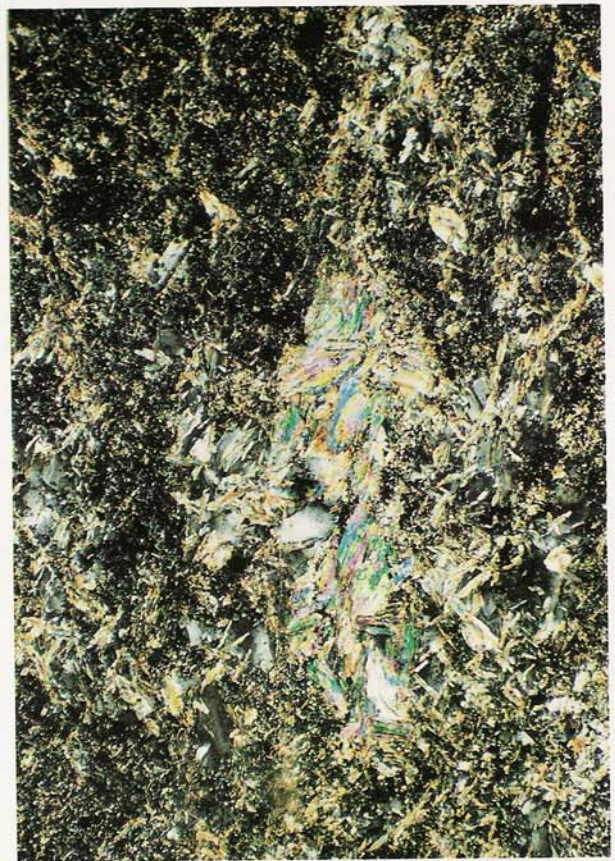
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QUARTZ (Jasperoid)

SiO₂

Environment: Sediment-hosted

Alteration: Silicification

Characteristics

Large masses of jasperoid form rugged prominent outcrops and tend to have sharp contacts with unreplaced host rocks. Typical outcrops are light grey to black in colour unless oxidation has resulted in staining by iron oxides. Alteration may be bedding-controlled or fault-controlled.

Hand Specimen: Jasperoid may exhibit two textural varieties in hand specimen: breccia and aphanitic. Brecciated jasperoid is characterized by multiple quartz veining events. In the aphanitic variety, faint relict bedding is commonly preserved.

Thin Section: A complex history of multiple veining events can be recognized in the breccias. Some of the larger veins are open-space fillings and may contain barite. Clasts consist of quartz and clay minerals. Aphanitic jasperoid may show several quartz morphologies (xenomorphic, subhedral, euhedral). The molecular replacement of carbonate by quartz may faithfully preserve fossils.

Related Minerals

Associated: barite, kaolinite

Accessory: anatase, illite, smectite, pyrite

Discussion

Jasperoid is a common epigenetic alteration product in which there is massive replacement of limestone by silica. Jasperoid bodies are localized on faults (fracture control) and may spread laterally in a favourable bed (bedding control). Many jasperoids contain economic silver and gold. At the Mercur sediment-hosted Au deposit, Utah, Ag:Au ratios vary from 1:10 to >10:1 and $\delta^{18}\text{O}$ ranges from -1 to +27 per mil suggest that mixing of an unevolved meteoric water with an isotopically evolved meteoric water was responsible for jasperoid formation. Fluid inclusion data from sediment-hosted jasperoids in the U.S.A. indicate a mean homogenization temperature of ~200°C and variable salinities.

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Figures

- 36.1 OC. Bedding controlled jasperoid north of the Mercur sediment-hosted Au mine (in background), Utah.
- 36.2 HS. Brecciated jasperoid from Carrie Steel Fault zone in the Mercur sediment-hosted Au mine, Utah. The veining forms a dense stockwork. All clasts are completely silicified. The dark colour is from carbonaceous matter.
- 36.3 TS (PPL). Aphanitic jasperoid showing replacement of Mississippian fossil by silica. From the Mercur pit in the Mercur sediment-hosted Au mine, Utah. FOV = 230 μm .
- 36.4 TS (XPL). Aphanitic jasperoid showing replacement of fossil. Same view as Figure 36.3. FOV = 230 μm .

Submitted by

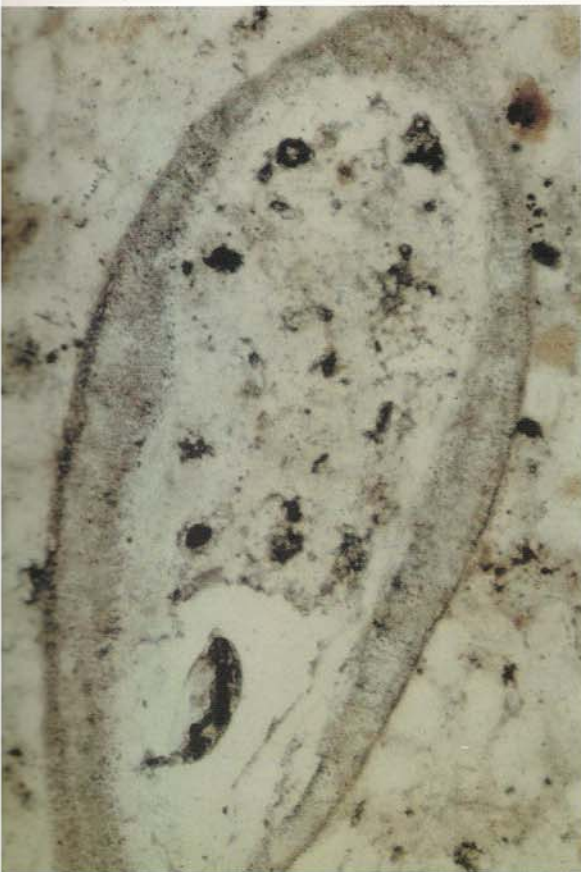
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QUARTZ

SiO₂/SiO₂ • nH₂O

Environment: *Volcanogenic massive sulphide, Epithermal*

Alteration: *Silicification*

Characteristics

Quartz or related polymorphs occur either in void spaces (vesicles, open fractures and between clasts in fragmental rocks), or as a partial to total replacement of rock. Replacement may be texturally destructive and results in hard, resistant outcrops. Silica polymorphs range from crystalline quartz to porcelaneous "chalcedony" and opaline silica.

Hand Sample: Replacement silicification is generally inferred from a bleached appearance and increased hardness of the rock. Other alteration types have a similar appearance (e.g. adularization).

Thin Section: Silicification of rock matrix is best recognized in thin section. Quartz is generally microgranular and floods the groundmass. Open spaces such as vesicles, vugs and fractures may also be infilled, often with slightly coarser quartz. In many cases selective silicification will preserve primary textures.

Related Minerals

Associated: "adularia", albite, calcite, chlorite, epidote-zoisite, illite, pyrite, sericite

Accessory: apatite, magnetite, rutile (anatase)

Discussion

Zones of silicified rocks are common in many types of hydrothermal systems, where silica precipitation is typically a result of decreasing fluid temperatures. In volcanogenic massive sulphide deposits, silicification is most common adjacent to feeder pipes but may also affect the uppermost 50 to 100 metres of the footwall. Silicification in epithermal systems can be pervasive over large (>100m²) areas; it may be associated with sericite and "adularia", and in some cases, with mineralization. Silicification in both environments may be structurally controlled, forming envelopes around quartz veins or stockwork zones, or it may be stratigraphically controlled by more permeable units. In geothermal/epithermal systems, laterally continuous replacement zones of opaline silica or "chalcedony" may mark the paleowater table.

References

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Figures

- 37.1 OC. Silicified porphyritic latite cut by pyrite-filled fractures; the porphyritic texture is still visible. Sleeper low-sulphidation epithermal Au-Ag deposit, Nevada. FOV = 30 cm.
- 37.2 OC. Partly silicified porphyritic andesite, with silicification as coalesced envelopes around fractures, leaving kernels of less altered andesite with visible porphyritic texture. Temora high-sulphidation epithermal Au deposit, New South Wales. FOV = 25 cm.
- 37.3 TS (XPL). Silica flooding of the matrix and quartz-filled vesicles in the immediate footwall of the H-W volcanogenic massive sulphide deposit, Vancouver Island, British Columbia. FOV = 0.32 mm.
- 37.4 TS (XPL). Former olivine phenocrysts in a matrix of plagioclase microlites, all completely replaced by fine quartz; altered Pliocene basaltic andesite at the McLaughlin epithermal Au deposit, California. FOV = 0.27 mm.

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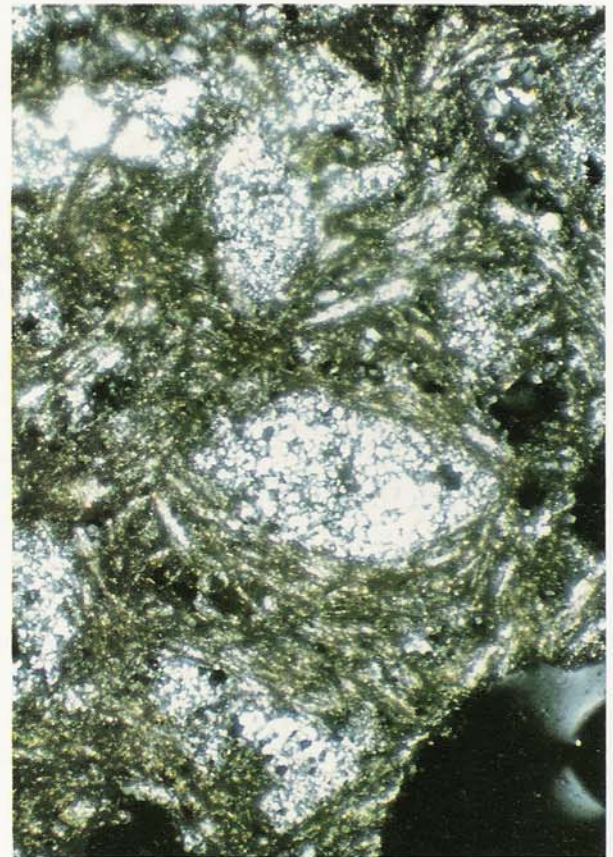
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QUARTZ (Vuggy)

SiO₂

Environment: Epithermal

Alteration: Vuggy quartz, Vuggy silica, Residual silica

Characteristics

Vuggy quartz alteration is characterized by fine-grained quartz with numerous open spaces that may be partly filled by a variety of minor minerals. Vugs typically form through dissolution of fragments or phenocrysts in the host rocks.

