



A Key for Identification of Rock-forming Minerals in Thin-Section

Andrew Barker

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Andrew J. Barker
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Andrew Barker, June 2014, Southampton

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Introduction

Being able to accurately identify minerals in thin-section is an essential skill for any geologist, and is vital for the correct interpretation of rocks and their petrogenesis. It can be a particularly challenging prospect for students new to the subject. However, with a basic understanding of microscopy, petrology and optical mineralogy, coupled with some reference text books, it is soon possible to identify some of the major rock-forming minerals with confidence. However, being able to move beyond this, to efficiently and reliably identify newly encountered unknown minerals can prove difficult. Students may resort to flicking through the pages of one of the many beautifully illustrated atlases of rock-forming minerals (e.g. MacKenzie & Adams, 1994; MacKenzie & Guilford, 1980) or may use an optical mineralogy book such as Kerr (1977), or the superb *“Introduction to Rock-forming Minerals”* by Deer et al. (1992, 2013). To the novice, however, the latter can seem impenetrable at first glance, but with time becomes an essential companion. It is hoped that by producing a key to mineral identification, an efficient and systematic approach to identifying minerals in thin-section will be provided. This is not intended to replace the detailed optical mineralogy text book, but rather to complement it.

More than a century ago, Johannsen (1908) produced a *“Key for the determination of rock-forming minerals in thin sections”*, which although largely forgotten is a very useful publication. Johannsen (1908) used combinations of various optical properties to separate minerals into small groups. Although not providing a unique solution, it gives the reader a short-list of possibilities, that can be further refined with reference to other optical properties not previously considered. In terms of a “modern” equivalent to this, the closest would be the “Mineral Tables” in Chapter 10 of Kerr (1977), but even this is now more than 35 years old. Like Johannsen’s key, the tables of Kerr (1977) and Ehlers (1987b) provide the petrologist with a systematic approach to narrow down to a group of minerals with similar properties, after which, the detailed optical characteristics of each should be considered before concluding on the identity of the mineral in question. The present author has always found Kerr (1977) to be an excellent text, and very easy to use, but once again, the Tables of this text do not provide a unique solution for mineral identification.

The present key, comprises eight “Sections”, and as far as possible attempts to key out to a specific mineral. The key assumes that the user has a basic understanding of optical mineralogy and is able to determine essential mineral properties in thin-section using plane-polarised and cross-polarised light. Even so, a brief summary of

mineral properties in thin-section is provided in the introduction. In some cases it may be necessary to determine an optic figure for closely similar minerals. However, this is something not routinely employed as it is technically more challenging, and may not be feasible in small, deformed, or heavily included crystals. If this point is reached and uncertainty remains concerning the mineral identification, consider all remaining possibilities (usually only two or three minerals). It may be necessary to employ analytical techniques if the identity of the mineral is still in question.

The present key is designed in a manner comparable to dichotomous botanical keys such as Clapham *et al.* (1981) and Stace (1999), which are widely used by botanists in the UK. It involves a stepped sequence defining characteristic features to arrive at a unique mineral identification. At this point, it should be stated that the present author strongly encourages all those using the key to start by building up a full portfolio of properties for a given mineral before trying to identify it. Only then should the stepped sequence of the key be used.

Starting from couplet 1 (in the appropriate Section), successive numbered steps give two options for a particular characteristic (sometimes with letter-coded illustration). Decide which option fits the mineral being identified and go to the next step as indicated by the number to the right-hand side. Repeat the process until the point where a mineral is named. Having keyed-out the mineral, cross-check with an optical mineralogy text book (eg Kerr, 1977; Ehlers, 1987a, b; Deer *et al.*, 1992, 2013), to confirm that all the properties agree. Also check that the rock and mineral assemblage seem realistic. If the result seems impossible or unlikely, back-track to points of uncertainty. For example, if uncertain whether a particular mineral is moderate or high relief, follow what you think first of all (eg high), but if this fails to produce a realistic answer, back track and follow the other route (ie moderate relief). Please also recognise that whilst 150+ of the most common rock-forming minerals are included in the key, other minerals are not, so some minerals may not key-out.

The key has been designed in such a way as to prioritise those properties that are most easily defined, and thus less ambiguous. It is hoped that this will minimise the chance of misidentification and enable the less experienced petrologist to use the key with confidence. Since in many cases (eg small crystals) the idealised crystal form and characters may not be encountered, the key attempts to “error-trap” by including some minerals in more than one Section (eg plagioclase feldspars may seemingly lack cleavage and often not show twinning in metamorphic rocks). Recognising that end-sections and side sections of minerals such as amphiboles and pyroxenes have different properties, they can be keyed out in different Sections. To aid in the identification of closely similar minerals that have very different petrogenesis, the bulk rock chemistry, environment of formation, and P-T-fluid conditions may be referred to. To the purist some aspects of this approach may seem rough and ready, but to the student or practising geologist who does not have the time or suitable crystals to check 2V optic axial angles and optic sign, this guide should prove highly useful. It should be stated, however, that when using shape, textural relationships or occurrence as primary identifiers, caution must be exercised. Such characteristics can be broadly useful, in the same way that in botanical keys plants may have an association with a particular habitat or geographical area. Ultimately, however, it is the anatomical features of the plant and optical properties of the mineral that are critical to the correct identification. In all cases, therefore, once a mineral identification has been arrived at using the key, it is recommended that

a final check of all properties is made with reference to an optical mineralogy text such as Kerr (1977) or Deer *et al.* (1992, 2013).

To the beginner, it is hoped that the key provides a systematic approach to defining unknown minerals, rather than simply defining a few of the optical properties then searching through a mineralogy or petrology text hoping to find a mineral that matches. A glossary is given at the back to provide definitions of various technical terms used in the key and introductory sections. Also included are a tabulation of mineral abbreviations used on photographs, a polarisation colour chart, and birefringence values for all minerals referred to in the key.

1.1 Photographs and their captions

Unless otherwise stated, all photographs have been taken by the author. In addition to naming the mineral, each image includes details of the image magnification, a scale-bar, and whether taken in plane-polarised light (PPL), cross-polarised light (XPL), or reflected light (RL). Wherever possible, brief details are given of the rock type and sample location.

Image magnifications and scale-bars

The majority of photographs were taken at x50 or x100 magnification (as specified), with the original horizontal fields of view in such images being 2.7 mm and 1.35 mm, respectively. Unless specified otherwise, all scale-bars represent a distance of 0.25 mm on the image. Where higher magnifications (x400, field of view 0.34 mm, i.e. 340 μm) and close-ups are shown, the field of view is considerably smaller and an appropriate scale-bar is given.

1.2 Crystal systems

Before proceeding to consider rock-forming minerals in thin-section using a polarising microscope it is useful to firstly consider the fundamental crystal systems and the inherent link with particular crystal shapes, forms and mineral cleavage orientations. It is outside the scope of the present text to cover this in detail, but a basic awareness of angular and length relationships for crystals of particular systems is helpful when identifying minerals based on cleavage orientations, and crystal shapes formed by thin-sections cut both perpendicular and oblique to crystallographic axes.

The schematic illustrations of Fig. 1.1 show the principal crystal systems of rock-forming minerals. The varying fundamental relationships between principal cell lengths a , b , c , and angles α , β , γ are specified for each system beneath the respective diagrams. The principal crystallographic axes x , y , z are also shown. To avoid any confusion, please note that the present author has used the x , y , z notation for consistency with Deer *et al.* (1992, 2013), but in other texts (e.g. Kerr, 1977; Ehlers 1987a, b), the principal crystallographic axes are labelled a , b , c .

In the rather special case of the hexagonal system, rather than defining the cell dimensions in terms of two horizontal axes (a , b) as in other systems, there are three axes (a_1 , a_2 , a_3) of equal length and angular relationship (120°), perpendicular to the

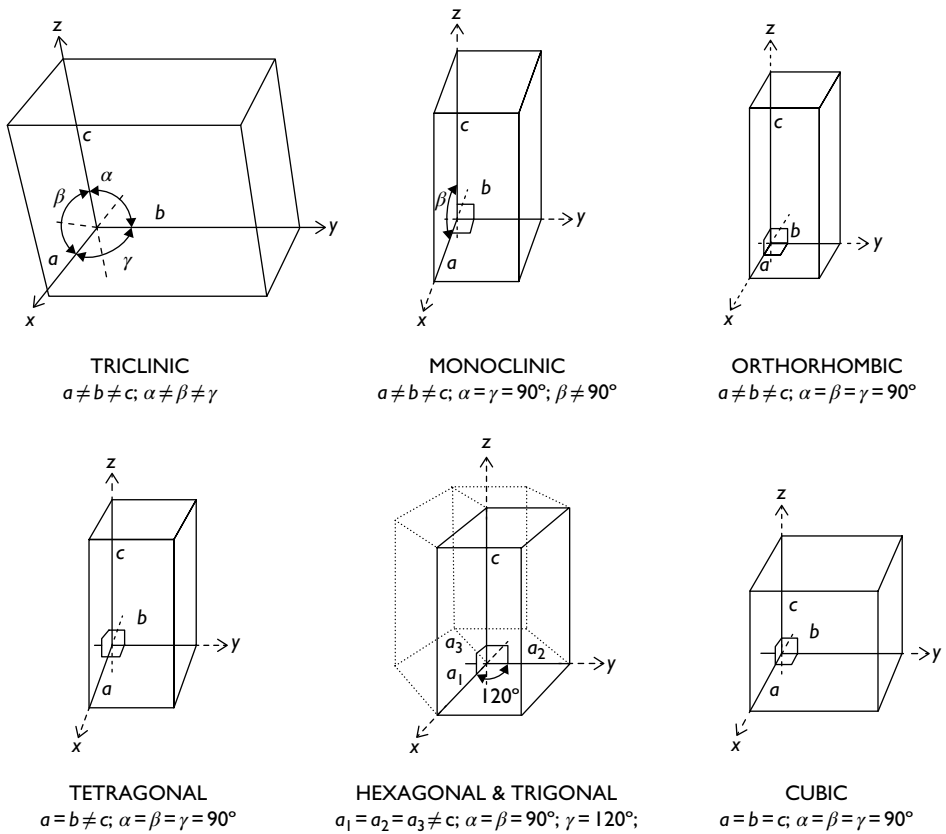


Figure 1.1 Various crystal systems represented as unit cell with lattice parameters a, b, c (lengths) and α, β, γ (angles), with crystallographic axes x, y, z .

vertical c -axis (e.g. Beryl). For further detail on crystal systems of minerals, the text by Wenk & Bulakh (2004) provides a useful introduction.

1.2.1 Miller indices

Miller (1839) devised a convenient method for describing the lattice planes of a mineral with reference to the orientation of the plane with respect to the three principal crystallographic axes (x, y, z of Fig. 1.1). With the exception of the slightly more complicated hexagonal system (see above), which has four axes, and thus four digits, the index is given as a three digit integer value. The figures are derived from the reciprocal values of the axis intercepts, normalised to the lowest common denominator to give integers.

If we consider the cubic system illustrated in Fig. 1.1, the diagram below (Fig. 1.2a) depicts a simple cubic mineral (e.g. pyrite, fluorite) with Miller indices given for the three visible faces. The top face, being parallel with axes x and y and perpendicular to z has the Miller index (001). The face front left is perpendicular to x and parallel to y and z , so has the index (100), and finally the face front right is parallel to x and z and perpendicular to y so has the index (010).

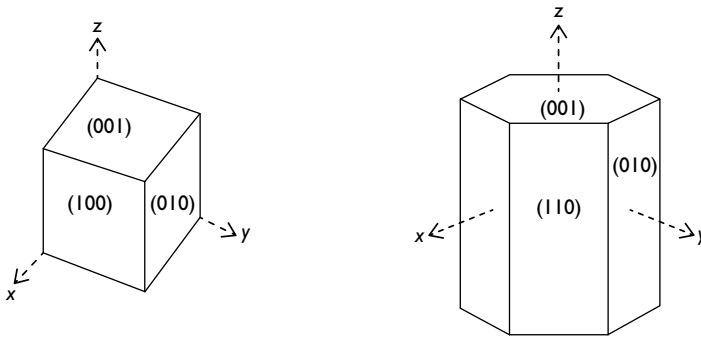


Figure 1.2 Miller indices for selected faces on a) simple cube (e.g. pyrite, fluorite), and b) staurolite.

For faces perpendicular to the negative end of a particular axis the notation is with a bar above the integer, so the face on the bottom of the cube (Fig. 1.2a) illustrated (not visible), would be $(00\bar{1})$, the one back right (hidden) would be $(\bar{1}00)$, and the one back left (hidden) would be $(0\bar{1}0)$. A face at a 45° angle to (100) and (010) would have the value (110) , (see Fig. 1.2b) and so on. It is outside the scope of present text to provide a more detailed account of Miller indices, but for further information see Wenk and Bulakh (2004). The reason for briefly mentioning Miller indices in this introduction is because on some occasions within the mineral key, reference is made to particular crystal faces, cleavage or twinning in specific planes using Miller indices. For example, see couplet 2. of Section 1.

1.3 Mineral properties in plane-polarised light (PPL)

1.3.1 Shape and form

Many crystals, especially those of fine grained aggregates, or forming the matrix of rocks, have rather poor crystal form, and would be described as anhedral or irregular. Other crystals, however, may show rather good crystal form, indicative of the crystal system of the particular mineral concerned. This is especially true of phenocrysts, porphyroblasts and vein minerals, where unimpeded growth has occurred. If some of the crystal faces are present, the crystal is said to be subhedral, and if all sides of the crystal are well formed it is described as euhedral. Fig. 1.3 illustrates a few examples of distinctive crystal shapes, and the mineral key itself includes schematic illustrations of all shapes and forms as necessary. For more detailed information on the topic see Barker (1998, pp 65–75), MacKenzie *et al.* (1982), and Table 10.3 of Kerr (1977). The latter provides a very useful summary of minerals commonly observed with euhedral form, grouped according to form (e.g. acicular, lath-like, radiating).

1.3.2 Textural relationships

As well as general shape providing a clue to the identity of well-formed minerals, there are also textural features that can sometimes further aid identification, and may sometimes be referred to in the mineral key presented in part 2. Some of these features such

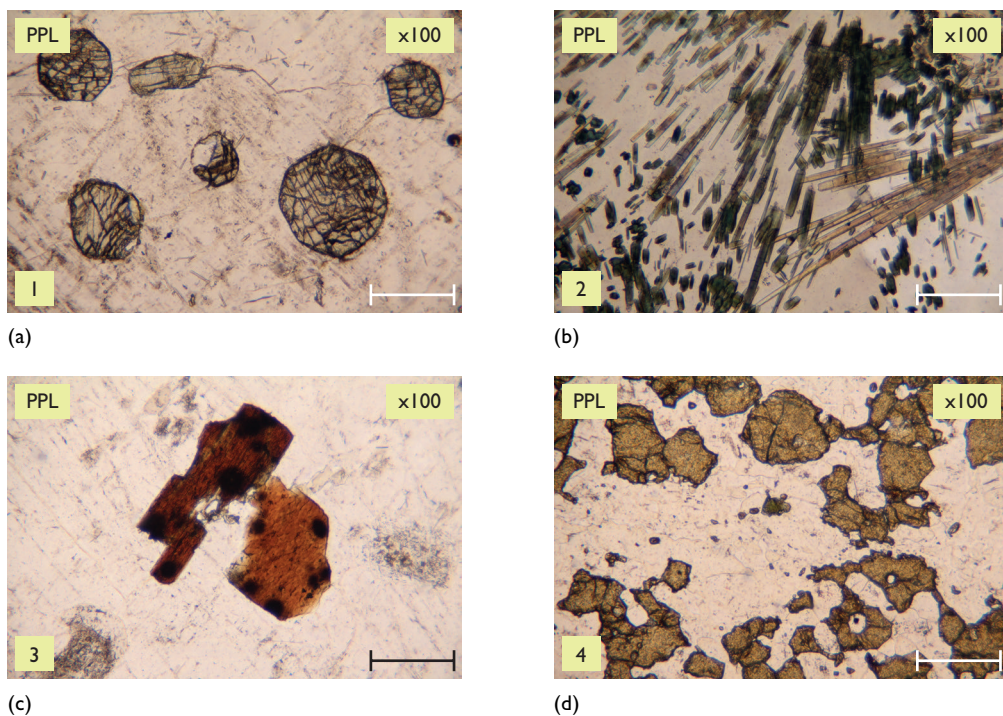


Figure 1.3 Examples of different crystal shapes/forms: (a) Spodumene end-section; the classic euhedral octagonal shape of pyroxenes. Granite pegmatite; Leinster, Ireland. (b) Radiating acicular tourmaline (schorlite); Luxullyanite, Cornwall, England. (c) Two biotite crystals; the one on the left showing the typical subhedral lath-shaped side-section of biotite with {001} parallel cleavage traces along the length of the crystal, and parallel with crystal sides, whereas the subhedral, roughly hexagonal crystal to the right, with no cleavage, is a view straight down the z-axis (\equiv c-axis) of the crystal, thus displaying the (001) face (ie end-section). Granite; St. Jacut, Brittany, France. (d) Anhedral spessartine garnet; Nisserdal, Telemark, Norway.

as porphyroblasts, phenocrysts, and colour zoned minerals due to chemical zonation, are evident in plane-polarised light (PPL). Other features, however, such as twins, and chemical zonation in colourless minerals (e.g. plagioclase, vesuvianite) only become more apparent in cross-polarised light (XPL) due to changes in interference colours (see 1.4.2 and 1.4.3 below). Mineral intergrowths can be seen in PPL if the intergrown phases have contrasting optical properties, but for minerals with similar properties such intergrowths are only obvious in XPL (see myrmekite image 116b below).

Phenocrysts of igneous rocks, and porphyroblasts of metamorphic rocks, are easily observed and, often easily identified, by virtue of their large size providing good information on most if not all of the mineral's optical properties. Their occurrence as phenocrysts or porphyroblasts in itself can be strongly indicative of particular minerals. Table 1 gives a list of commonly observed phenocrysts and porphyroblasts of igneous and metamorphic rocks, and Fig. 1.4 illustrates several representative examples. If the phenocryst or porphyroblast has abundant inclusions, the respective terms poikilitic and poikiloblastic are used (see Fig. 1.4c).

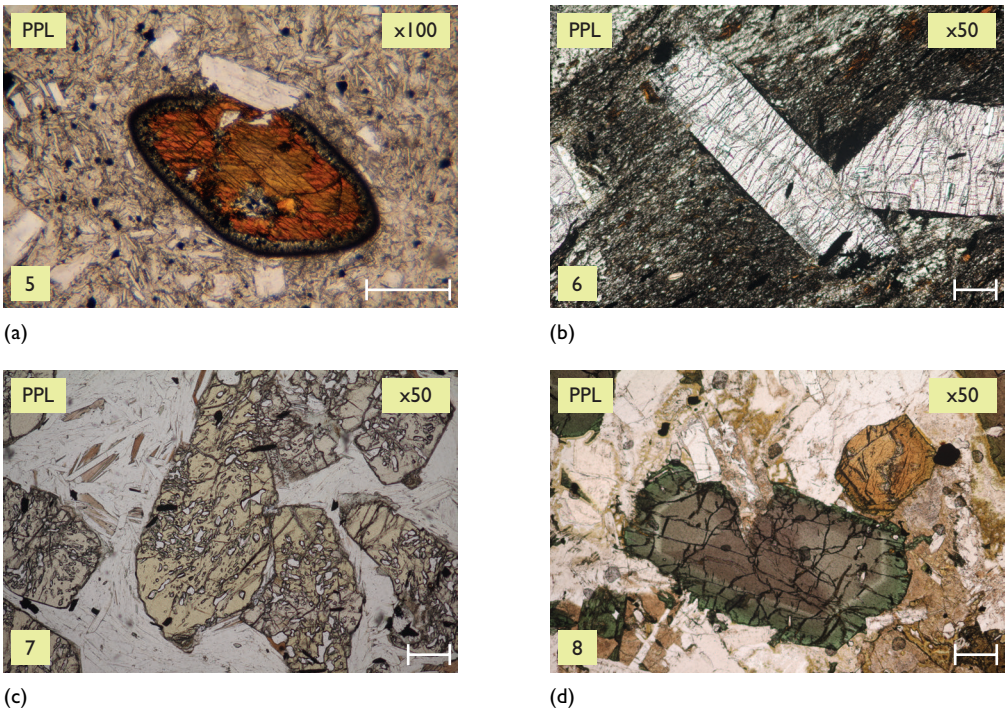


Figure 1.4 Textural relationships in plane-polarised light; a) Oxo-hornblende phenocryst in andesite; Mt. Shasta, CA, USA. b) Andalusite (var. chistolite) porphyroblasts in chistolite slate; Skiddaw Granite aureole, Lake District, England. c) Poikiloblastic staurolite porphyroblasts in stt-and-schist; Nauyago, Ghana. d) Colour zonation in titanaugite phenocryst in zeolite-basalt; Scawt, Antrim, N. Ireland.

Table 1.1 Minerals commonly occurring as phenocrysts or porphyroblasts.

Phenocrysts (<i>igneous rocks</i>)		Porphyroblasts (<i>metamorphic rocks</i>)	
Hornblende	Augite	Garnet	Hornblende
Biotite	Olivine	Staurolite	Actinolite
Quartz	Pigeonite	Andalusite	Lawsonite
Plagioclase	Orthopyroxene	Kyanite	Plagioclase (albite)
Orthoclase	Anorthoclase	Biotite	K-feldspar
Sanidine	Oxo-Hornblende	Chlorite	Pyrite
Nepheline		Chloritoid	Dolomite
Leucite		Cordierite	
Analcite		Muscovite	

1.3.3 Mineral cleavage

The distinction between those minerals that show cleavage from those that do not is one of the most useful characteristics for distinguishing some of the major mineral groups in both hand-specimen and thin-section. Minerals such as amphiboles,

pyroxenes and micas have well developed cleavage, whereas common minerals such as quartz, garnet and olivine lack cleavage. In thin-section, the trace of cleavage is observed, and depending on the crystal orientation with respect to the thin-section cut one or more cleavage traces will be seen. Minerals such as micas (e.g. muscovite and biotite) display a single well developed cleavage trace $\{001\}$ in almost all crystals within a thin-section (Fig. 1.5a). The only exceptions are crystals cut parallel to $\{001\}$, which show no cleavage (see hexagonal biotite crystal in Fig. 1.3c). Other minerals such as pyroxenes and amphiboles, have two well developed cleavages, and whilst only displaying a single cleavage trace in side-sections, generally show two well developed cleavages in end-sections (see Fig. 1.5b). The end-section angular relationships between cleavage traces are particularly useful for distinguishing pyroxenes from amphiboles. The former displays cleavage intersecting at approximately 90° , whereas the latter gives an acute angle cleavage intersect of approximately 60° . Presence or absence of cleavage provides such an important division of minerals, and for those minerals with cleavage there is the further possibility of dividing according to the number of cleavages present. In view of this, the number of cleavage traces present, provides much of the basis for construction of the broad sub-divisions (“Sections”) of the present mineral key (see 2.1 below). Accordingly, identifying cleavage (or lack of it) is critical to deciding which Section of the present Key to start in (see pg.33 below).

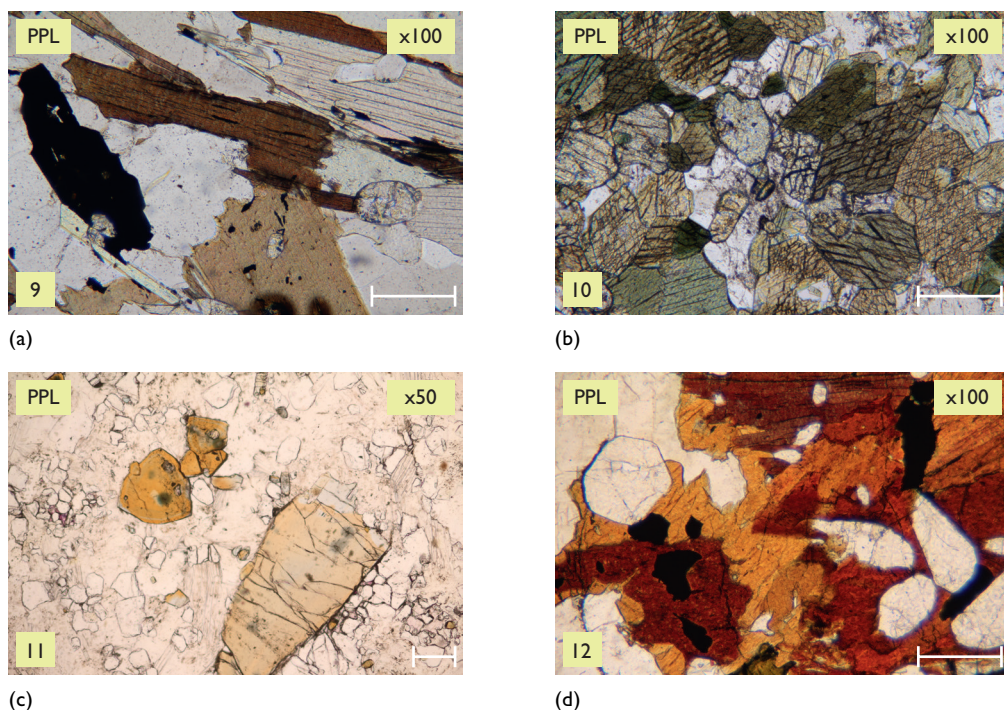


Figure 1.5 Cleavage traces in minerals. a) Single cleavage traces $\{001\}$ in biotite and muscovite. Biotite schist; Dublin, Ireland. b) Two cleavage traces $\{110\}$ at 56° and 124° in end-sections of hornblende. Hornblende gneiss; Sleat, Skye, Scotland. c) Irregular but somewhat arranged fractures (not cleavage) in oblique section of tourmaline (main crystal, lower right). Also note the end-section of yellow-green tourmaline (left centre) showing the classic triangular form with curved convex-outward faces. d) Colourless apatite crystals with no cleavage, including euhedral hexagonal crystal (left) in larvikite; Dalheim, Larvik, Norway.

1.3.4 Colour and Pleochroism

Whether a mineral is coloured or colourless in plane-polarised light is a difference, which forms the basis for several of the broad sub-divisions (“Sections”) in the present key for mineral identification. Furthermore, many coloured minerals show pleochroism (i.e. mineral colour changes as the microscope stage is rotated in PPL). Such variations are due to the orientation of the crystal (and its lattice) with respect to the two rays of plane-polarised light.

At this point it is necessary to give a brief explanation of the relationships between optic axes (vibration directions) α , β , γ , and crystallographic axes x , y , z , previously discussed (1.2 above). It may seem slightly confusing that α , β , γ are used for optic axes, as well as the angles between x , y , z crystallographic axes (see Fig. 1.1). However, the present author has followed the convention of this notation to be consistent with Deer *et al.* (1992, 2013). To avoid any confusion, please note that the published literature is inconsistent on this matter, and sources such as Kerr (1977) and Ehlers (1987a, b) use X , Y , Z for α , β , γ .

Deer *et al.* (1992, 2013) contains extensive information on all rock-forming minerals, and is highly recommended as a final check for mineral identifications arrived at using the present key. Please note that all further reference to α , β , γ in the present publication is always in relation to the principal optic axes (vibration directions). The optic axes, which are at 90° to each other, also show a direct relationship with variations in refractive index, with α being the smallest refractive index, γ being the largest, and β being an intermediate value.

The relationships and terminology described in the preceding paragraph are those for biaxial minerals; namely those belonging to the orthorhombic, monoclinic and triclinic mineral systems. These account for the vast majority of minerals, but for uniaxial minerals (those of tetragonal, hexagonal and trigonal systems), a slightly different arrangement exists. These minerals have a unique orientation, namely the z ($\equiv c$) vertical crystallographic axis, along which the crystal appears isotropic. The axes in the horizontal plane are equal to one another (see Fig. 1.1) and thus have the same refractive index. The index of refraction of the light ray vibrating parallel to the z -axis is by convention for uniaxial minerals given the notation ϵ (epsilon), whereas the vibration direction perpendicular to this in the horizontal plane has the symbol ω (omega) (see Ehlers, 1987a for further detail). For cubic minerals, the lattice dimensions and atomic arrangements are identical in all directions, giving three crystallographic axes perpendicular to one another and of equal dimension. This in turn gives a constancy of refractive indices, which in turn gives optic axes that are identical and parallel with crystallographic axes.

Returning to consider pleochroic schemes of minerals, there are specific colours associated with particular orientations of a given mineral. Because of the relationships outlined in the preceding paragraphs, coloured minerals of the cubic system have identical refractive indices in all directions, so do not show pleochroism. Coloured uniaxial minerals (e.g. tourmaline) may show two different colours in a pleochroic scheme by virtue of the difference between the two optic axes ϵ and ω , whereas biaxial minerals (e.g. hornblende) may show up to three different colours as they have three different axes α , β , γ .

Pleochroic colours in relation to specific optic axes may be relatively easily determined for euhedral and subhedral elongated crystals with distinctive length and end-sections. Where minerals are anhedral and granular, although it is not usually possible to determine the specific orientation of individual crystals, it should usually be possible

to deduce the pleochroic scheme by rotating the microscope stage and looking for different colours in the same field of view (see Fig. 1.6d).

Fig. 1.6 illustrates a few examples of pleochroic minerals. In Fig. 1.6a, b the mineral illustrated is biotite, a common mineral that soon becomes familiar to all petrologists. With the polariser oriented E-W, the biotite (similarly aligned) shows a strong red-brown colour, whereas by rotating the stage, and thus minerals, through 90° (polariser maintained with E-W orientation), the biotite colour changes to pale brown or yellow-brown (Fig. 1.6b). This is a consistent relationship, so if you are not sure which way the polariser is oriented for a given microscope, take a known biotite-bearing sample and check which orientation of biotite produces the strongest colour. Once done, the pleochroic schemes of other unknown minerals can be determined in relation to particular optic axes, such as actinolite (Fig. 1.6c), and piemontite (Fig. 1.6d).

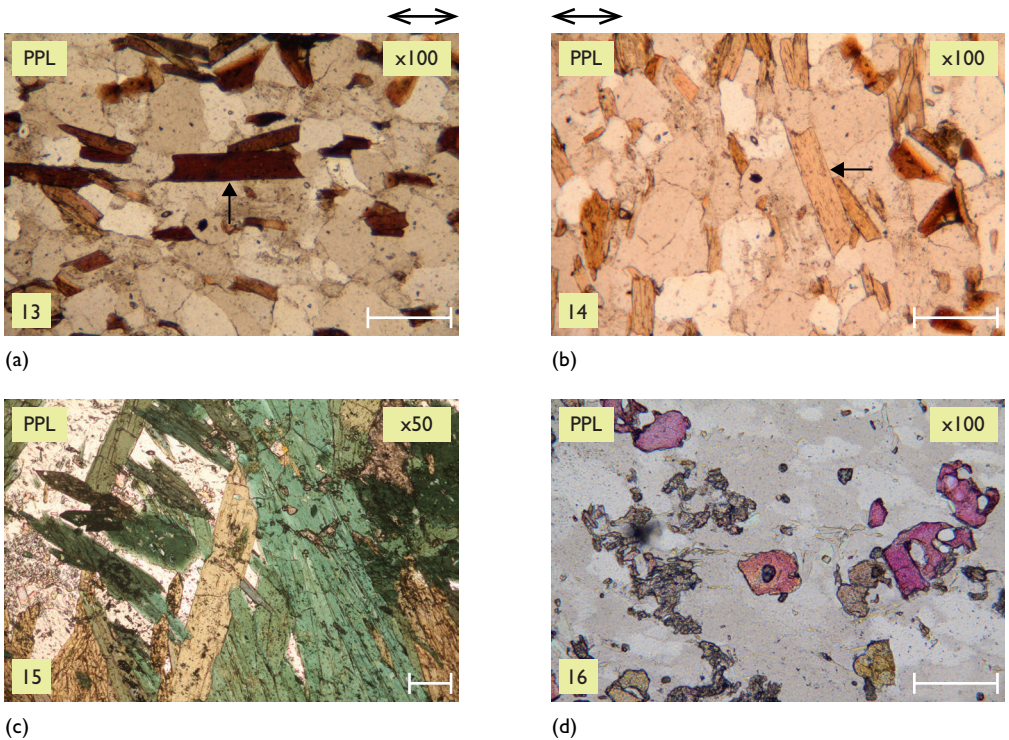


Figure 1.6 Colours and pleochroism. a) Biotite in garnet mica schist; Ross of Mull, Scotland. b) The same biotite as a), but rotated through 90° to illustrate pleochroism. The double-headed arrows beside the images indicate the polarisation vibration directions. c) Actinolite crystals in a range of orientations, showing the pleochroic scheme α = yellow-green, β = green, γ = dark green/blue-green; Epidote-actinolite hornfels; locality unknown. d) Piemontite, showing a spectacular pleochroic scheme: α = orange, β = violet, γ = red; Pennsylvania, USA.

1.3.5 Relief

An accurate evaluation of mineral relief is a crucial for the correct identification of minerals using the present key. For consistency, the descriptive terms “low”, “medium”, “high” and “very high” relief, used in this key, are defined in Table 1.2 in relation to a specified range of refractive index values.

Table 1.2 Sub-divisions of mineral relief, used throughout the present key, in relation to defined refractive index ranges.

Relief		RI
+ve	very high	> 2.000
	high	1.640–1.999
	medium	1.565–1.639
	low	1.542–1.565
	Canada Balsam	1.537–1.542–1.550
–ve	low	1.510–1.542
	medium	1.440–1.509
	high	< 1.440

The “relief” of a mineral is a function of mineral refractive index, which as described in the previous section varies according to the orientation of crystallographic axes, and optic axes. The relief of a mineral is best judged in relation to the mounting medium, or surrounding crystals of known relief, such as quartz (low relief), muscovite (medium relief) or garnet (high relief).

Raising the sub-stage condenser and closing the diaphragm is recommended in order to enhance relief and make it easier to judge the relative relief of minerals. Compare for example, the bright but rather “flat” looking, poorly contrasted image of Fig. 1.7a (diaphragm fully open), with the same field of view in Fig. 1.7b, correctly adjusted. In the latter, the high relief sillimanite (centre) is easily identified, whereas in the former the relief of minerals is so subdued that it is much less easy to judge relief and thus recognise the sillimanite.

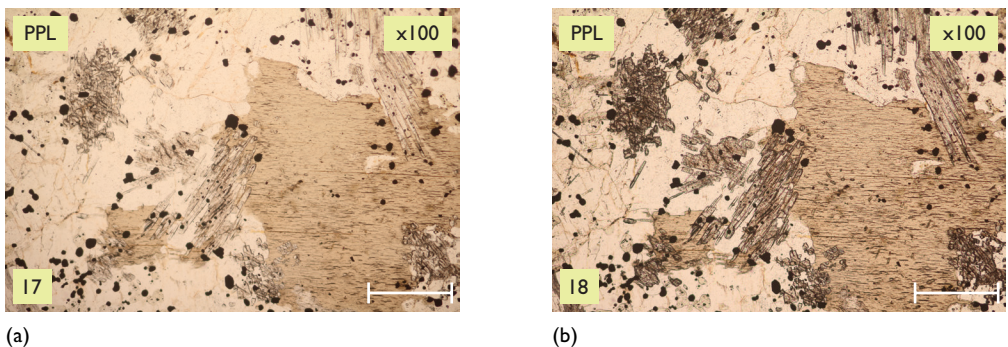


Figure 1.7 Enhancing relief by correct adjustment of the microscope; a) poorly adjusted microscope, making it difficult to identify high relief sillimanite (centre and top); b) ideal set-up, with sub-stage condenser raised and diaphragm closed down to enhance the relief of the sillimanite. Also notice the improved definition of biotite cleavage. Bt-Sil hornfels in contact aureole of granite; Grampian Highlands, Scotland.

The “Becke line” test is a method used to determine whether a mineral is of higher or lower relief than its neighbour, or with respect to the mounting medium. Those minerals with relief higher than the mounting medium (the majority) are said to have positive relief, whilst those minerals with relief, and thus refractive indices, lower than the mounting medium are described as having negative relief. Correct evaluation of mineral relief is crucial and is the basis for many of the fundamental divisions in the various Sections of the mineral key. Although not crucial for most minerals, the determination of whether a mineral has positive or negative relief can be vital for some.

The “Becke line” method relates to the bright line that may be seen at the boundary between a mineral and the mounting medium, or between neighbouring minerals with different refractive indices. This is best seen at high magnification (x400) with the sub-stage condenser raised and the diaphragm closed. By raising the tube of the microscope, to slightly de-focus, the line is observed to move onto the material with the higher refractive index. Fig. 1.8 shows this nicely, with Fig. 1.8a showing the Becke Line at the junction between the mounting medium (left and upper) and microcline (lower right quadrant). Notice how by slightly raising the microscope tube the Becke line has moved onto the microcline (Fig. 1.8b) thus demonstrating that the microcline has higher (and positive) relief relative to the mounting medium. For further explanation of this technique see MacKenzie & Adams (1994), Kerr (1977) and Ehlers (1987a, b).