Hand Specimen: The quartz is usually grey and sugary to microcrystalline, with vugs variable from < 1 mm up to 50 mm. Vugs may be lined by quartz, enargite, pyrite, and other minor minerals. In many cases, the sulphides are oxidized, resulting in extensive limonite and jarosite coatings around vugs.

Thin Section: Quartz forms a dense mosaic texture. Vugs are lined by euhedral quartz and other minerals, and may be filled. The quartz may contain irregular clots of rutile, pyrite and other sulphides. In some cases, the quartz is cut by veinlets of secondary quartz, sulphides and sulphates (alunite or barite). Original volcanic (porphyritic or breccia) and sedimentary textures may be visible.

Related Minerals

Associated: alunite, jarosite, limonite, pyrite, quartz, sulphur

Accessory: barite, enargite, kaolinite, pyrophyllite, rutile (anatase), tennantite

Discussion

Vuggy quartz alteration forms by reaction of extremely low-pH aqueous fluids or vapours with rocks. These fluids effectively remove all components in the rock, apart from SiO₂ (quartz) and TiO₂ (rutile), leaving residual vuggy quartz. On the margins of the alteration zone, vuggy quartz may grade into quartz-alunite and quartz-kaolinite (or pyrophyllite at higher temperatures) alteration. This change reflects the partial neutralization of the low-pH fluids during reactions with wallrocks. Vugs in the alteration zone may be filled by late quartz, sulphides, sulphates or sulphur. Stable isotope data indicate that the low-pH fluids are of magmatic origin. Vuggy quartz alteration forms the core of many high-sulphidation Au-Cu deposits, and occurs in the upper parts of some porphyry deposits and the eroded centres of some strato-volcanoes.

References

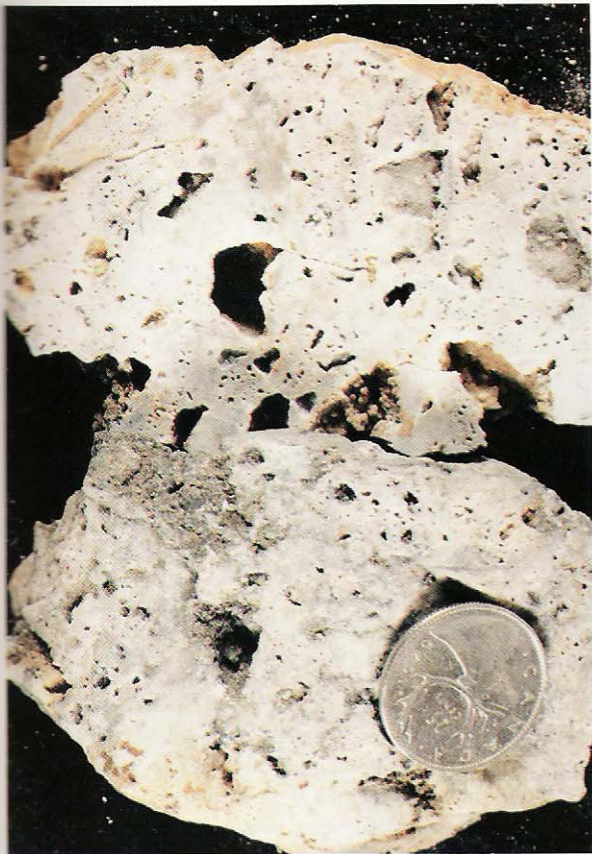
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Figures

- 38.1** HS. Vuggy quartz from the core of the mineralized zone at the Kasuga high-sulphidation Au-Cu deposit, Japan. Vugs are selectively leached fragments. Some vugs are lined by enargite and pyrite. FOV = 12 cm.
- 38.2** HS. Partly oxidized vuggy quartz developed in a volcanic fragmental rock (pyroclastic or volcanoclastic). Paradise Peak high-sulphidation Au deposit, Nevada, U.S.A. The feldspar phenocrysts were selectively leached or replaced by quartz and minor amounts of alunite (white mineral). FOV = 10 cm.
- 38.3** TS (XPL). Vuggy quartz with vugs lined by subhedral quartz. Sample as in Figure 38.1. FOV = 4.2 mm.
- 38.4** TS (XPL). Vuggy quartz with ghosts of feldspar phenocrysts. The feldspars have been replaced by quartz or alunite (birefringent mineral), or have been leached, leaving vugs. Sample as in Figure 38.2. FOV = 4.2 mm.

Submitted by:

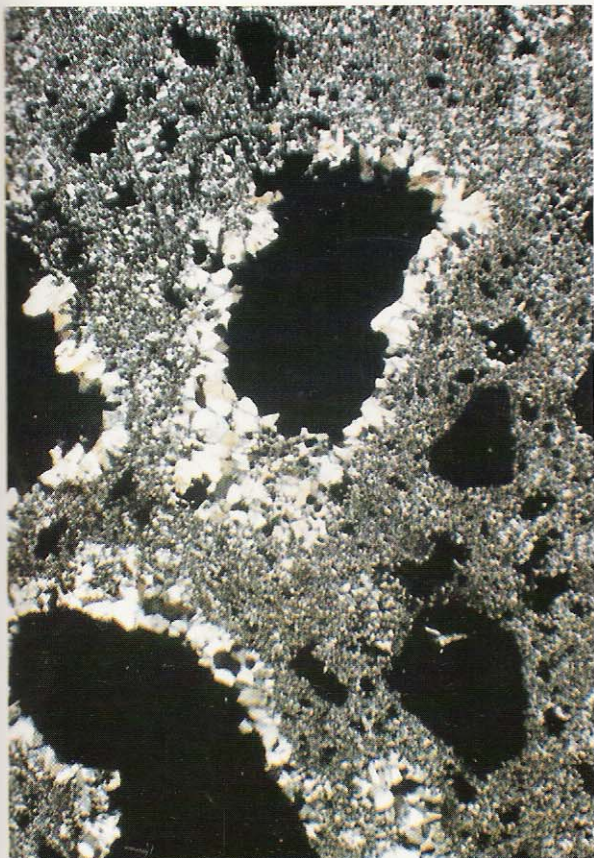
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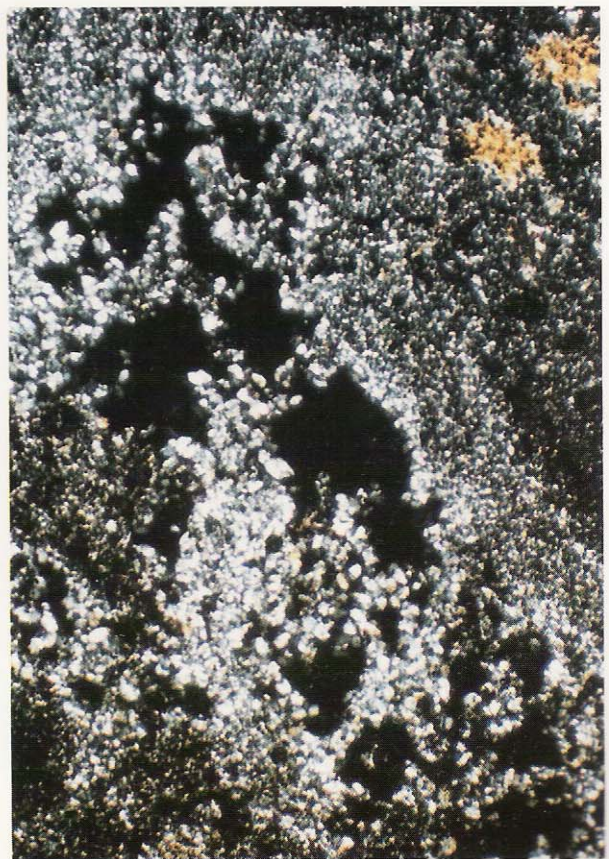
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RUTILE (Anatase)

TiO₂

Environment: *Intrusion-related, Epithermal*

Alteration: *Potassic, Sericitic, Greisen, Advanced Argillic*

Characteristics

During hydrothermal alteration, rutile or anatase forms a fine-grained alteration product of titanium-bearing minerals such as biotite, titanite and ilmenite; these occur disseminated in quartz-rich alteration.

Hand Specimen: When visible in hand specimen, rutile occurs as prismatic, acicular or granular crystals which typically have a brown to pinkish brown colour and are less commonly yellow or black.

Thin Section: Hydrothermal rutile occurs as ragged aggregates of subhedral grains and less commonly as small prismatic or pyramidal (anatase) crystals. It exhibits high relief, red brown, amber or yellow-brown colours and may be opaque. Birefringence is very high but interference colours are masked by the total reflection and the strong colour. Distinguishing rutile from anatase petrographically in typical fine-grained alteration is virtually impossible.

Related Minerals

Associated: biotite, chlorite, ilmenite, magnetite, quartz, sericite, titanite

Accessory: apatite, bornite, chalcopyrite, dickite, kaolinite, K-feldspar, pyrite, tourmaline

Discussion

Hydrothermal alteration of titanium-bearing minerals commonly releases titanium, resulting in the formation of rutile or anatase. In porphyry systems, secondary rutile may occur along the cleavage of primary biotite that has been replaced by secondary biotite or chlorite. Replacement of most titanium-bearing minerals results in aggregates of subhedral rutile, with rare euhedral prismatic grains in the matrix. Rutile is a common alteration mineral in greisen alteration of rocks containing titanium minerals, such as metasediments hosting tin lodes. In high-sulphidation environments, vuggy quartz may contain in excess of 5% rutile (anatase) occurring as prismatic grains and clusters. In this environment, the rutile represents the immobile residuum from intense leaching of the rock, although there is also evidence for local hydrothermal transport and redistribution of titanium.

References

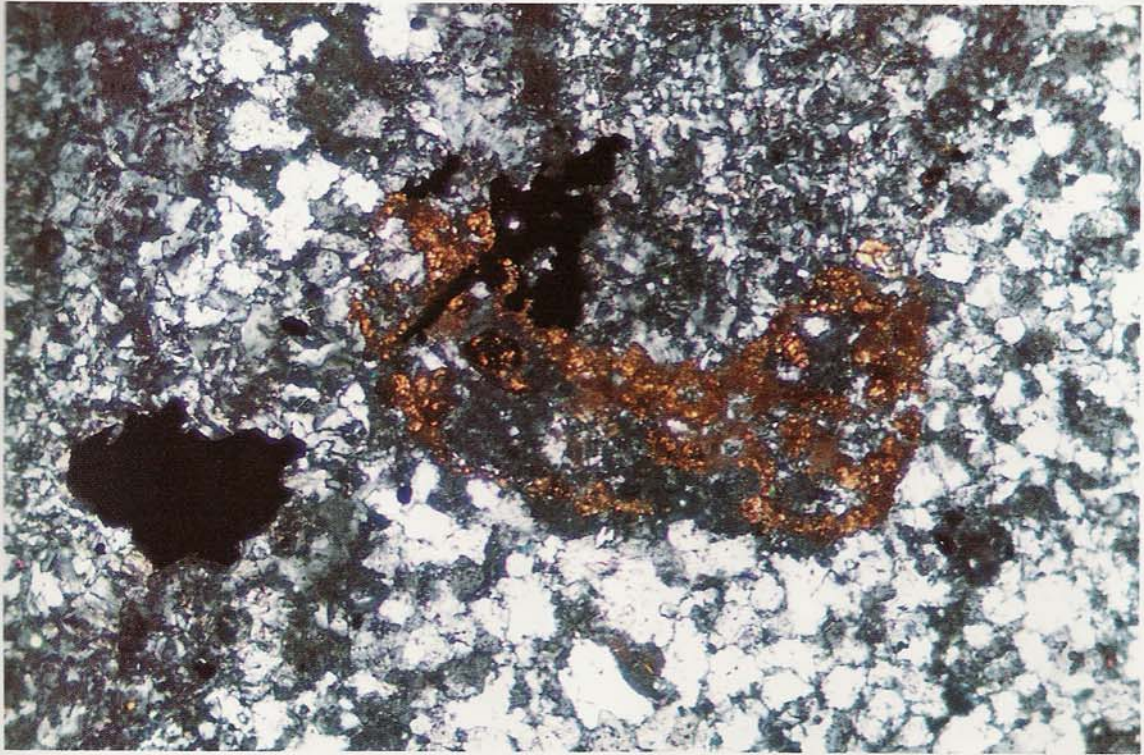
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Figures

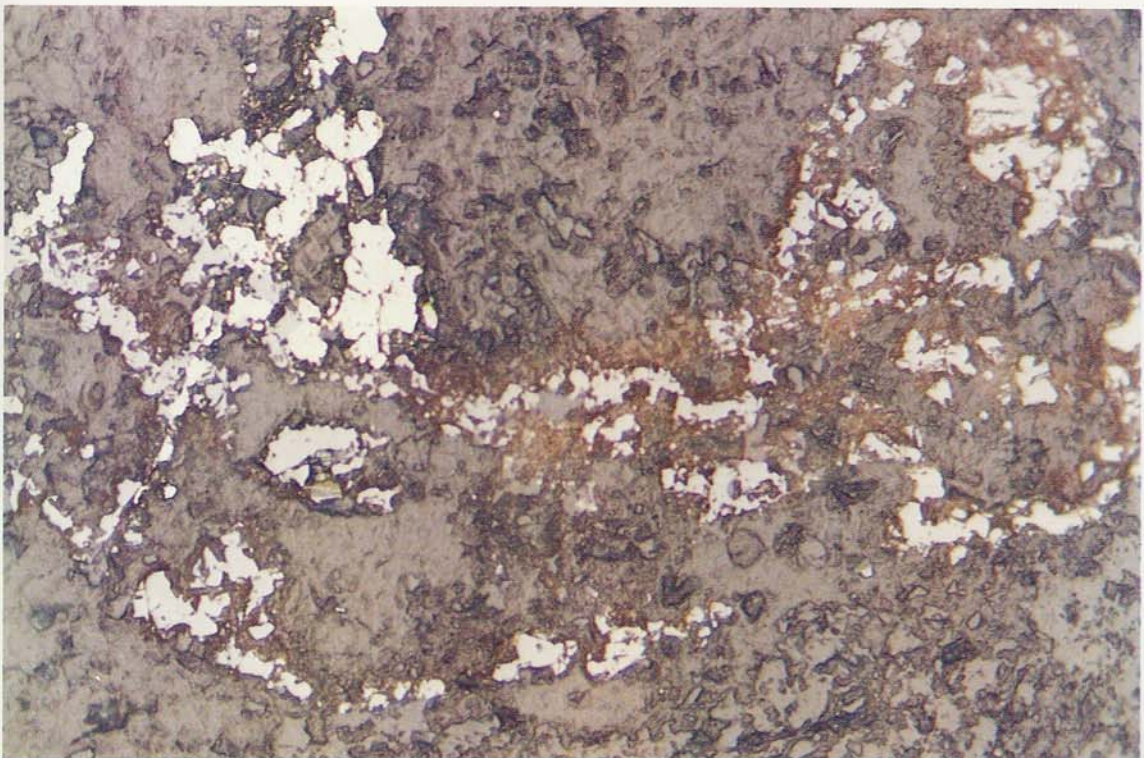
- 39.1 TS (XPL). Phenocryst replaced by rutile, dickite (below), quartz and sulphides. Miwah prospect, Aceh, Indonesia. FOV = 1.3 mm.
- 39.2 TS (RL). Phenocryst replaced by rutile, dickite (below), quartz and sulphides. Miwah prospect, Aceh, Indonesia. FOV = 0.65 mm.

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39.1



39.2

SCAPOLITE

$(\text{Na,Ca,K})_4[\text{Al}_3(\text{Al,Si})_3\text{Si}_6\text{O}_{24}](\text{Cl,CO}_3,\text{SO}_4,\text{OH})$

Environment: Skarn

Alteration: Calc-silicate

Characteristics

Scapolite forms a solid solution series comprising marialite (Na-rich) and meionite (Ca-rich) end members. In the exoskarn environment, fine to coarse-grained marialite scapolite tends to occur with diopsidic pyroxene proximal to granitic intrusions. Retrograde scapolite may occur in the endoskarn.

Hand Specimen: Scapolite varies widely in colour from white, grey, pink, green, brown, to purple. It commonly occurs in veins, columnar aggregates or microgranular masses and exhibits a prismatic habit. In outcrop and hand specimen, scapolite can be difficult to distinguish from feldspar.

Thin Section: Scapolite varies in relief and birefringence with composition (notably in its Na and Ca contents); its refractive indices range from 1.54 to 1.60, and birefringence from weak to strong. It is uniaxial negative and generally has good {100} and {110} cleavages. Scapolite occurs commonly as a replacement after plagioclase. The presence of worm-like inclusions of quartz results in characteristic texture.

Related Minerals

Associated: calcic amphibole, calcite, dolomite, garnet, phlogopite, plagioclase, pyroxene, wollastonite

Accessory: apatite, epidote, K-feldspar, prehnite, quartz, sulphides, titanite, tourmaline

Discussion

Scapolite is a common gangue mineral in a wide variety of ore deposits, particularly skarns. It is also present in hydrothermally-altered basic igneous rocks, in regionally and contact metamorphosed rocks, including meta-evaporites, and in some alkaline porphyry deposits. Scapolite has a wide stability field, and the presence of a number of important volatile species makes it an excellent indicator of the composition of the ore-forming fluids. Marialitic scapolite is commonly associated with very high NaCl in hydrothermal fluid, but the presence of dissolved CO_3^{2-} and Ca^{2+} in an alkaline fluid is also critical to the formation of scapolite.

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Figures

- 40.1** HS. Pyroxene skarn (very pale green) with scapolite veins (white). Copper Mountain porphyry Cu-Au deposit, British Columbia. FOV = 22 cm.
- 40.2** HS. Pyroxene-phlogopite skarn (associated with U, Th, and REE mineralization) containing dark, prismatic crystals of scapolite. Renfrew County, Ontario. FOV = 10 cm.
- 40.3** TS (XPL). Scapolite exhibiting characteristic worm-like intergrowth texture due to abundant inclusions of quartz. Lower ore zone of the Golden Giant mine, Hemlo gold deposit, Ontario. FOV = 0.2 cm.
- 40.4** TS (XPL). Vein-filling of coarse scapolite (moderate to high birefringence) cutting pyrrhotite-arsenopyrite-gold ore (opaque) at the Nickel Plate Au skarn deposit, Hedley district, British Columbia. FOV = 3 cm.

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40.1



40.2



40.3



40.4

SILICA-CARBONATE

Environment: Epithermal

Alteration: Silica-carbonate

Characteristics

Outcrops of silica-carbonate-altered serpentinite are commonly dark green to light brown in colour, due in part to alteration of associated iron sulphides. Outcrops typically stand out in relief and form structurally controlled linear belts. Centres of the alteration bodies are typically cryptocrystalline silica (>85 wt. % SiO₂). Magnesite (MgCO₃) occurs peripherally either as massive replacement or cross-cutting veinlets.

Hand Specimen: The central silica-rich core is translucent, almost glassy, dark green to white mottled cryptocrystalline silica and often is fractured and mineralized with cinnabar on fracture coatings or in hydrothermal veins. The peripheral zones are dominated by several percent white to tan-coloured magnesite.

Thin Section: The central siliceous core typically displays well-preserved serpentinite mesh textures. The silica replaces the serpentinite minerals on a very fine scale and is best identified by its optical properties.

Related Minerals

Associated: ankerite, antigorite, chrysotile, dolomite, lizardite, pyrite (talc is not observed)

Accessory: aragonite, calcite, chromite, cinnabar, hydrocarbons, metacinnabar, native mercury

Discussion

Silica-carbonate alteration of serpentinite is a structurally controlled, low-temperature alteration formed by CO₂-rich springs. The alteration is common in ultramafic terranes, where it occurs in mercury deposits, precious metal epithermal deposits and as apparently barren alteration assemblages. Examples occur in southern Queensland, along the Pinchi Fault, British Columbia and in the coast ranges of California. The alteration is typically an early event, producing a brittle lithology which is subsequently brecciated and may host cinnabar coating fractures or hydrothermal veins. Silica-carbonate assemblages, found as halos around active CO₂-rich springs, are in isotopic equilibrium with the springs at temperatures as low as 17°C. Similar silica-carbonate assemblages are also inferred to have formed at temperatures approaching 200°C, suggesting a wide stability field for this alteration assemblage.