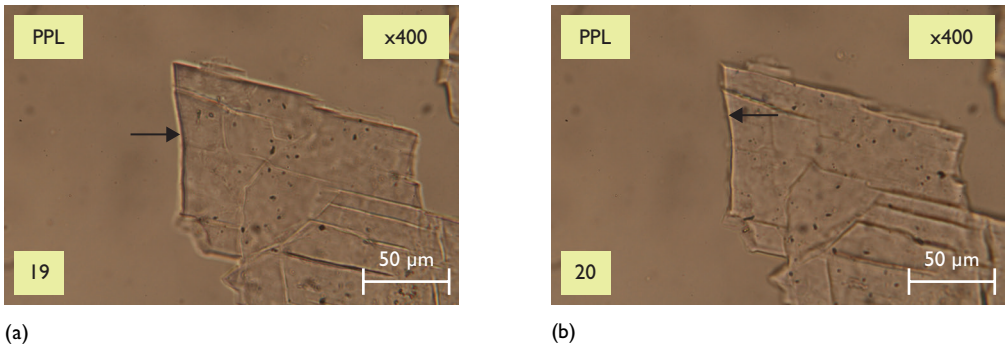
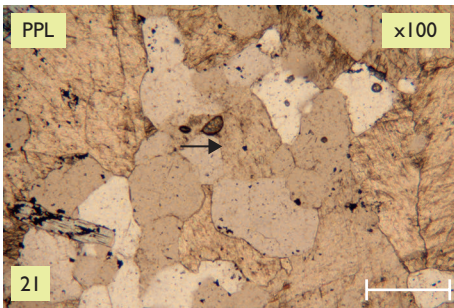
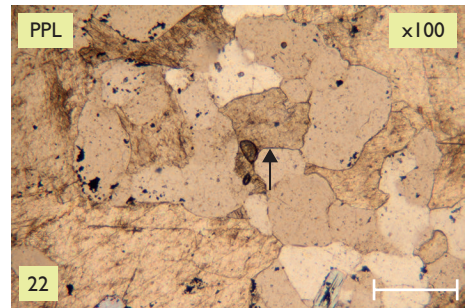


Figure 1.8 Determination of relative relief of adjacent minerals using Becke line technique. a) Initial position with Becke Line at junction between mounting medium left and microcline (lower right quadrant); b) By raising the microscope tube to slightly de-focus, the Becke line has moved onto the higher (positive) relief microcline.

By virtue of pronounced differences in refractive indices in different crystallographic orientations, some minerals, most notably carbonate minerals (e.g. calcite and dolomite) show marked change in relief when the microscope stage is rotated. This produces an effect known as “twinkling”, where the relief of individual crystals rises and falls as the stage is turned. This is often best observed by looking at two adjacent crystals of the same mineral, one showing low relief, and one high, then watching as their relative relief switches when the stage is turned. In Fig. 1.9, two images of the same field of view of an impure Cal-Qtz marble, show differences in the relief of calcite. The second image is rotated through 90° relative to the first. Notice how the calcite crystal in the centre (arrowed) changes from low/moderate relief in Fig. 1.9a to high relief in Fig. 1.9b. This reflects the full range of refractive indices from $\epsilon = 1.486$ (medium -ve relief) to $\omega = 1.658$ (high +ve relief), but not all crystal cuts will be as favourably oriented with respect to the crystallographic axes and some may show little or no twinkling.



(a)



(b)

Figure 1.9 a) Impure regionally metamorphosed marble from Troms, Norway, comprised largely of calcite and quartz. The images show how individual grains of calcite show “twinkling” due to changing relief as the microscope stage is rotated; b) same field of view as in a), but rotated 90° clockwise. Note how the calcite crystal arrowed changes relief, relative to other calcite grains, and to adjacent quartz.

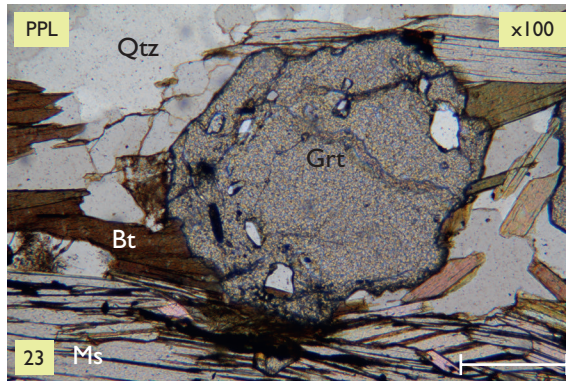


Figure 1.10 High relief garnet porphyroblast in a matrix of moderate relief muscovite and biotite, and low relief quartz; garnet-mica schist, Ross of Mull, Scotland.

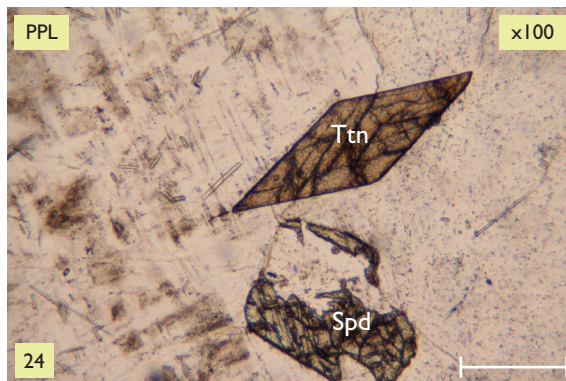


Figure 1.11 Diamond-shaped crystal of titanite (=sphene), above, with adjacent crystal of spodumene (below) set in a background of microcline. Spodumene granite; Leinster, Ireland.

Figures 10 & 11 show two commonly encountered high relief minerals, namely garnet (Fig. 1.10) and titanite (Fig. 1.11). Fig. 1.10 is a particularly nice example, as it shows the difference between quartz (low relief), muscovite and biotite (medium relief), and garnet (high relief).

1.4 Mineral properties in cross-polarised light (XPL)

1.4.1 Birefringence and interference colours

In unpolarised light, the light oscillates in all directions perpendicular to the light (propagation) source. When the light passes through the polariser, below the microscope stage, the light becomes polarised so that beyond the polariser it only vibrates in a single plane. However, on passing through a crystal in a thin-section, the polarised light ray splits into two waves (the ordinary and extraordinary), vibrating in separate planes at right-angles to each other. These two waves propagate at different rates as a function of the crystal system, but do not interfere with each other. However, with the analyser inserted, with its polaroid filter at 90° to that of the original polariser, it produces cross-polarised light. The two out-of-phase waves are now brought back into the same plane. Since they are out of phase with each other, there is a resulting interference of the waves and this is what gives rise to the interference colours of minerals seen in cross polarised light, and a value for birefringence (δ), which varies from one anisotropic mineral to the next. In essence it is a summation of the various individual wavelengths in the white light “rainbow” spectrum (ie red, orange, yellow, green, blue, indigo, violet) which are slightly out of phase with each other. In cubic minerals the waves completely cancel each other out, such that the crystals appear constantly black in cross-polarised light and are said to be isotropic.

Multiple orders (1st, 2nd 3rd etc) of interference colours are produced to give the classic Michel-Lévy interference colour chart seen in most optical mineralogy books, and also included at the back of the present mineral key. The magnitude of birefringence (δ) for anisotropic minerals is directly related to the difference between maximum and minimum refractive indices, and thus optic axes. For biaxial minerals, $\delta = \gamma - \alpha$, whilst for uniaxial minerals $\delta = \epsilon - \omega$. Although the birefringence (δ) of a mineral has a defined value (or range), the interference colours observed will vary according to the thickness of the thin-section and the orientation of individual crystals. By convention, the standard thin-section thickness is 30 μm , and throughout the present mineral key the interference colours referred to are those associated with this standard thickness. If for any reason a thicker thin-section is used, higher order interference colours will be observed for a given birefringence, with the reverse true for thinner slides. For a standard 30 μm thickness thin-section, the boundaries between interference colour orders repeat at intervals approximating to $\delta = 0.018$. Hence the boundaries are at $\delta = 0.018$ (top 1st order), 0.037 (top 2nd order), 0.056 (top 3rd order), 0.074 (top 4th order) (see Demange (2012) for further detail). Since birefringence is directly related to differences in refractive indices for a given mineral, it means that minerals showing “twinkling” (e.g. calcite, dolomite) must always have high order interference colours. Note that all values for δ given in the present publication are based on data presented in Deer *et al.* (1992, 2013).

Making the correct assessment of a mineral's birefringence based on its interference colour in thin-section is crucial for the effective use of the present key. There are,

however, some important points to be aware of in order to make the correct determination. Assuming that the thin-section is at the required thickness, the other factor, mentioned above, that substantially influences the interference observed for a given crystal is its orientation with respect to the thin-section cut. If the crystal is cut perpendicular, or very close to perpendicular to, the z -axis ($\equiv c$ -axis), the grain will show dark grey to black (isotropic) interference colours, by virtue of looking right down the axis. For other orientations, however, higher interference colours will be seen (unless of course it is a mineral with very low birefringence!).

The highest interference colour observed, and the one on which the birefringence of a mineral should be based, will only be seen in crystals perfectly oriented with respect to the maximum and minimum optic axes (thus giving the greatest refractive index differences). All other orientations will be oblique cuts and thus show lower interference colours. This is also important when determining extinction angle (see below).

In a thin-section the majority of crystals will be oblique cuts and thus showing a spread of colours (e.g. Fig. 1.12) slightly below the true maximum value. It is important therefore to look at the full spectrum of interference colours for the population of grains of a particular mineral, and from this identify the highest interference colour represented. If only one or two crystals of the mineral of interest are present (i.e. very small sample size), it should be realised that the birefringence could well be higher than the maximum interference colour that these few crystals might suggest. This is simply because with just a few crystals, and most likely they are oblique cuts, the peak interference colour may not be represented. In view of this, always err towards the higher side of any couplet in the key involving interference colours if you find yourself with a borderline situation. Hard minerals like corundum can sometimes be a problem as they are not always ground down to the required $30\ \mu\text{m}$ thickness (by virtue of their hardness) so may give slightly elevated interference colours because of the thicker section.

Having identified the individual crystal(s) with maximum interference colour (for a particular mineral), as described in the previous paragraph, the maximum intensity of interference colour for any crystal is always seen at the mid point between extinction

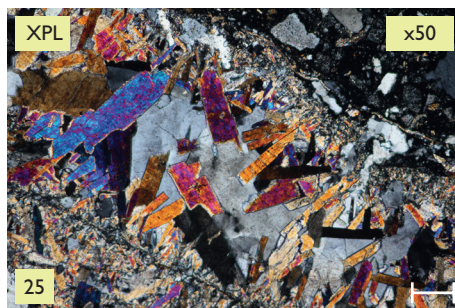


Figure 1.12 Prehnite ($\delta = 0.020\text{--}0.033$) showing range of interference colours due to orientation of crystals in relation to thin-section cut. Highest interference colour from these crystals is 2nd Order blue (see crystal at 45° towards top left), but note all the lower 1st ord. yellow, orange, red and purple interference colours. It is very important to recognise the highest colour for a given mineral (see text for further detail). Prh-qtz vein cutting volcanoclastic sediments; Roseland, Cornwall, England.

positions. With the exception of isotropic crystals (which stay black), when the microscope stage is rotated, the crystal will be seen to pass through extinction (go black) four times in each 360° rotation (ie once every 90°). For minerals such as muscovite, with extinction parallel to the cross-wires (ie N-S and E-W), the maximum intensity of interference colour will be in the 45° position (ie NE-SW or NW-SE). See for example the muscovite and talc crystals in the combined set of images (Fig. 1.14), and the prehnite crystals in Fig. 1.12 above. Also see the radiating zeolites (Fig. 1.14, mid top row) with first order birefringence, noting that the horizontal and vertical crystals are at extinction, demonstrating they have straight extinction, whilst the crystals oriented NW-SE show peak 1st Order white interference colours.

Finally, be aware that whereas colourless minerals (e.g. muscovite) show interference colours exactly as they appear on the colour chart (Fig. 1.13a), minerals with strong colour in plane-polarised light (e.g. biotite, rutile) (Fig. 1.13b), will generally have their interference colours masked to a lesser or greater extent, making it difficult to judge the interference colours (and thus birefringence value).

To the inexperienced petrologist, it is not always easy to judge the Order that the different interference colours observed in thin-section relate to. A useful tip to help with this is to look for crystals that have a thinned or tapered edge (see Fig. 1.15). Being thinned, the interference colour represented at the edge will be less than that of the standard $30\ \mu\text{m}$ thin-section. Indeed, the thinned edge often shows the full spectrum of colours going down through the orders from whatever the maximum value the crystal is showing. The multiple bands in the crystal edge zoning of the 3rd order phlogopite of Fig. 1.15c, is clearly very different to the zoning at the edge of the top 1st/low 2nd order colours of sillimanite and augite (Fig. 1.15 a, b). The sillimanite and augite examples clearly show the simple gradation down through top first order purple/red then mid first order orange/yellow/white, and just about into lower first order grey.

Anomalous Berlin blue/Prussian blue or brown interference colours are seen in some anisotropic minerals that have first order birefringence (e.g. chlorite, zoisite, melilite, vesuvianite) (see Fig. 1.16). Such colours occur in place of the greys that should be shown for a mineral of such birefringence. So why are the colours anomalous compared to those predicted by the Michel-Lévy colour chart for white light? At the start of this

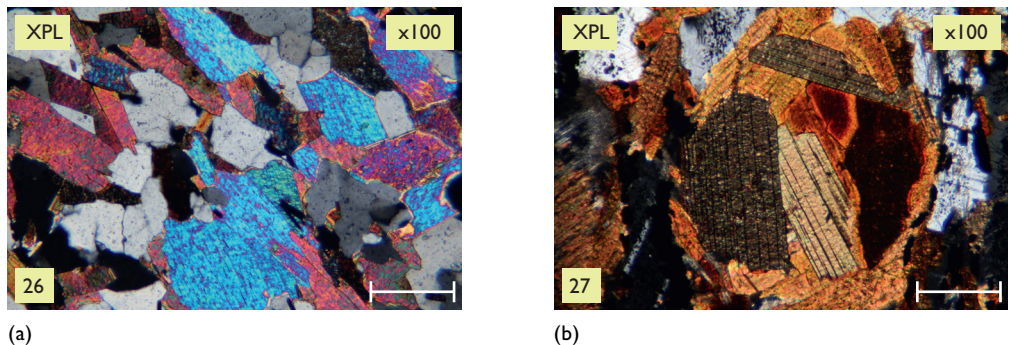
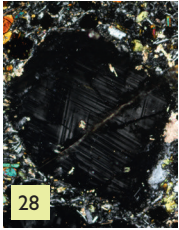


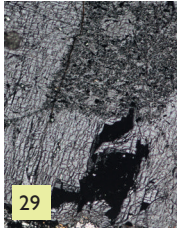
Figure 1.13 Comparison of two minerals with similar birefringence to illustrate how the interference colours of a colourless mineral such as a) muscovite, are close to that on the Michel-Lévy colour chart, whilst those of b) biotite, in most orientations are strongly masked by the strong background colour of the mineral.

1st Order

Low

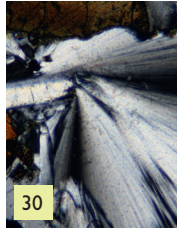


Leucite



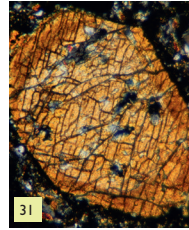
Andalusite

Mid

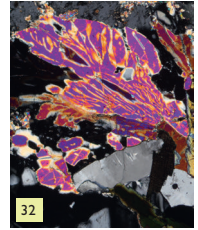


Zeolite

High



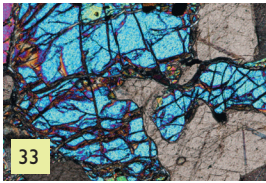
Augite



Cancrinite

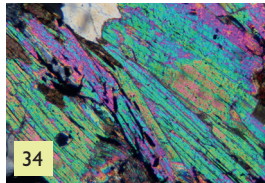
2nd Order

Low



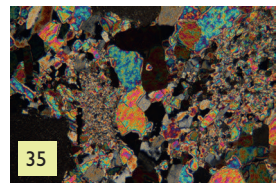
Olivine

Mid



Muscovite

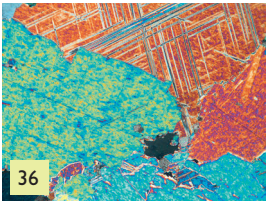
High



Anhydrite

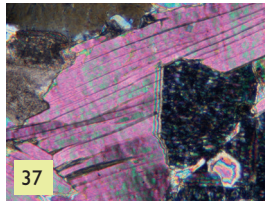
3rd Order

Low



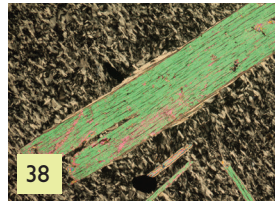
Anhydrite

Mid

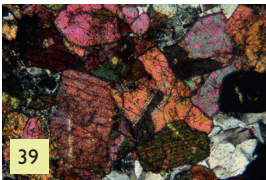


Phlogopite

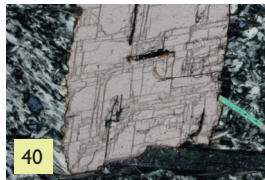
High



Talc

4th Order

Cassiterite

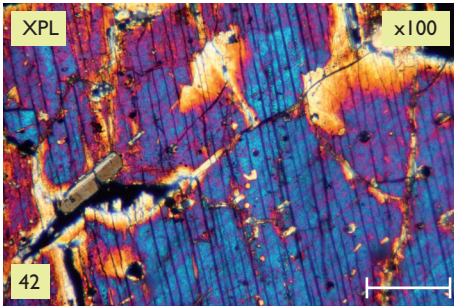
5th Order

Dolomite

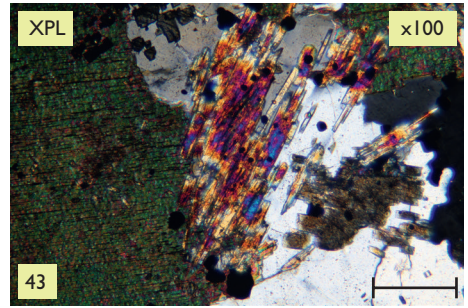


Rhodochrosite

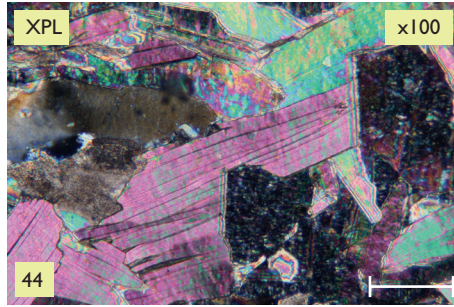
Figure 1.14 Examples of minerals representing different interference colours according to the various levels of birefringence (see colour chart and Appendix 1 for full range of colours, and Appendix 2 for minerals listed in birefringence (δ) order).



(a)

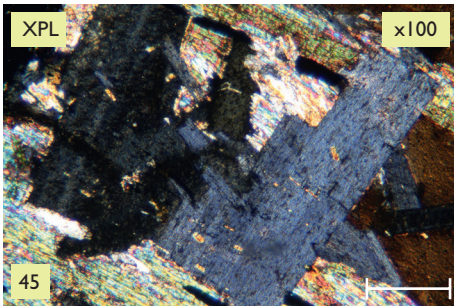


(b)

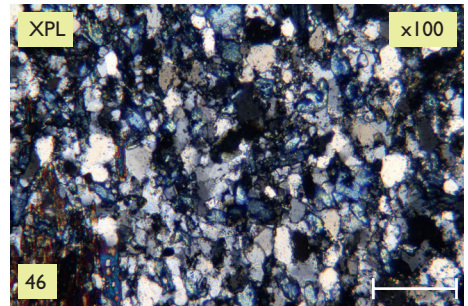


(c)

Figure 1.15 Representative examples of thinned crystal edges as an aid to determine the maximum interference colour of a given crystal; a) augite in gabbro; Isle of Skye, Scotland; b) sillimanite in sil-kfs-hornfels; Aberdeenshire, Scotland; c) phlogopite; Bavaria, Germany. In the phlogopite example, note the multiple bands of interference colours at the thin left edge of the crystal at extinction lower centre (and other crystals). These display a sequence of interference colours covering several orders, and show the mineral is of 3rd order birefringence.



(a)



(b)

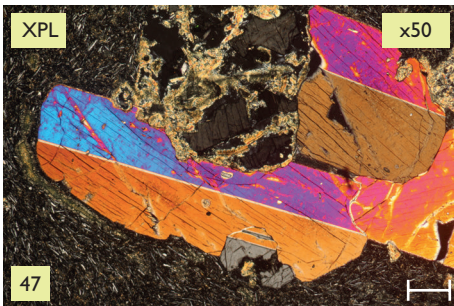
Figure 1.16 Anomalous interference colours typical of certain minerals that based on their birefringence should show 1st Order grey-white-pale yellow interference colours, but in fact show anomalous Berlins blue/Prussian Blue or brown interference colours. a) late-stage chlorite cross-cutting schistosity in grt-mica schist; Troms, Norway; b) zoisite in Hbl-Qtz-Zo hornfels; Isle of Man, England.

section it was explained that the interference colours are produced by a composite summation of the various waves (relating to the colours of the “rainbow” spectrum, each with different wavelength) that make up white light with the analyser inserted (Fig. 1.5–21 of Kerr, 1977 gives a good illustration of this). The cause of the anomalous colours is when a mineral shows significant variation in birefringence due to different wavelengths of light. This gives rise to a lowering in intensity of certain colours, such that the combination of waves produces a colour that differs from that predicted by the Michel-Lévy chart. Although when first encountered, these unusual colours seem rather confusing, if correctly recognised, they can in fact be very useful for the identification of those few minerals that show them.

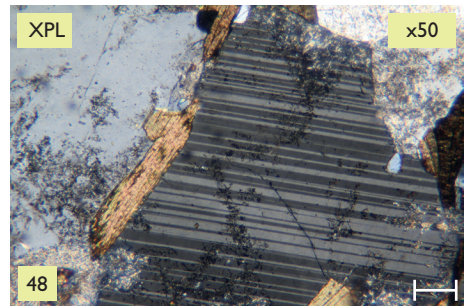
1.4.2 Twinning

Twinning is commonly observed in many minerals, especially those of igneous and metamorphic rocks. For some minerals the presence of twins is more or less ubiquitous, yet for other minerals twinning is rarely seen. In view of this, presence of twinning can sometimes be helpful for mineral identification.

The “simple twin” (Fig. 1.17a), is one of the commonest types of twin observed, and a wide variety of minerals show this. Such twins are particularly prevalent in phenocrysts of igneous rocks. They generally form by mirroring of the crystal structure



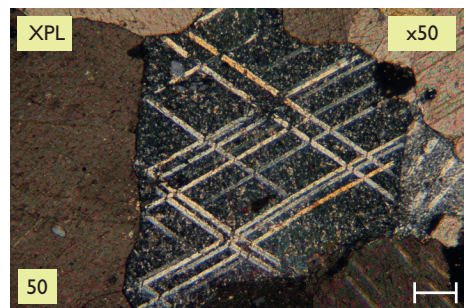
(a)



(b)



(c)



(d)

Figure 1.17 Twinned crystals. a) Simple twin (diopside) in boninite; Japan; b) multiple lamellar (polysynthetic) twinning (plagioclase) in granite; St.Jacut, Brittany, France; c) cross-hatched twinning (microcline) in granite, Penmaenmawr, Wales; d) deformation twins (calcite) in marble; Donegal, Ireland.

each side of a particular crystallographic plane as the crystal has grown. Individual minerals have a tendency for developing twins in specific orientations relative to the crystal lattice and specific planes. Because the two halves of the twin are differently oriented within the plane of the thin-section they show different interference colours (Fig. 1.17a), and are thus a very obvious features.

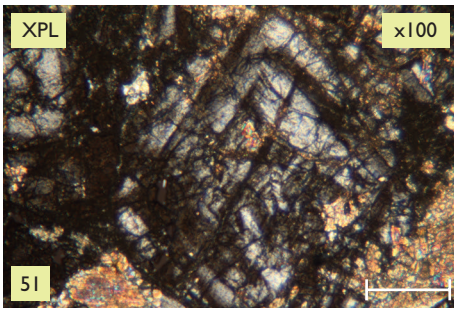
Other minerals may show multiple, or polysynthetic twinning (Fig. 1.17b). This is particularly common in plagioclase of igneous rocks, yet plagioclase porphyroblasts in regional metamorphic greenschist facies metabasites do not show such twinning due to the shear stress at the time of growth. Multiple lamellar twinning forms by repeat alternations of the crystal lattice about a particular plane (010) in the crystal lattice. The regularity is such that alternate lamellae are identically oriented and thus have the same interference colour. This shows up well in the main plagioclase crystal of Fig. 1.17b, with one half of the alternating twins at extinction and the other half of the alternating twin lamellae showing showing 1st Order light grey-white interference colours.

Another distinctive type of twinning is “cross-hatched” or “tartan-twinning”, which is diagnostic of microcline (Fig. 1.17c). Such twinning comprises combinations of albite-twinning and pericline twinning, parallel to {010} and {100} respectively, and thus best displayed as two sets of twins at 90° to each other in planes cut approximately parallel to (001). It is outside the scope of the text to discuss feldspar twinning in any further detail, but for additional information see Deer *et al.* (1992, 2013).

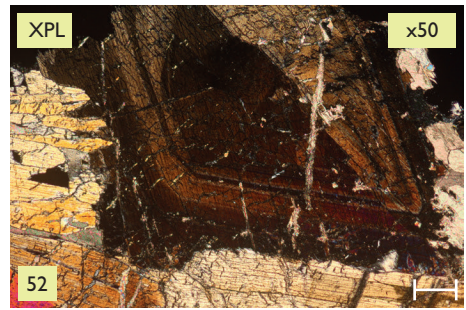
A final and quite different type of twinning to consider is that of deformation twinning (Fig. 1.17d). This type of twinning is especially common in carbonate minerals (e.g. calcite, dolomite) in regional metamorphic environments and shear zones, but may also be seen in highly deformed pyroxenes and plagioclase. Unlike the primary twins described above, deformation twins are secondary in nature, having developed after original crystal growth. They form by shear along particular planes of the crystal structure and commonly give rise to more than one set of deformation twins in different orientations. Rather than intracrystalline slip, deformation twins form by twin-glide, giving rise to reorientation of the crystal lattice into the twinned position. In carbonate minerals the narrow deformation twins generally show brighter, lower order, interference colours (e.g. 2nd/3rd order) compared with the high order pastel shades (5th order) of the intervening areas of the crystal. The twins and their orientations are best observed when the main area of the crystal is placed into the extinction position.

1.4.3 Zoning

Various forms of zoning may be recognised in crystals, including concentric (growth) zoning, formed due to chemical changes as the crystal grew. This is particularly common in igneous phenocrysts, but can also be seen in metamorphic minerals of skarns such as vesuvianite (Fig. 1.18a) and diopside (Fig. 1.18b). Other types of zoning include crystallographically controlled zoning, such as the distinctive “hour-glass” zoning of chloritoid (Fig. 1.18c), and “sector-zoned” titanite (Fig. 1.18d) and cordierite (Fig. 1.18e). A final type is the well known “chiastolite-cross” (Fig. 1.18f) of andalusite (var. chiastolite) often seen in metapelitic rocks within the contact aureole of granites. Although most types of zoning are not unique to specific minerals, they are sufficiently distinctive for a few minerals that they can be a useful aid to identification.



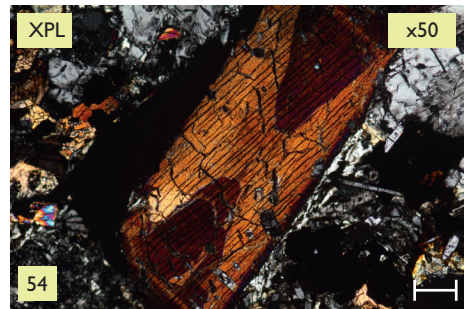
(a) Vesuvianite (concentric zoning)



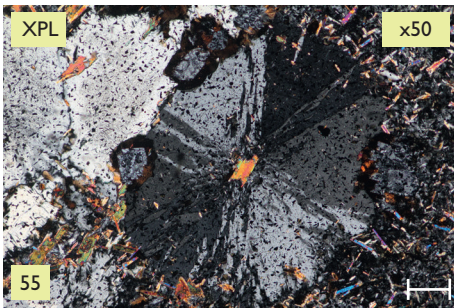
(b) Diopside (chemical zoning) -skarn



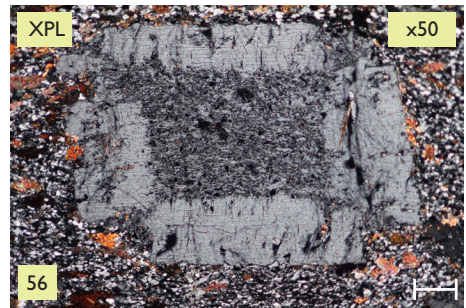
(c) Chloritoid (hour-glass zoning)



(d) Titanite (sector zoned)



(e) Cordierite (sector zoning)



(f) Andalusite (Chialstolite cross)

Figure 1.18 Various types of zoning in crystals. a) Concentric zoning (vesuvianite) in skarn; Donegal, Ireland; b) chemically zoned diopside in calc-silicate skarn; Loch Ailsh, Assynt, Scotland; c) hour-glass zoning (chloritoid [*ottrelite*]) in chloritoid phyllite; Ottere, Belgium; d) sector zoned titanite in nepheline syenite; Saxony, Germany; e) Sector zoning/sector trilling (cordierite) in cordierite-andalusite slate, Connemara, Ireland; f) chialstolite cross (andalusite) in cordierite-andalusite slate; Connemara, Ireland.

1.4.4 Extinction angles

When describing birefringence, in 1.4.1 above, it was stated that when the microscope stage is rotated in cross polarised light, the crystal under consideration will go into extinction four times in a complete 360° rotation (ie once every 90°). Whilst this is true of all anisotropic minerals, the position at which extinction occurs varies from

one mineral to the next as a function of crystal system and specific mineral properties. The extinction angle also varies from one crystal to the next as a function of crystal orientation in the plane of the thin section.

It is easiest to define extinction in relation to elongate crystals and those with well developed cleavage and/or crystal faces (seen as flat edges in thin-section). If the crystal goes into extinction with the flat edge of crystal length in a position parallel with the N-S (vertical) or E-W horizontal position it is said to have straight or parallel extinction (i.e. 0°) (see Fig. 1.19). If the microscope eye-piece (ocular) contains N-S and E-W oriented cross-hairs this can be accurately determined; if not judgement by eye will be required. Similarly, length-section crystals showing a good cleavage trace (usually parallel to crystal edge), can also have their extinction angle easily determined. If the crystal goes into extinction with the cleavage trace N-S and E-W oriented, it too is said to show straight extinction (see vertically oriented central biotite crystal of Fig. 1.13a, and stilpnomelane of Fig. 1.19a). For small elongate grains with no obvious cleavage and poorly defined crystal edges, the best way to assess the extinction angle is to line up the

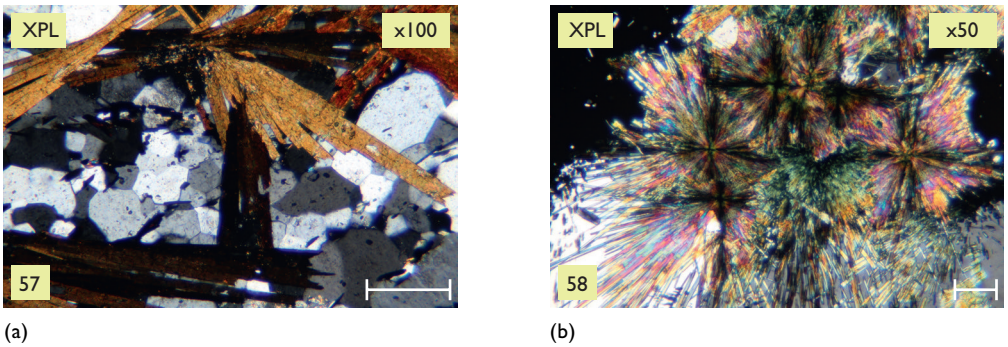


Figure 1.19 Minerals showing straight extinction. a) Stilpnomelane (note lower left E-W crystal and central N-S crystals at extinction), in metamorphosed siliceous ironstone; Laytonville Quarry, California, USA; b) Radiating tourmaline crystals in Luxullyanite; Cornwall, England. Note: Those crystals in the E-W and N-S positions are at extinction, thus giving a series of black crosses; one cross for each radiating cluster.

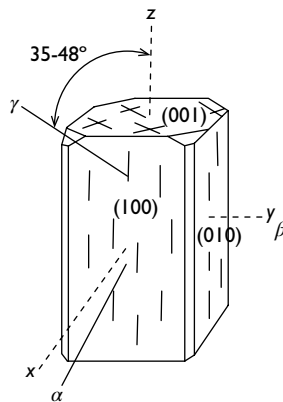


Figure 1.20 Augite crystal showing extinction angle based on the angular difference between γ optic axis and z- crystallographic axis.

length of the crystal N-S. If it shows extinction when aligned this way, it can reasonably be interpreted as being straight extinction.

For minerals with straight (=parallel) extinction, there is parallelism between the crystallographic axes and optic axes (vibration directions). However, minerals showing inclined extinction (e.g. clinopyroxenes, clinoamphiboles), have varying levels of angular difference between the optic axes and the crystallographic axes. Augite for example (Fig. 1.20), shows a maximum difference between the γ -axis (optical axis) and the z -axis (crystallographic axis), $\gamma : z$ of $35\text{--}48^\circ$, in side-sections cut parallel to the x - z plane.

If the crystal being observed in thin-section is not roughly parallel with the plane containing x - z axes, (010), the angular difference $\gamma : z$ will be less than the maximum extinction angle (i.e. it gives an apparent $\gamma : z$ angle). It is therefore essential when determining the extinction angle for a mineral that the value is measured for a representative sample of crystals to find out what the maximum (and thus true) extinction angle is. Those crystals with the favourable orientation, containing the z -axis, will be those showing the highest interference colours, and conversely those showing the lower or lowest interference colours should be avoided. The significance of this was also discussed in relation to interference colours and determination of birefringence (see 1.4.1, above). The present mineral key uses the broad distinction between straight and inclined extinction minerals as one of the fundamental divisions (Section 2). Within Section 2 many of the couplets then rely on the precise value for extinction angle, hence the importance of selecting the right crystals for this determination. Accurate measurements can be made by positioning the crystal in the centre of the field of view, and lined up with the cleavage trace or crystal edge N-S.

Once done, the orientation of the microscope stage is recorded using the fixed vernier scale present on one edge. Having noted a figure for the first position, the stage (and crystal) are then rotated left and right from the N-S position to find the point of extinction. The new position of the microscope stage is then recorded, and the difference between the two gives the extinction angle. By convention, this is always quoted as the lower angle. If for example, a mineral went extinct when angled 31° to the left of the N-S position, it will also show extinction at 59° to the right, since extinction happens every 90° . In this case, the extinction angle is correctly recorded as 31° . If there are enough suitable crystals in the thin-section, the present author recommends checking the extinction angle on at least five suitably oriented crystals, and preferably

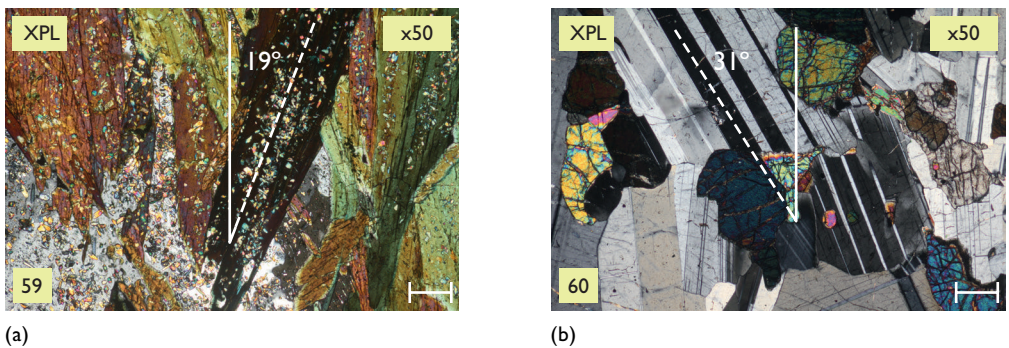


Figure 1.21 Minerals showing inclined extinction. a) actinolite in albite-epidote hornfels; locality unknown, and, b) plagioclase in troctolite; Sierra Leone.

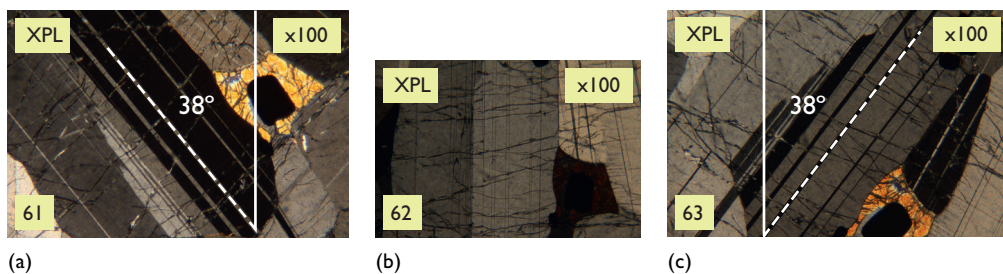


Figure 1.22 central image (b) is plagioclase with optimum orientation as shown by equal illumination in N-S position; a) and c) are the same plagioclase rotated left to the position with one set of twins at extinction, and right to the position where the other set goes into extinction. Extinction angles have been measured and displayed. The average of the two gives the extinction angle for the crystal. Note that such averages should only be calculated if the left and right angular values for extinction are broadly similar (which indicates the crystal was ideally oriented). Anorthitic plagioclase in anorthosite; Rhum, Scotland.

ten. Fig. 1.21 shows examples of inclined extinction for actinolite (Fig. 1.21a) and plagioclase (Fig. 1.21b).

When measuring extinction of multiple lamellar twinned plagioclase, look for crystals with equal illumination when in N-S position relative to cross-wires (Fig. 1.22b), then rotate left and right in turn (Fig. 1.22a-c) to measure extinction angle of each twin set. If the crystal is to be regarded as reliable for extinction angle determination, the value obtained turning left should be the same or very close to the value obtained when turning right. In this example the extinction angle is 38° indicating the plagioclase in question is a Ca-rich labradorite (An_{68}), bordering on bytownite. When the extinction position bisects the angle between two cleavages, as typically occurs in end-sections of pyroxenes, it is said to be symmetrical extinction.

1.4.5 Length-fast and length-slow crystals

In 1.4.1, it was explained how white light is polarised into a single plane when it passes through the lower polariser. This polarised light hits the underside of the thin-section as a wave vibrating in a single plane. However, immediately on entering the crystal the light splits into two rays (ordinary ray and extraordinary ray), vibrating in separate planes at right-angles to each other. These rays move at different velocities as a function of the crystallographic structure and atomic arrangement. They are generally referred to as the “fast ray” and “slow ray”. When the analyser is inserted (polariser at 90° to that of lower polariser), because one ray is moving faster than the other, they are out of phase with one another, and combine to produce the interference colours of cross-polarised light. This is true for anisotropic minerals, but for cubic minerals, which have identical atomic arrangement in all directions, the rays move at the same rate and thus combine perfectly to cancel out and give darkness (ie the mineral is isotropic).

The two rays described above for anisotropic minerals have different refractive indices, the “slow ray” always having a higher refractive index than the “fast ray”. Because

of these differences, determination of the fast and slow vibration directions has proved to be a very useful way of identifying certain minerals that are otherwise quite similar to each other. The method involved with this simple but effective technique will now be described.

Unless adjusted for some reason, remember that the polarisers of the microscope should be aligned with one polariser parallel to E-W and the other parallel to N-S. By inserting the analyser, so that the thin-section is viewed in cross-polarised light, the stage is rotated to find the extinction position of the mineral (see 1.4.4). Bearing in mind the orientation of the polarisers, the positions of extinction (at 90° intervals), give the orientations of the vibration planes of the fast and slow rays. When the mineral goes black, the vibration directions of the rays are essentially parallel to the polarisers. At this stage, however, there is no way of knowing which orientation represents the fast ray, and which the slow ray. For minerals with straight extinction, the rays are parallel with the crystallographic axes, whereas in the case of inclined extinction, the rays (optic axes) are oblique to the crystallographic axes (see 1.4.1 above).

Having established the orientation of the rays based on mineral extinction positions, the mineral is then rotated to a position at 45° to the extinction position (ie bisects the 90° angle between extinctions). At this position the crystal will show maximum intensity of interference colour. If we take the case of a mineral showing straight extinction, the crystal would be rotated to either the NW-SE or NE-SW position.

The next step is to insert a mica ($\lambda/4$) plate (retardation $\Delta = 150$ nm), a gypsum (λ) plate ($\Delta = 550$ nm) or a quartz wedge (typically ranges from $\Delta = 0$ –50 nm up to $\Delta = 2200$ nm). The retardation due to the quartz wedge increases progressively with increasing thickness of the wedge (see Kerr, 1977, for further detail). The choice of accessory plate to use depends on the birefringence of the mineral under investigation. The mica plate is typically used for those minerals with very low anisotropy (low 1st order interference), the gypsum (λ) plate for minerals with greater anisotropy (e.g mid first order to second order). The quartz wedge, because of its tapered nature of gently increasing thickness produces interference colours from low first order to fourth order. It is a good general purpose accessory plate, but is especially useful for determining the orientation of fast and slow rays in minerals with high order interference (e.g. carbonate minerals).

It is standard for most microscopes to have the accessory plate insertion position as from NW or SE. Fig. 1.23 gives a schematic representation of a typical gypsum (λ) plate, with “fast” and “slow” orientation indicated (Fig. 1.23a). On insertion of the plate from the NW, a crystal oriented length-wise NW-SE, would be interpreted as “length-fast” if the interference colour increased on insertion of the plate (Fig. 1.23b). Conversely, a crystal is “length-slow” if it shows a decrease in interference colour when the plate is inserted with the crystal length aligned NW-SE (Fig. 1.23c). In each case, if the crystal is turned through 90°, the colour reverses (Fig. 1.23b, c).

It is straightforward to explain why the particular colours occur, as they are simply the combination (addition or subtraction) of the retardation value (Δ) of the mineral, based on its birefringence (Appendix 1), with that of the accessory plate used. If we consider the case of an andalusite crystal showing 1st order white interference colours ($\Delta = c.200$ nm) in XPL, when the gypsum plate ($\Delta = 550$ nm) is inserted (see Fig. 1.24b), the combined Δ value obtained will be either an addition ($\Delta = 550 + 200 = 750$ nm;

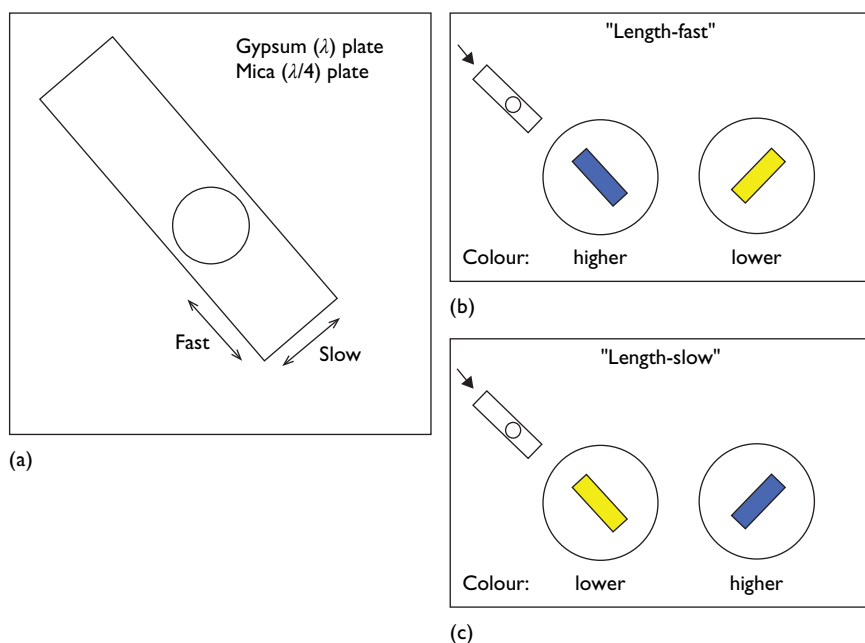


Figure 1.23 Schematic illustration of changing interference colours of “Length-fast” and “Length-slow” minerals when a gypsum (λ) plate ($\Delta = 550$ nm) is inserted. a) orientation of accessory plate at point of insertion varies between microscopes, many have the plate inserted NW-SE. Fast and slow vibration directions indicated; b) for length-fast crystals, when the plate is inserted as shown, with the crystal aligned with its “fast” orientation parallel to the “fast” direction of the plate (left), the interference colours of the mineral will be observed to increase. With the crystal oriented with its “fast” orientation (length) at 90° to the inserted plate (right), the interference colours will be lower; c) length-slow crystals show the reverse relationship, with crystals aligned with their “slow” direction parallel to the “fast” direction of the inserted plate showing a decrease in interference colours, whilst at 90° to this the crystal shows higher colours. Note that the blue and yellow used in the diagram are representative of the change for crystals with 1st order grey/white interference colours when the gypsum plate is inserted, they do not necessarily reflect the various colours that may be seen at other values of birefringence and when using other accessory plates.

2nd order blue-green) when the fast ray of the plate and that of the crystal are aligned, or subtraction when the slow ray of the crystal aligns with the fast ray of the plate (ie $\Delta = 550 - 200 = 350$ nm; 1st order yellow).

Fig. 1.24 illustrates some representative examples of length-fast and length slow crystals. Notice how the two intergrown chloritoid crystals of Fig. 1.24a have the NW-SE oriented crystal showing the high colour and the NE-SW crystal showing the low colour. Compare this with the schematic representation in Fig. 1.23b for length-fast crystals. Also note the three crystals of andalusite (var. chiastolite) in Fig. 1.24b, the NW-SE oriented crystal (centre) showing the high colour, the NE-SW crystal (right) showing the low colour, and the horizontal crystal (left edge), oblique to insertion direction (and at extinction when plate was inserted) showing a colour intermediate between the two, close to that of the gypsum plate. Tourmaline (Fig. 1.24c) is another commonly encountered length-fast crystal, in this case producing a combined 3rd order green colour.

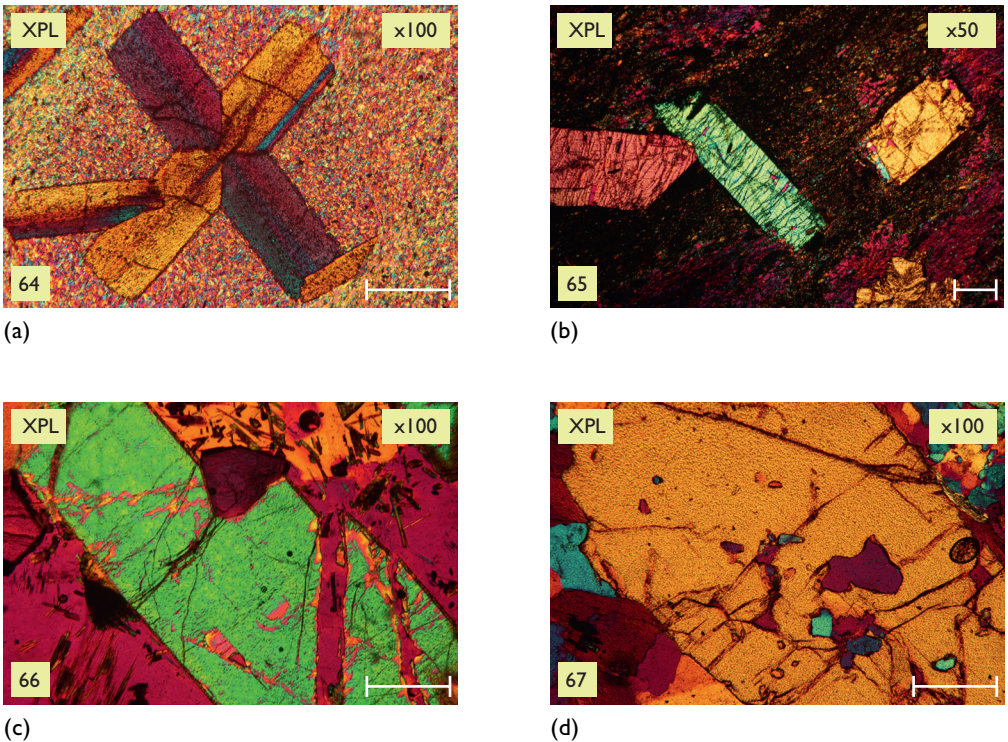


Figure 1.24 Representative examples of length-fast and length-slow crystals; λ -plate inserted from NW in all cases. a) Chloritoid (length-fast), in chloritoid phyllite; Tarkwa, Ghana; b) Andalusite (length-fast) in andalusite slate; Skiddaw Granite aureole, Cumbria, England; c) Tourmaline (length-fast), in tourmaline-quartz vein rock; Cornwall, England; d) Staurolite (length-slow), in staurolite schist; Snake Creek, Mt. Isa region, Queensland, Australia.

The staurolite (Fig. 1.24d), showed 1st order grey/white interference colours prior to insertion of the gypsum plate. With the plate inserted, and with length oriented NW-SE, it now shows its length-slow character, with lower colours (1st order yellow-orange) compared to the gypsum red, exactly the opposite of chloritoid and andalusite above.

1.4.6 Interference figures

All previously described thin-section properties of minerals are observed in what is termed orthoscopic illumination. This involves the various light rays moving in parallel paths upwards through the lens system of the microscope (and through the thin-section) up to the eye-piece where an image of the thin-section field of view is projected. By contrast, interference figures are produced using conoscopic illumination. This involves light being converged to a point within the thin-section, and beyond this, the light leaves the thin-section as a slightly conical beam. A close working distance between objective lens and thin-section is required for the divergent conical beam of light to form an interference figure on the top curved surface of the objective lens. This can be viewed by taking the eye-piece out and looking straight down the microscope tube at

the tiny image on the upper surface of the objective lens. More conveniently, however, most good polarising microscopes will have a Bertrand lens fitted at some point up the microscope tube. Inserting (or flipping) this lens in position projects the interference image from the top of the objective lens up to the eye-piece for the viewer to observe. The interference figure comprises a series of dark lines (“isogyres”), relating to the optic axes; a simple cross for uniaxial minerals and two curved black lines for biaxial minerals. For further detail on the topic of interference figures, the interested reader is referred to Kerr (1977), Ehlers (1987a,b) and Demange (2012).

To obtain a good interference figure, it is important to select an end-section (or side-section) crystal with low interference colour (1st order very dark-grey to black), as such crystals are cut close to parallel with crystallographic axes. Even with this, it may not always be possible to obtain a good interference figure, but use of unsuitably oriented, appreciably deformed, or heavily included crystals, will undoubtedly produce failure.

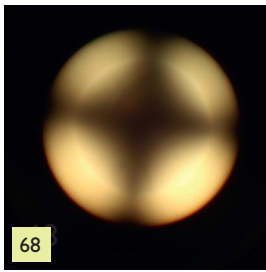
As stated above, interference figures can only be produced in conoscopic illumination (= convergent polarised light). This is achieved by raising the sub-stage condenser to just below the microscope stage, then flipping the front lens of the sub-stage condenser “in”. This will give convergent light in a small central area of the field of view of the crystal of interest. This is also useful when working at high magnification and needing increased illumination.

Working in cross-polarised light (essential for interference figures), it is best to start at low magnification (i.e. $\times 10$ eye-piece and $\times 10$ objective = $\times 100$ magnification), then work up to progressively higher magnification, re-focusing each time. Typically through the $\times 20$ objective ($\times 200$ magnification) and finally $\times 40$ objective ($\times 400$ magnification). Once at $\times 400$ magnification, insert the Bertrand lens, and if the crystal is close to the ideal orientation and not heavily included or deformed, it should be possible to obtain an interference figure.

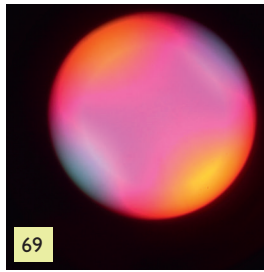
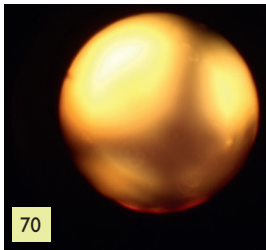
For best results, as well as being favourably oriented to the optic axis, the single crystal of interest needs to fill the entire field of view. This is why it is usually necessary to work at $\times 400$ magnification. Another reason for working at high magnification is because of the requirement to have a very short working distance between the objective lens and the thin-section. This is needed so that on leaving the thin-section, the diverging cone of light is still reasonably tight, and so forms a sharp interference figure on the upper surface of the objective lens. The Numerical Aperture (NA) of the objective lens (usually marked on the side of the lens, along with magnification), is important, as it directly relates to the maximum angular spread of light rays that can be transmitted. Generally speaking, the higher the magnification of the objective, the higher the NA value of the lens, but as some high magnification lenses are designed for greater working distance they will have lower NA. It is advisable to check the lens you are using. The images shown in Fig. 1.25 and Fig. 1.26, below, were all taken using a $\times 40$ objective, with NA = 0.65. This is a fairly typical NA value for a lens of such magnification. If the crystal of interest is reasonably large and inclusion free it may be possible to obtain a reasonable optic figure at $\times 200$ magnification ($\times 20$ objective), although from the author's experience best results are usually obtained at higher magnification ($\times 400$).

Uniaxial figures

If in the plane of the thin-section, the crystal has been cut exactly perpendicular to z -axis ($\equiv c$ -axis) such as the example of quartz in Fig. 1.25a, a perfect interference figure will be formed. For uniaxial minerals, this is a “cross”, with dark lines (isogyres)



(a) Quartz (uniaxial)

(b) λ -plate inserted (uniaxial +ve)

(c) Tourmaline (uniaxial off-centre)

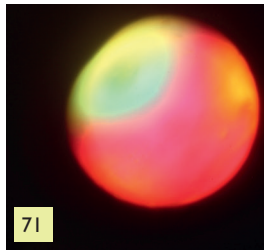
(d) λ -plate inserted (uniaxial -ve)

Figure 1.25 Uniaxial interference figures (magnification $\times 400$ in all examples); a) The classic uniaxial cross in a single large quartz crystal cut perpendicular to the z-axis (\equiv c-axis) (see earlier section), with Bertrand lens inserted; b) is the same view as (a), with Bertrand lens in, but now with the addition of a sensitive tint (gypsum) λ -plate inserted from the NW orientation [quartz wedge could also be used]. The lower colours in the NW and SE quadrants and band of higher colours NE-SW demonstrates that the quartz is uniaxial positive; c) Tourmaline (end-section) view with Bertrand lens inserted, showing uniaxial cross (slightly off-centre); d) is the same view, with additional insertion of gypsum λ -plate from NW. The colour arrangement is the reverse of that seen for quartz in (b), and shows that tourmaline is uniaxial negative.

oriented N-S and E-W, and crossing in the centre to divide the field of view into four quadrants. More usually however, the crystallographic axes are not so perfectly aligned and the interference figure will be off-centre, as in the tourmaline of Fig. 1.25c. Even this example, however, would be regarded as good. Most commonly the alignment is much less good, and what should appear as a cross in the case of uniaxial minerals, has the centre of the “cross” at the edge or outside the field of view. In such cases, when the microscope stage is rotated, each arm of the “cross” rotates into the field of view and out again in sequence (see Fig. 1.6–10 of Ehlers, 1987a). Such situations are normal and still of use, since by rotation of the stage the uniaxial character can still be confirmed.

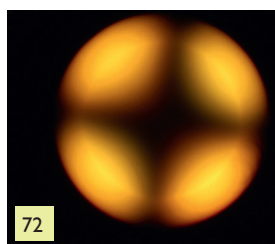
Having confirmed the uniaxial nature of the mineral, the next step is to determine the optic sign. This is done by inserting the gypsum “red” plate or quartz wedge. The choice depends on the appearance of the interference figure, which will vary according to the birefringence of the mineral. If the interference figure is essentially a black cross, with white quadrants, as typifies a 1st Order birefringence mineral such as quartz (Fig. 1.25a), the gypsum (λ) plate is inserted. With insertion from NW-SE, if the NW-SE quadrants go to lower colours (1st order yellow-orange), whilst the NE-SW quadrants change to higher colours (2nd order blue or blue-green), the mineral is uniaxial positive (see Fig. 1.25b). If the reverse is true, the mineral is uniaxial negative.

As previously discussed in 1.4.5, above, the colour formed is essentially the gypsum (λ “red”) plate Δ value (550nm), plus or minus the Δ value relating to the birefringence of the mineral. In off-centre examples, by knowing which quadrant of the cross is in the field of view, based on which way the arms of the cross rotate in, the optic sign (+ve or -ve) can still be determined according to whether the quadrant turns blue or else orange-red (see examples in Fig. 1.25).

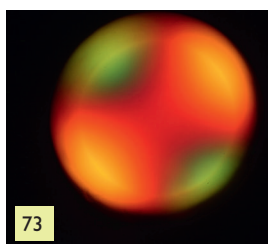
Biaxial interference figures

The approach to selecting an appropriately oriented crystal is the same as that described for uniaxial minerals. In general end-sections close to perpendicular with the z -axis of the crystal and showing low birefringence are the best choice, and once again, deformed or heavily included crystals are best avoided.

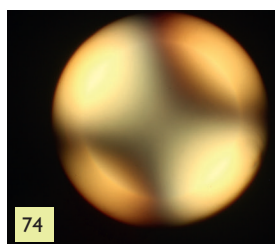
Having selected the crystal of interest, the same procedure as that described above, for uniaxial crystals, is undertaken. Assuming the crystal has a favourable orientation, when the Bertrand lens is inserted, if a well-centred interference figure is produced, the pattern observed will either be of two boomerang-like curved isogyres arching towards the centre of the field of view (Fig. 1.26c), or else something that looks very like a uniaxial cross (Fig. 1.26a). The latter occurs in cases where the $2V$ angle (optic axial angle) is very low (0 – 10°), whereas the latter forms with higher $2V$ values.



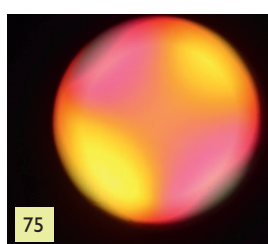
(a) *Phlogopite* (biaxial) $\beta = 1.597$



(b) *Phlogopite* with λ -plate inserted (biaxial -ve) ($2V=0$ – 10°).



(c) *Muscovite* (biaxial) $\beta = 1.596$



(d) *Muscovite* with λ -plate inserted (biaxial -ve)

Figure 1.26 Biaxial minerals (magnification $\times 400$ in all examples); a) *Phlogopite* with low $2V$ angle (0 – 10°) shows what at first glance appears to be a “uniaxial cross”, but on rotation the two isogyres fluctuate in and out slightly revealing that the crystal is actually a biaxial mineral with very low $2V$; b) is the same field as shown in a), but with the λ -plate inserted. Higher colours NW-SE and lower colours NE-SW demonstrate that *phlogopite* is biaxial -ve; c) *Muscovite* with two nicely defined isogyres arching half-way across the field of view with a boomerang-like angular curvature indicative of $2V$ c. 30 – 45° ; d) the same field of view as c), with λ -plate inserted. Higher colours NW-SE and lower colours NE-SW demonstrate that *phlogopite* is biaxial -ve.

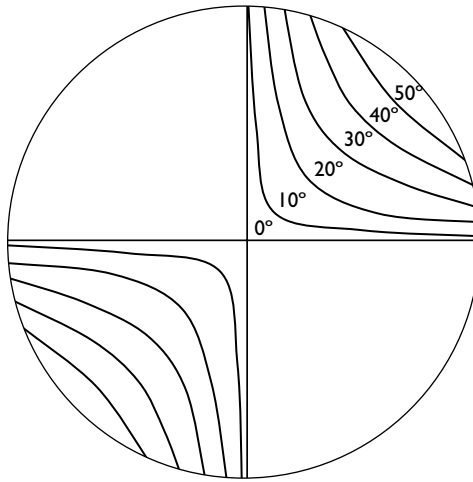


Figure 1.27 Schematic representation of biaxial mineral 2V angles for comparison to aid estimation of 2V for an unknown mineral. $\beta = 1.60$, N.A. = 0.85 (diagram created based on information in Ehlers, 1987a).

Table 1.3 Maximum 2V value (at edge) where both isogyres can be observed in the field of view, as a function of Objective lens Numerical Aperture (NA) and average refractive index of the mineral (β).

	$\beta = 1.4$	$\beta = 1.5$	$\beta = 1.6$	$\beta = 1.7$	$\beta = 1.8$	$\beta = 1.9$
NA = 0.85	74°	68°	64°	60°	56°	53°
NA = 0.65	55°	51°	48°	45°	42°	40°

In cases that look like a cross, to prove that the crystal under consideration is a biaxial mineral with low 2V rather than a uniaxial mineral, rotation of the microscope stage should provide the necessary proof. If the stage is rotated, slight movements in and out will prove the existence of two biaxial isogyres, whereas if there is no such movement the crystal under examination is uniaxial.

Assuming that an appropriate crystal is available, quantifying the 2V angle for minerals that have $2V < c.60^\circ$ is relatively straightforward, as there is a regular relationship between the position and curvature of the isogyres (Fig. 1.27). This is based on the extent to which the apex of the curve arches towards the centre of the field of view, and how close the isogyres are to the edge. However, for minerals with $2V > 60^\circ$, the angle is much harder to determine because in most cases, both isogyres will not usually be in the field of view together.

Knowing the Numerical Aperture (NA) value of the objective lens being used is especially important when determining the 2V value for biaxial minerals (see below), as it influences the maximum 2V value where both isogyres are present in the field of view. In fact, it is slightly more complicated than this, because the β -index (intermediate refractive index of the mineral) also has an effect. In simple terms, the higher the NA

value of the lens, and the lower the β value of the mineral, the greater the maximum value of $2V$ with both isogyres observable in the field of view. Table 1.3 (above) provides a simplified summary of this for objective lenses with $NA = 0.85$ and 0.65 , and a selection of β values (information derived from Fig. 1.8–18 of Ehlers, 1987a).

For a helpful tabulation of biaxial minerals, arranged in ascending order of $2V$ angle, and also listing corresponding β values for each mineral, Charts 5 & 6 in Ehlers (1987a) are extremely useful. Likewise, in Kerr (1977), Tables 10–9 and 10–10 and Charts A–G provide similar data.

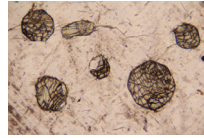
There are advanced techniques described by Ehlers (1987a) for estimation of the $2V$ angle for minerals with high $2V$ (isogyres outside the field of view), but these go well beyond what can reasonably be addressed in the present publication. In the present mineral key, whenever $2V$ angle forms the final discriminator for two closely similar minerals it is often just a case of deciding whether the $2V$ angle is low or high that is needed, so obtaining a more precise estimate is not usually crucial.

Key to rock-forming minerals in thin-section

2.1 TO DECIDE WHICH SECTION

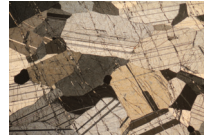
To use the key, firstly define whether the mineral is colourless or coloured in plane-polarised light, and whether it shows cleavage. If it is a cleaved mineral, it is necessary to define the number of cleavage traces present. Finally, it is necessary to determine whether the mineral has straight or inclined extinction. Once defined, use the list below to decide which Section to use to key-out the mineral.

Section 1: 2 (or 3) cleavage traces observed



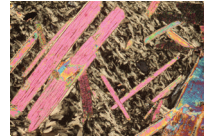
pg.35

Section 2: 1 cleavage trace, INCLINED extinction



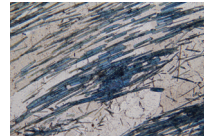
pg.53

Section 3: 1 cleavage trace, STRAIGHT extinction, COLOURLESS



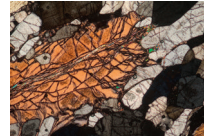
pg.71

Section 4: 1 cleavage trace, STRAIGHT extinction, COLOURED



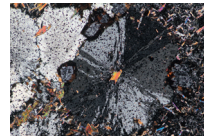
pg.87

Section 5: Imperfect cleavage, parting or arranged fractures



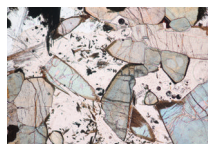
pg.97

Section 6: 0 cleavage, COLOURLESS



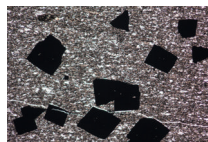
pg.111

Section 7: 0 cleavage, COLOURED



pg.131

Section 8: OPAQUE minerals



pg.145

2.2 Symbols & abbreviations

(□) = end-section

(■) = side-section

(...) = small crystals (eg fine granules, inclusions); cleavage or other diagnostic properties not evident.

// = parallel

 α , β , γ = optic axes (and refractive indices) δ = birefringence value Δ = retardation value

+ve = positive

- ve = negative

2V = optic axial angle

birefr. = birefringence

brn. = brown

c'less. = colourless

clv. = cleavage(s)

grn. = green

interf. = interference

L/W = length/width ratio of prismatic crystals

met. = metamorphism

Mod = moderate

NA = Numerical Aperture (of objective lens)

ord. = order

pleochr. = pleochroism

RI = refractive index

RL = reflected light

rlf. = relief

 x , y , z = crystallographic axes

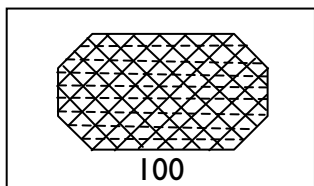
yell. = yellow

This key covers more than **150 of the most commonly encountered rock-forming minerals**, plus a few rarer but noteworthy minerals (e.g. indicative of P-T conditions, ore deposits or fluids). In some cases it may not be possible to key out specific minerals, since several minerals have very similar properties. In such cases the use of a microprobe or other analytical techniques may be necessary to determine the mineral.

2 (or 3) cleavage traces

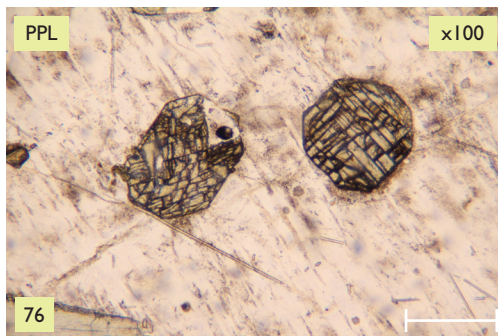


- 1 3 CLEAVAGE TRACES 2
- 2 Cleavage traces 4
- 2 Isotropic 3
- Non-isotropic (c'less; 2 clv. at 93°; strong parting // 100) (1a) **SPODUMENE (□)**

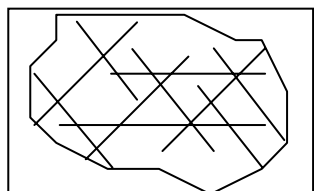


(1a)

Spodumene in granite; Leinster, Ireland



- 3 Colourless (or pale purple); (3 cleavage traces at 60–70°) (1b) **FLUORITE**

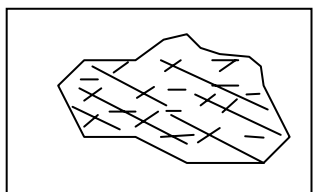


(1b)

Fluorite (arrowed) in hydrothermally altered garnet-rich quartzo-feldspathic metavolcanic rock; Nisserdal region, Telemark, Norway.

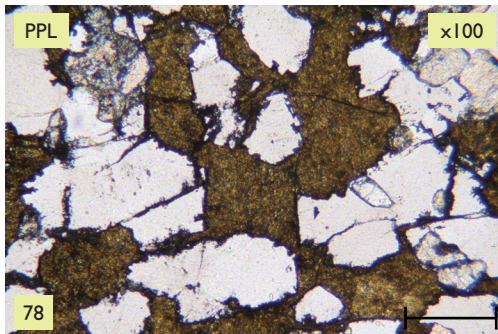


- Yell.-brn. or brown (1 strong clv. + intersecting partings) (1c) **SPHALERITE**

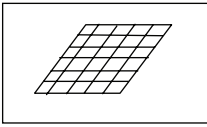


(1c)

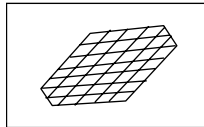
Sphalerite in Zn-ore deposit; Zinkgruvan, Sweden.



- | | | |
|---|--|--------------------------|
| 4 | 2 CLEAVAGE TRACES at 60° ($\equiv 120^\circ$) | 5 |
| | 2 CLEAVAGE TRACES at $> 60^\circ (< 120^\circ)$ | 14 |
| 5 | COLOURLESS (or very pale green or brown) | 6 |
| | COLOURED (good pleochroism) | 9 |
| 6 | Top 1 st ord./2 nd ord. birefr.; colourless to pale green. | 7 |
| | 3 rd order birefr., pale yellowy brown. | GRUNERITE (□) |
| 7 | Symmetrical extinction “diamond”-shaped (1d) | 8 |
| | Symmetrical extinction “truncated diamond”-shaped (1e) | CUMMINGTONITE (□) |

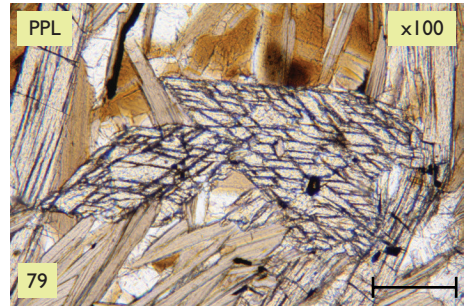


(1d)



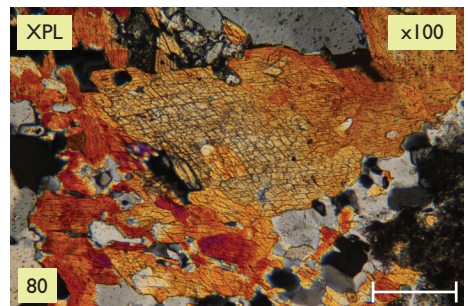
(1e)

- | | | |
|---|--|--------------------------|
| 8 | Biaxial +ve (meta-ultramafics, other Mg-Fe rich rocks) | ANTHOPHYLLITE (□) |
|---|--|--------------------------|



Anthophyllite (end-section) in anthophyllite-bt-grt gneiss; Finland.

- | | | |
|--|--|----------------------|
| | Biaxial -ve (calc-silicate rocks, other Ca-Si-Fe rich rocks) | TREMOLITE (□) |
|--|--|----------------------|

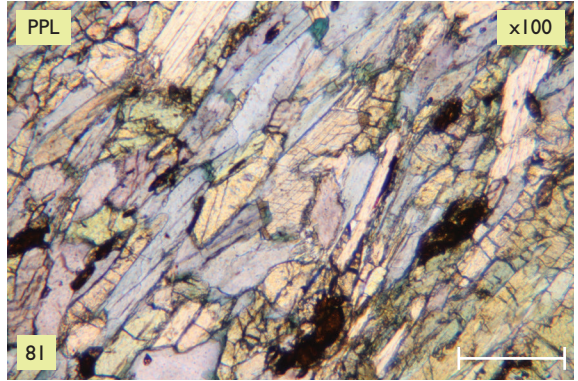


Tremolite (end-section) in calcareous semipelite schist; Mangkuma-Ketembe, Ghana.

- 9 Blue/violet pleochroism, 1st ord. yell./orange birefr. 10
Not blue/violet pleochroism 11

10 Colourless/lavender blue pleochroism; **GLAUCOPHANE/CROSSITE(□)**

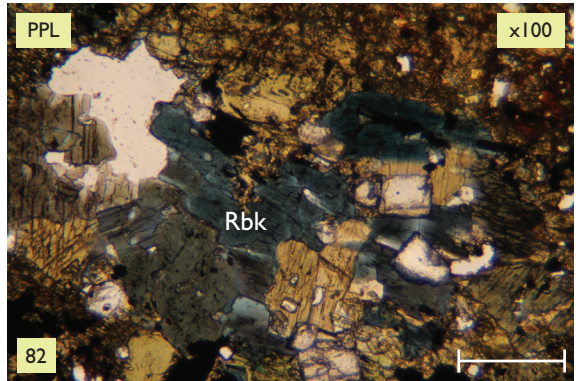
Glaucoaphane (end and side-sections) in glaucophane schist (blueschist); Ile de Groix, Brittany, France.



Intense prussian blue-indigo blue-green pleochroism.

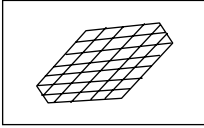
RIEBECKITE(□)

Riebeckite (end-section) in sodic granite; Drammen, Norway.



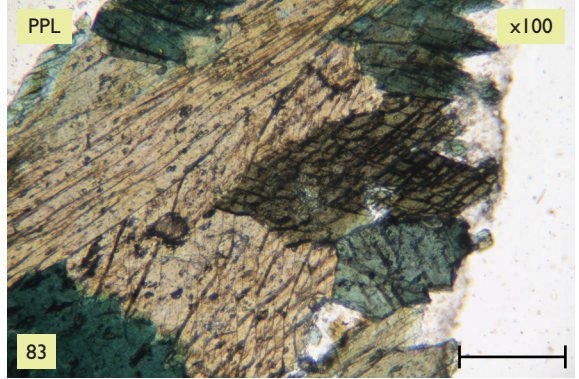
- 11 Green, yellow-green, blue-green pleochroism 12
Brown, greenish brown, yellow-brn, red-brown pleochroism 13
- 12 Typical amphibole 6-sided diamond-shaped end-section (1e) well developed cleavage. Green, blue-grn. to yellow green pleochroism (mafic rocks).