References

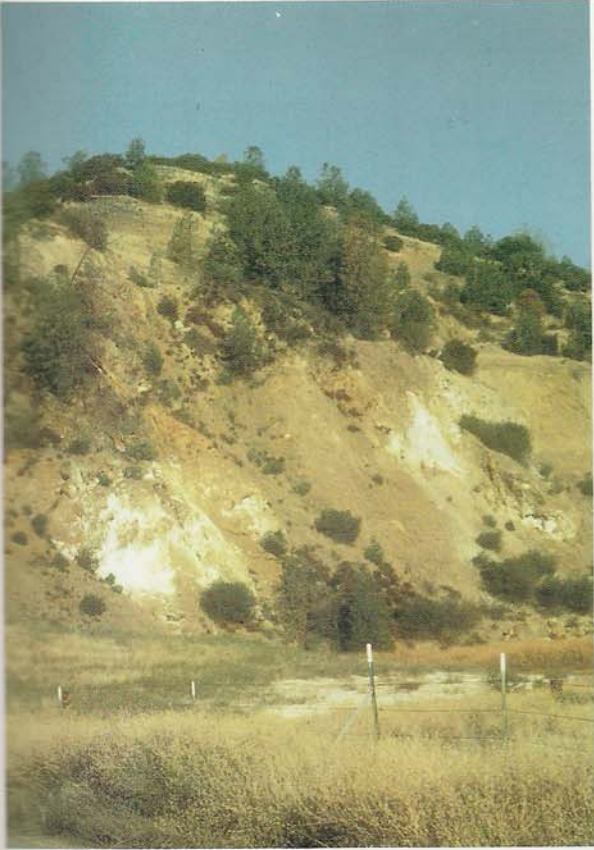
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Figures

- 41.1 OC. Silica-carbonate-altered serpentinite at the Knoxville Mercury deposit, northern California. The reddish colour is due to the weathering of pyrite and the white colour is sulphates, part of an argillic overprint.
- 41.2 HS. Silica-carbonate-altered serpentinite hosting mercury ore (location as for Figure 41.1). The dark green material is cryptocrystalline silica, the yellow spots are iron oxides, and the red is cinnabar formed as fracture coatings. FOV = 9 cm.
- 41.3 TS (XPL). Opaline silica (sample >90% SiO₂) replacement of serpentinite, preserving the original mesh textures. Sample is from the Soda Springs, near Lake Pillsbury, northern California. FOV = 0.32 mm.
- 41.4 TS (XPL). Magnesite veinlets cross-cutting mesh-textured serpentinite. This texture is typical of the peripheral zone around a central siliceous core (location as for Figure 41.3). FOV = 0.32 mm.

Submitted by:

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41.1



41.2

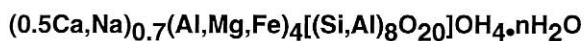


41.3



41.4

SMECTITE



Environment: Epithermal

Alteration: Argillic

Characteristics

Smectite, which refers to any mineral in the smectite group, typically occurs in altered volcanic and sedimentary rocks as a replacement mineral in association with low-temperature zeolites, or less commonly, as open-space fill. Volcanic glass is especially susceptible to replacement by smectite.

Hand Specimen: Replacement of rock-forming minerals and volcanic glass by smectite can produce a bleached appearance, with tan to light-medium green colours; specimens are easily scratched, and some spall in water.

Thin Section: Smectite is very fine grained (<0.01mm) and normally colourless, except that iron-bearing types may be brown or dull green. Smectite is usually non-pleochroic and weakly birefringent.

Related Minerals

Associated: "chalcedony", chlorite, cristobalite, illite-smectite

Accessory: calcite, clinoptilolite, mordenite, pyrite

Discussion

Smectite is a general term for a group of clay minerals of which montmorillonite is the most common. These clays form in the presence of both neutral and acid cool thermal fluids, and are stable up to about 140°C. Consequently, smectite commonly occurs above or adjacent to epithermal mineralization. Interlayered illite/smectite or illite prevails at higher temperatures. Smectite can also occur as open-space fill, where its accuracy as a geothermometer is less certain. X-ray diffraction analysis is necessary to confirm its presence and character.

References

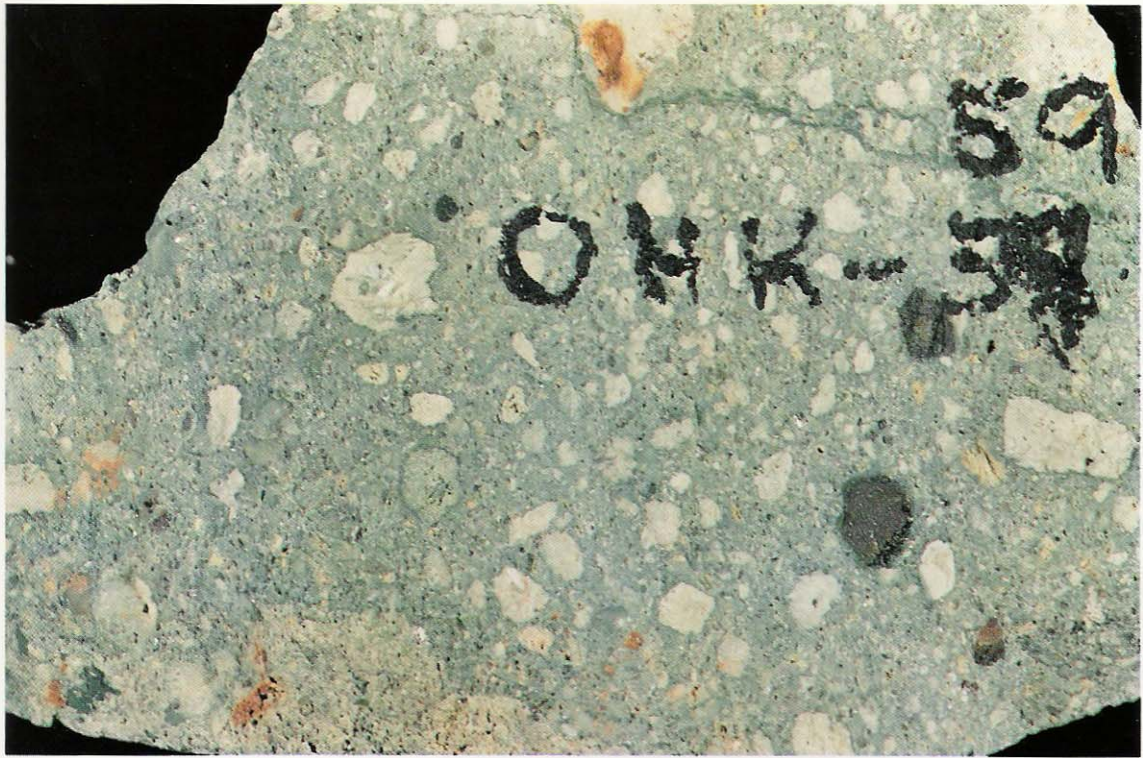
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Figures

- 42.1 HS. Moderately altered rhyolite ignimbrite in which primary feldspars are partly dissolved, and glass has converted to smectite (giving it the green colour) and mordenite. White to light green clasts are pumice; the dark grey clasts are lithic fragments. Sample is from the margin of the Ohakuri epithermal deposit, New Zealand. FOV = 5 cm.
- 42.2 TS (PPL). Moderately altered rhyolite ignimbrite in which primary feldspars are partly dissolved and glass has converted to smectite (medium-dark brown) and mordenite (colourless needles). Sample is from the margin of the Ohakuri epithermal deposit, New Zealand. FOV = 2 mm.

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42.1



42.2

TITANITE

CaTiSiO₅

Environment: *Intrusion-related, Skarn, Epithermal*

Alteration: *Potassic, Sericitic, Calcic*

Characteristics

Titanite occurs as an accessory mineral formed during the hydrothermal alteration of titanium-bearing phases such as biotite, augite, hornblende, and ilmenite. Titanite may be altered to undefined mixtures called leucoxene.

Hand Sample: Hydrothermal titanite is rarely visible in hand specimen; coarse grains are pink to brown or yellow-green and occur as rhombic crystals.

Thin Section: Titanite occurs as massive, anhedral grains and aggregates intergrown with other hydrothermal minerals, and as minute elongate lenses or thin granules along the cleavages of mafic minerals such as biotite. Rarely, it occurs as euhedral rhombic and wedge-shaped crystals, which may show a weak to moderate {110} cleavage. Titanite is characterized by high relief and extreme birefringence.

Related Minerals

Associated: actinolite, biotite, calcite, chlorite, clinopyroxene, epidote, garnet, ilmenite, quartz, wollastonite

Accessory: rutile (anatase)

Discussion

Titanite is a common alteration product of titanium-bearing minerals, which may be directly replaced by titanite, or may contribute titanium to hydrothermal fluids thereby allowing local redistribution and the growth of titanite in nearby pore space or vugs. Calcium activity must be sufficiently high to stabilize titanite. Titanite forms over a large temperature range (at least 200-400°C) in a variety of hydrothermal environments, including intrusion-related and skarn systems and the deeper parts of geothermal/epithermal systems.

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Figures

- 43.1 TS (PPL). Crystals of titanite in a fine-grained matrix of quartz, carbonate, epidote and chlorite. Sample is from a porphyry prospect in Sulawesi, Indonesia. FOV = 2.6 mm.
- 43.2 TS (XPL). Crystals of titanite. Sample as in Figure 43.1. FOV = 2.6 mm

Submitted by

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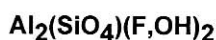


43.1



43.2

TOPAZ



Environment: Intrusion-related

Alteration: Greisen

Characteristics

Topaz is typically related to granophile-element (Sn, W, Li, Ta) mineralization and associated greisen alteration. Alteration occurs in veins, and as pervasive coalescing zones in granitic rocks. Pervasive alteration locally forms banded (layered) quartz-topaz and quartz-mica greisen.

Hand Specimen: The presence of topaz is usually indicated by the associated phases, particularly quartz, fluorite and muscovite in altered granitic rocks. Milky white quartz with colourless quartz and topaz are typical.

Thin Section: Subhedral to euhedral habits and high relief relative to quartz are distinguishing characteristics. Most commonly, topaz occurs in the cores of veins with hydrothermal quartz mantled by moderately greisenized granite composed of altered feldspar (dark turbid) and quartz. However, it is particularly evident in association with fluorite.

Related Minerals

Associated: fluorite, muscovite, quartz, chlorite, biotite

Accessory: bismuthinite, cassiterite, molybdenite, wolframite

Discussion

Topaz is often associated with intense greisenization occurring within the contact zone of Sn-W-Mo granites and rhyolites and, to a lesser extent, in distal wallrocks, depending on the type of protolith. Topaz forms by intense leaching (high fluid/rock) of alkali elements in the presence of low-pH fluids to produce an aluminous residuum. The low pH and high a_F required to hydrolyze feldspar and mica to form topaz over other aluminosilicate phases are the same conditions required to release, complex, and transport some of the mineralizing elements associated with greisen systems. Topaz may also occur in other types of aluminous alteration (advanced argillic); for example, in alteration that hosts disseminated gold mineralization in deposits in South Carolina.

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Figures

- 44.1 OC. Magmatic-hydrothermal breccia with chlorite-topaz-muscovite-quartz (greisenized) matrix, which characteristically hosts the first-phase porphyry W-Mo-Bi mineralization. A flow-layered rhyolite dyke/pipe cuts the breccias. Fire Tower Zone, Mount Pleasant, New Brunswick. FOV = 2 m.
- 44.2 OC. Rhythmically banded topaz-quartz and mica-quartz assemblages within the core of the weakly mineralized True Hill granite porphyry (cupola C), New Brunswick. FOV = 25 cm.
- 44.3 TS (PPL). Fluorite-topaz-quartz greisen with microlites of topaz visible in fluorite and anhedral quartz, True Hill granite porphyry, New Brunswick. FOV = 2.1 mm.
- 44.4 TS (PPL). Massive fluorite-biotite-topaz-quartz (\pm phengitic muscovite and chlorite) greisen from coalescing greisen vein network with cassiterite (Sn) mineralization, Disappointment Lake, Mount Douglas granite, southwestern New Brunswick. FOV = 2.1 mm

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44.1



44.2

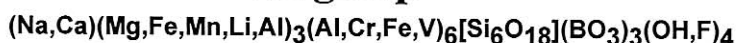


44.3



44.4

TOURMALINE group



Environment: Intrusion-related

Alteration: Tourmalinization

Characteristics

Tourmaline, a trigonal borosilicate, is an effective 'colouring agent' in altered rocks, and fine-grained lithologies; rocks with ≥ 10 volume percent of the mineral frequently are dark bluish to black. It is often conspicuous in veins, vein envelopes and hydrothermal breccias, as well as in associated plutonic rocks and pegmatites.

Hand Specimen: In hand specimen, tourmaline may form dense, dark masses, either monomineralic or intergrown with quartz. It is commonly black or in some cases brown, with vitreous luster (more exotic colours are mostly confined to pegmatites) and hard. Crystals ≥ 2 mm in size are generally prisms with rounded triangular cross-sections, finely striated parallel to the c axis.

Thin Section: Tourmaline is strongly pleochroic, with high relief. Better-crystallized examples vary in habit from stubby prisms to elongate needles (η mm to several mm in length), occurring singly or in radiating clusters. It is often zoned, with strong colour variations. Colours include yellow, brown, green and even an intense inky blue. Brown tourmaline may display bluish pleochroic haloes.

Related Minerals

Associated: albite, biotite, carbonates, muscovite, quartz

Accessory: albite, apatite, carbonates, cassiterite, chlorite, fluorite, gold, magnetite, sulphides, topaz, wolframite

Discussion

Tourmaline is found in rock-forming proportions (≥ 5 volume percent) in quartz-tourmaline veins and quartz-tourmaline rock (extreme acid alteration of granite). The same mineral pair forms the matrix that cements and sometimes replaces lithic clasts in many hydrothermal breccias. The borosilicate also occurs in sheeted veins and greisens. Metallogenic associations include polymetallic Cu-Sn-W-(Ag) vein, mesothermal Au-(Ag) lode and porphyry Cu-Mo deposits. It also occurs in and near the apices of strongly differentiated granitic bodies, and sometimes in late volatile-rich veins and pegmatites associated with intermediate to basic intrusions.

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Figure

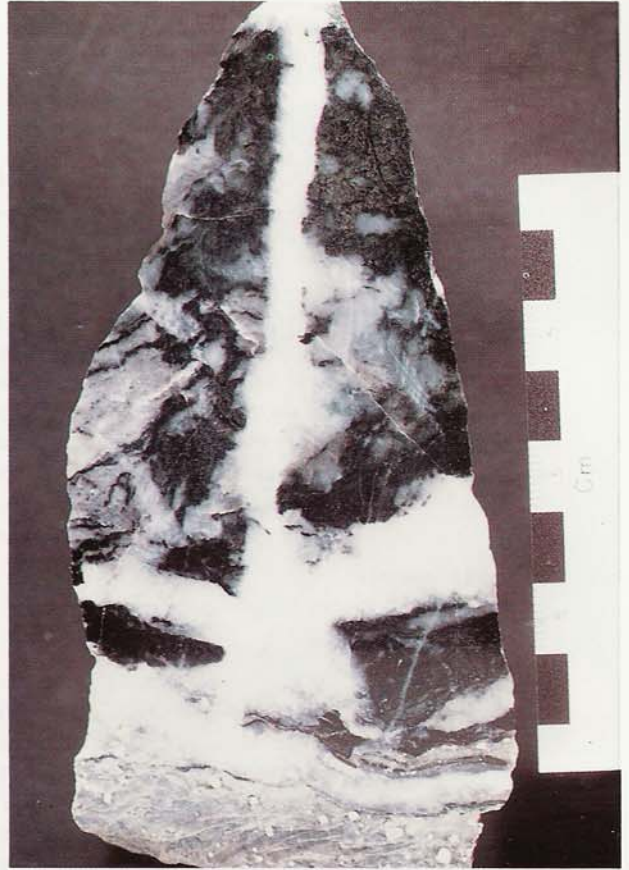
- 45.1 OC. Tourmaline-cemented hydrothermal breccia, with quartz vein cutting both matrix and the highly kaolinized granite clasts. Wheal Remfry china-clay pit, Cornwall, S.W. England. FOV = 25 cm.
- 45.2 HS. Multistage, brittle quartz-tourmaline veining and adjacent pyritic, chloritic schist with minor chromiferous muscovite (bottom). Buffalo Ankerite gold mine, in the Archean Abitibi greenstone belt, Timmins, Ontario. FOV = 15 cm.
- 45.3 TS (PPL). Zoned tourmaline crystals. From the alteration zone over an irregular Sn orebody, Botallack mine, Land's End granite, west Cornwall, England. FOV = 1.8 mm.
- 45.4 TS (XPL). Tourmaline in intimate association with a volatile-rich association of gangue phases. These include sodic illite, iron-rich chlorite, and (most of the opaque material) abundant native gold, plus quartz, carbonates and albite. High-grade vein in the Hoyle Pond mine, east of Timmins, Ontario, Canada. FOV = 0.6 mm.

Submitted by

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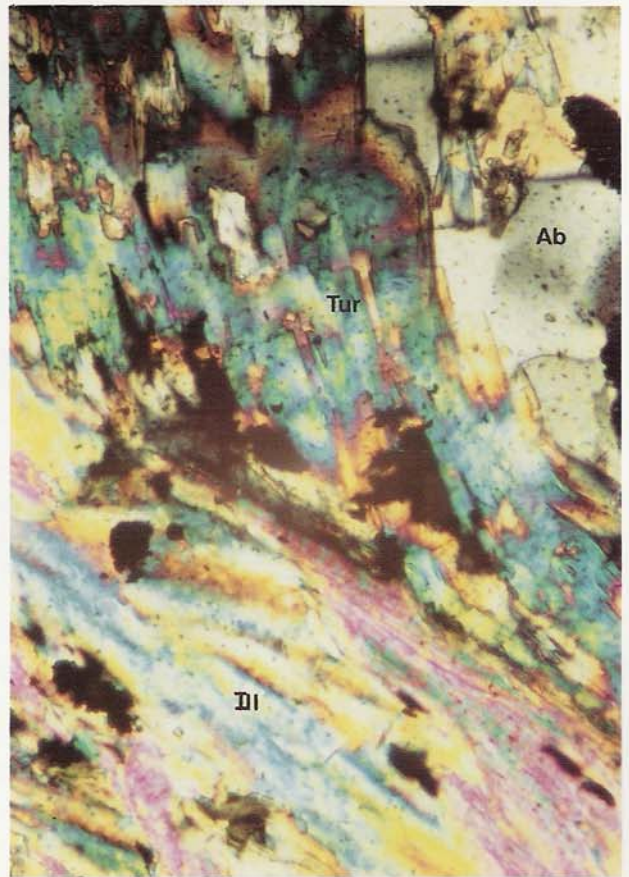
45.1



45.2



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45.4

TOURMALINE group

$(\text{Na,Ca})(\text{Mg,Fe,Mn,Li,Al})_3\text{Al}_6[\text{Si}_6\text{O}_{18}](\text{BO}_3)_3(\text{OH,F})_4$

Environment: Sediment-hosted massive sulphide

Alteration: Tourmalinite

Characteristics

Tourmalinite forms very hard, tough chert-like outcrops which produce a distinctive ringing sound when hit with a hammer; outcrops tend to be resistant to erosion. Preferential replacement of fine-grained (argillite) beds leads to interbedded tourmalinite and sandy beds in turbiditic strata.

Hand Specimen: Tourmalinite displays a characteristic conchoidal fracture and black (less commonly pale to dark brown) colour on the fresh broken surface; the appearance is similar to that of chert. Tourmaline occurs in veins, as bedded or fracture-controlled disseminations and replacements of matrix and clasts in fragmental rocks. A close spatial association with sulphides is common, especially pyrrhotite as stringers.

Thin Section: Tourmalinite typically replaces feldspars and clays, leaving the detrital quartz framework intact except in tourmaline-pyrrhotite veinlets. Tourmaline forms extremely fine felted needles <10 µm in size.

Related Minerals

Associated: chlorite, Mn-garnet, pyrrhotite, quartz, sericite

Accessory: apatite, axinite, biotite, cassiterite, rutile, titanite, zircon

Discussion

An excellent example of tourmalinite occurs at the Sullivan sedimentary exhalative Pb-Zn deposit in British Columbia, Canada. The tourmalinite is closely associated with sulphide networks in the >400 m thick by 1 km diameter vent zone (hydrothermal upflow zone). In contrast to volcanogenic massive sulphide deposits, in which tourmaline compositions become more Mg-rich toward the centre of the deposit, the composition of the tourmaline at Sullivan is consistent at intermediate dravite-schorl with a Fe:(Fe+Mg) ratio of about 0.45 for the fine felted material. This changes to dravite/uvite, with ratios as low as 0.15 where recrystallized by albite-chlorite alteration, and to schorl with a ratio up to 0.9 where recrystallized adjacent to later gabbro intrusions. Na:(Na+Ca+K) ratios grade from sodic in the felted tourmaline to calcic in the recrystallized dravite/uvite.