HORNBLLENDE / ACTINOLITE(□)



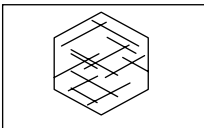
(1e)

Actinolite (end-section) in act-ab-czo hornfels; locality unknown.



Equal-sided hexagon (1f), weak cleavage; pale green to slaty blue pleochroism (Al-rich pelite).

CHLORITOID(□)



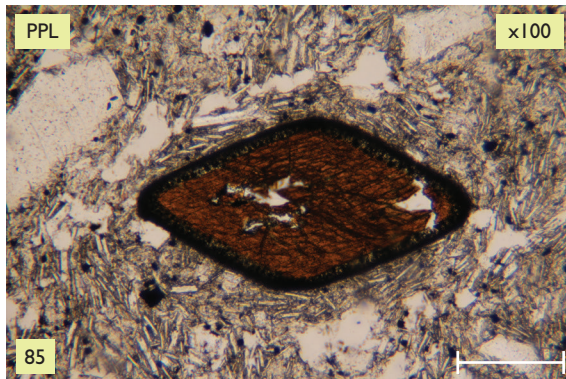
(1f)

Chloritoid (end-section) in chloritoid phyllite; Tarkwa, Ghana.



- 13 Pale yellow/yell.-brn. to dark chestnut brown pleochroism. $2V = 44-90^\circ$. A common mineral found in a various volcanic rocks from basalts and andesites to trachytes.

brown HORNBLLENDE (Oxo-HORNBLLENDE)(□)



Oxo-hornblende phenocryst in andesite; Plomb du Cantal, France.

Note: The black iron-oxides often seen around the edge of Oxo-hornblendes result from resorption effects. Such crystals probably crystallised as typical magnesio or ferrohornblende but were transformed during later stage oxidation (Deer et al., 2013).

- Brownish yellow/yell.-brn to red-brn. pleochroism. $2V = 74-82^\circ$. Alkaline volcanic rocks only.

KAERSUTITE(□) (previously called BARKEVIKITE)

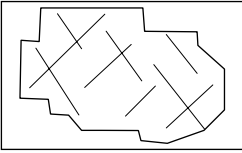


Kaersutite phenocrysts in syenogabbro ("lugarite"); Lugar Sill, Lugar, Ayrshire, Scotland.

Note: Most hornblendes are pleochroic in shades of yell.grn.-green-blue-grn. However, high temperature hornblendes may be green to brown, or brown pleochroic. The amphibole KAERSUTITE, found in alkaline volcanic rocks, with yell.brn.-red-brn.-greenish brown pleochroism is difficult to distinguish from brown hornblendes. Also consider AENIGMATITE, a very dark brown, high relief almost isotropic mineral of nepheline and sodalite syenites. Its extinction angle is 66° .

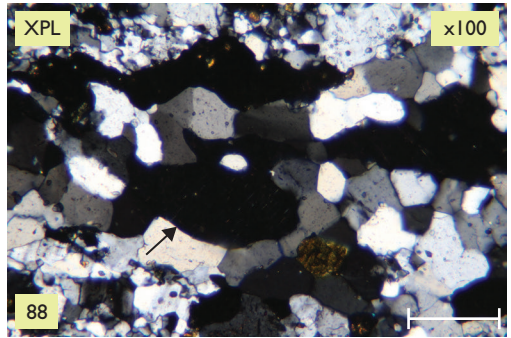
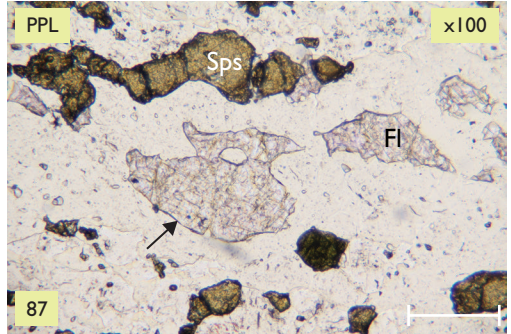
- 14 **2 CLEAVAGES** at c.67–75° (\equiv 113–105°) 15
 Cleavages at >75° 19

- 15 Isotropic (usually 2 feint clv. but sometimes 3 at 60–70°) (1g) **FLUORITE**



(1g)

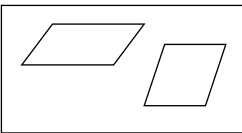
Fluorite (arrowed) in hydrothermally altered garnet-rich quartzo-feldspathic metavolcanic rock; Nisserdal region, Telemark, Norway.



Fluorite (arrowed) in hydrothermally altered garnet-rich quartzo-feldspathic metavolcanic rock; Nisserdal region, Telemark, Norway.

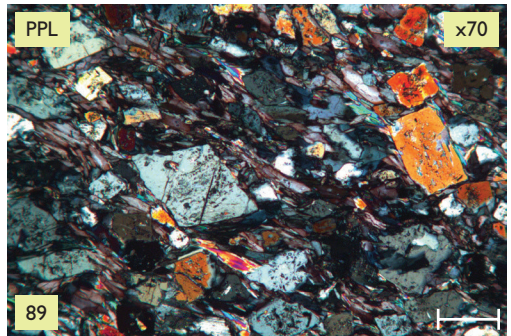
- Non-isotropic 16
 16 Relief varies on rotation (“twinkling”); high order birefringence. 17
 No change in relief on rotation; top 1st ord. birefr.; (lozenge-shaped) (1h).

LAWSONITE(□)



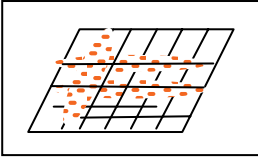
(1h)

Lawsonite (rectangular and lozenge-shaped sections) in glaucophane schist (blueschist); Orhaneli, NW Turkey (photo courtesy of Giles Droop).



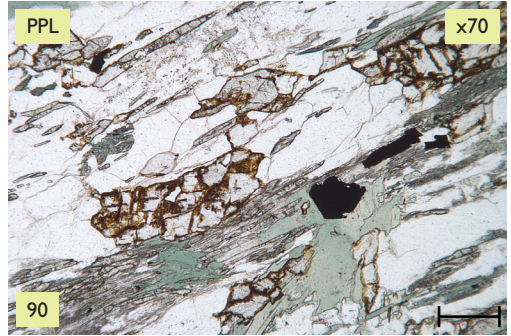
17 Yell.-brn./orange-brown Fe-staining along clv. traces (1i)

ANKERITE (or Fe-Calcite, Siderite)



(1i)

Ankerite (irregular porphyroblasts, showing 'rusty' alteration along cleavage) with quartz, chlorite and epidote in greenschist; Döllach, Austria (photo courtesy of Giles Droop).

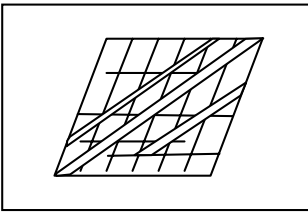


No significant Fe-staining along cleavage traces

18

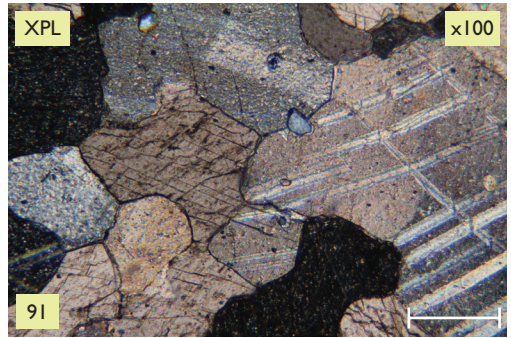
18 Some deformation twins (if present) bisect acute cleavage angle (1j)

CALCITE



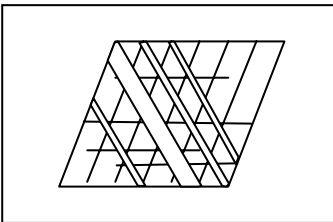
(1j)

Calcite (with deformation twins) in marble; Troms, Norway.



Some deformation twins (if present) bisect obtuse cleavage angle (1k)

DOLOMITE



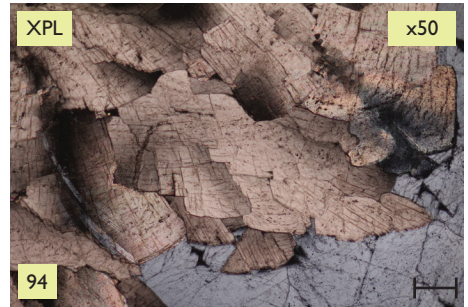
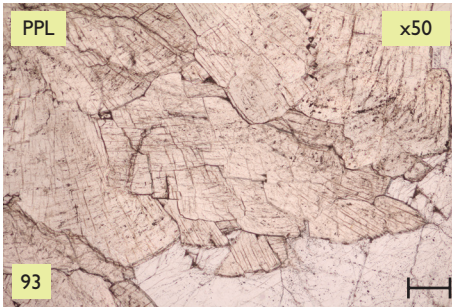
(1k)

Dolomite in chl-talc-dol schist; Ghana



(Note: Magnesite (of serpentinites) is optically indistinguishable from calcite/dolomite).

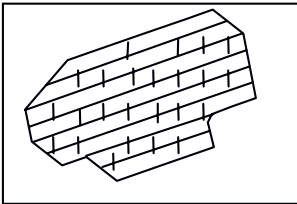
RHODOCHROSITE



Rhodochrosite in vein; Sri Lanka.

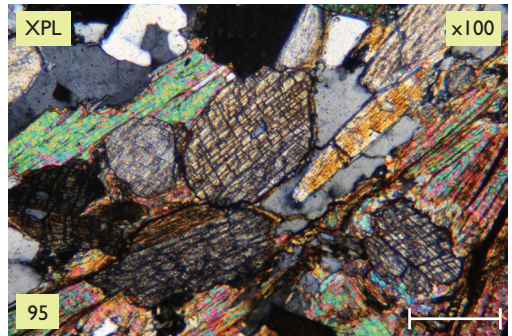
Note: Rarer RHODOCHROSITE ($MnCO_3$) (above) is also similar in appearance to calcite and dolomite, but is typically colourless to pale pink or pale pinkish-brown in PPL.

- 19 **2 CLEAVAGES** at c. $78-85^\circ$ ($\equiv 102-95^\circ$) 20
 Cleavages at c. 90° 21
- 20 1st ord. yellow/orange, HIGH relief, $2V = 82-83^\circ$; regional met. metapelites, or some eclogites; common. (11) **KYANITE**



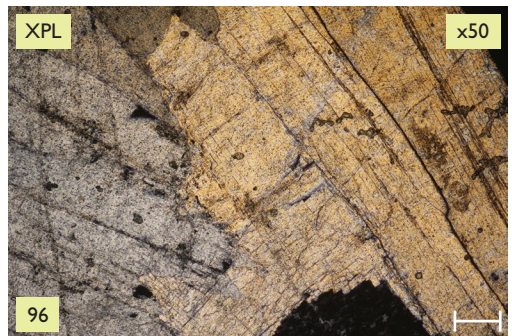
(11)

Kyanite in ky-bt schist; Ross of Mull, Scotland.



Max 1st ord. yellow/orange MOD (to high) relief, $2V = 37^\circ$; barium-rich rocks and veins.

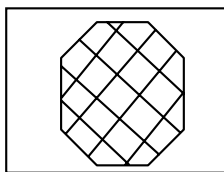
BARYTES



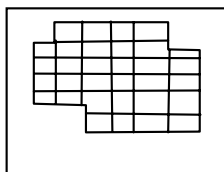
Barytes in vein; Porth y Corwgl, Anglesey, Wales.

Note: Corundum with well developed parting could possibly be confused, see Section 5.

21 **2 CLEAVAGES at 90° (1m or 1n);**



(1m)



(1n)

ISOTROPIC (or almost so)
ANISOTROPIC

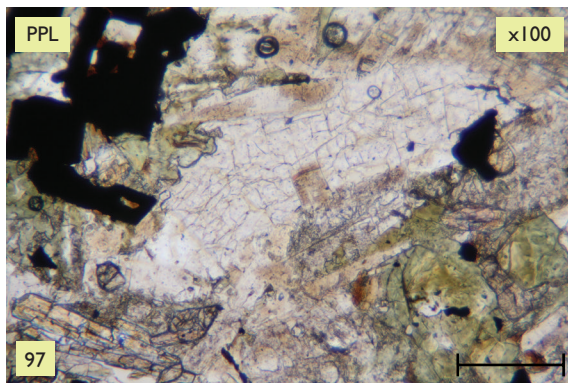
22
24

22 High relief (1n)
Low or moderate relief

PERICLASE
23

23 Colourless (primary mineral or vesicle fill of basic and intermediate igneous rocks)

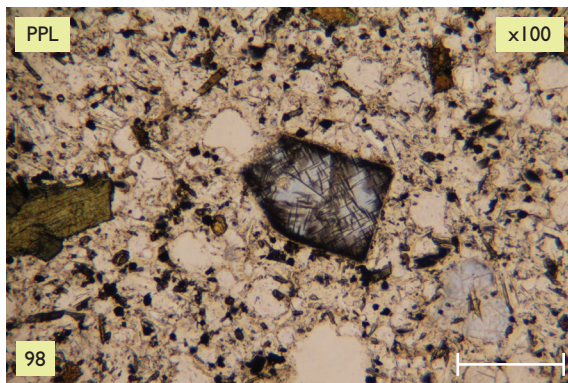
ANALCITE



Analcite in teschenite; Edinburgh, Scotland.

Colourless to pale blue; weak cleavage, but aligned inclusions common (primary mineral in phonolites, nepheline syenites and other alkaline igneous rocks)

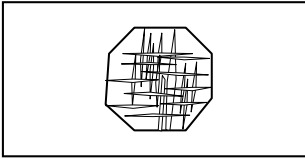
SODALITE, NOSEAN, HAÜYNE



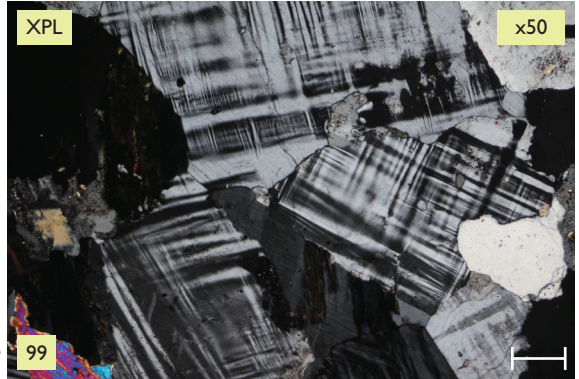
Häuyne in leucite tephrite; Tavolato, Rome, Italy.

24 Cross-hatched twinning evident (1o)

MICROCLINE



(1o)



Microcline in granite; Penmaenmawr, Wales.

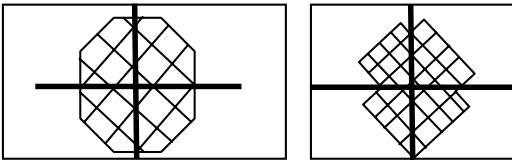
Note: Relatively rare ANORTHOCLASE is similar to microcline, but has ultra-fine twinning.

Not showing cross-hatched twinning

25

25 Symmetrical (c.40–45°) extinction (1p)

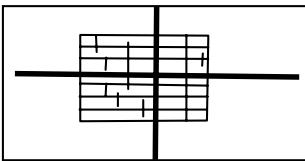
26



(1p)

Extinction // to cleavage (1q)

39



(1q)

26 1st order grey/white interference colours

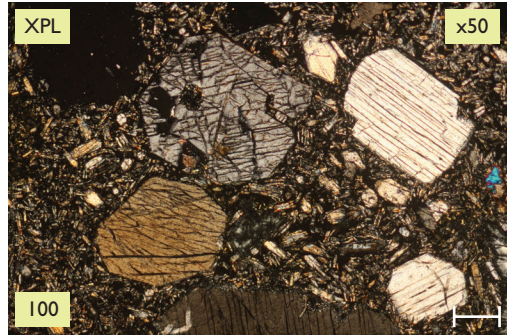
27

Interference colours above 1st ord. grey/white

28

27 Mafic/ultramafic rock

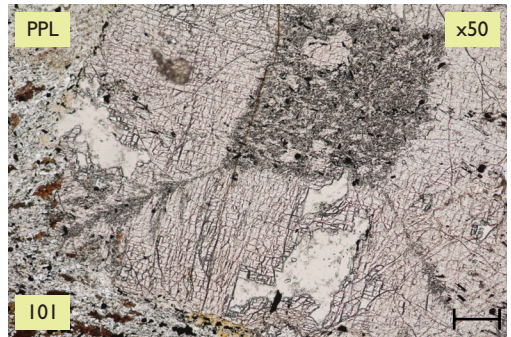
ENSTATITE(□)



Enstatite (end and side sections) in boninite; Chichijima, Bonin Islands, Japan.

Meta-pelite/mudrock (Al-rich)

ANDALUSITE(□)



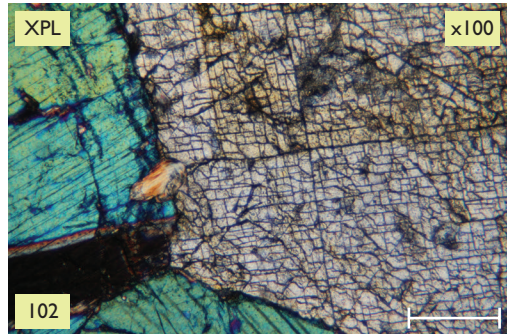
Andalusite (end-section) in cordierite and slate; Connemara, Ireland.

28 Colourless
Weakly or strongly coloured in PPL

29
32

29 Calc-silicate rock/marble/skarn

DIOPSIDE(□)



Diopside in calc-silicate skarn; Loch Ailsh, Assynt, Scotland.

Not calc-silicate rock/marble/skarn

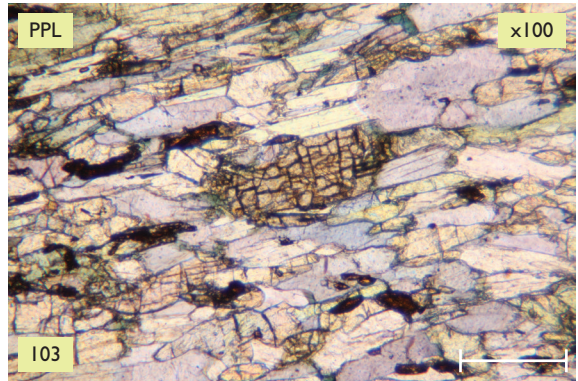
30

30 Blueschist facies metamorphic rock

JADEITE(□)

Jadeite (end section) in blueschist;
Ile de Groix, Brittany, France.

Note: *Omphacite* (colourless to pale
grn. is similar).



Igneous rock

31

31 Granitic pegmatite (Li-rich)

SPODUMENE(□)

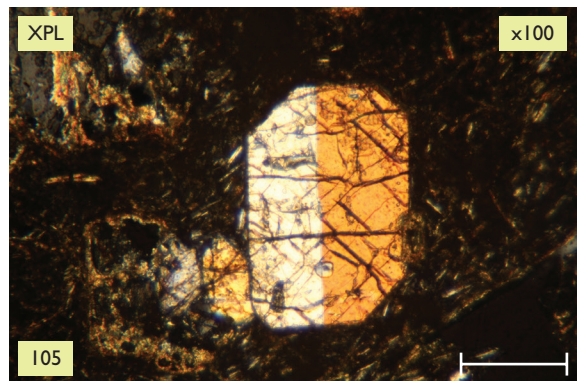
Spodumene (end-section) in granite
pegmatite; Leinster, Ireland.
(see start of Section I for enlarge-
ment of this image).



Alkali-olivine basalt & alkali igneous rocks.

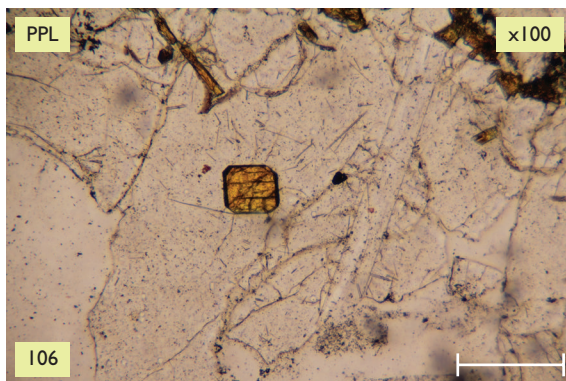
DIOPSIDE(□)

Diopside (end-section, with simple
twin) in basalt; ODP Hole 793B,
Izu-Bonin Arc, Japan.



- | | | |
|----|--|------------------------------------|
| 32 | Green/yell.-grn./violet or brown pleochroism.
Pleochroism weak or absent. | 33
34 |
| 33 | Green/yellow-green pleochroism | AEGIRINE/AEGIRINE-AUGITE(□) |

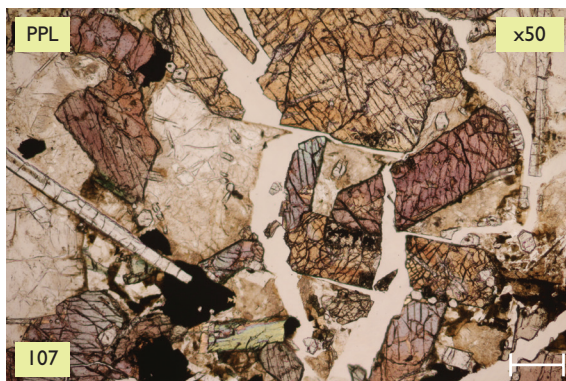
Aegirine-augite in leucite tephrite;
Vesuvius, Italy.



Greenish/brownish to violet pleochroism

TITANAUGITE(□)

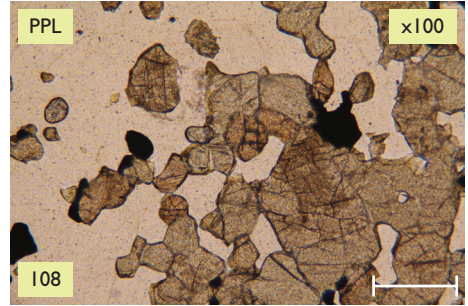
Titanaugite (end and side sections) in nepheline syenite; Saxony, Germany.



- | | | |
|----|-------------------------------------|----------|
| 34 | Weakly pleochroic
Non-pleochroic | 35
37 |
|----|-------------------------------------|----------|

- 35 Max 1st ord. yell./orange interf. colours ($\delta = 0.010-0.016$). Weak pink to grn. pleochr.

HYPERSTHENE(□) (= $\text{En}_{50}\text{Fs}_{50} - \text{En}_{70}\text{Fs}_{30}$)

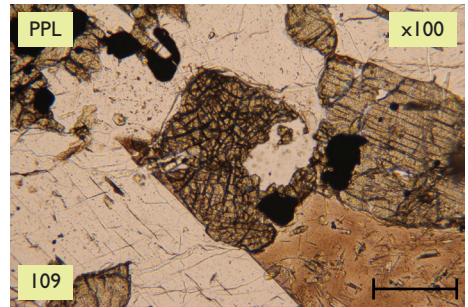


Hypersthene in granulite; Hartmannsdorf, Saxony, Germany.

1st ord. orange to 2nd ord. grn. interf. colours. Weak c'less to pale grn. or yell. grn. pleochr. 36

- 36 2V 0–30°; weak c'less/pale yell.-grn. to brownish pleochr. 2nd ord. blue to bright green interf. colours ($\delta = 0.021-0.029$). Typical pyroxene of andesites and dacites.

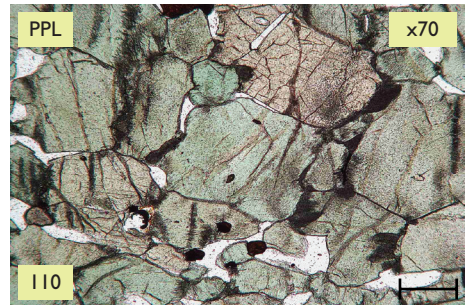
PIGEONITE(□)



Pigeonite (end-section) in andesitic pitchstone; Ardnamurchan, Scotland.

2V 56–84°; weak c'less to pale grn. pleochr. 1st ord. orange to 2nd ord. bright grn. iterf. colours ($\delta = 0.012-0.028$). Typical pyroxene of eclogites.

OMPHACITE(□)



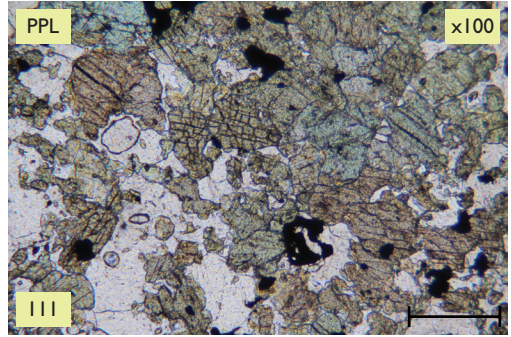
An Fe-rich omphacite (end-section, with slight green to colourless pleochroism) with quartz and rutile in eclogite; Totaig, Glenelg, Scotland. (photo courtesy of Giles Droop).

37 Calc-silicate rock/skarn (brownish grn.).

HEDENBERGITE(□)

Hedenbergite (end and side sections) in skarn; Camas Malag, Skye, Scotland.

(Note: v. similar to augite).



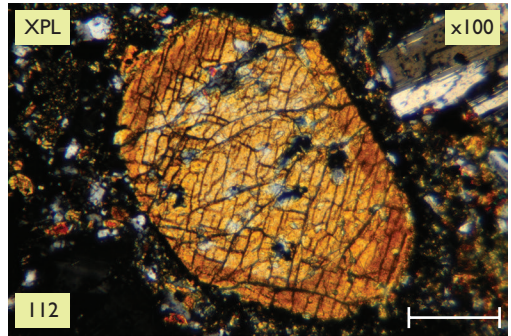
Igneous rock (pale brown or greenish brown)

38

38 $2V = 25-60^\circ$ (biaxial +ve). Very common pyroxene in mafic and ultramafic igneous rocks.

AUGITE(□)

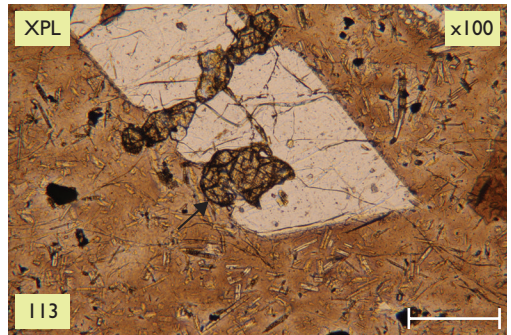
Augite (end section) in gabbro; Loch Coruisk, Skye, Scotland.



$2V = 0-30^\circ$ (biaxial +ve). Polysynthetic twins common in (100). Typical pyroxene of andesites and dacites.

PIGEONITE(□)

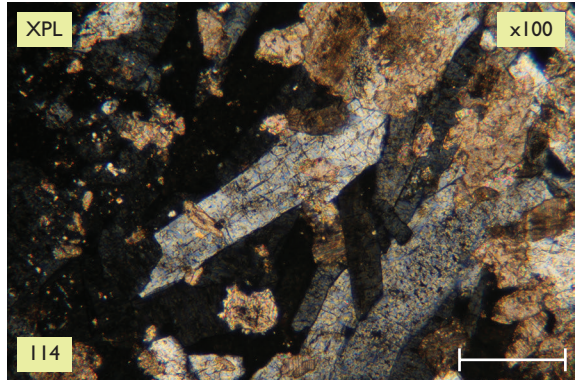
Pigeonite (end and side sections) in andesitic pitchstone; Ardnamurchan, Scotland.



39 1st ord. grey to v. pale yellow interference colours.

CELESTINE

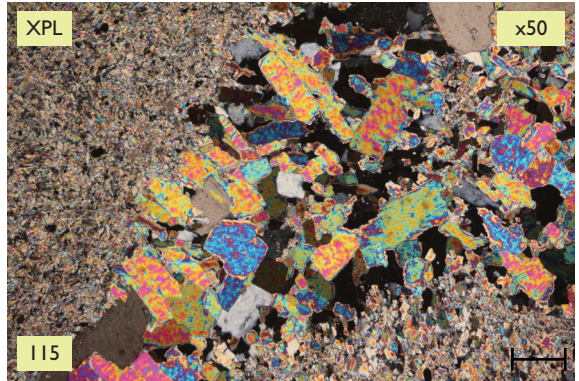
Celestine in Jurassic limestone;
Durlston, Dorset, England.



3rd order interference colours.

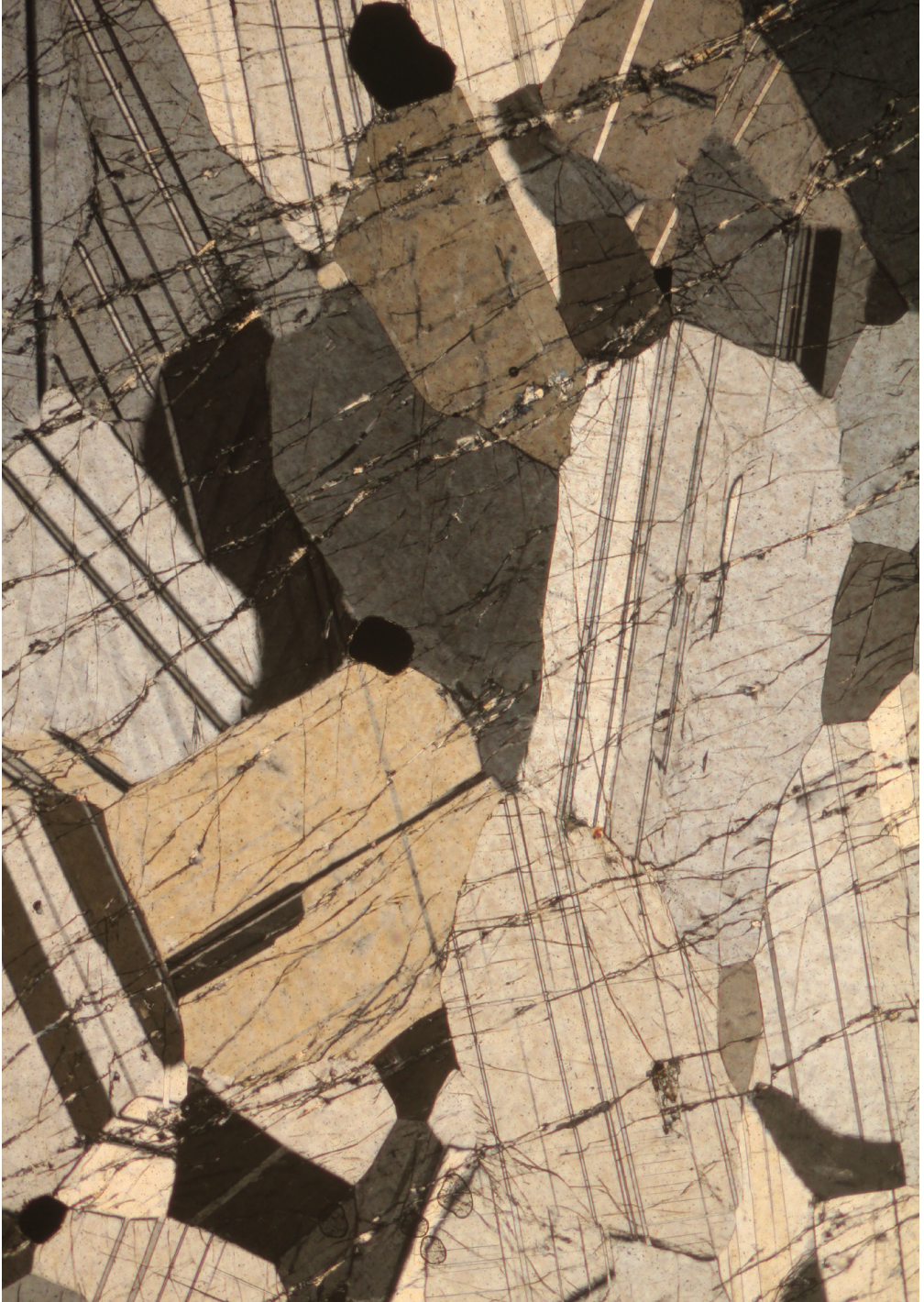
ANHYDRITE

Anhydrite in anhydrite marl
from borehole; Selby, Yorkshire,
England.

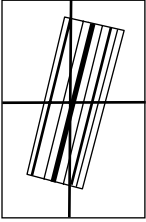


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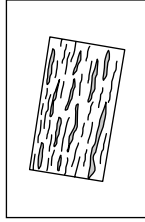
I Cleavage trace, inclined extinction



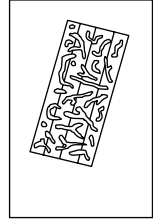
- 1 1st ord. grey/white (or pale yellow) interf. colours, with multiple lamellar twins (2a) or streaky/braided intergrowths (2b) or vermicular intergrowths (2c); colourless. 2
Coloured, or colourless, but lacking multiple lamellar twins or intergrowths (2c) (may show simple twins). If showing polysynthetic twins (2a) then higher than 1st ord. grey interference colours (see 2m) 8



(2a)

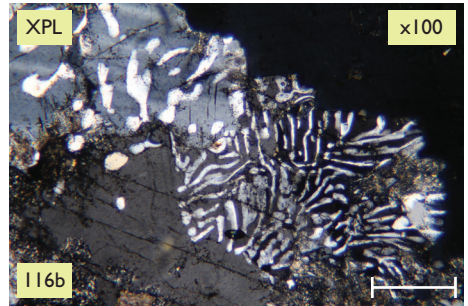


(2b)



(2c)

- 2 Streaky/braided intergrowths or Vermicular intergrowths
PERTHITE (Micropertchite) **MYRMEKITE (pl + qtz intergrown)**

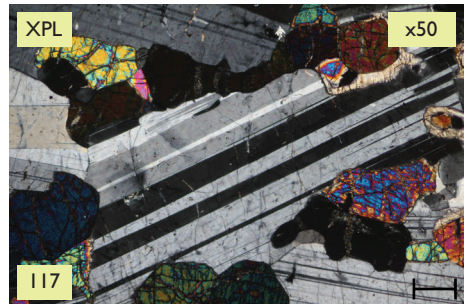


(a) Micropertchite in syenite; Fredricksvarn, Norway; (b) Myrmekite (i.e. plagioclase [mid grey 1st Ord. background] with intergrown vermicular quartz [white 1st Ord.]) in augen gneiss; Bettyhill, Tongue, Scotland.

Multiple lamellar albite/albite-carlsbad twins (no braided intergrowths)

PLAGIOCLASE 3

Note: $\delta = 0.007-0.010$ (1st order grey/white) for Albite-Labradorite, but increasing to $\delta = 0.010-0.013$ (yellow) for Bytownite and Anorthite.

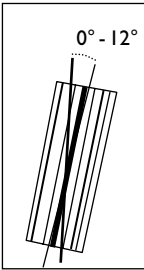


Plagioclase (labradorite) in troctolite; Sierra Leone.

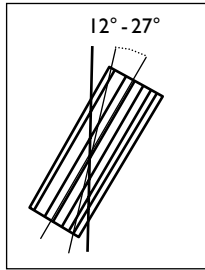
- 3 Max. Extinction angle $< 12^\circ$ (2d)
 Max. Extinction angle $> 12^\circ$

OLIGOCLASE

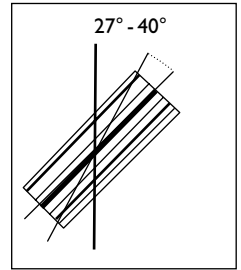
4



(2d)



(2e)



(2f)

- 4 Max. Extinction angle $12-27^\circ$ (2e)
 Max. Extinction angle $> 27^\circ$

5

6

- 5 Low +ve relief
 Low -ve relief

ANDESINE

ALBITE

- 6 Max. Extinction angle $27-40^\circ$ (2f) ($\delta = 0.008-0.009$)
 Max. Extinction angle $> 40^\circ$ max. interf. colour to 1st ord pale yell.