References

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Figures

- 46.1 OC. Interbedded footwall tourmalinite (black) and unaltered sediments (grey), illustrating bedding control of alteration, from the Sullivan mine, British Columbia. FOV = 1.25 m. (Photograph courtesy Cominco Ltd.)
- 46.2 HS. Tourmalinized footwall conglomerate (black, conchoidal fracture, pyrrhotite blebs/stringers), from the Sullivan Mine, British Columbia. FOV = 16.7 cm. (Photograph courtesy Cominco Ltd.)
- 46.3 TS (PPL). Tourmaline-pyrrhotite stringers and fine tourmaline replacement of interstitial feldspar and mica between detrital quartz. Sullivan mine, British Columbia. FOV = 4.2 mm.
- 46.4 TS (PPL). Fine tourmaline needles after interstitial feldspar and mica between detrital quartz (note also large zoned tourmaline crystal - bottom left, possibly of detrital origin). North Star deposit, 3 km south of Sullivan, British Columbia. FOV = 0.25 mm.

Submitted by:

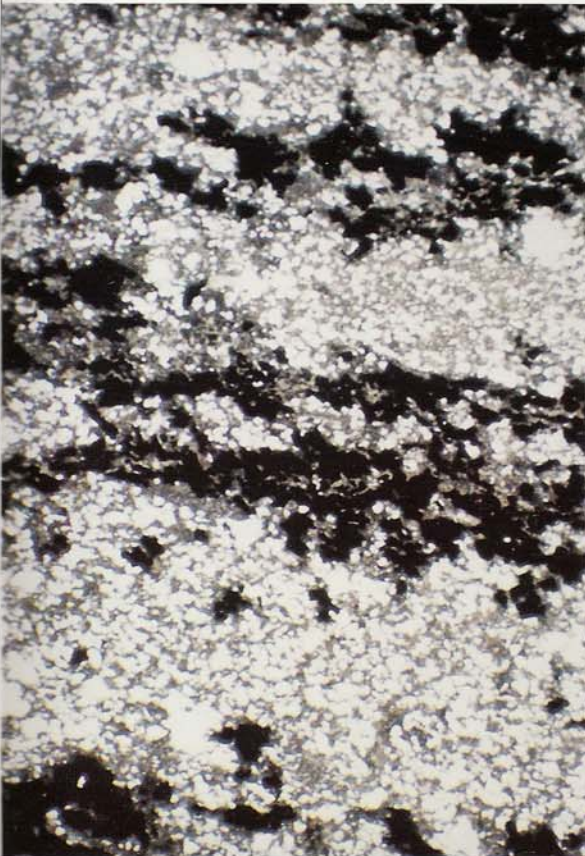
Craig H.B. Leitch, Consultant, Salt Spring Island, British Columbia
Robert J.W. Turner, Geological Survey of Canada, Vancouver, British Columbia



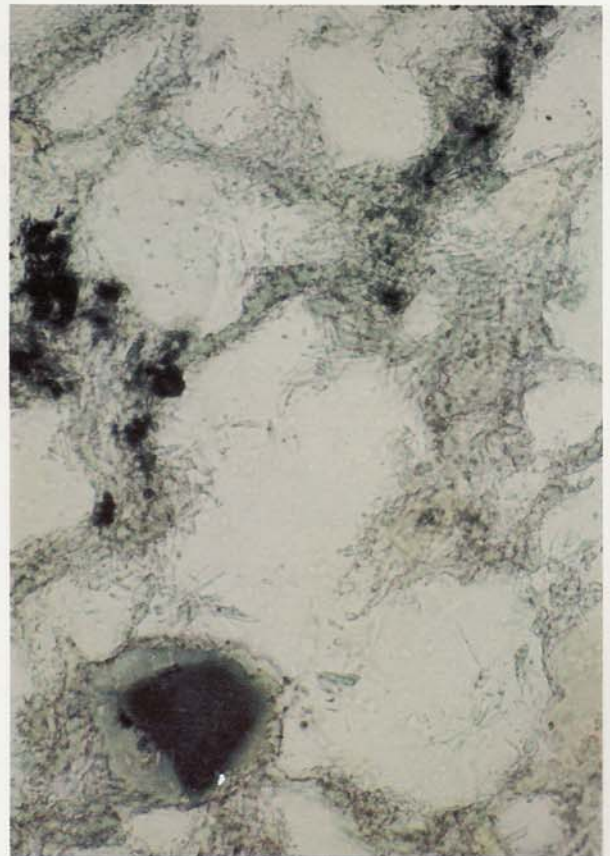
46.1



46.2



46.3



46.4

VESUVIANITE (Idocrase)



Environment: Skarn

Alteration: Calc-silicate

Characteristics

Vesuvianite is a tetragonal mineral with poorly developed cleavage. It occurs mainly in skarns and in regionally or contact metamorphosed limestones. It is also present in some nepheline syenites and in some mafic and ultramafic rocks.

Hand Specimen: Vesuvianite occurs as prismatic crystals, often with striations parallel to their length, as columnar aggregates, or as granular masses. Some massive vesuvianite is difficult to distinguish from garnet, epidote or pyroxene. Crystals are generally less than 0.5 cm in length, but some exceed 15 cm; they are generally brown, olive green or amber, or more rarely yellow, red or blue.

Thin Section: Vesuvianite is typically colourless but can be pale brown, yellow or very pale blue. It has an imperfect cleavage parallel to {110} and is generally uniaxial negative. However, some varieties are optically positive and biaxial. Elongate crystals are length fast with parallel extinction. Birefringence is weak to very weak, with or without anomalous colours. Crystals can exhibit pronounced oscillatory (compositional) zoning.

Related Minerals

Associated: calcite, epidote, garnet, pyroxene, quartz, wollastonite

Accessory: fluorite, helvite, magnetite, scapolite, sulphides

Discussion

Vesuvianite is highly variable in its Al, Fe, Ti and Mg contents. The mineral can be enriched in elements such as F, Cl, Sn, Zn, Cu, Pb, Cr, B, Bi, U, Th, and light rare-earth elements; B-rich crystals are optically positive whereas B-free vesuvianite is optically negative. In British Columbia, trace quantities of vesuvianite occur in all classes of skarn deposits, but the mineral is usually more abundant in W and Sn skarns. Some Fe and F-rich Sn skarns contain unusual "wrigglite" textures comprising thin, rhythmic layers dominated by either magnetite, garnet, fluorite or vesuvianite.

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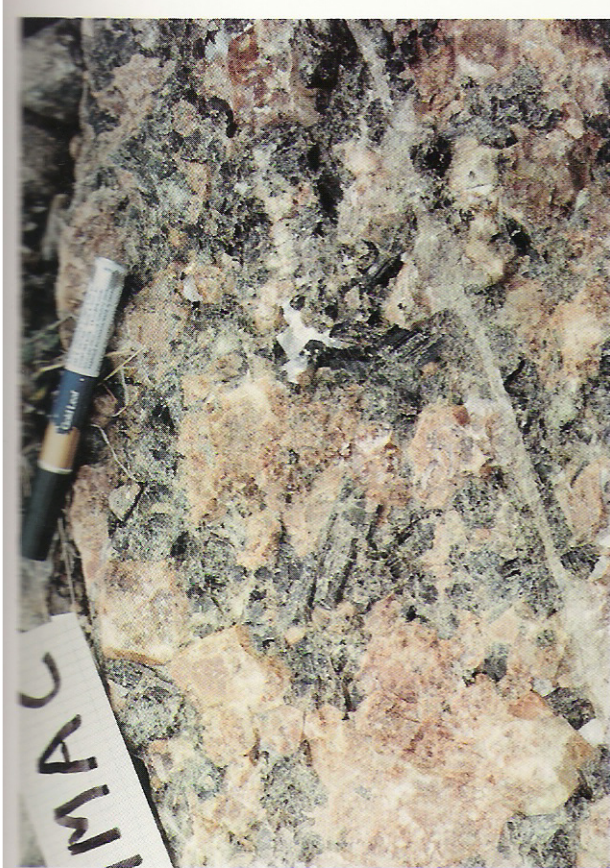
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Figures

- 47.1 OC. Large prismatic crystals of vesuvianite (dark olive-brown) intergrown with garnet (light reddish-brown) and calcite (white). Dimac (Silence Lake) W skarn deposit, southeastern British Columbia. FOV = 45 cm.
- 47.2 OC. "Wrigglite" skarn with alternating layers of F-rich vesuvianite (light brown), F and Sn-rich grossular garnet (pink), magnetite (black), and fluorite. Daybreak Sn-W skarn occurrence, Atlin, northern British Columbia. FOV = 20 cm.
- 47.3 TS (PPL). Large crystal of vesuvianite, showing high relief. Sample from skarn prospect in British Columbia. FOV = 2.5 mm.
- 47.4 TS (XPL). Vesuvianite with micrometre-scale oscillatory zoning (centre of photograph). Sample from skarn prospect in British Columbia. FOV = 5 mm.

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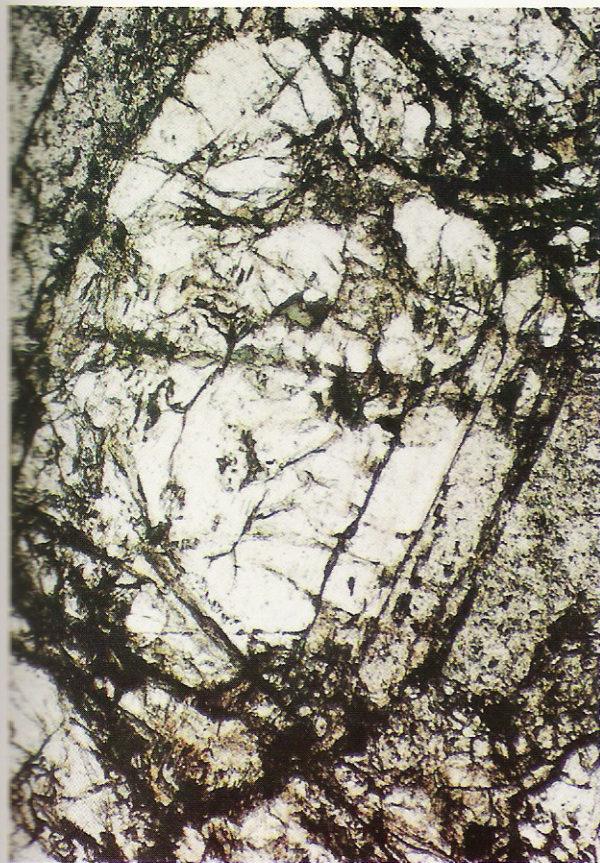
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47.1



47.2



47.3



47.4

WAIRAKITE



Environment: Epithermal

Alteration: Propylitic

Characteristics

Wairakite is a zeolite that occurs in altered volcanic and sedimentary rocks as a replacement mineral or as open-space fill.