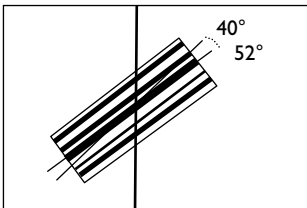
LABRADORITE

7

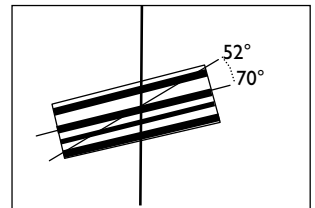
- 7 Max. Extinction angle $40-52^\circ$ (2g). ($\delta = 0.009-0.012$)
 Max. Extinction angle $52-70^\circ$ (2h). ($\delta = 0.012-0.013$)

BYTOWNITE

ANORTHITE

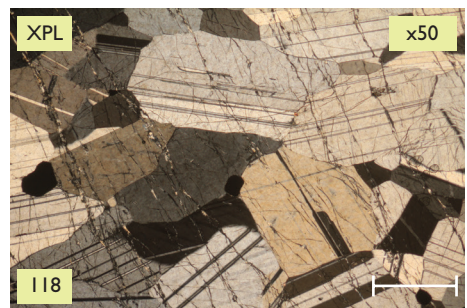


(2g)

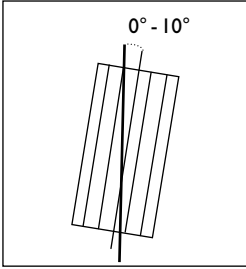


(2h)

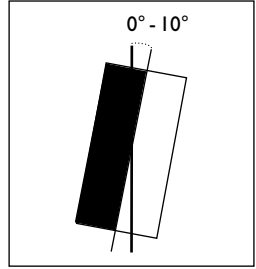
Plagioclase (bytownite) in anorthosite layer;
 Rhum, Scotland. (see start of Section 2 for an
 enlargement of this image).



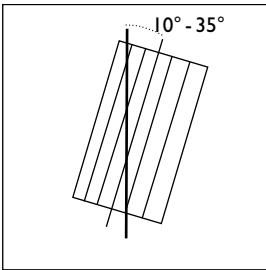
- 8 Max. Extinction angle $< 10^\circ$ (2i) or (2j) 9
 Max. Extinction angle $> 10^\circ$ (2k) or (2l) 16



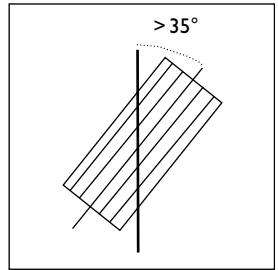
(2i)



(2j)



(2k)

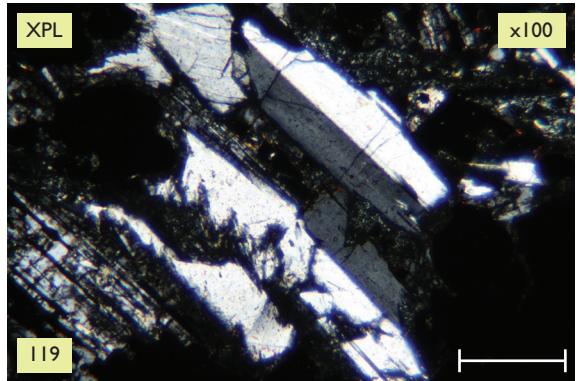
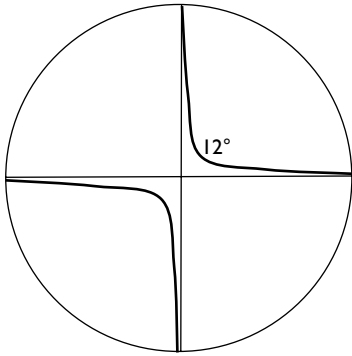


(2l)

- 9 Colourless 10
 Coloured 13
- 10 Max. 1st ord. grey/white (often simple twins) (2j) 11
 Higher than 1st ord. grey/white 12

11 $2V < 12^\circ$

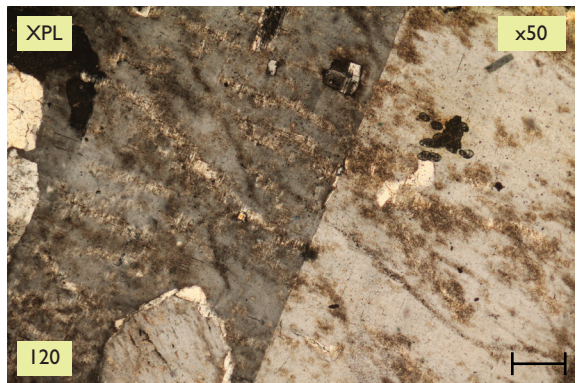
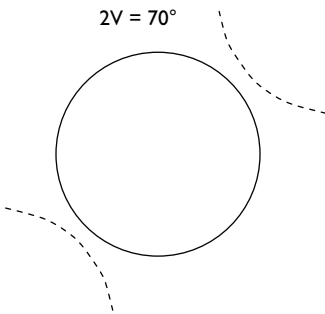
SANIDINE



Sanidine in sanidine facies mafic hornfels; Cushendell, Antrim, N.Ireland.

$2V = 70^\circ$

ORTHOCLASE

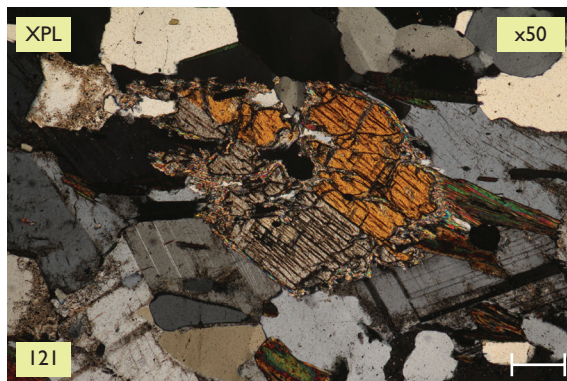


Orthoclase in granite; Carnmenellis, Cornwall, England.

Note: Rhombic form of Orthoclase (ADULARIA) occurs in certain potassic alteration zones of hydrothermal ore deposits.

- 12 Max. 1stord. yell./orange interf. colours; common in high pressure metapelites and some eclogites.

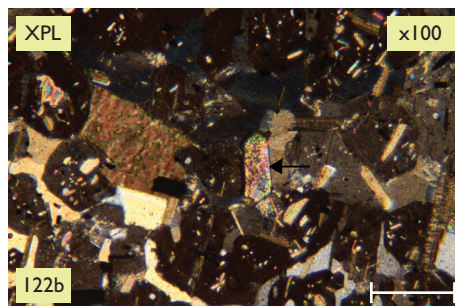
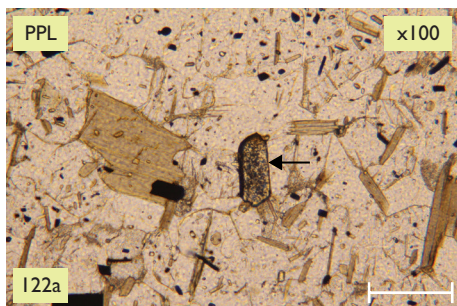
KYANITE



Kyanite in kyanite gneiss; Loch Assapol, Mull, Scotland.

- Upper 3rd (to 4th) ord. interf. colours; common accessory phase in granites, pegmatites and as detrital crystals in sedimentary/metasedimentary rocks.

MONAZITE



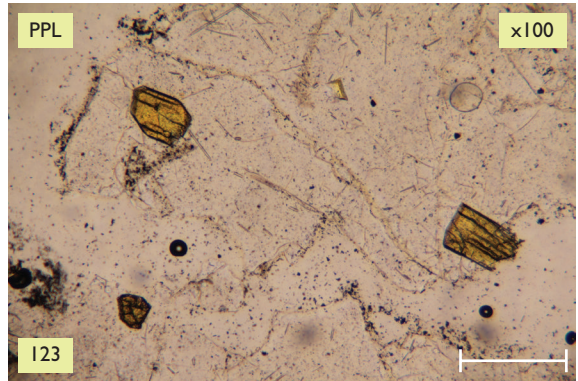
Monazite (arrowed) in Crd-Bt-Qtz-Ilm metasedimentary rock; locality unknown.

- 13 Grn. to grn.-brn., or yell-grn. to blue/blue-grn. pleochroism. 14
 Colourless/blue/violet pleochroism 15

14 Green to green-brown pleochroism

AEGIRINE(■)

Aegirine-augite in leucite tephrite; Vesuvius, Italy.



Yell.-grn. to blue-grn./blue pleochroism.

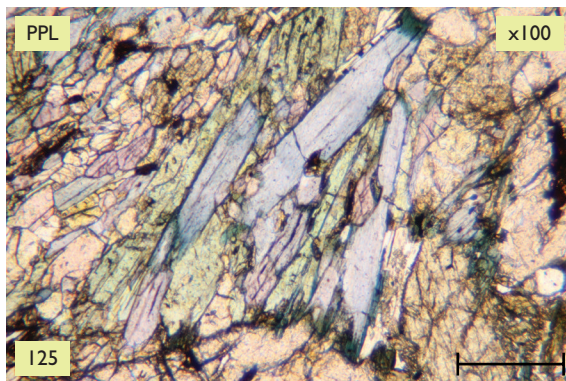
ARFVEDSONITE(■)

Arfvedsonite in syenite; Oslo region, Norway.



15 Colourless/blue pleochroism; max.ext. = 14° (often $<10^\circ$)

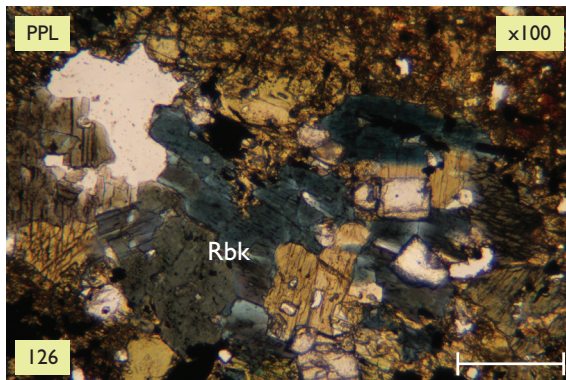
GLAUCOPHANE / CROSSITE (I)



Glaucophane in glaucophane schist (blueschist); Ile de Groix, Brittany, France.

Intense prussian blue/indigo blue/green pleochroism.

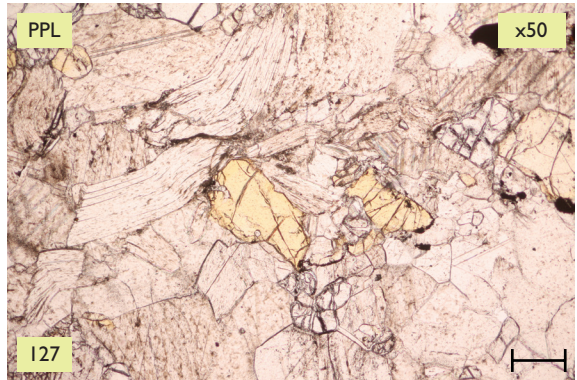
RIEBECKITE (I)



Riebeckite in sodic granite; Drammen, Norway.

- | | | |
|----|--|----|
| 16 | Max. Extinction angle $10-35^\circ$ (2k) | 17 |
| | Max. Extinction angle $>35^\circ$ (2l) | 30 |
| 17 | Pleochroic | 18 |
| | Non-pleochroic | 24 |

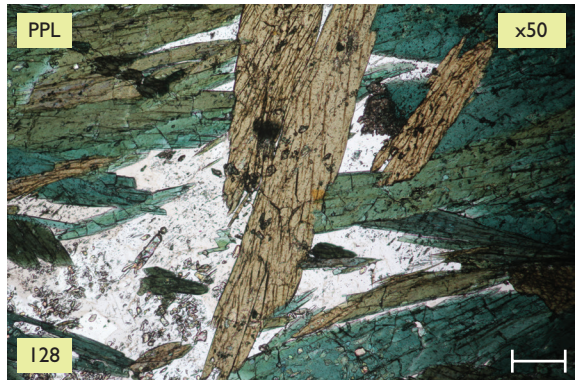
- 18 Grn/yell., grn/blue-grn, grn/brn or yell.brn-red-brown pleochr. 19
 C'less/pale yellow pleochroism **CHONDRODITE**



Chondrodite in mineralised skarn; Ottawa, Canada.

- 19 Max.extinction angle generally $10-19^\circ$ 20
 Max.extinction angle generally $>19^\circ$ 23
 20 Green, yellow-green, blue-green or greenish-brown pleochroism 21
 Yellow-brown, brown, orange-brown or red-brown pleochroism 22
 21 Green to yell.-grn., or green to dk.grn./blue-green pleochroism. Greenschist
 metamorphic rocks, altered mafic rocks (common). **ACTINOLITE (I)**

Note: Hornblende, ext. angle $12-34^\circ$, although usually with higher ext. angle, can be similar (see below). Pumpellyite, ext. angle 22° although usually very fine needles, is also similar to fine acicular actinolite.

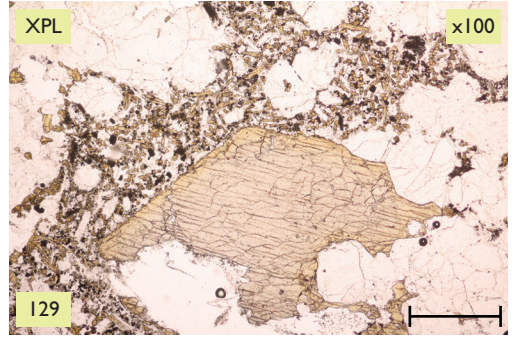


Actinolite in act-ab-czo hornfels; locality unknown.

Green/ yellow-grn. / greenish brown pleochroism; extinction angle 0–20°. Igneous rocks.

AEGIRINE-AUGITE (■)

Aegirine-augite in leucite tephrite. The rim of the phenocryst and all the small coloured groundmass crystals are aegirine-augite composition. The core of the phenocryst has more augitic composition; Vesuvius, Italy.



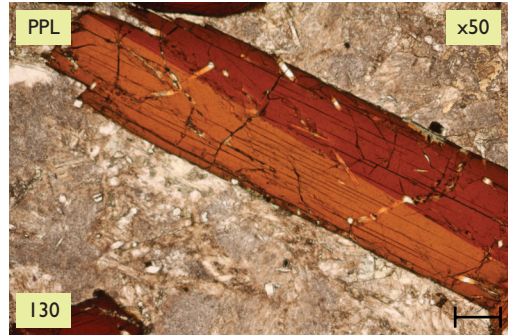
Brownish yellow/pale yellow to red-brn./orange brn./ greenish brn. pleochroism. Extinction angle 0–19°. Igneous rocks.

KAERSUTITE (■)

22 Strongly coloured; yell.-brn to red.brn or red.brn to grn-brn. **KAERSUTITE (■)**

Note: The amphibole KAERSUTITE, found in alkaline volcanic rocks, is very similar and thus difficult to distinguish from brown hornblendes (see below).

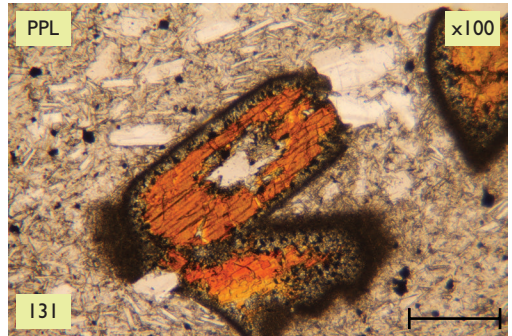
Kaersutite phenocryst (side section - twinned) in syenogabbro (“lugarite”); Lugar Sill, Lugar, Ayrshire, Scotland.



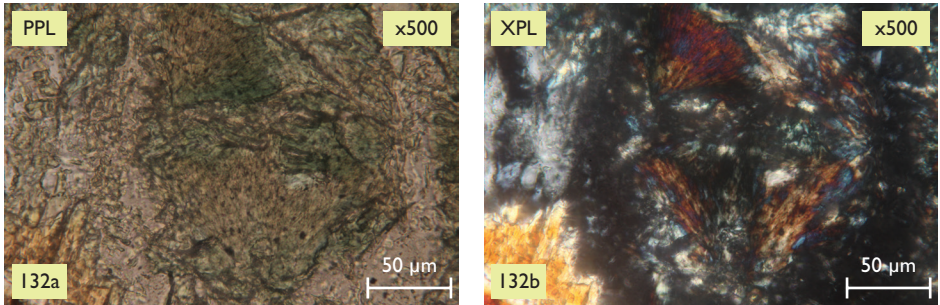
Strongly coloured; pale yellow/yell.brn. to dark brn/chestnut brown or red.brn. **OXO-HORNBLLENDE (brown Hornblende) (■)**

Note: Crystals of kaersutite and oxo-hornblende are commonly seen with a rim of iron oxides (magnetite), formed during late stage oxidation (Deer et al., 2013).

Oxo-hornblende (side section) phenocryst in andesite; Mt.Shasta, CA, USA.



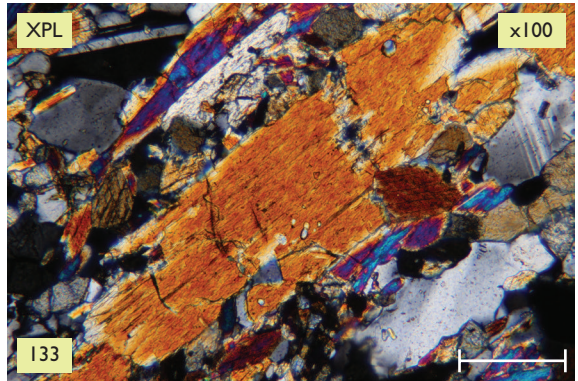
- 23 Granular or radiating fibres (high rlf.); c'less to green, or pale yell.brn pleochr.; ext. angle = 4–22°; low temperature metamorphism. **PUMPELLYITE**



Pumpellyite (highly magnified) in sub-greenschist facies metavolcanic rock; Roseland, Cornwall, England. Note: *Acicular actinolite*, ext. ang. 0–18°(see above), can look similar.

Prismatic/rectangular (med/high rlf.); green/yell.-grn. /blue-green or brown pleochr.; max. extinction angle 13–34°(typically 20–34°); various igneous/ metamorphic rocks; (common) **HORNBLLENDE (I)**

Note: Most hornblendes are pleochroic in shades of yell.grn.-green-blue-grn. However, high temperature hornblendes may be green to brown, or brown pleochroic (*Oxo-Hornblende*). The amphibole *KAERSUTITE* (see above), found in alkaline volcanic rocks, with yell. brn.-red-brn.-greenish brown pleochroism and maximum extinction angle of 19° is difficult to distinguish from brown hornblendes.



Hornblende in Hornblende gneiss; Sleat, Skye, Scotland.

- 24 1storder grey/white interference colours (ext.15–18°)
ZEOLITE mineral (e.g. SCOLECTITE)
 Higher than 1storder grey interference colours 25

25 High relief, max. 1storder yellow/orange interf. colours.

KYANITE



Kyanite in kyanite eclogite from kimberlite pipe; Roberts Victor Mine, South Africa.

Higher than 1storder orange interf. colours.

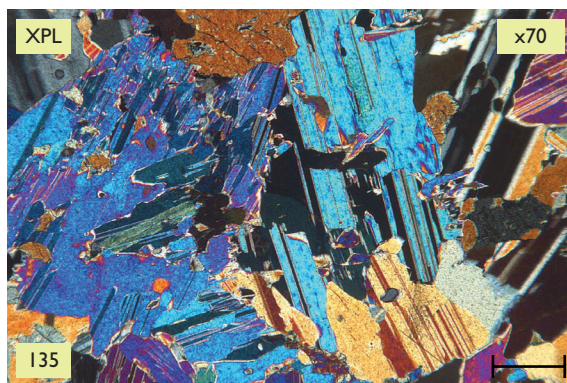
26

26 Top 1storder or 2ndorder interference colours.

27

3rdorder birefr.; (ext.10–15°); often multiple lamellar twins; pale yellowy brown.

GRUNERITE



Grunerite (side section) showing multiple-twinning in meta-ironstone; Erikstad, Hinnøy, Lofoten Is., Norway (photo courtesy of Giles Droop).

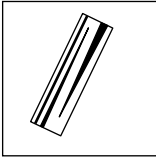
27 Max. extinction 10–20°

28

Max. extinction >20°

29

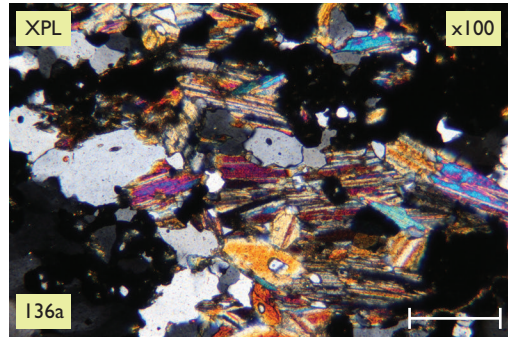
- 28 Abundant narrow polysynthetic twins // {100} (2m). Meta-ultramafics, other Mg-Fe rich rocks.



(2m)

Cummingtonite (with characteristic polysynthetic twinning), in cum-grt-bt-qtz skarn/meta-ironstone; Zinkgruvan, Sweden.

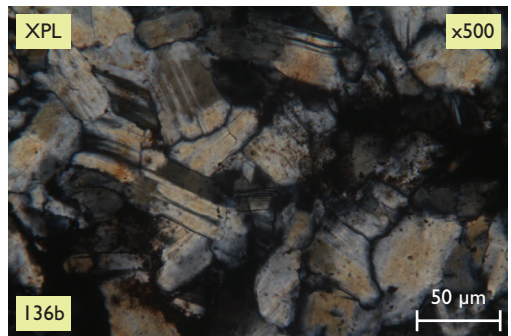
CUMMINGTONITE (I)



Laterites, bauxites and other aluminous rocks.

*Note: In side-section **GIBBSITE**, a common aluminium hydroxide of laterites and bauxites is similar, although crystals less elongate. Gibbsite often shows polysynthetic twinning parallel to {001}. Its birefringence is slightly lower than cummingtonite. In end-section the two minerals are easily distinguished as cummingtonite (an amphibole) shows two cleavages at 120°, whereas gibbsite has none, and appears as mica-/clay-like platelets.*

GIBBSITE (I)

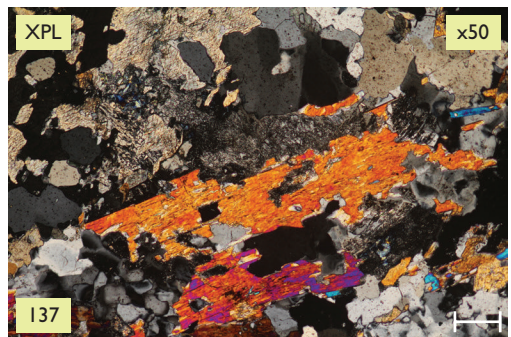


Gibbsite in laterite; Suriname.

Few or no twins. Calc-silicate (Ca-Si-Fe rich) rocks.

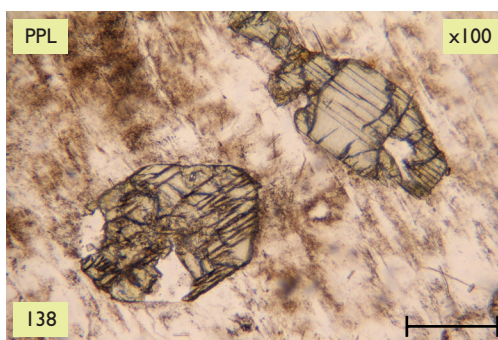
TREMOLITE (I)

Tremolite in qtz-cal-tr calc-silicate rock; Mangkuma-Ketembe, Ghana.



29 Granitic pegmatites (max. extinction = 23–27°)

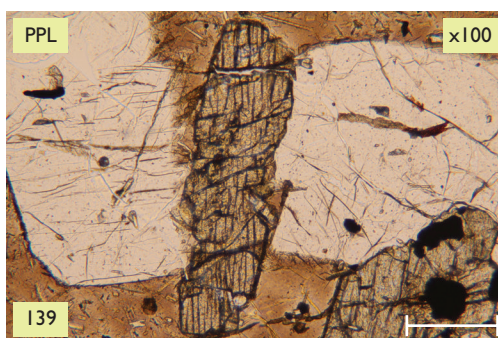
SPODUMENE (■)



Spodumene (side section) in granite pegmatite; Leinster, Ireland.

Mafic igneous rocks (max. extinction = 22–45°)

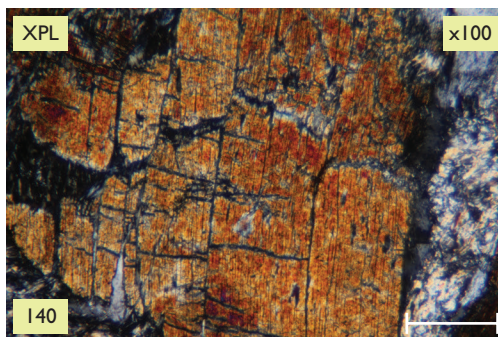
PIGEONITE (■)



Pigeonite (side-section) in andesitic pitchstone; Ardnamurchan, Scotland.

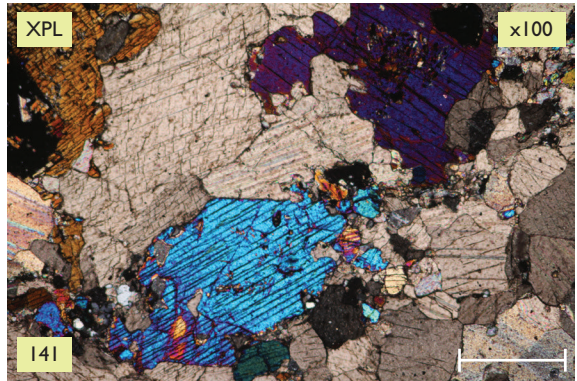
Max. Ext. angle > 35° (generally 40–45°) (= Clinopyroxene)

- | | | |
|----|--|--------------------|
| 30 | Colourless | 31 |
| | Coloured (including weakly coloured) | 34 |
| 31 | Max. top 1 st ord. violet to low 2 nd ord. bright blue interf. colours ($\delta = 0.006-0.021$).
Blueschist facies metamorphic rock. Max. extinction 30–44° | JADEITE (■) |



Jadeite (side section) in jadeite blueschist; Corsica, France.

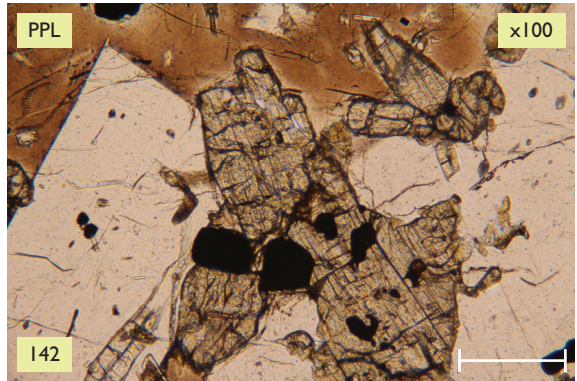
Max. low to mid 2nd ord. interf. colours ($\delta = 0.023-0.031$). Not blueschist facies metamorphic rock. 32

32 Calc-silicate rock (max.ext. $37-45^\circ$).**DIOPSIDE(I)**

Diopside in calc-silicate skarn;
Loch Ailsh, Assynt, Scotland.

Igneous rock

33

33 $2V = 0-30^\circ$ (generally colourless, but may show weak pleochroism to pale yellowish/brownish-grn.)**PIGEONITE(I)**

Pigeonite (side-section) in andesitic
pitchstone; Ardnamurchan,
Scotland.

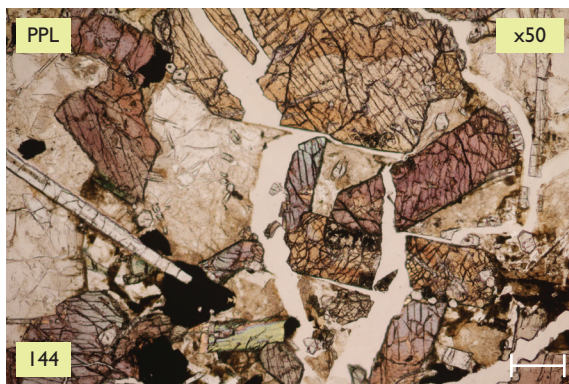
 $2V = 58-60^\circ$ **DIOPSIDE(I)**

Diopside (twinned side-section)
phenocryst in basalt; Izu-Bonin
Arc, Japan.

34	Pleochroic (weak or strong)	35
	Non-pleochroic	38
35	Strongly pleochroic	36
	Weakly pleochroic	37
36	Pleochroic green/brown to violet.	

TITANAUGITE (I)

Titanaugite (end and side sections) in nepheline syenite; Saxony, Germany.

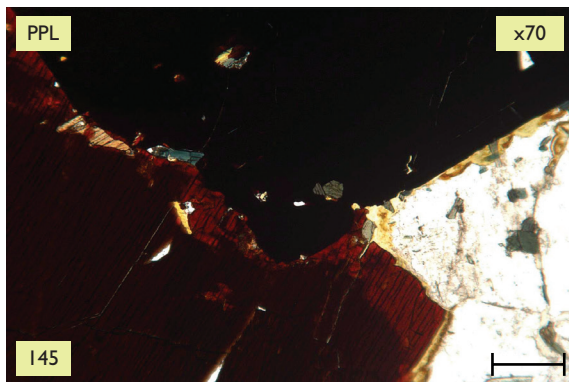


Pleochroic from red-brn./dk. brn./brownish black

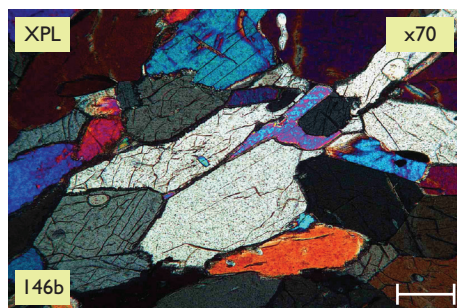
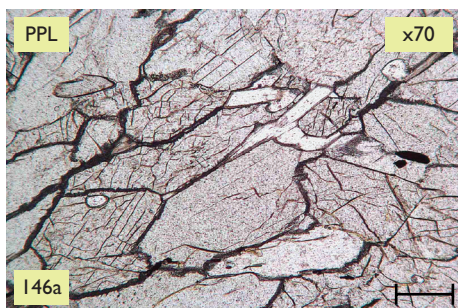
AENIGMATITE (I)

Note: Also check brown HORNBLLENDE and KAERSUTITE in the 10–35° extinction angle part of the key (couplet 16. pg.60).

Aenigmatite (side section) showing cleavage and pleochroism (from red-brown to virtually opaque) in nepheline aenigmatite pegmatite; Kirovsk, Kola Peninsula, Russia (photo courtesy of Giles Droop).

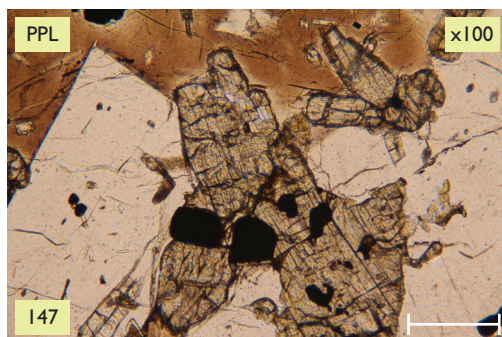


- 37 1st ord. orange to 2nd ord. bright grn. iterf. colours ($\delta = 0.012-0.028$). $2V = 56-84^\circ$; weak c'less to pale grn. pleochr. Typical pyroxene of eclogites. **OMPHACITE**(■)



Omphacite (long- and cross-sections, with 'fuzzy' alteration rims) with phengite in eclogite; locality unknown (photos courtesy of Giles Droop).

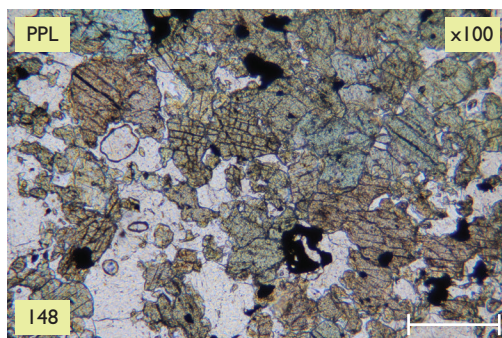
- 2nd ord. blue to bright green interf. colours ($\delta = 0.021-0.029$). $2V = 0-30^\circ$; weak c'less/pale yell.-grn. to brownish pleochroism. Typical pyroxene of andesites and dacites. **PIGEONITE**(■)



Pigeonite (side-section) in andesitic pitchstone; Ardnamurchan, Scotland.

- 38 Calc-silicate rock/skarn (brownish green). ($\delta = 0.025-0.034$). $2V = 52-64^\circ$.

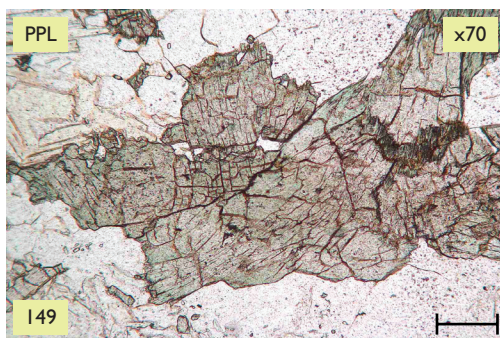
HEDENBERGITE(■)



Hedenbergite (end and side sections) in skarn; Camas Malag, Skye, Scotland.

Not calc-silicate rock/skarn

- 39 Pale green. 1st ord. orange to 2nd ord. green iterf. colours ($\delta = 0.012-0.028$). 2V 56–84°. Typical pyroxene of eclogites. **OMPHACITE**(■)

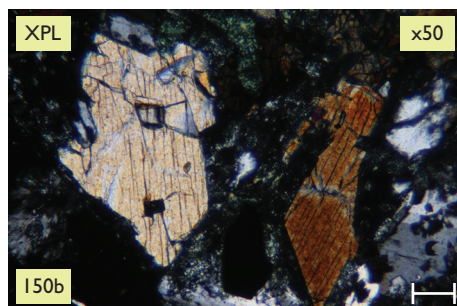
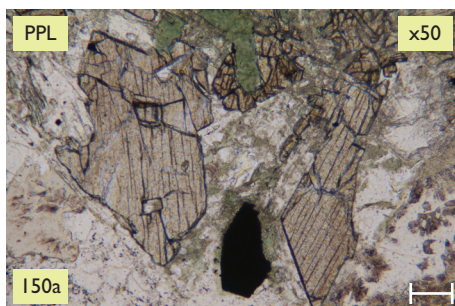


Omphacite (end and side sections) with phengite in eclogite; Syros, Greece (photo courtesy of Giles Droop).

Pale brown, yellowish brn., grn.brn., or yell.grn

40

- 40 2V = 30–50°. ($\delta = 0.018-0.033$). Pale brown, yellowish brn. or grn.brn. Very common in mafic/ultramafic rocks). **AUGITE**(■)



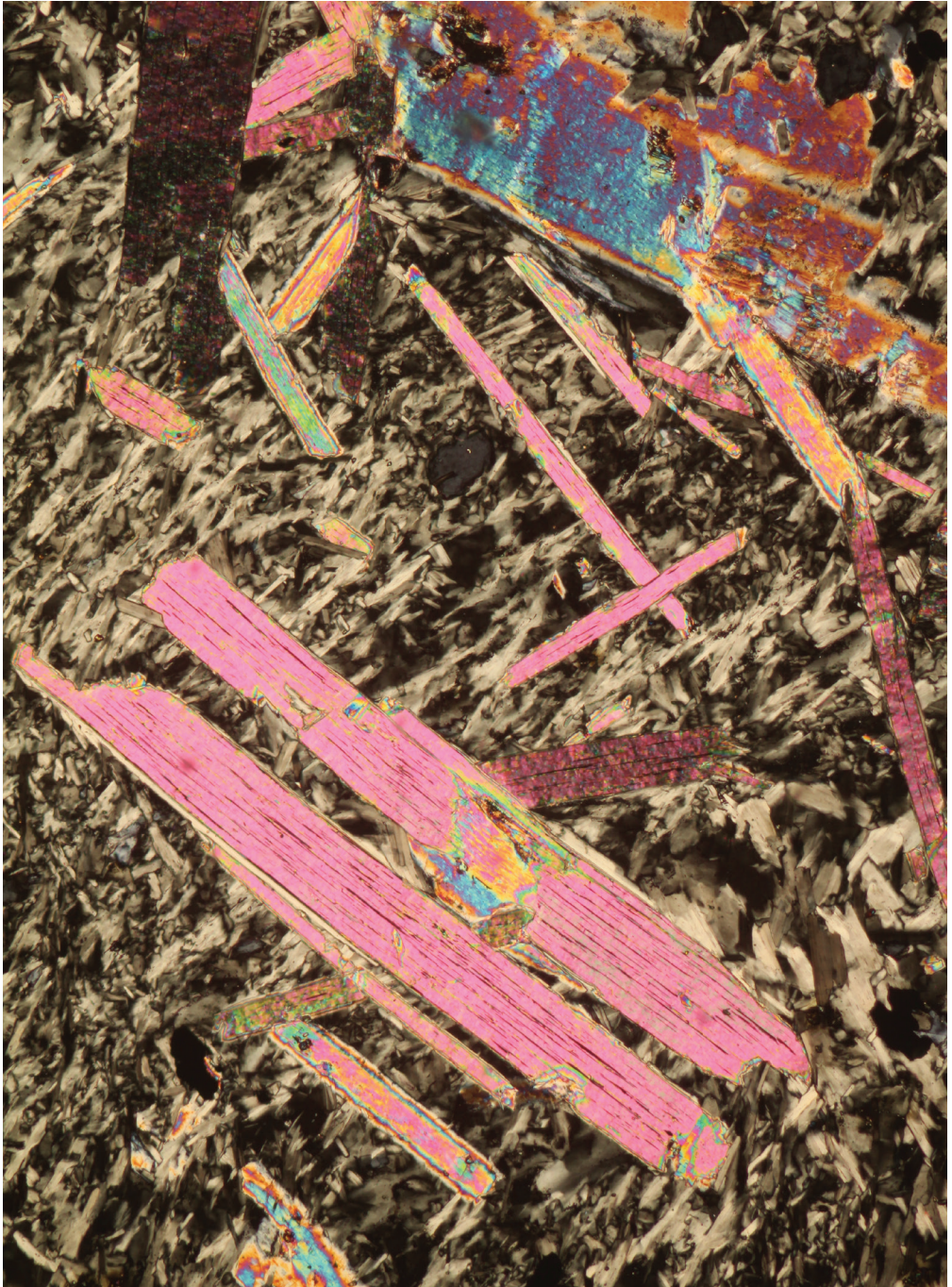
Augite (side section) in amygdaloidal basalt; Uig, Skye, Scotland.

- 2V = 0–30°. ($\delta = 0.021-0.029$). Pale yell.-grn. to brownish Typical pyroxene of andesites and dacites. **PIGEONITE**(■)

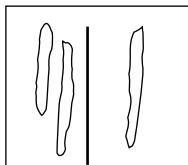


Pigeonite (side-section) in andesitic pitchstone; Ardnamurchan, Scotland.

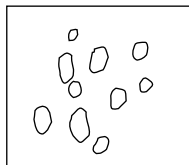
I Cleavage trace, straight extinction, colourless



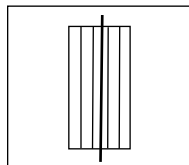
- | | | |
|---|---|----|
| 1 | High (or Mod./High) relief | 2 |
| | Low/Moderate relief | 14 |
| 2 | 1 st Ord. grey/white (or anomalous blue) interference colours. | 3 |
| | Higher than 1 st Ord. white interf. colours. | 6 |



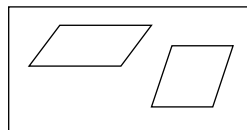
(3a)



(3b)

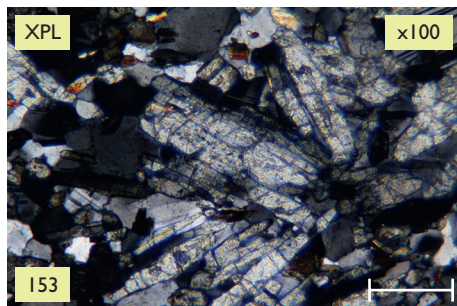
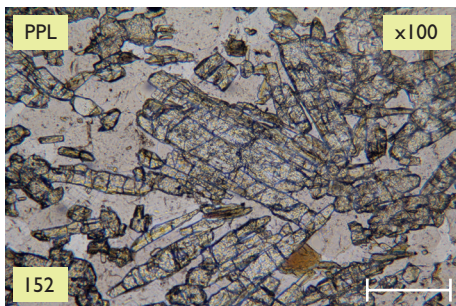


(3c)



(3d)

- | | | |
|---|---|----------------|
| 3 | Fractured needles/rods (3a), or small granules (3b) | 4 |
| | Rectangular or prismatic (3c), or rhombic (3d), but not rod-like. | 5 |
| 4 | RI 1.69–1.72 (high); $\delta = 0.003–0.008$, but often anomalous blue. | ZOISITE |

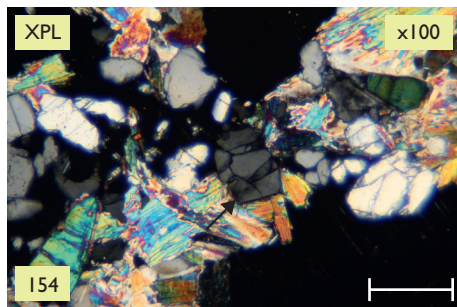


Zoisite in epidote amphibolite; Gratangen, Troms, Norway.

RI 1.61–1.64 (mod-high) $\delta = 0.008–0.010$; accessory mineral in granitic rocks.

TOPAZ

Note: Poorly formed small
ANDALUSITE crystals look similar.



Topaz in greisen (i.e mica-rich hydrothermally altered rock) associated with granite; St. Michael's Mount, Cornwall, England.

- 5 High relief, (biaxial +ve); ($\delta = 0.008-0.009$). Crystals length-slow. Mafic/ultramafic rock. **ENSTATITE(■)**



Enstatite in boninite; Chichijima, Bonin Islands, Japan.

Mod./high relief, (biaxial -ve); interf. colours reach 1st ord. yellow in some crystals ($\delta = 0.009-0.012$). Crystals length-fast. Metapelite/mudrock (Al-rich).

ANDALUSITE(■)

Note: Also check Barytes, which is much less common, but has similar properties (see 8. below).



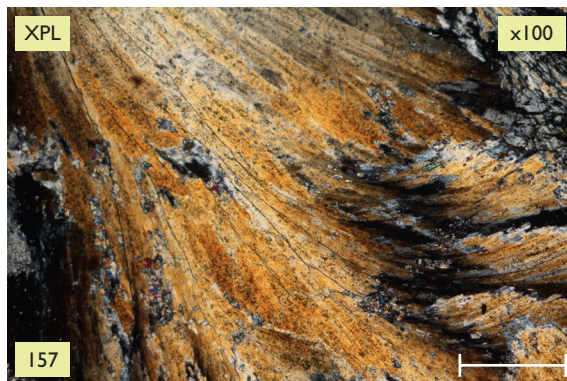
Andalusite (var. chialstolite) porphyroblasts in chialstolite slate; Skiddaw Granite aureole, Lake District, England. See Image 65 demonstrating length-fast nature of this crystal

- | | | |
|---|---|----|
| 6 | 1 st Order yellow/orange interference colours. | 7 |
| | Higher than 1 st order yell./orange interf. colours. | 10 |
| 7 | Mod-High relief (RI = 1.62-1.65). | 8 |
| | High relief (RI = 1.71-1.73). | 9 |

- 8 Fibrous or rod-like aggregates (often radiating). Biaxial -ve, $2V = 36-60^\circ$. $\delta = 0.013-0.014$. May show v.slight inclined extinction ($0-4^\circ$). Calc-silicate rocks.

WOLLASTONITE

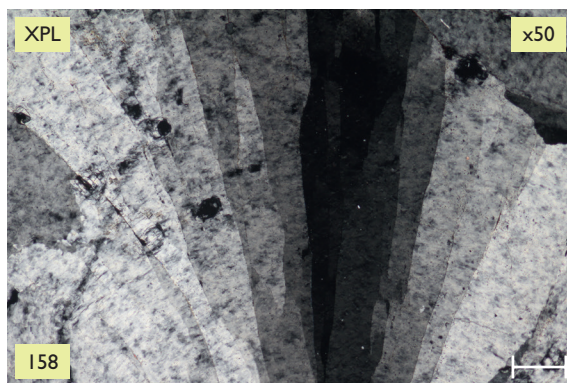
Wollastonite in calc-silicate rock in the contact aureole of the Dartmoor Granite; Meldon, Devon, England. Note the N-S oriented crystals (left) and E-W oriented crystals (centre right) showing straight extinction.



Prismatic/bladed crystals (sometimes radiating), or polygonal/granular aggregates. Biaxial +ve, $2V = 37^\circ$. Interf. colours range up to 1st ord. yellow ($\delta = 0.012$), but most crystals are typically 1st ord. light grey/white. Occurs in Ba-mineralised areas/rocks.

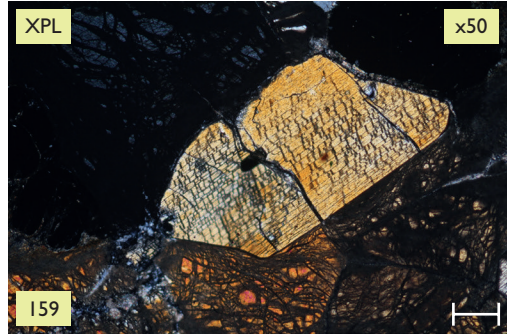
BARYTES

Barytes in vein; Porth y Corwgl, Anglesey, Wales. Note the N-S oriented central crystal showing straight extinction.



- 9 Rectangular/prismatic (3c), not rod-like; $\delta = 0.012-0.016$. $2V = 78-83^\circ$. High-P metapelites and Al-rich eclogites. **KYANITE**

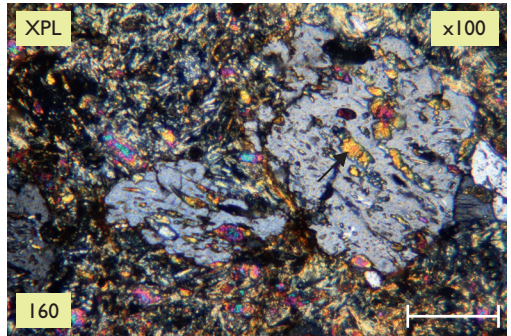
Kyanite in kyanite eclogite within kimberlite pipe; Roberts Victor mine, South Africa.



Needles, rods or small blebs (3a, 3b). $\delta = 0.004-0.015$.

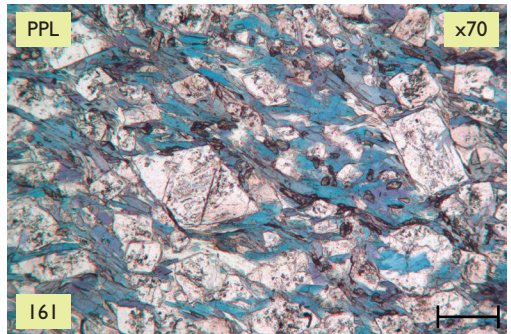
CLINOZOISITE

Clinozoisite arrowed in albite of ab-act-chl-clz hornfels; Donegal, Ireland.



- | | | |
|----|---|------------------|
| 10 | Top 1 st order to mid 2 nd Order interf. colours. | 11 |
| | High order (i.e mid 3 rd and 4 th ord.) interf. colours. | 13 |
| 11 | Squat rectangle/rhomb/lozenge (L/W typically = 2) (3d) Max. 1 st ord. red/violet interf. colours ($\delta = 0.019-0.021$). | LAWSONITE |

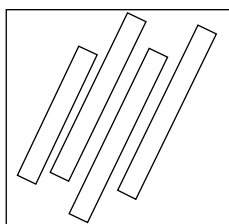
Lawsonite (rectangular and lozenge-shaped sections) in glaucophane schist (blueschist); Orhaneli, NW Turkey (photo courtesy of Giles Droop).



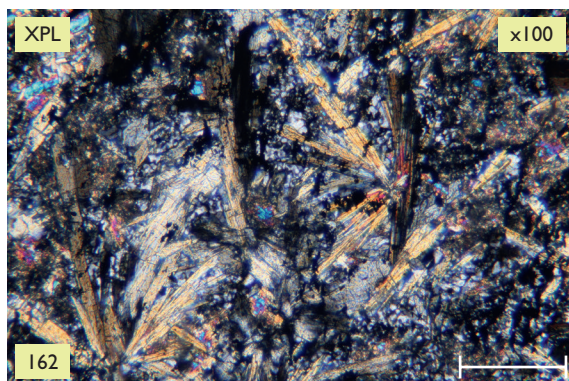
Elongate rectangle (L/W > 3) (3e). Max. 2nd ord. blue/grn. interf colours. 12

12 $\delta = 0.016-0.025$; biaxial +ve; $2V = 70-90^\circ$.

ANTHOPHYLLITE (I)



(3e)

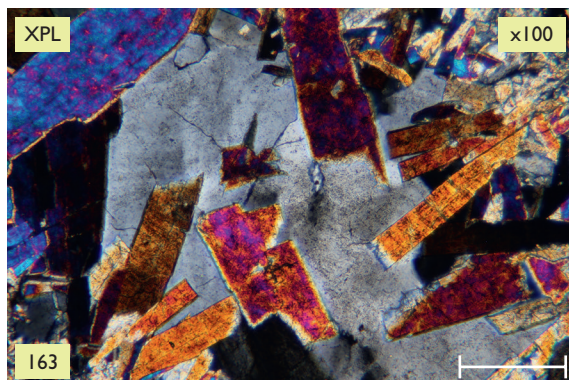


Anthophyllite in cordierite-anthophyllite hornfels; Kenidjack, Cornwall, England. Note the N-S oriented crystal (upper centre) showing straight extinction.

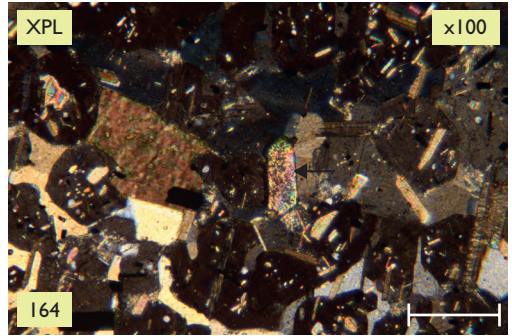
$\delta = 0.020-0.033$; biaxial +ve; $2V = 64-71^\circ$.

PREHNITE (I)

Prehnite in Prh-qtz vein cutting volcanoclastic sediments; Roseland, Cornwall, England. Note the N-S oriented crystal (left) and E-W oriented crystal (right) showing straight extinction. Also see Fig. 1.12 for lower magnification view of the same vein.



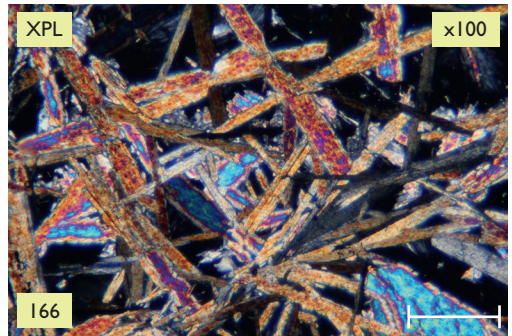
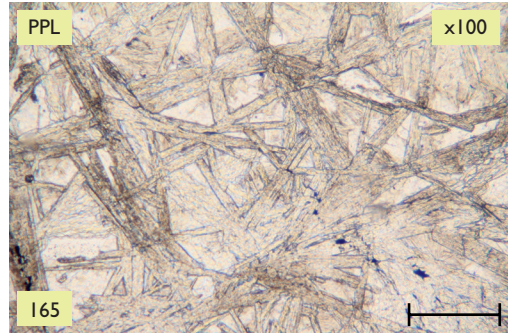
- 13 Biaxial +ve (low $2V$; $6-19^\circ$), small elongate blebs (3b); granitic rocks (rare accessory phase) and metasedimentary rocks; $\delta = 0.045-0.075$. Actually $2-10^\circ$ extinction angle, but may appear parallel. **MONAZITE**



Monazite in Crd-Bt-Qtz-Ilm metasedimentary rock; locality unknown.

- Biaxial +ve (large $2V$; $84-86^\circ$), platy, aluminous rocks (rare); $\delta = 0.040-0.050$.

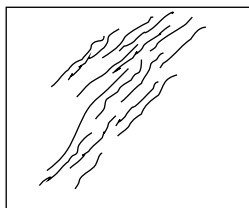
DIASPORE



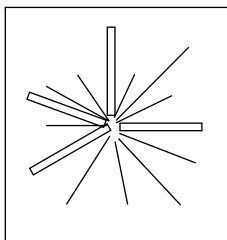
Diaspore; Wonderstone Quarry, South Africa.

- 14 1st order grey/white/yellow interference colours 15
 Higher than 1st order yellow interference colours 23

- 15 Fibrous (3f) or radiating acicular crystals (3g). 16
 Anhedral/granular or prismatic crystals. 17



(3f)

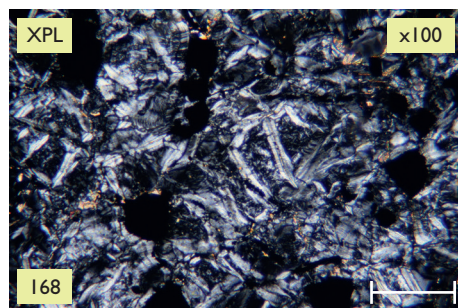


(3g)

- 16 Low relief

ZEOLITE
 (e.g. THOMSONITE, MESOLITE)
 colourless

or **SERPENTINE**
 (e.g. ANTIGORITE) usually c'less/pale
 green

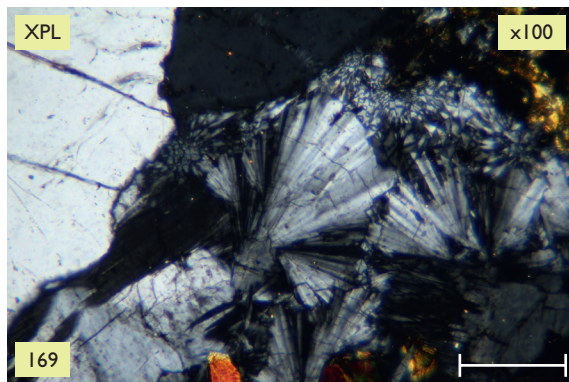


Zeolites as cavity fill in altered gabbro; Scawt, Antrim, N.Ireland.

Serpentine aggregate in serpentinised ultra-mafic rock; Lizard, Cornwall, England.

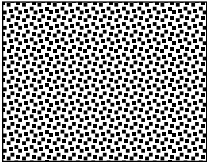
Medium relief (1st order grey/white (sometimes to yellow) interf. colour)

ZEOLITE (eg NATROLITE)



Zeolite in cavity within leucitophyre; Eifel, Germany.

17 Fine-grained aggregate (3h)



(3h)

CLAY MINERALS (e.g ILLITE)



Andalusite porphyroblast pseudomorphed to an aggregate of clay minerals and sericite in andalusite slate; contact aureole of Skiddaw Granite, Lake District, England.

Not fine-grained aggregate

18

18 Low relief

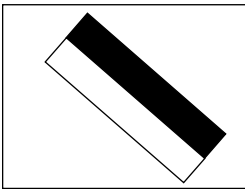
19

Medium relief

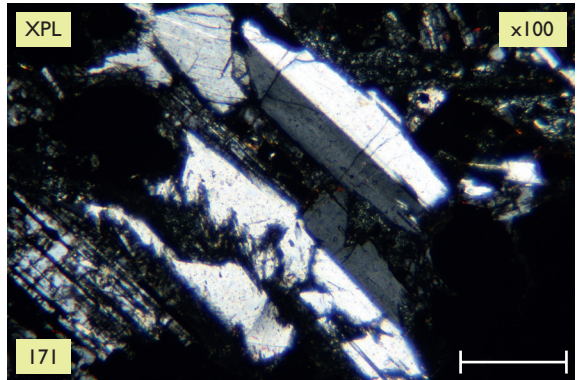
21

19 Simple twinning (3i) typical, 1st ord. grey/white; $\delta = 0.006-0.008$. Some sections show // extinction, but others c.5–9°.

SANIDINE



(3i)



Sanidine in sanidine facies mafic hornfels; Cushendell, Antrim, N.Ireland.

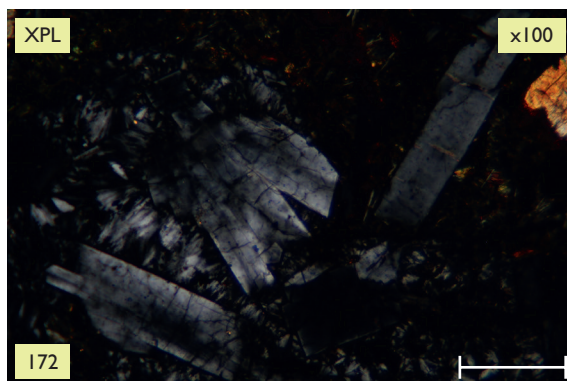
Lacks simple twinning, v.low relief.

20

20 V.low relief. 1st ord. dk.grey/grey interf. colours; $\delta = 0.003-0.005$; igneous rocks.

NEPHELINE

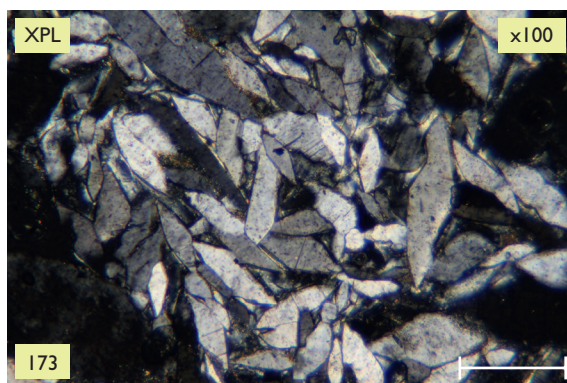
Nepheline in nephelinite; Bohemia, Czech Republic.



Low -ve relief; 1st ord. grey/white interf. colours (occasionally to straw yellow), $\delta = 0.009$, sedimentary rocks (evaporites).

GYPSUM

Gypsum in evaporite; Kirkby Thore, Cumbria, England.

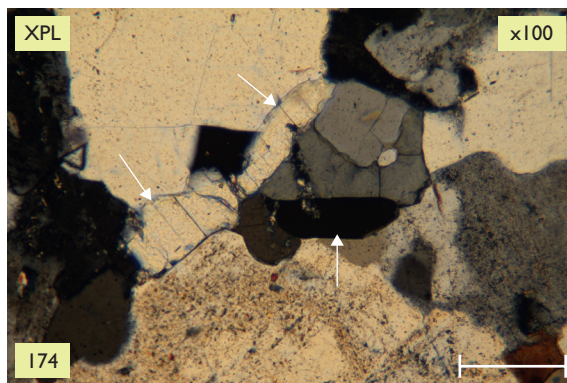


21 Med. -ve relief (= Zeolite mineral)
Med. +ve relief. Accessory mineral in granitic rocks.

22

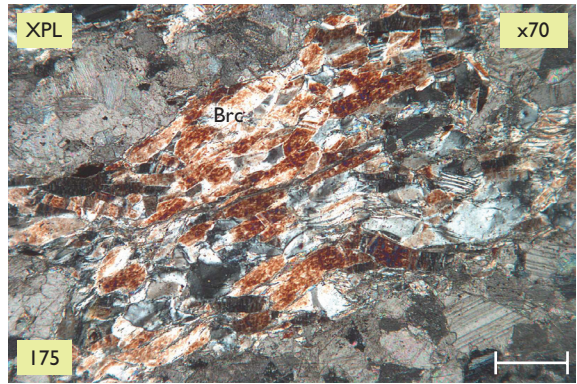
TOPAZ

Cluster of topaz crystals in granite (Note: horizontal crystal in centre of image showing straight extinction); Cornwall, England.



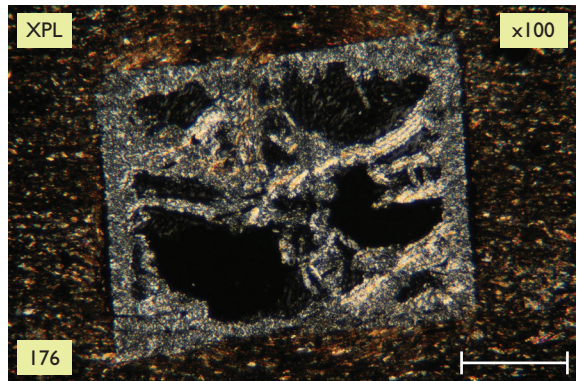
- | | | |
|----|--|--------------------------------------|
| 22 | Biaxial –ve figure
Biaxial +ve figure; typically associated with mafic metavolcanic rocks and basalts (low-T metamorphism). | STILBITE
HEULANDITE |
| 23 | 1 st order yellow to mid 2 nd order interf. colours.
Higher than mid 2 nd order interf. colours. | 24
28 |
| 24 | Fine aggregates (3h)
Prismatic (3c), acicular (3g) or large anhedral crystals. | 25
26 |
| 25 | Max. 1 st order violet interf. colours; $\delta = 0.012-0.020$. Calc-silicate rock/marble, or serpentinite. | BRUCITE |

Brucite (showing upper-first-order interference colours) with calcite in brucite marble; Qadda, Saudi Arabia (photo courtesy of Giles Droop).



Interf. colours to mid 2nd order (and higher); typically $\delta = 0.010-0.036$.
certain **CLAY MINERALS** (e.g. Smectite)

Clay minerals (e.g. smectite) with chlorite forming pseudomorph after andalusite in andalusite slate; Skiddaw granite aureole, Lake District, England.



26 Low relief
Medium relief

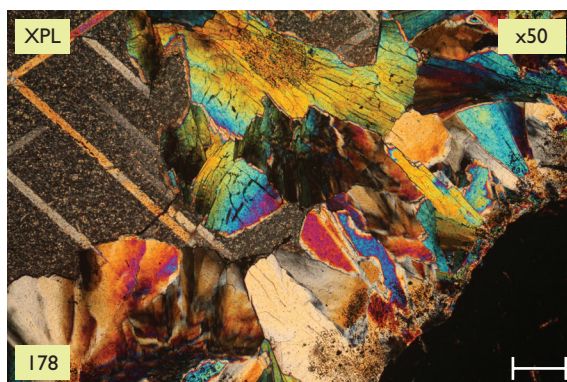
27

PREHNITE

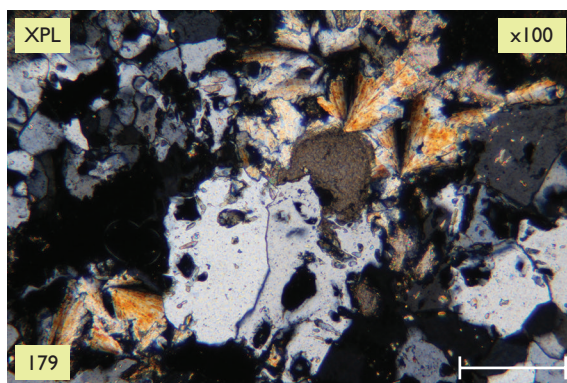
Prehnite in Prh-qtz vein cutting volcaniclastic sediments; Roseland, Cornwall, England. Also see Images 25 and 163 for XPL view of the same vein.



Prehnite as cavity fill in prehnite-pumpellyite facies metabasalt; Barrhead, Glasgow, Scotland.

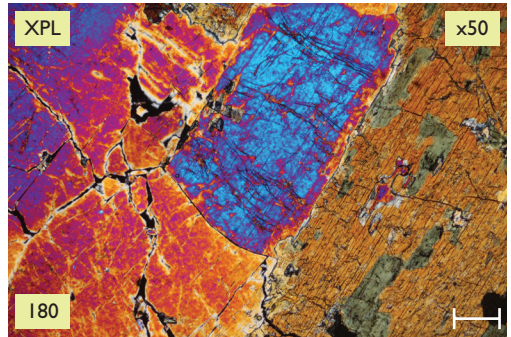


Hemimorphite (Zn-silicate) found associated with Zn-ore deposits is optically similar to prehnite, although often acicular. This example is in a Zn-mineralised siliceous rock; Minera, Wrexham, Wales. Note the N-S and E-W oriented crystals in the radiating aggregates displaying straight extinction. Barytes and celestine, both at the high end of medium relief may also appear similar, as can certain medium relief zeolites that have 1st order yellow/orange birefringence (e.g. natrolite $\delta = 0.012$).

or HEMIMORPHITE

27 Low (+ve) relief; calc-silicate rock/skarn.

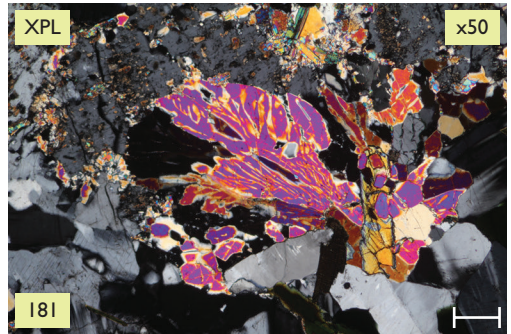
SCAPOLITE



Scapolite in skarn; Arendal, Norway.

Low (-ve) relief; nepheline syenite or related rock.

CANCRINITE

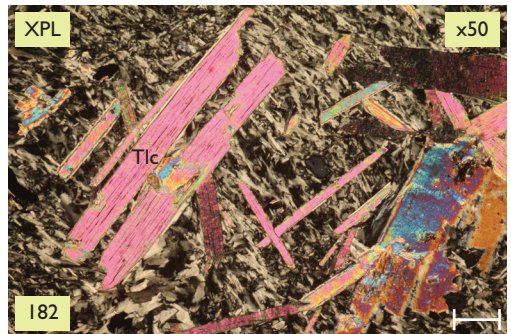


Cancrinite in understaurated kfs-feldspathoid alkali igneous rock termed miassite; Miass, Urals, Russia. Note the straight extinction of the E-W oriented crystal left of centre.

28 Mod. relief. Elongate rectangles (3e), laths (3c), or fine aggregates (3h). 29
 Low (or mod.) relief; rectangular laths (3c) or short squat prisms (3d). 31

29 $2V = 0-30^\circ$. Marble, calc-silicate or meta-ultramafic rock.

TALC

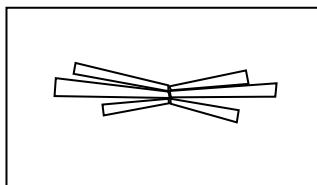


Talc in chl-talc-dol schist; Ghana. (see start of Section 3 for an enlargement of this image).

$2V > 30^\circ$. Not marble, calc-silicate or meta-ultramafic rock. 30

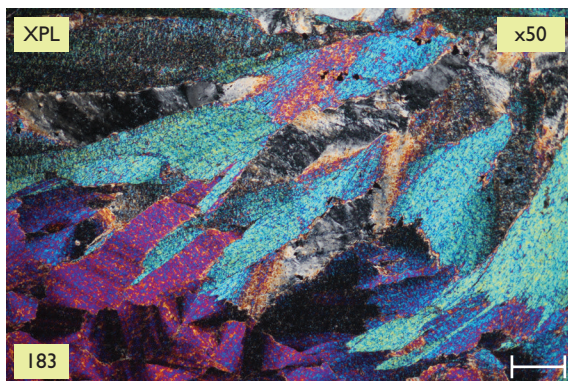
- 30 Radial aggregates of crystals (3g) or “bow-tie” (3j). $2V = 53-62^\circ$. Aluminous pelites and hydrothermal ore deposits.

PYROPHYLLITE



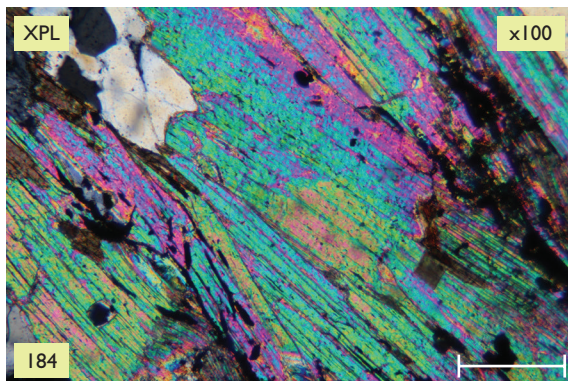
(3j)

Pyrophyllite in pyrophyllite rock; Tres Cerritos, Mariposa County, California, USA.



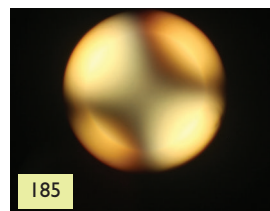
- Not radiating aggregates. $2V = 28-47^\circ$. Very common mineral in a wide range of rock types.

MUSCOVITE



Muscovite in muscovite schist; Ghana.

Muscovite interference figure, with isogyres arching half-way across the field of view with a boomerang-like angular curvature indicative of $2V$ c. $30-45^\circ$.

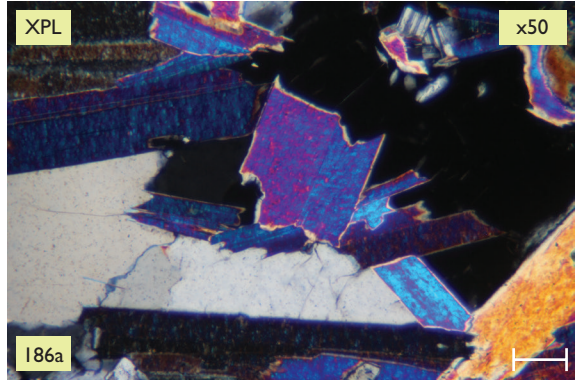


Notes: (a) Fine grained muscovite (or paragonite) is referred to as *SERICITE*. (b) **PARAGONITE** (Na-white mica) is much rarer than *MUSCOVITE*, but optically indistinguishable. (c) *LEPIDOLITE*, a lithium mineral of certain granite pegmatites is also very similar; see 31. below).

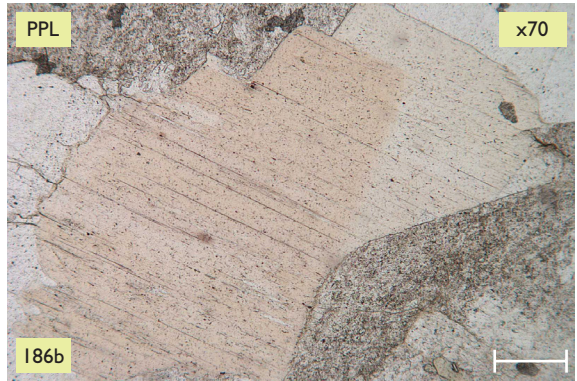
- 31 Low to Mod relief. RI = 1.52–1.59. Max. top 2nd ord. interf. colours ($\delta = 0.018$ –0.038). Biaxial –ve figure; $2V = 0$ –58°; granite pegmatites and high T veins. Crystals may show very slightly inclined extinction (up to 6°).

LEPIDOLITE or ZINNWALDITE

Lepidolite (colourless in PPL) in aplite; Meldon Quarry, Devon, England.



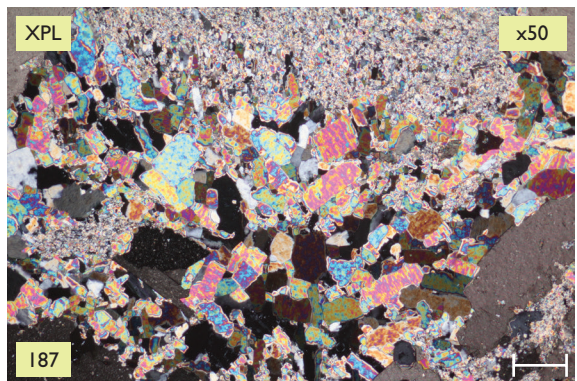
Zinnwaldite (colourless to v.pale brown in PPL) with altered feldspar in zinnwaldite granite; Gunheath, Cornwall, UK (photo courtesy of Giles Droop).



Mod. rlf. RI = 1.57–1.61. Low to mid 3rd ord. interf. colours ($\delta = 0.040$); Biaxial +ve figure; sedimentary rocks, especially associated with salt deposits and evaporites.

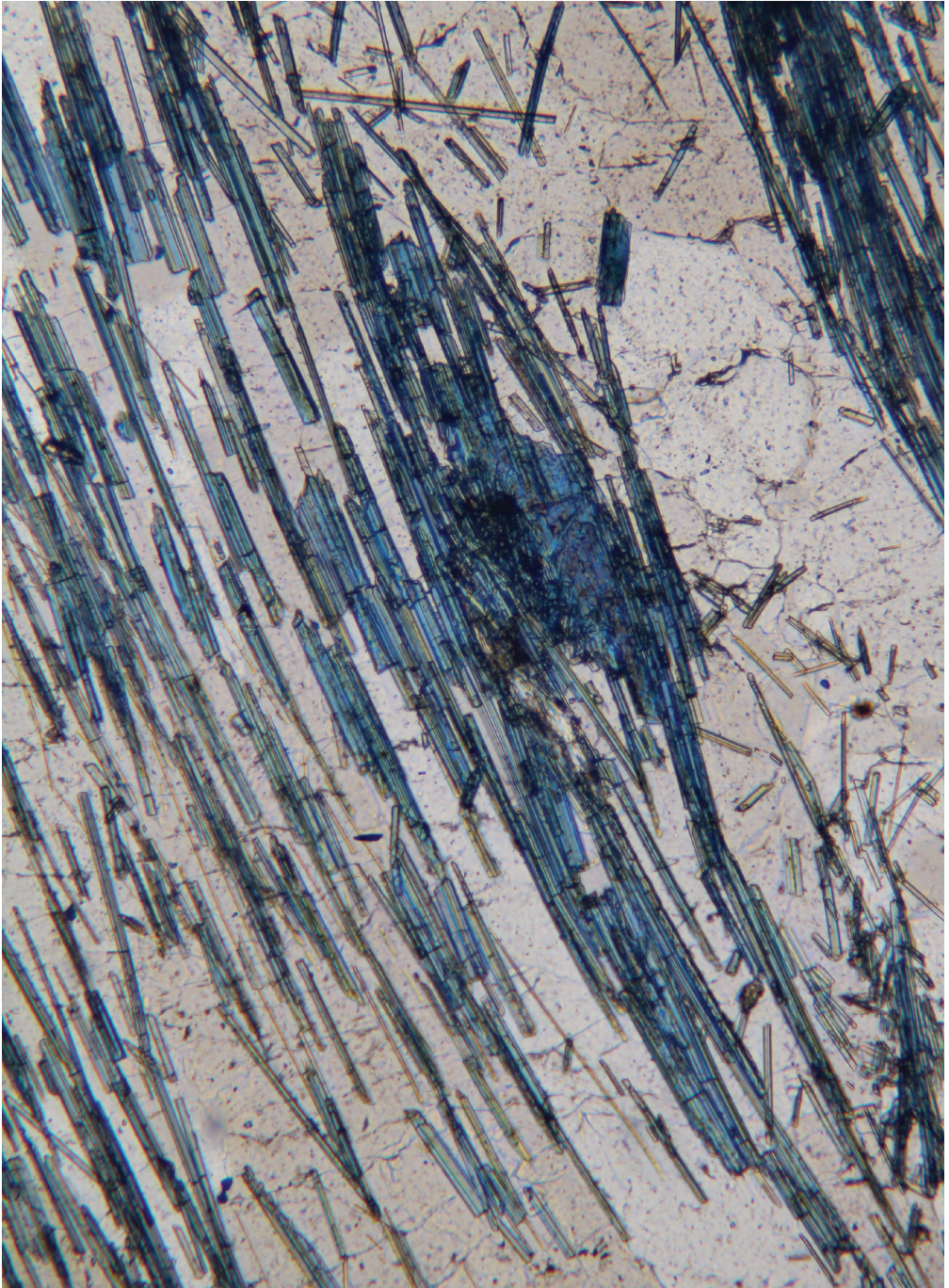
ANHYDRITE

Anhydrite in anhydrite marl from borehole; Selby, Yorkshire, England.