Hand Specimen: Wairakite is white to colourless and forms euhedral pseudo-dodecahedral crystals up to about 5 mm in diameter in vug and vein fillings.

Thin Section: Wairakite occurs as anhedral to euhedral crystals depending whether it is a replacement phase (of glass or Ca-plagioclase) or open space fill. It has negative relief and typically displays two perpendicular polysynthetic sets of twin lamellae, a distinctive feature giving an appearance similar to microcline. The poor cleavage and lower interference colours, however, distinguish it from feldspar.

Related Minerals

Associated: calcite, epidote

Accessory: "adularia", albite, chlorite, illite, pyrite, quartz

Discussion

Wairakite is not commonly reported for epithermal deposits, but it can occur in close association with low-sulphidation mineralization. However, wairakite is very common and widespread in modern geothermal systems, and it is a useful geothermometer, being stable at temperatures hotter than about 210°C; at cooler temperatures laumontite forms instead. Wairakite stability also depends on there being relatively low concentrations of aqueous CO₂, otherwise, its place is taken by calcite. The occurrence of wairakite indicates zones of moderate permeability.

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Figures

- 48.1** DC. Vug filled with clear isometric crystals of wairakite. Sample is drill core from the Kawerau geothermal system, New Zealand. FOV = 8 cm.
- 48.2** TS (XPL). Intensely altered dacite containing wairakite, epidote, illite and quartz. Visible are anhedral wairakite crystals with their distinctive sets of twin lamellae. Sample is from drill core at the Broadlands-Ohaaki geothermal system, New Zealand. FOV = 2 mm.

Submitted by

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48.1



48.2

WOLLASTONITE

Ca(SiO₃)

Environment: Skarn

Alteration: Calc-silicate

Characteristics

Under temperate weathering, wollastonite-rich outcrops are characterized by positive relief. In the crystal structure, some Fe, Mn, Mg and Al can substitute for Ca.

Hand Specimen: Wollastonite is commonly vitreous and white but can be pale grey, brown, yellow, green or red in colour. The mineral generally occurs as aggregates of elongate, prismatic, radiating crystals, as compact granular masses, layers, or as veins. Tabular crystals are rare. Wollastonite has a white streak and dissolves in concentrated HCl acid whereas tremolite, which can visually resemble wollastonite, does not. Wollastonite can give a variety of fluorescent colours in ultraviolet light.

Thin Section: Wollastonite has a fairly high relief and weak birefringence, with colours up to first-order orange. In longitudinal sections, wollastonite can be either length slow or length fast, and it shows parallel or almost parallel extinction. On (010) sections, wollastonite has two perfect cleavages, {001} and {100}, at an angle of about 84 degrees, whereas optically similar tremolite has a cleavage angle of about 56 degrees. Wollastonite is often partly altered to quartz and calcite.

Related Minerals

Associated: calcic amphibole, calcite, garnet, clinopyroxene, quartz, tremolite

Accessory: clinozoisite, epidote, graphite, prehnite, scapolite, sulphides, vesuvianite, zoisite

Discussion

Wollastonite is found in thermally and regionally metamorphosed carbonates, in exo- and endoskarns, and in some carbonatites. Its formation is dependent on fluid and host-rock composition, fluid CO₂ content, and pressure and temperature conditions. Carbonates that contain too much Mg or Fe crystallize tremolite or clinopyroxene instead of wollastonite. Some skarns contain wollastonite-rich zones that separate the distal marble from more proximal zones of garnet or pyroxene-rich skarn. Rarely, wollastonite can form wriggly textures consisting of rhythmic interlayers of wollastonite, pyroxene and sulphides. In British Columbia, wollastonite is more common in W and Sn skarns, where the associated plutons are silica-saturated; it is very rare in Fe skarns.

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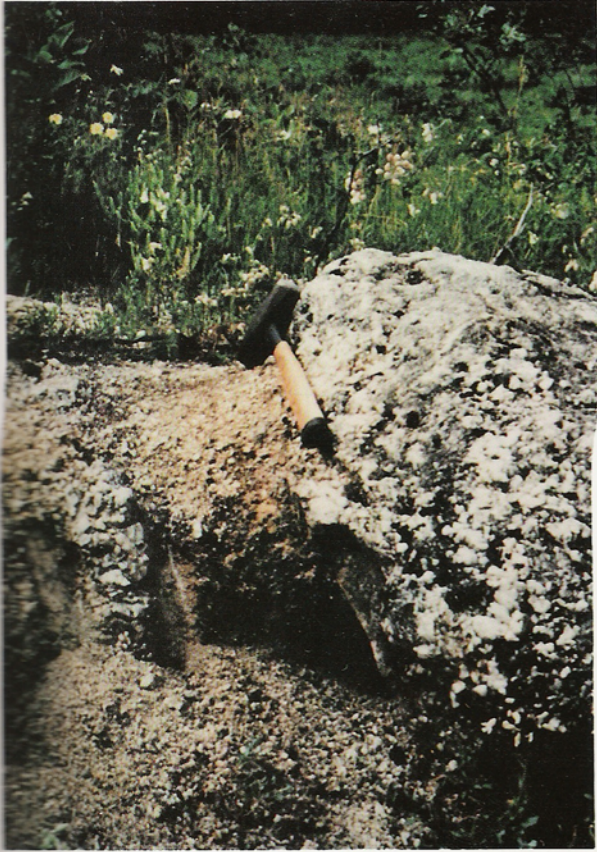
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Figures

- 49.1 OC. Interlayers of marble (buff-weathering and negative relief) and coarse-grained, wollastonite-rich rocks (white and with positive relief). Saint Sauveur area, Quebec. FOV = 1.5 m.
- 49.2 OC. Veins and irregular masses of coarse wollastonite (white and vitreous) cutting garnet exoskarn (brown). Mineral Hill wollastonite deposit, Sechelt, British Columbia. FOV = 30 cm.
- 49.3 TS (PPL). Exoskarn with radiating crystals of high-relief wollastonite and small inclusions of clinopyroxene. Little Billie Cu-Au mine, Texada Island, British Columbia. FOV = 3 mm.
- 49.4 TS (XPL). Exoskarn with elongate crystals of low-birefringent wollastonite and small inclusions of clinopyroxene. Little Billie Cu-Au mine, Texada Island, British Columbia. FOV = 3 mm.

Submitted by

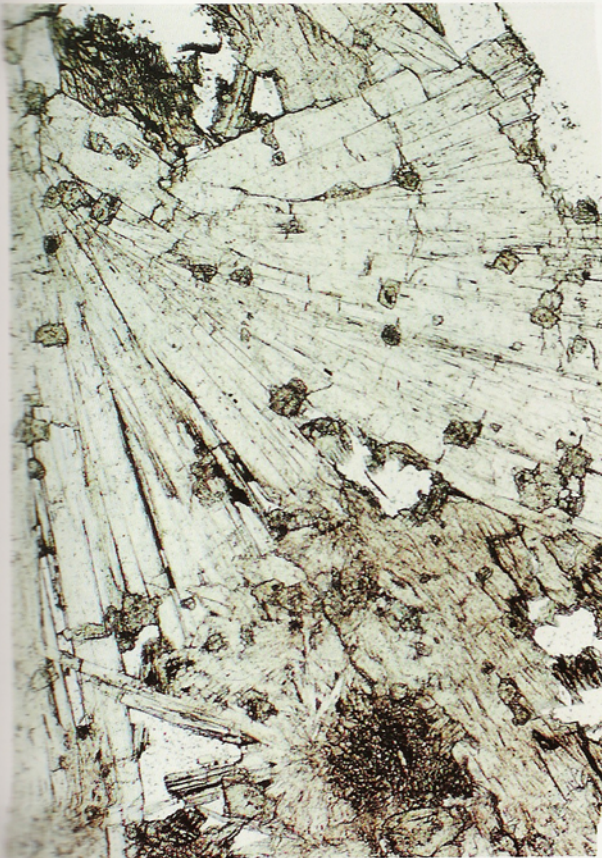
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49.1