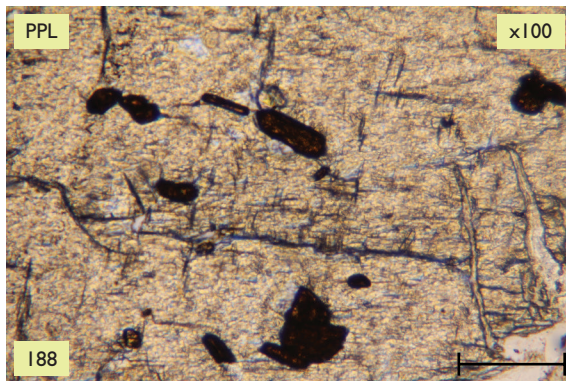
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I Cleavage trace, straight extinction, coloured



- | | | |
|---|---------------------------|---------------|
| 1 | Non-pleochroic | 2 |
| | Pleochroic | 3 |
| 2 | Red-brown (v.high relief) | RUTILE |

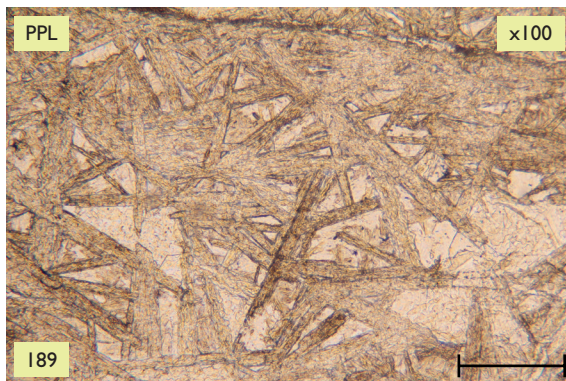
Rutile inclusions in kyanite, within kyanite schist; Loch Assapol, Mull, Scotland. Note: Much rarer, cassiterite (Sn-ore mineral) is also a very high relief brown or yellow-brown (or red-brown) mineral with high interference colours. It has polygonal to short prismatic form. (see pg. 107 (photo 231) and pg. 137 (photo 296a–b))



Colourless-very pale blue (high relief)

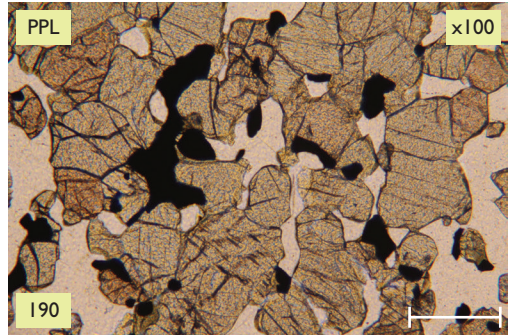
DIASPORE

Diaspore; Wonderstone Quarry, South Africa.



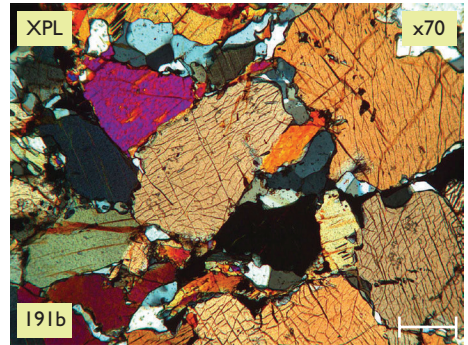
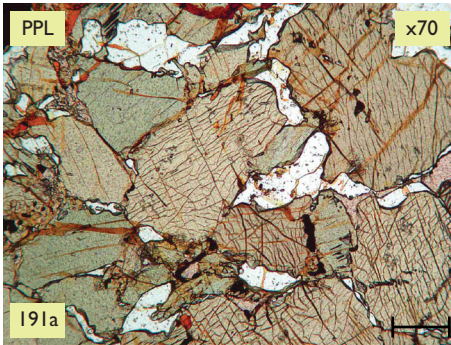
- | | | |
|---|---|---|
| 3 | Weak/mod. pleochroism (pink/pale brn./pale grn.). | 4 |
| | Strong pleochroism. | 5 |

- 4 Weak pleochroism; 1st order yellow/orange interf. colours **HYPERSTHENE**(**▣**)
(= orthopyroxene)



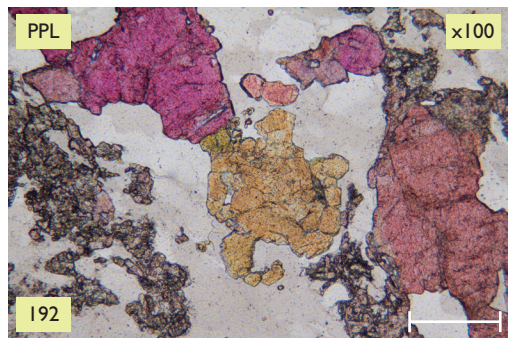
Hypersthene in granulite; Hartmannsdorf, Saxony, Germany.

- Mod. pleochroism: Top 1st/Low 2nd ord. interf. colours. **FERROSILITE**(**▣**)



Ferrosilite (in various orientations, showing cleavage and pleochroism) with quartz in garnet-quartz-ferrosilite-granofels (a meta-ironstone); Mt Towla area, Zimbabwe (photos courtesy of Giles Droop).

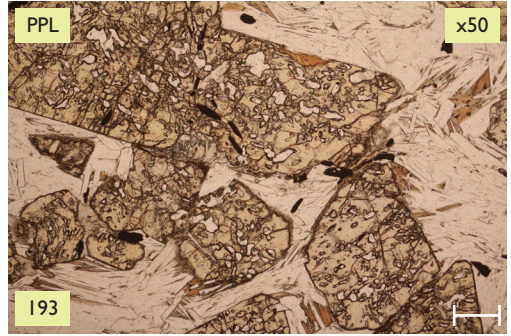
- 5 Red to violet to orange-yell. pleochroism (depends on section) **PIEMONTITE**



Piemontite. Pennsylvania, USA.

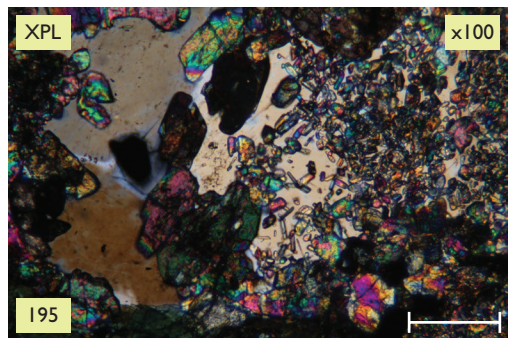
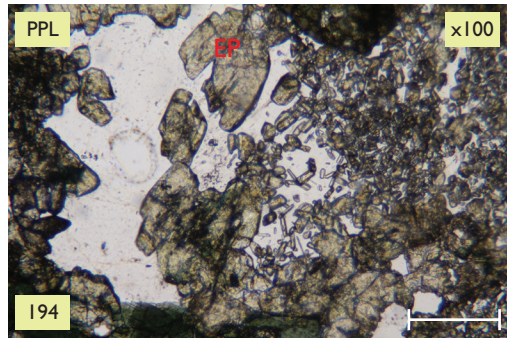
Not extreme red/violet/orange/yellow pleochroism.

- 6 Colourless/pale yell./bright yell./yell.-green pleochr. 7
 Pleochr. in green, brown (includes yell. → brown), or blue/violet. 8
- 7 1st order yellow interf. colours (colourless/pale yell./yell. pleochroism). Commonly as porphyroblasts. Weak cleavage trace. **STAUROLITE**



Staurolite porphyroblasts in stt-bt-schist; Cloncurry, Queensland, Australia.

Max. high 2nd ord interf.colours (colourless/pale yell./yell.-grn. pleochr.). High relief granular aggregates/ small rods. **EPIDOTE**

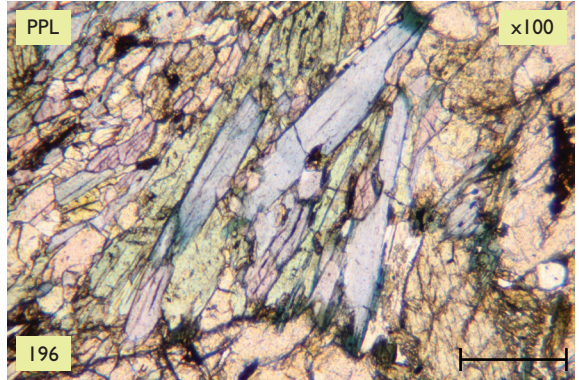


Epidote in epidote-actinolite hornfels; Ghana.

- 8 Blue or blue/violet pleochroism. 9
 Green, blue-grn., or green/brown pleochroism. 11

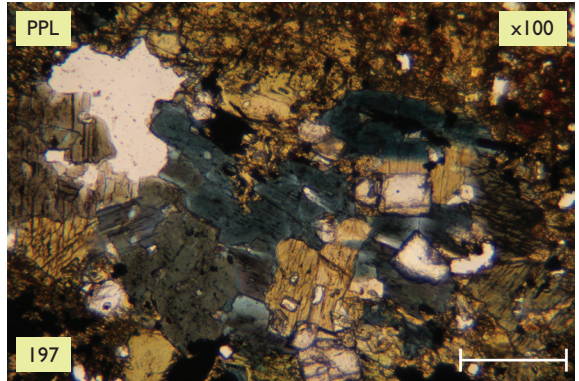
- 9 Granite, syenite or aluminous metasediment. 10
 Not granite, syenite or Al-metased (c'less/blue-violet). **GLAUCOPHANE(■)**

Glauco-phane in glaucophane schist (blueschist); Ile de Groix, Brittany, France.



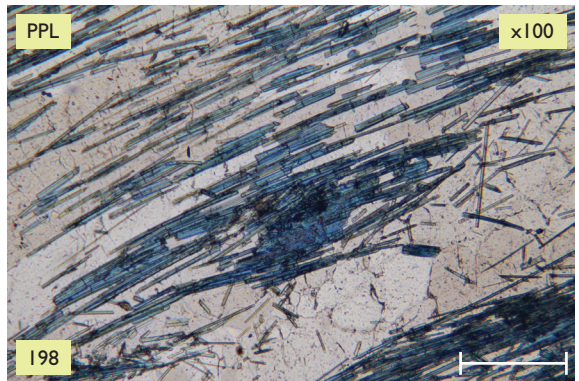
- 10 Blue/light blue/blue-grn. plchr. (Na-rich igneous rock). **RIEBECKITE(■)**

Riebeckite in sodic granite; Drammen, Norway.



- C'less/blue pleochr. Al-metased or granite pegmatite. **DUMORTIERITE**

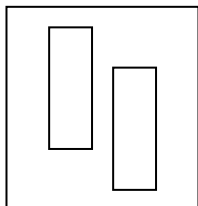
Dumortierite in dumortierite-qtz rock; locality unknown. (see start of Section 4 for an enlargement of this image)



- 11 C'less to GREEN (or blue-grn./tourquoise) pleochr. 12
 C'less/pale BROWN to dk.brn., yell-brn., or brn.- grn. pleochr. 15

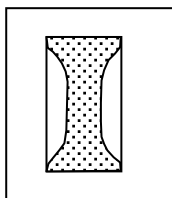
- 12 High relief 13
 Medium (or low) relief 14
- 13 Prismatic/rectangular (4a), often with “hour-glass” structure (4b), or lamellar twinning.

CHLORITOID



(4a)

Chloritoid in chloritoid phyllite; Tarkwa, Ghana.



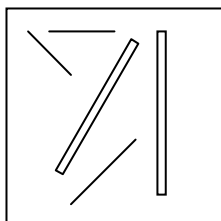
(4b)

Chloritoid [*ottrelite*] (with hour-glass zoning) in chloritoid phyllite; Ardennes, Belgium.



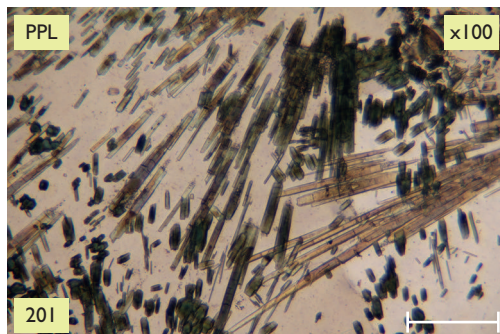
Acicular/rodded (4c) or columnar. Cross-fractures evident in rods, but cleavage traces are weak.

TOURMALINE (schorl)

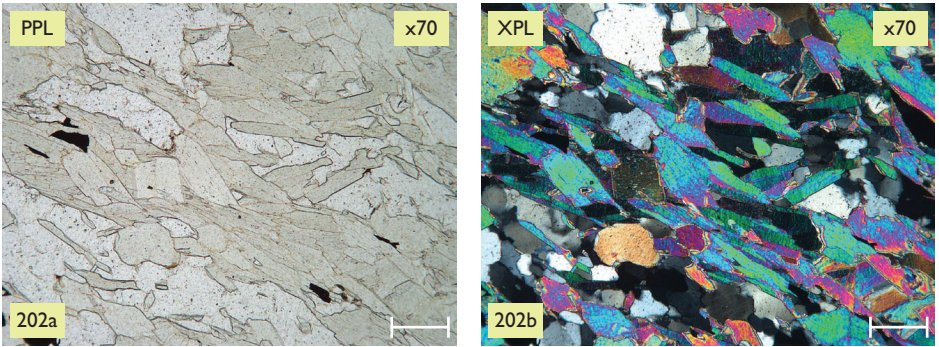


(4c)

Radiating acicular tourmaline (schorlite) in Luxullyanite; Cornwall, England. Note the strong pleochroic scheme as displayed by differently oriented crystals in top right quadrant of image.



14 C'less to pale grn., 2nd/3rd order birefringence. **PHENGITE** (+ some Biotites).

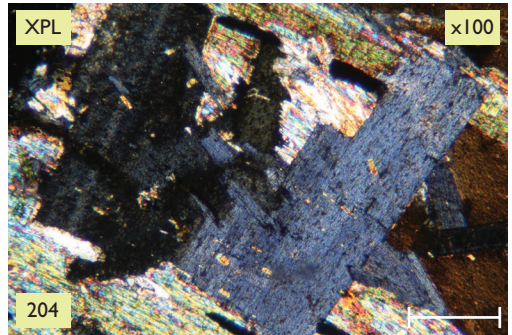
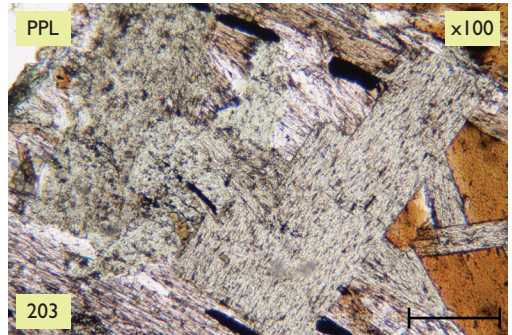


Phengite in quartz phengite schist; Mallnitz, Austria (photo courtesy of Giles Droop).

Note: *Cr-muscovite* (*FUCHSITE*) is similar.

C'less to pale grn., 1st ord. grey or anomalous “berlin blue”.

CHLORITE

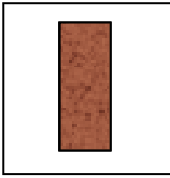


Late overprinting chlorite porphyroblasts in garnet mica schist; Gratangenfjord, Troms, Norway. Note the anomalous 'Berlin blue' interference colours in XPL.

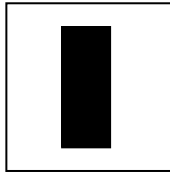
15 Medium relief
High relief

16
18

16 Mottled (4d) at extinction



(4d)

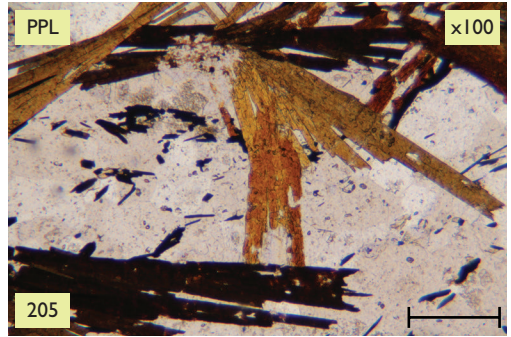


(4e)

Smooth (4e) at extinction (intense yell.-brn. pleochr.)

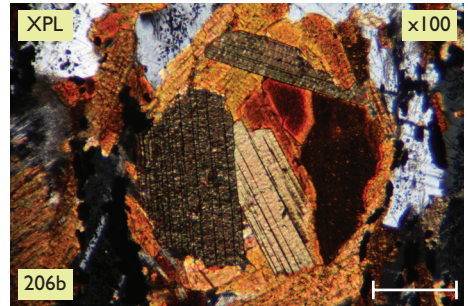
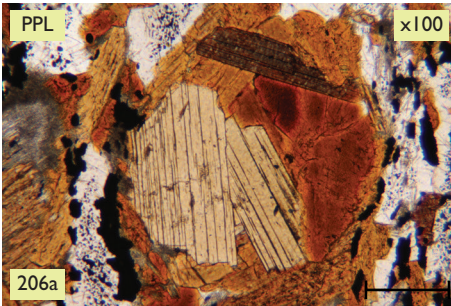
STILPNOMELANE

Stilpnomelane in blueschist facies siliceous meta-ironstone; Laytonville Quarry, CA, USA. Note the strength of pleochroism as shown by the central N-S oriented crystal compared with the E-W oriented crystals top and bottom.



17 Strongly pleochroic (pale brn. or yell.-brn. to dark brn./red-brn).

BIOTITE

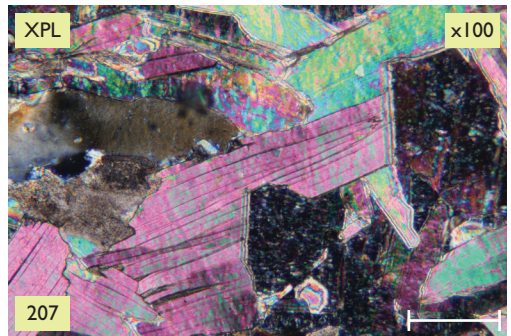


Biotite in grt-crd-sil schist; La Hoya, Andalucia, Spain.

Pale yell./pale brn. pleochr. (in marble, ultrabasic rock).

PHLOGOPITE

Phlogopite; Pfaffenreuth, Bavaria, Germany.



18 Light brown-brown pleochroism. 1st order orange $\delta = 0.013$ to 2nd order red $\delta = 0.036$ interference colours.

ALLANITE

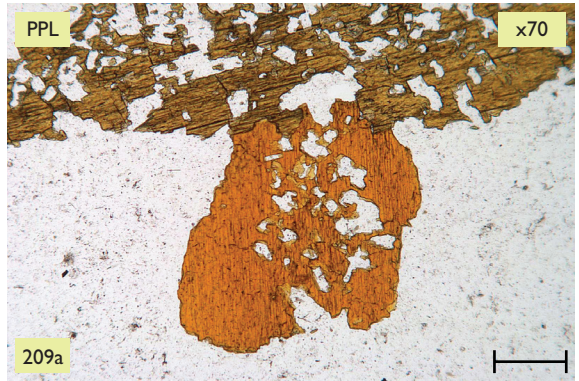
Allanite in vein associated with diorite; West Labelle Diorite, Great Slave Lake, Canada.



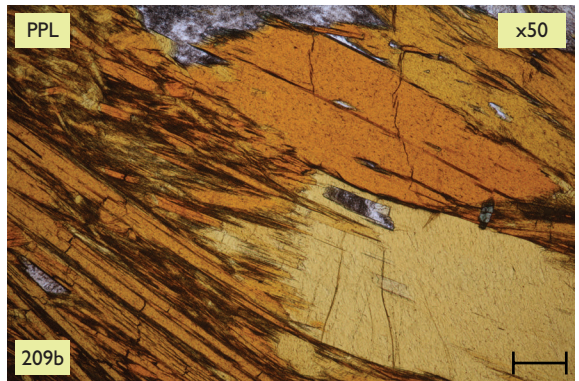
Brown to yellow pleochroism. 4th order interference colours, $\delta = 0.060$ but often masked by strong absorption colours.

ASTROPHYLLITE

(209a) Astrophyllite (showing cleavage and pleochroism) in syenite; Greenland (photo courtesy of Giles Droop).

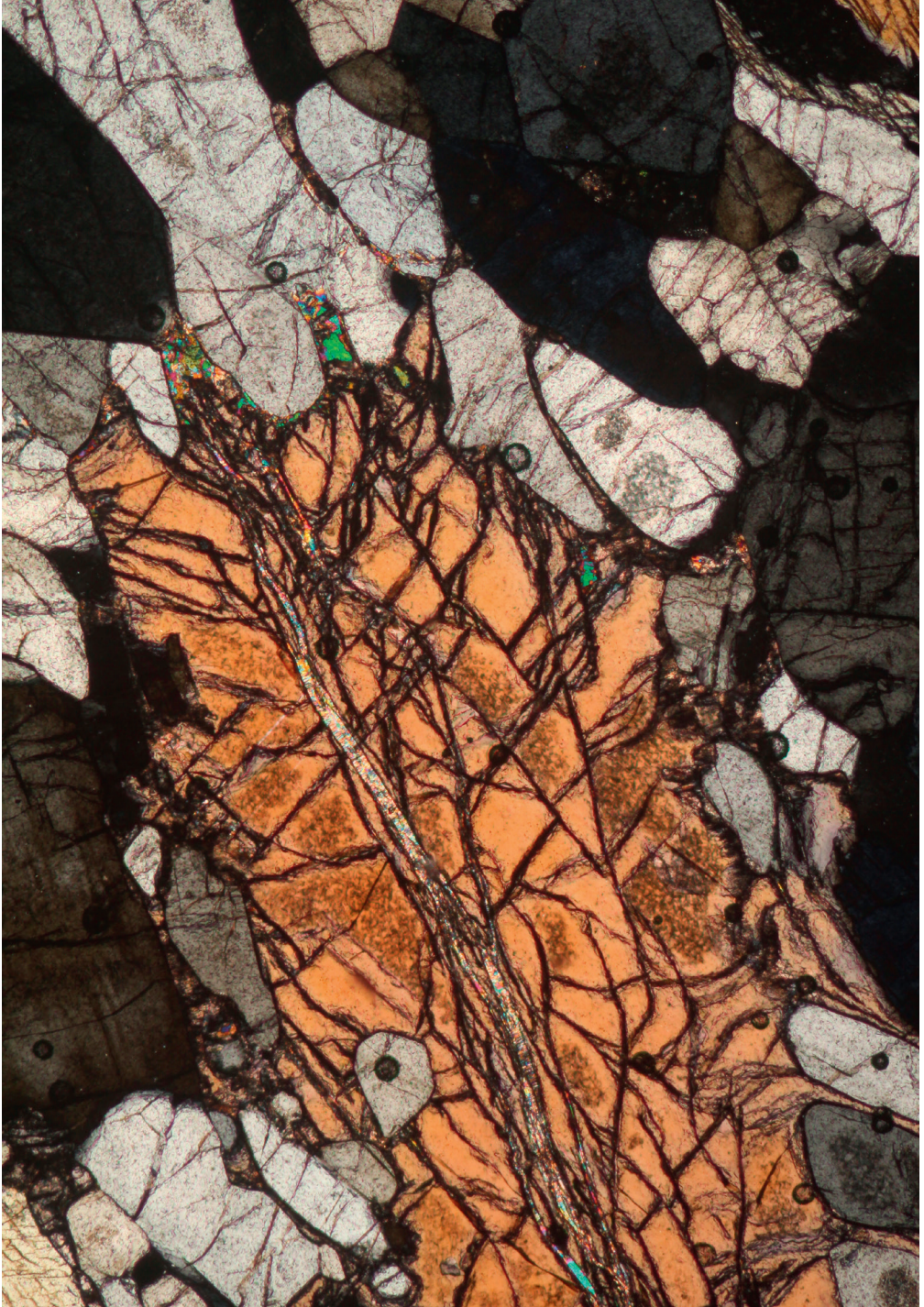


(209b) Astrophyllite in syenite; Kola Peninsular, Russia.



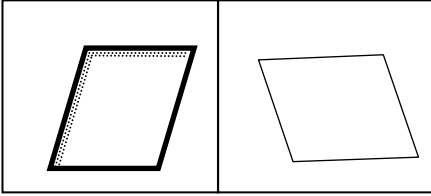
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Imperfect cleavage, parting or arranged fractures



- 1 Relief varies on rotation (“twinkling”) (5a); extreme 5th order interf. colours.

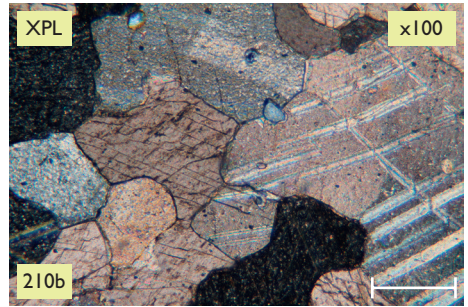
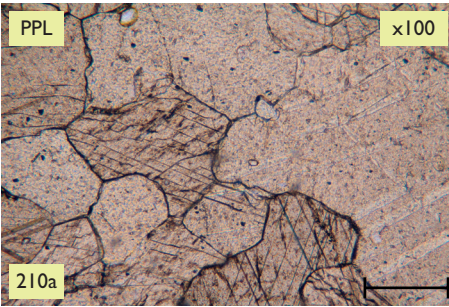
Carbonate mineral: e.g. CALCITE, DOLOMITE or ARAGONITE.



Note: Rarer RHODOCHROSITE ($MnCO_3$) is also similar in appearance, but is typically colourless to pale pink in thin section.

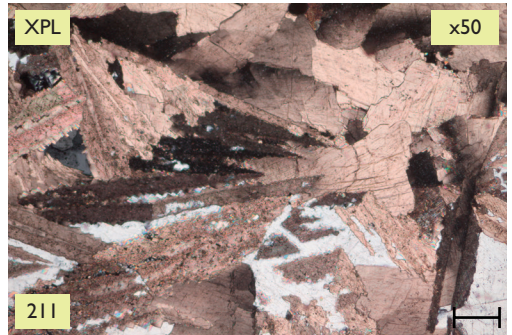
(5a)

CALCITE



Calcite in marble; Troms, Norway.

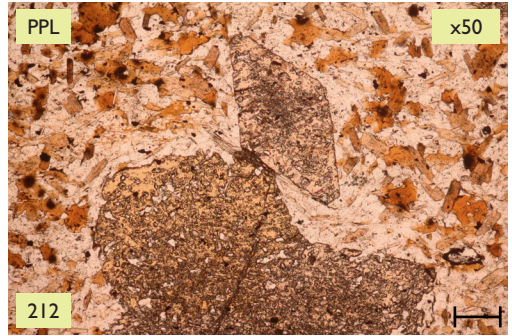
RHODOCHROSITE



Rhodochrosite in vein; Sri Lanka.

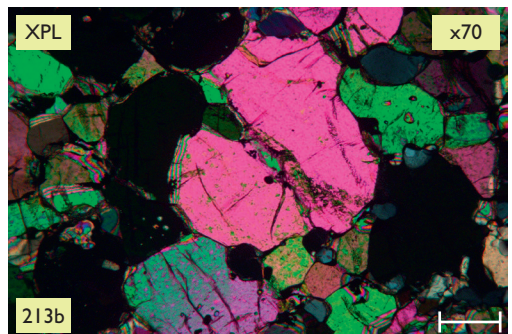
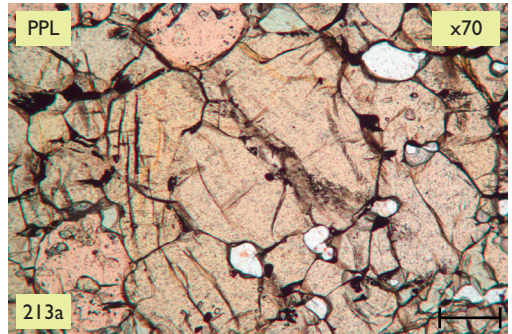
- | | |
|--|----|
| Relief stays constant on rotation; generally 1 st to 4 th order interf. colours. | 2 |
| 2 High relief | 3 |
| Low or moderate relief | 20 |
| 3 Pleochroic | 4 |
| Non-pleochroic | 10 |

- 4 C'less to yell. or pale yell. to bright yell., or pale yell. to orange-brn. 5
 Pleochr. is green, blue-grn., brown or purple. 8
- 5 1st ord. yell./orange interf. colours ($\delta = 0.011-0.014$); metapelites (often porphyroblasts). Colourless to yellow pleochroism. **STAUROLITE**



Staurolite in stt-bt-schist; Nauyago, Ghana.

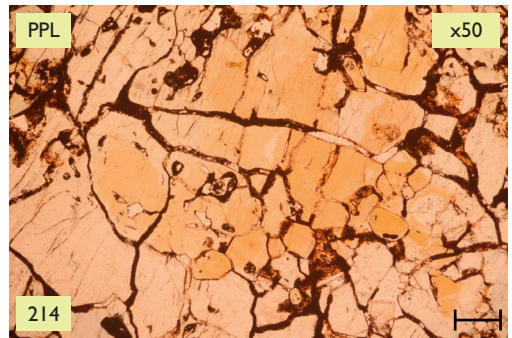
- Higher than 1st ord. yell./orange interf. colours. 6
- 6 2nd order interf. colours. 7
 3rd order bordering 4th ord. interf. colours (yellow-peach to pale pink) ($\delta = 0.052$). C'less to pale yellow pleochroism. **FAYALITE**



Fayalite in various orientations, showing weak pleochroism in pale yellows (213a), with garnet, (isotropic) apatite and rare hedenbergite (213b) in eulysite (a meta-ironstone); Tunaberg, Södermanland, Sweden (photos courtesy of Giles Droop).

- 7 Max. low to mid 2nd ord. interf. colours (bright blue to bright green) ($\delta = 0.021-0.029$). C'less to yellow pleochroism. Uniaxial +ve interf. figure.

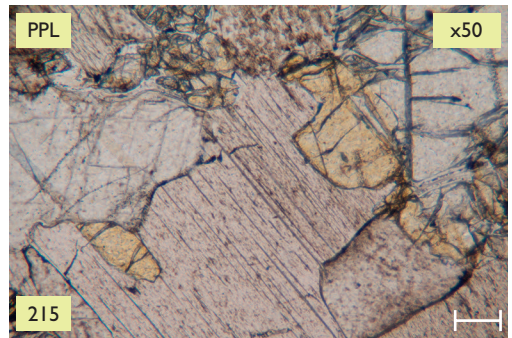
TOURMALINE (Dravite)



Tourmaline (Dravite); locality unknown.

- Mid to upper 2nd ord. interf. colours ($\delta = 0.028-0.037$). C'less to pale yellow or golden yellow (sometimes yell.-grn.) pleochroism. Biaxial +ve interf. figure. Calc-silicate rocks (skarns).

HUMITE Gp. (e.g Chondrodite, Clinohumite)



Clinohumite in mineralised skarn; Ottawa, Canada.

- 8 Spectacular purple to brown pleochroism.

YODERITE

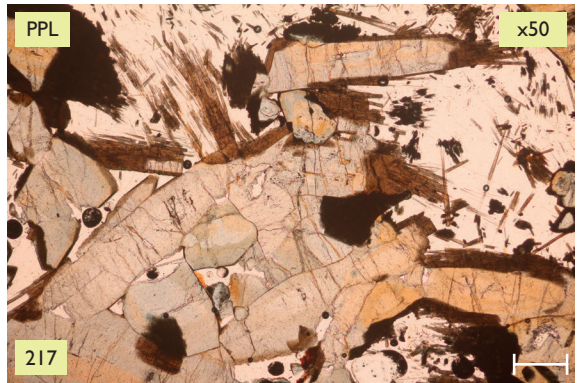


Yoderite in yoderite-tlc-qtz schist; Mpwapwa, Tanzania.

Not purple to brown pleochroism.

9 Green to blue-grn. or grn. to yell.-grn. pleochr. **TOURMALINE (Schorlite)**

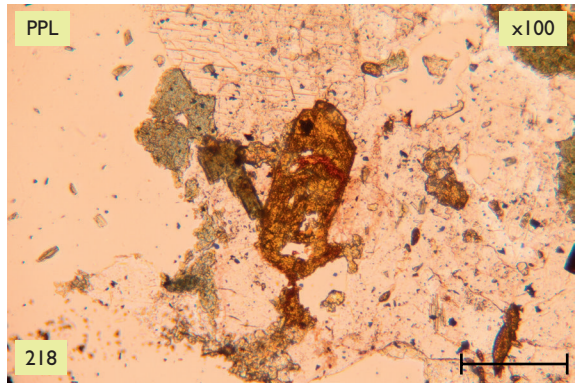
Tourmaline (end and side sections) in quartz-tourmaline rock; Roche, Cornwall, England.



Pale brown to brown pleochroism:

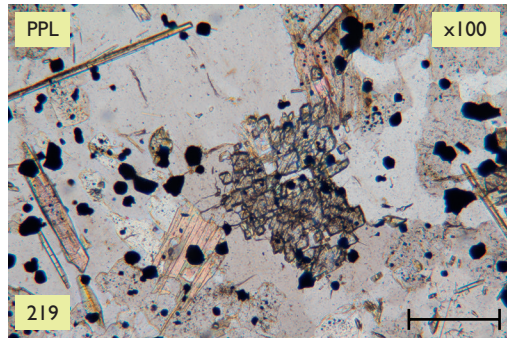
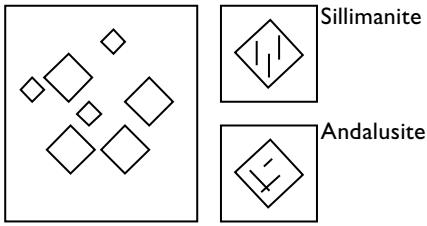
ALLANITE (= ORTHITE)

Allanite in syenite; Ghana.



- | | | |
|----|--|----|
| 10 | Colourless | 11 |
| | Brown, yellow or yell.-brn; v.high relief. | 19 |
| 11 | 1 st order to low 2 nd order interference colours | 12 |
| | Mid 2 nd order interference colours or higher | 18 |
| 12 | 1 st order grey/white interf. colours (and/or anomalous purplish/blue). | 13 |
| | Higher than 1 st order grey/white interf. colours | 15 |

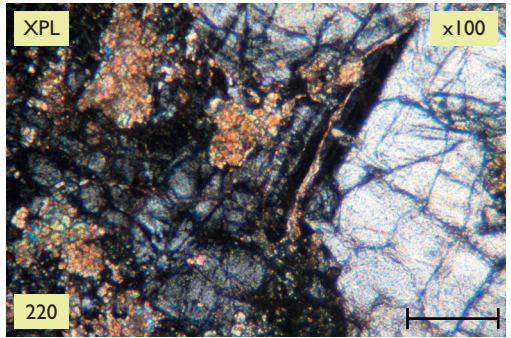
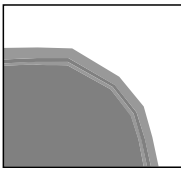
- 13 Small squares (b) often clustered together (schist, pelitic hornfels). 1st order grey.
SILLIMANITE (■) (or poorly formed **ANDALUSITE**)



(5b)
 Sillimanite (end-sections) in sil-bt-hornfels; Aberdeenshire, Scotland.