49.2



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49.4

TABLE 2: OPTICAL PROPERTIES OF MINERALS

| Mineral | Crystal System Form | Relief | Birefringence | Extinction | Interference Figure |
|---|---|--|-----------------------|--|---------------------------------|
| Mineral Colour/Pleochroism | Cleavage | Birefringence | Interference Colours* | Extinction Twinning | Interference Figure |
| Actinolite colourless, green/slight pleochroism | Monoclinic rhombohedral to pseudohexagonal cross-section, prismatic crystals, fibrous <i>I perfect</i> | moderate to high moderate to strong <i>I - high to 2-middle</i> | | parallel or inclined, symmetrical in cross-section simple and lamellar | biaxial - 2V 75-88° |
| “Adularia” colourless | Monoclinic pseudo-rhombic, rhombic in cross-section <i>I - perfect, I good, I poor</i> | low weak <i>I - grey</i> | | parallel combined polysynthetic albite and pericline | biaxial - 2V highly variable |
| Albite colourless | Triclinic plates or lath-shaped sections <i>I - perfect, I good, I poor</i> | low weak <i>I - pale yellow</i> | | inclined albite and simple Carlsbad | biaxial + 2V 77-82° |
| Alumite colourless | Hexagonal granular, plumose or flaky aggregates, rarely tabular to pseudocubic rhombohedral <i>I fair</i> | fair moderate <i>I - grey to 2- blue</i> | | parallel, except cross-section | basal sections: uniaxial + |
| Andalusite colourless or rarely reddish/ coloured variety weak rose-red to pale green | Orthorhombic elongate prisms with nearly square cross-section <i>I - good, I - poor</i> | fairly high weak <i>< I - yellow</i> | | parallel, symmetrical in cross-section rare | biaxial - 2V 71-88° |
| Anhydrite colourless | Orthorhombic massive, fibrous or radiating aggregates, tabular crystals <i>I perfect, I very good, I good</i> | moderate strong <i>< 3- green</i> | | parallel simple and multiple | biaxial + 2V 42-44° |
| Apatite usually colourless but also coloured/weak to moderate in coloured varieties | Hexagonal prismatic to tabular <i>I poor and I very poor</i> | high variable <i>variable</i> | | parallel in elongate section | uniaxial - biaxial |
| Barite colourless | Orthorhombic granular or platy aggregates, tabular or prismatic <i>I perfect, I very good, I fair to good</i> | fairly high weak <i>< I - yellow</i> | | parallel, symmetrical to cleavages in cross-section possible glide | biaxial + 2V 36-40° |
| Biotite brown or green/ strong pleochroism | Monoclinic tabular, hexagonal cross-section <i>I perfect</i> | fair strong <i>< 2- red</i> | | parallel or slightly inclined rare mica | biaxial - 2V 0-25° |
| Calcite colourless | Hexagonal hexagonal, rhombohedral <i>I perfect</i> | varies with rotation of stage extreme <i>> 3</i> | | symmetrical to cleavage lamellar and possibly simple | uniaxial - |
| Carbonate colourless, cloudy, grey, yellow, pink | Hexagonal granular, lamellar or fibrous aggregates, crystals hexagonal, rhombohedral or prismatic <i>I perfect</i> | changes from high to low on rotation extreme <i>> 3</i> | | symmetrical to cleavage lamellar and possibly simple | uniaxial - |

| Mineral | Crystal System Form Cleavage | Relief Birefringence Interference Colours* | Extinction Twinning | Interference Figure |
|---|--|--|--|---|
| Chlorite light to medium green/weak colourless to green | Monoclinic Triclinic commonly plates or scales similar to micas, rarely tabular; sheaves common <i>1 perfect</i> | fair to moderately high low < <i>1 white or yellow</i> | slightly inclined simple and lamellar | biaxial + or - 2V 0-60°(+) 2V 0-40°(-) |
| Chloritoid colourless, green, brown, grey, blue, yellow | Monoclinic Triclinic platy, pseudohexagonal tabular crystals <i>1 perfect, 2 imperfect</i> | high weak to moderate < <i>1 yellow</i> | almost parallel or inclined simple and lamellar | biaxial + or - 2V 36-72° (+) monoclinic 2V 55-88° (-) triclinic |
| Clinopyroxene colourless, green, brown/ absent to weak | Monoclinic columnar aggregates, prismatic crystals, 4 or 8-sided cross-sections <i>2 parallel intersect at 87°</i> | fairly high to high moderate to strong <i>1 - violet to 4</i> | inclined simple and lamellar | biaxial + or - 2V 0-40°, 54-75° (+) 2V 60-66° (-) |
| Cordierite colourless or pale blue/ may be pale blue, violet to pale yellow or green | Orthorhombic commonly anhedral grains, rarely hexagonal prismatic crystals <i>1 fair, 2 poor</i> | low weak < <i>1 - yellow</i> | parallel to cleavage lamellar and cyclic | biaxial - 2V 40-90° |
| Diaspore colourless to pale blue/ coloured variety shows pleochroism | Orthorhombic tabular, occasionally fibrous, fine-grained aggregate common <i>1 perfect</i> | high strong < 3 | parallel to cleavage | biaxial + 2V 84-86° |
| Dolomite colourless, grey, brown | Hexagonal rhombohedral <i>1 perfect</i> | varies with rotation of stage extreme > 3 - <i>white or grey</i> | symmetrical or inclined to cleavage lamellar, simple or glide | uniaxial - |
| Dumortierite colourless to blue, lavender, pink, red/ strongly pleochroic | Orthorhombic bladed, acicular, fibrous, pseudohexagonal cross-section <i>1 good, 2 poor</i> | high weak to moderate <i>1 - orange to 2 - blue</i> | parallel to length and cleavage traces cyclic | biaxial - 2V 13-55° |
| Epidote colourless to pale yellow, green and greenish brown/ weak to moderate | Monoclinic granular to columnar aggregates, columnar, bladed or fibrous crystals, pseudo-hexagonal cross-section <i>1 perfect</i> | high moderate to strong 1 to 3 | parallel in elongate section, inclined to cleavage rare lamellar | biaxial - 2V 64-90° |
| Fluorite colourless or pale purple, green | Isometric commonly anhedral, cubes modified by octahedral or dodecahedral faces less common <i>4 perfect</i> | fairly high | rare penetration | |
| Garnet colourless or pale version of hand sample colour | Isometric dodecahedral or trapezohedral crystals, 6 or 8-sided cross-sections | high | | |

| Mineral | Crystal System Form | Relief Birefringence | Extinction | Interference Figure |
|---|--|--|--|-------------------------------|
| Colour/Pleochroism | Cleavage | Interference Colours* | Twinning | |
| Hematite deep red-brown, opaque | Hexagonal commonly anhedral crystals, grains, masses and hexagonal plates | extreme extreme | rare lamellar | uniaxial - |
| Illite colourless | Monoclinic minute shreds and flakes in matted and plumose aggregates <i>1 perfect</i> | low moderate to strong 2 | | biaxial - 2V 1-25° |
| Kaolinite colourless to pale yellow/ slight pleochroism | Triclinic fine mosaic like masses; platy <i>1 perfect</i> | low weak <i>1 - grey and white</i> | almost parallel | biaxial - 2V 23-60° |
| Magnesite colourless | Hexagonal anhedral masses to veinlets, very fine grained <i>1 perfect</i> | changes from high to low on rotation extreme | symmetrical or inclined to cleavage | uniaxial - with many rings |
| Magnetite opaque | Isometric octahedral | | single or multiple | |
| Muscovite colourless to pale green or pink/ rare weak pleochroism | Monoclinic tabular crystals with hexagonal outline rare, irregular flakes or tablets more common <i>1 perfect</i> | moderate, changes with rotation strong 2 | parallel or almost parallel to cleavage rare mica | biaxial - 2V 30-47° |
| Plagioclase colourless | Triclinic tabular or platy <i>1 perfect, 1 good, 1 poor</i> | low weak <i>1 - grey or white</i> | variable according to composition albite, pericline and simple Carlsbad | biaxial + or - 2V 45-102° |
| Potassium feldspar colourless to cloudy | Monoclinic or Triclinic roughly tabular; massive, intergrown equant grains <i>1 perfect and 1 good</i> | low weak <i>1 - grey and white</i> | parallel or inclined albite, pericline, Carlsbad, Baveno and Manebach | biaxial - 2V variable |
| Pyrophyllite colourless | Monoclinic and Triclinic foliated, radial, columnar or massive flaky aggregates; fibrous <i>1 perfect</i> | low to moderate strong < 3 | parallel to elongate section, parallel or almost parallel to cleavage | biaxial - 2V 53-62° |
| Quartz (cryptocrystalline) colourless | Hexagonal minute crystals, often replacing on very fine scale | very low weak <i>1 - white</i> | parallel, symmetrical to cleavage common but rarely observed | uniaxial + rarely observed |
| Quartz (crystalline) colourless | Hexagonal hexagonal prism terminated by dipyramid | low weak <i>1 - white</i> | undulose if deformed rare Japan | uniaxial + |
| Pyrite opaque (brassy yellow in reflected light) | Isometric cubic, pyritohedral or octahedral crystals, possibly granular or radiating | | penetration | |

| Mineral Colour/Pleochroism | Crystal System Form <i>Cleavage</i> | Relief Birefringence <i>Interference Colours*</i> | Extinction Twinning | Interference Figure |
|--|--|---|---|--|
| Rutile brown/ weak | Tetragonal prismatic to acicular crystals, knee-shaped twins characteristic <i>1 good and 1 fair</i> | very high extreme <i>very high</i> | parallel in elongate section contact (knee-shaped) or cyclic | uniaxial + |
| Scapolite colourless | Tetragonal prismatic, occasionally acicular or bladed <i>2 good, 2 fair</i> | low to moderate weak <i>1 - grey, Berlin blue</i> | parallel to cleavage | uniaxial - |
| Sericite colourless to pale green or pink/ rare weak | Monoclinic fine ragged grains and aggregates <i>1 perfect</i> | moderate, changes with rotation strong < 2 | parallel or almost parallel to cleavage rare mica | biaxial - 2V 30-47° |
| Smectite colourless, Fe-varieties are brown and green | Monoclinic very fine grained aggregates <i>1 perfect</i> | low moderate < 2 | | biaxial - 2V 5-30° |
| Titanite brown, colourless or yellow | Monoclinic rounded or irregular anhedral grains, rhombic cross-section <i>1 good</i> | very high extreme | symmetrical simple, rare deformation induced lamellar | biaxial + 2V 17-40° |
| Topaz colourless | Orthorhombic stubby to elongate prisms, anhedral grains and irregular masses, cross-sections square to rounded diamond shape <i>1 perfect</i> | moderate weak <i>1 - grey, white or yellow</i> | parallel to cleavage in elongate section, symmetrical in cross-section | biaxial + |
| Tourmaline highly variable/strong, Mg-rich - brown, Fe-rich - brown, green, blue; isotropic cross-sections | Hexagonal irregular masses and prisms, stubby columnar to acicular crystals rare | high moderate to strong 2 | parallel in elongate section | uniaxial - |
| Vesuvianite colourless, pale yellow, brown or green/ weak pleochroism | Tetragonal stubby tetragonal prisms, anhedral grains, radial or columnar patterned aggregates <i>1 poor</i> | high weak <i>1 - grey, grey-green, purple or deep blue</i> | parallel in elongate section | uniaxial - |
| Wairakite colourless | Isometric cubic <i>1 poor</i> | moderate weak <i>1</i> | lamellar | uniaxial or anomalously biaxial (sign difficult to obtain) |
| Wollastonite colourless | Triclinic bladed, columnar, fibrous or granular <i>1 perfect, 2 good</i> | moderate to high weak < <i>1 - orange</i> | parallel or almost parallel common | biaxial - 2V 36-60° |

* Numbers 1 through 4 indicated order of interference colours (1 = 1st order, 2 = 2nd order etc.)

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