Polygonal, rectangular or anhedral crystals. 1st order grey/white or anomalous berlin blue interf. colours. Often zoned. 14

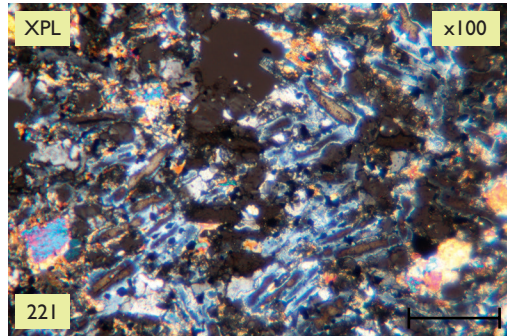
- 14 Polygonal or anhedral crystals, often with concentric zoning (5c). High relief (RI= 1.70-1.75) (calc-silicate/skarn):
VESUVIANITE (=IDOCRASE)



(5c)
 Vesuvianite (=idocrase) in calc-silicate skarn of contact metamorphism; Loch Auvre, Donegal, Ireland.

Note: Ca-garnets (e.g. grossular) are often anisotropic and show similar concentric zoning.

Rectangular crystals with straight extinction, and commonly with a central dark band/line in XPL. Mod/High relief (RI = 1.62-1.66). **MELILITE**

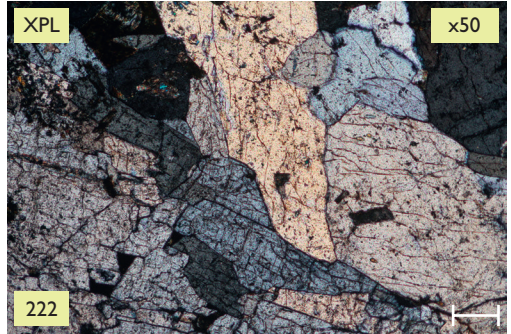


Melilite in vananzite (an undersaturated igneous rock); San Venanzo, Italy.

- 15 1st order straw yellow interf. colours. May show weak c'less to pale mauve/violet pleochr. in thick sections. (Contact metamorphic calc-silicate rocks and granite pegmatites).

AXINITE

Axinite in altered dolerite near granite intrusion; St.Columb Road, Cornwall, England.

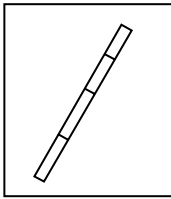


Max. upper 1st order or low 2nd order interference colours.

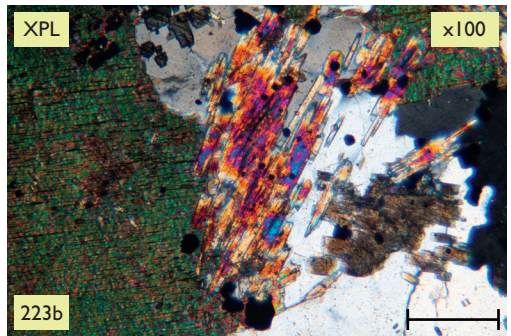
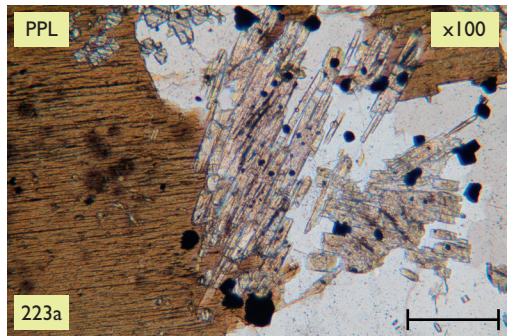
16

- 16 Rodded crystals with cross-fractures giving a “bamboo-like” appearance (5d) ($\delta = 0.018-0.022$).

SILLIMANITE



(5d)



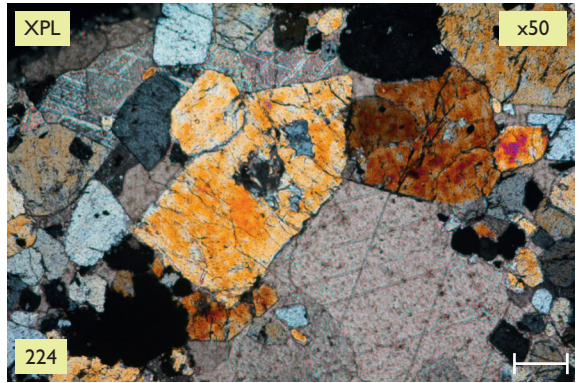
Sillimanite rods in sil-bt-hornfels (also note cluster of square end-sections top left); Weets, Grampian, Scotland.

Anhedral granular crystals or subhedral prismatic crystals.

17

17 1 imperfect parting (max.1st order red interf. colours).

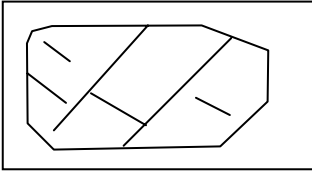
MONTICELLITE



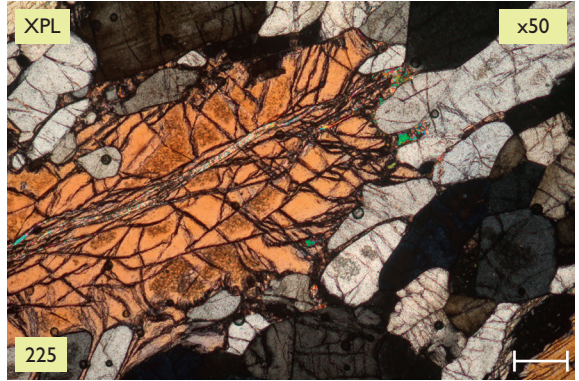
Monticellite in monticellite-magnetite skarn; Camas Malag, Skye, Scotland.

2 parting traces at 75-80° (e) (twinning common).

CORUNDUM



(5e)

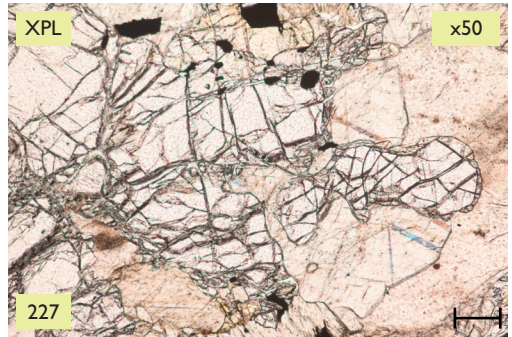
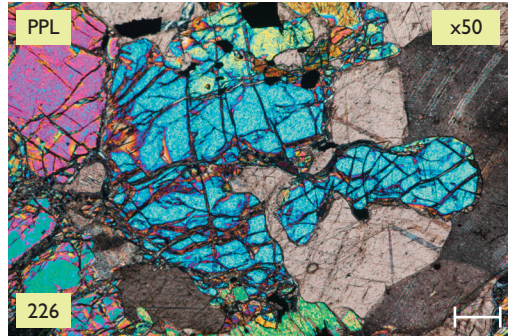


Corundum (with alteration to margarite along cracks) in anyolite (zoisite-edenitic hornblende-corundum(ruby) rock); Arusha region, Tanzania (see start of Section 5 for an enlargement of this image).

(Note: Corundum should be mid 1st order birefr. ($\delta = 0.008-0.009$) for 30 μ m thin-section, but extreme mineral hardness means that it is often thick, and thus gives interf. colours to low 2nd order)

18 Max. upper 2nd ord. interf. colours:

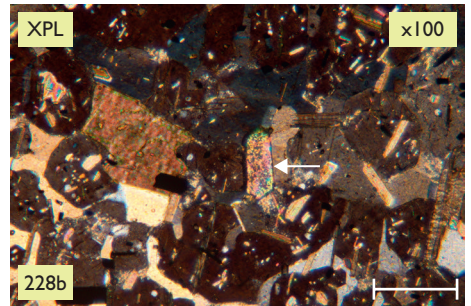
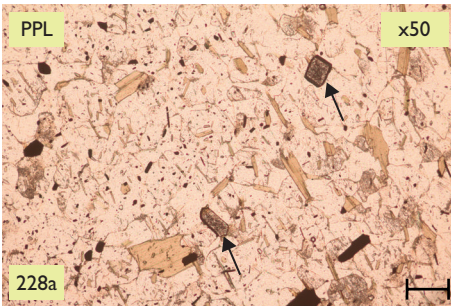
OLIVINE (Forsterite)



Olivine (forsterite) in contact metamorphosed olivine marble; Ottawa, Canada.

3rd/4th order interf. colours (in granite pegmatites and as detrital grains in sedimentary and metasedimentary rocks).

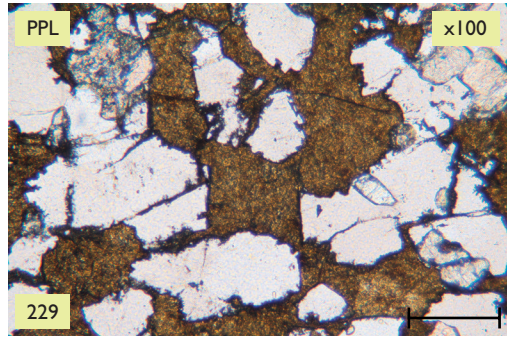
MONAZITE



Monazite (arrowed) in Crd-Bt-Qtz-Ilm metasedimentary rock; locality unknown.

19 Isotropic

SPHALERITE

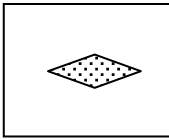


Sphalerite in Zn-mineralised quartz-rich host rock; Zinkgruvan, Sweden.

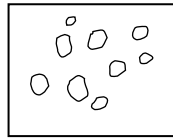
Note: Certain coloured garnets (e.g. spessartine) are also yellow-brown and isotropic, but don't really have arranged fractures (see Section 7).

High ord. interf colours; diamond-shape (5f), or granular (5g).

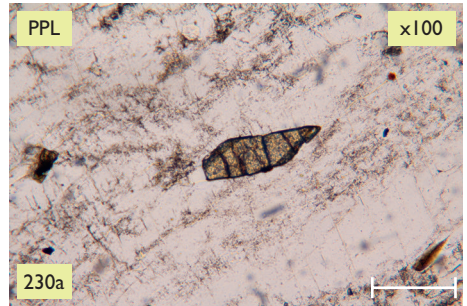
TITANITE (=Sphene)



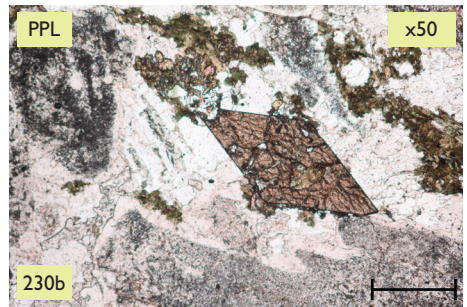
(5f)



(5g)



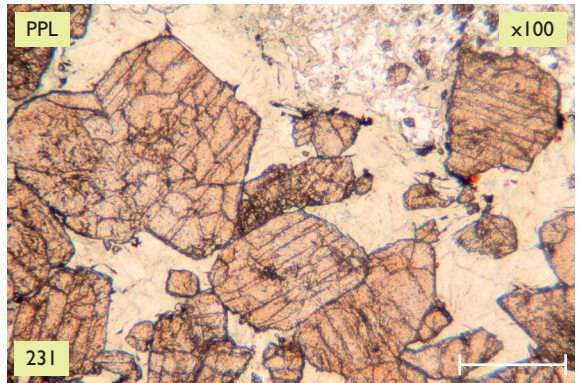
(a) Titanite (=sphene) in augen gneiss; Bettyhill, Tongue, Scotland.



(b) Euhedral (diamond-shaped) titanite in granite; locality unknown.

Note: Much rarer, cassiterite (Sn-ore mineral) is also a very high relief brown mineral with high interference colours. It has polygonal to short prismatic form (see image 231, top of next page, and images 296a-b).

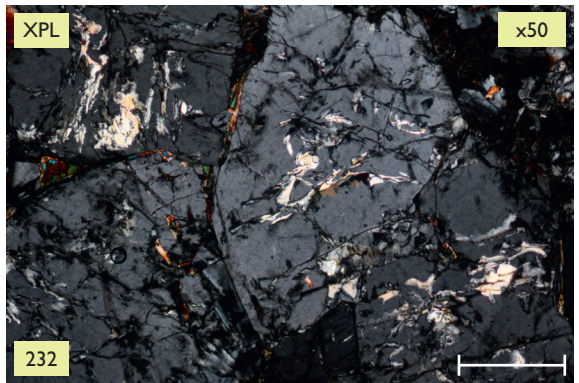
CASSITERITE



Cassiterite in cassiterite-rich vein rock within granite; East Pool and Agar Mine, Cornwall, England (also see image 296a–b).

20 Moderate relief.
Low relief (1st order grey/white interf. colours).

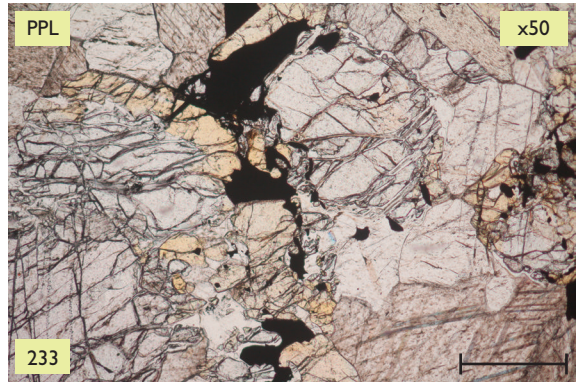
21
NEPHELINE



Nepheline in nephelinite; Bohemia, Czech Republic.

- 21 Yellow pleochroic (c'less to pale yellow, golden yellow, yell./brn. or orange-yellow). Towards the high end of moderate relief.

HUMITE Gp. (e.g. Chondrodite, Clinohumite)



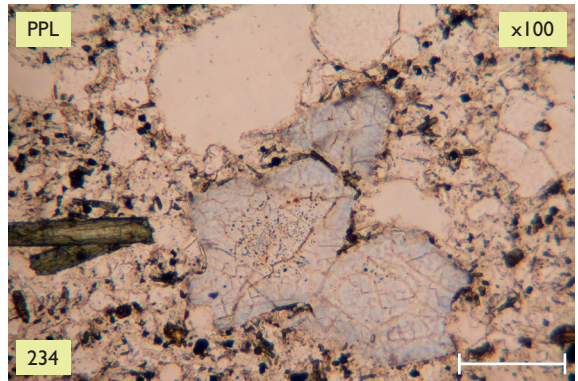
Chondrodite in mineralised skarn; Ottawa, Canada

Non-pleochroic

22

- 22 Isotropic (colourless or pale blue).

SODALITE/ NOSEAN/ HAÜYNE



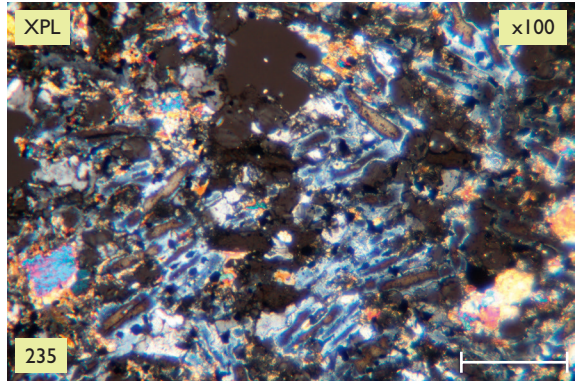
Häuyne in leucite tephrite; Tavolato, Rome, Italy.

1st order grey (or anomalous Berlin blue interf. colours)

23

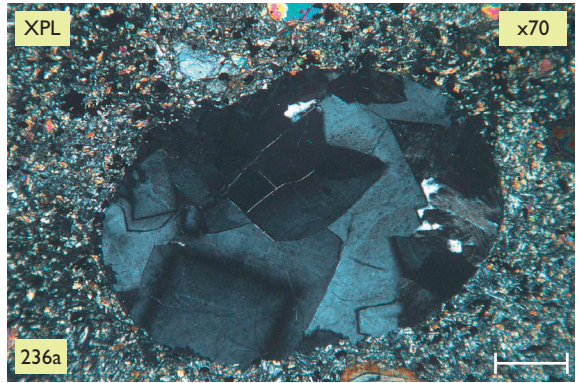
- 23 Straight extinction, commonly with a central dark band/line in XPL (often shows anomalous Berlin blue interference colours). **MELILITE**

Melilite in vananzite (an under-saturated igneous rock); San Venanzo, Italy.

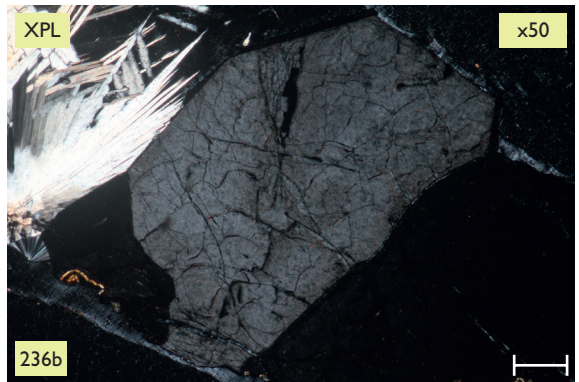


Symmetrical extinction (relative to clv./parting traces). **CHABAZITE**

(236a) Chabazite-filled amygdale within basalt; Réunion Island (photo courtesy of Giles Droop).

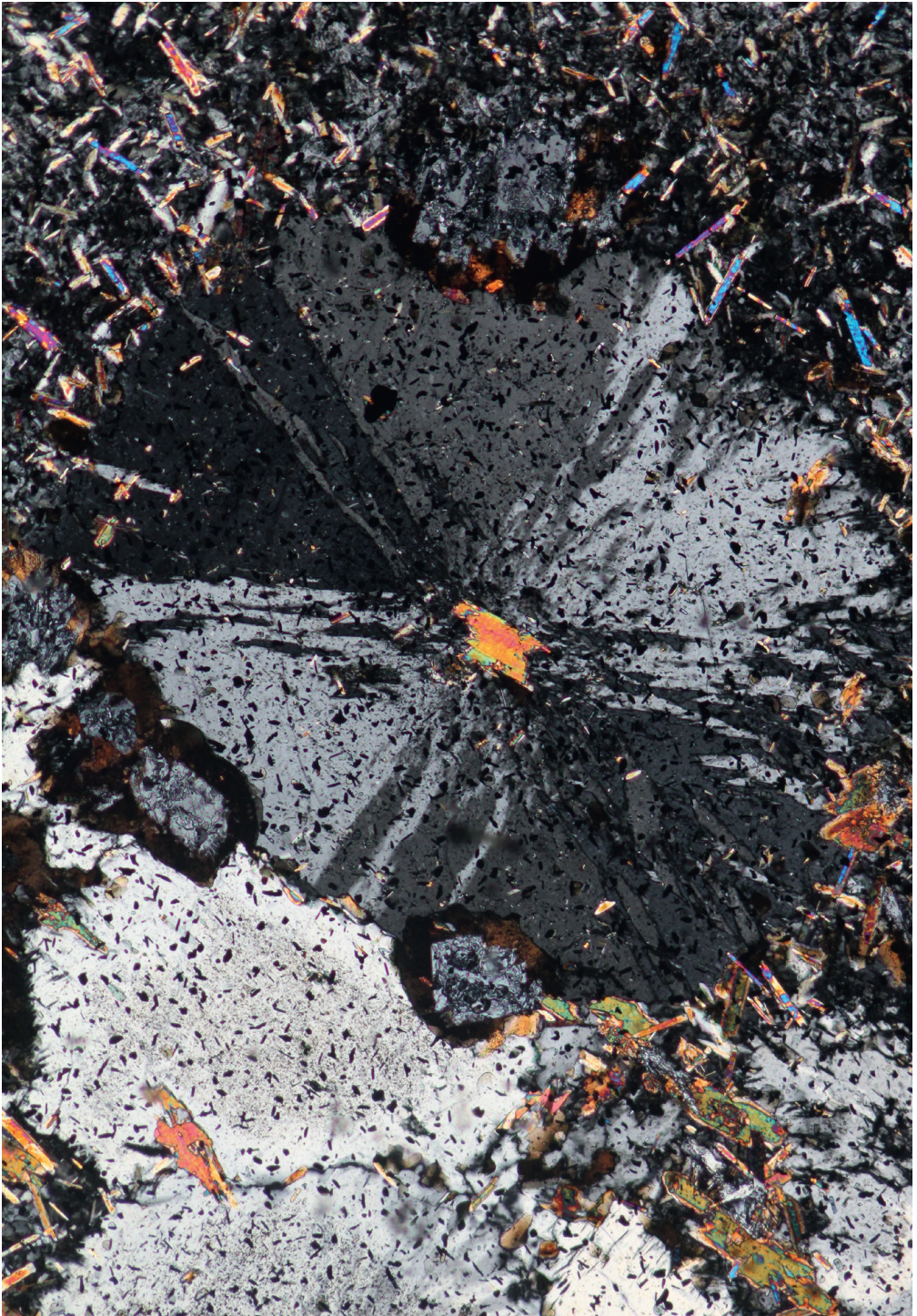


(236b) Chabazite showing perfect rhombohedral form due to unimpeded growth from vesicle wall; Talisker Bay, Skye, Scotland.



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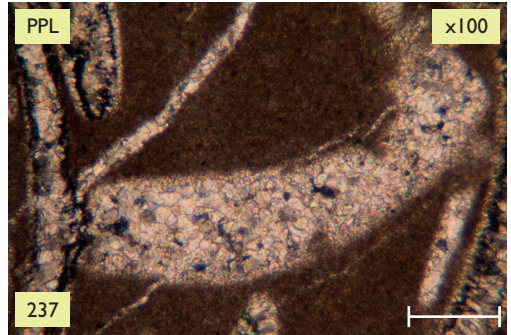
0 Cleavage traces, colourless



- 1 Relief varies on rotation (very high order interf. colours, granular).

CALCITE, DOLOMITE or ARAGONITE (...)

Note: microcrystalline calcite (grains $5\mu\text{m}$), of sedimentary rocks is termed MICRITE.



Granular calcite (micrite) in biomicritic limestone; Purbeck, Dorset, England.

Relief stays constant on rotation.

2

- 2 **HIGH RELIEF**

3

Low or moderate relief

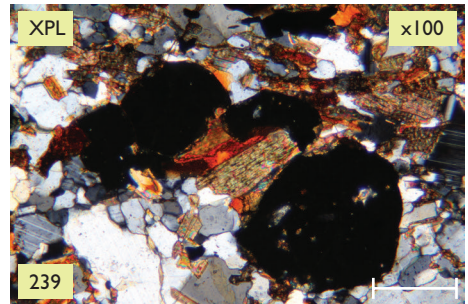
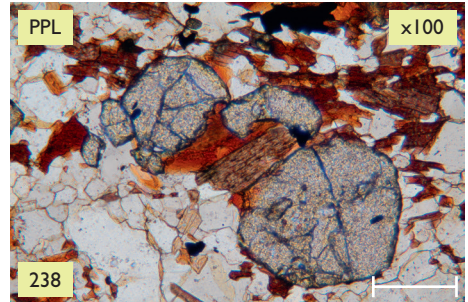
14

- 3 **Isotropic:**

GARNET

[Almandine (Fe), Pyrope (Mg), Spessartine (Mn), Grossular (Ca)]

Note: Although largely colourless in thin-section, some garnets may show colouration (see Section 7). Almandine (pale pink); Ti-andradites (pale yell-brn.-brn.), Uvarovite (green). Note: Grossular commonly shows a degree of anisotropy, with zoning picked out by variations in 1st order grey interf. colours.



Garnet (almandine-rich) in regional metamorphic garnet mica-schist; Garve, Scotland.

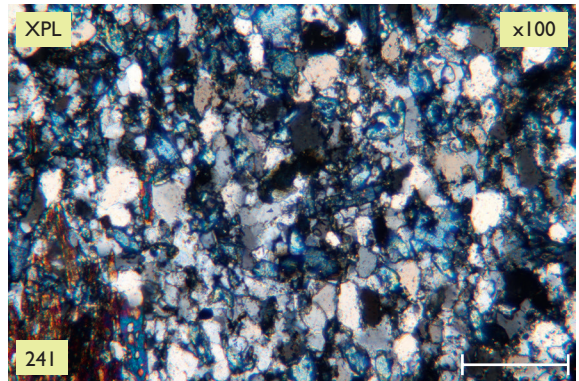
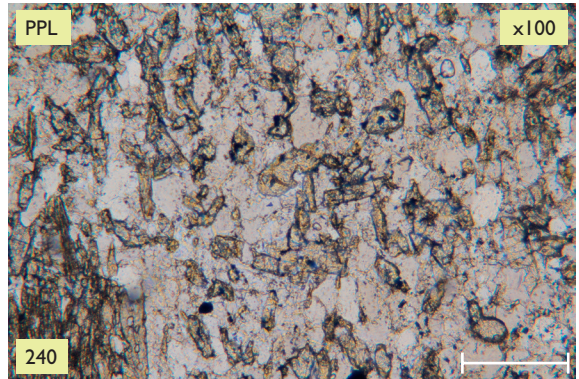
Anisotropic

4

- 4 1st order grey/white (or anomalous Berlin blue interf. colours). 5
Higher than 1st order grey interf. colours. 7

1st order grey/white (or anomalous Berlin blue) interference colours.

- 5 Biaxial +ve, // extinction, often shows anomalous Berlin blue interf. **ZOISITE**



Zoisite in qtz-zo-grt-hbl hornfels; Foxdale, Isle of Man.

Uniaxial -ve interference figure, // extinction.

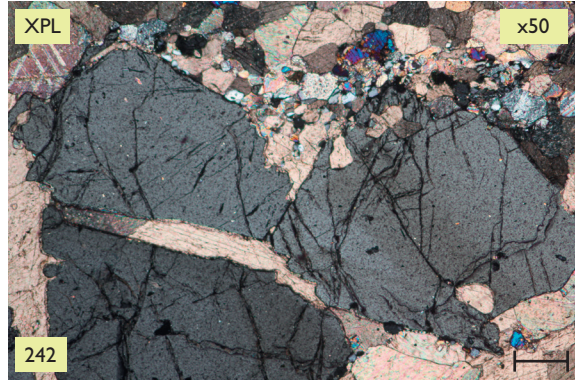
6

- 6 Often shows chemical (optical) zonation (see 5c). Calc-silicate rocks.

VESUVIANITE (= Idocrase)

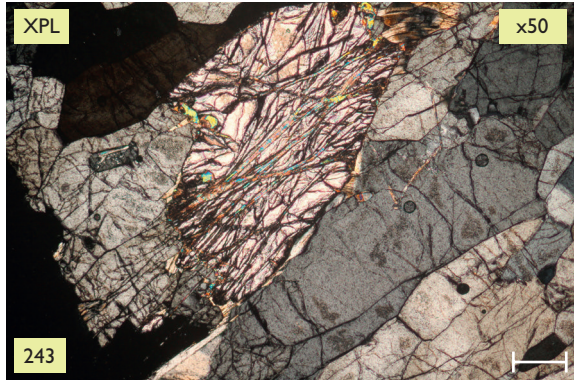
Note: Grossular and other Ca-garnets can be anisotropic with low 1st ord. birefringence, and thus difficult to distinguish from vesuvianite.

Vesuvianite (=idocrase) in marble; Loch Auvre, Donegal, Ireland.



Not chemically zoned. May show lamellar twinning. Al-rich, Si-poor rocks. Mostly uniaxial -ve, but some figures are biaxial 0-30°.

CORUNDUM



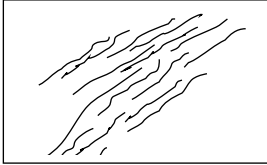
Corundum in anyolite (zoisite-edenicite hornblende-corundum(ruby) rock); Arusha region, Tanzania.

- 7 1st order yellow-orange interference colours. 8
Higher than 1st order yell./orange interf. colours. 11

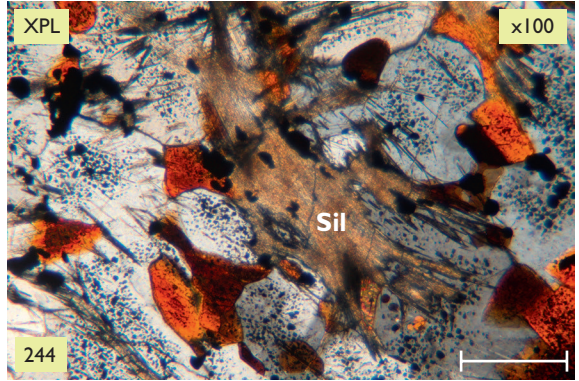
1st order yellow/orange interference colours

- 8 Pelitic rock or Al-rich silica-poor rock. 9
Calc-silicate rock or mafic rock. 10
- 9 Fibrous or hair-like mat of crystals (6a), // extinction (metapelite)

FIBROLITE (fibrous SILLIMANITE)



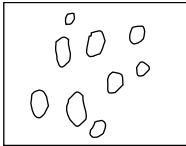
(6a)



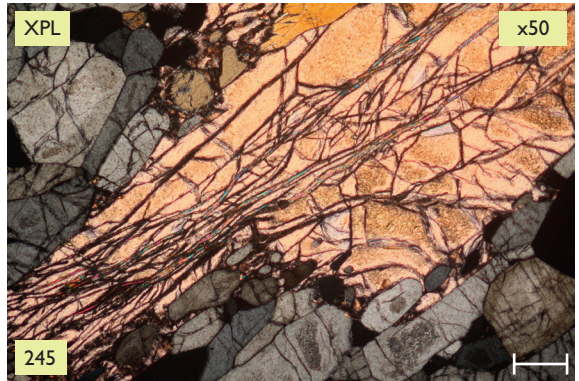
Sillimanite (fibrolite) in sillimanite schist; La Hoya, Spain.

Granular (6b) or porphyroblastic, // extinction, very high relief.

CORUNDUM



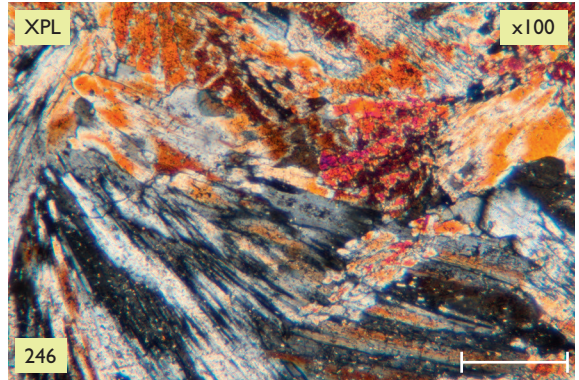
(6b)



Corundum in anyolite (zoisite-edenitic hornblende-corundum (ruby) rock); Arusha region, Tanzania.

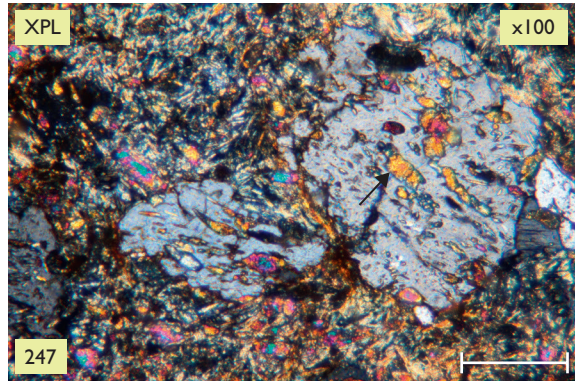
- 10 Biaxial -ve, // ext. (most sections); high-T calc-silicate rocks/skarns. Med to high relief. **WOLLASTONITE**

Wollastonite in calc-silicate rock in the contact aureole of the Dartmoor Granite; Meldon, Devon, England.



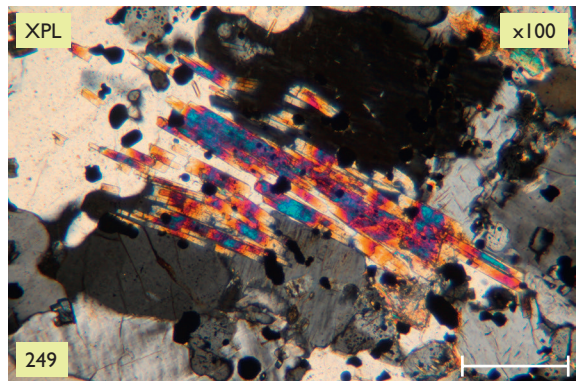
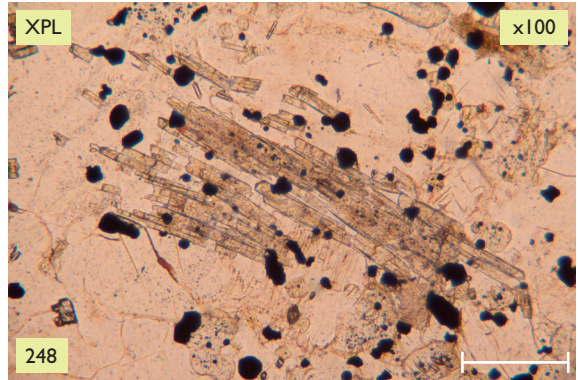
- Biaxial +ve, // ext. (length sections), calc-silicate and mafic rocks: **CLINOZOISITE**

Clinzoisite in albite of ab-act-chl-clz hornfels; Donegal, Ireland.



Top 1st order and low 2nd order interference colours

- 11 Top 1st order and low second order interf. colours. 12
 Mid second order or higher interf. colours. 13
- 12 Acicular or rodded (“bamboo cane”) appearance, // extinction. **SILLIMANITE**



Sillimanite showing rodded “bamboo-like” appearance in kfs-sil-bt hornfels; Weets, Grampian, Scotland.

Small granules (6b), // extinction, very high relief.

CORUNDUM

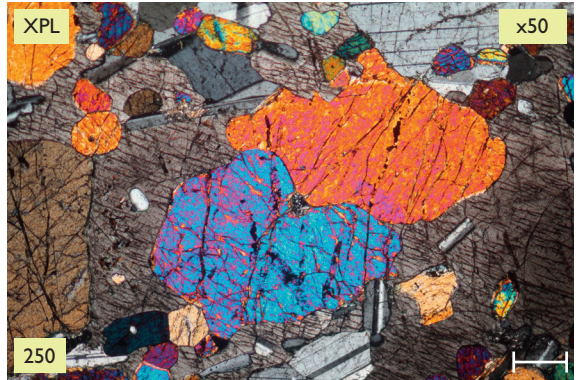
Note: Corundum should be mid 1st order birefr. for 30 μ m thin-section, but extreme mineral hardness means that it is often thick, and thus gives interference colours to low 2nd order.

Max. interference colours mid 2nd order or higher

13 Mid to upper 2nd order interference colours:

OLIVINE (Forsterite)

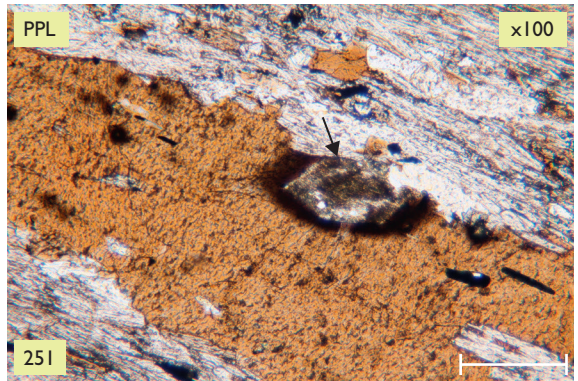
Olivine (forsterite) in gabbro cumulate; Duluth, Minnesota, USA.



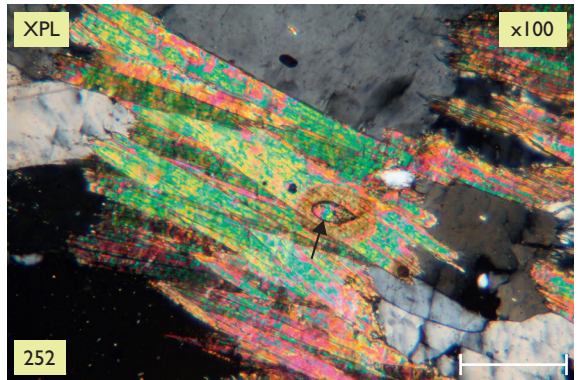
3rd/4th order interf. colours:

ZIRCON/ MONAZITE

Zircon inclusion with well developed pleochroic halo in biotite of garnet mica-schist. Although this is an exceptionally well-formed and relatively large zircon, small zircon grains with dark pleochroic haloes giving a “mouldy” appearance to the phyllosilicate mineral are commonplace in biotites and chlorites (also see Image 313a). The haloes are considered to result from decay of radioactive elements within the zircon; Gratangenfjord, Troms, Norway.



Zircon inclusion in biotite showing 3rd order interference colours and a faint pleochroic halo in the surrounding biotite; kyanite gneiss from Loch Assapol, Mull, Scotland.



LOW OR MODERATE RELIEF

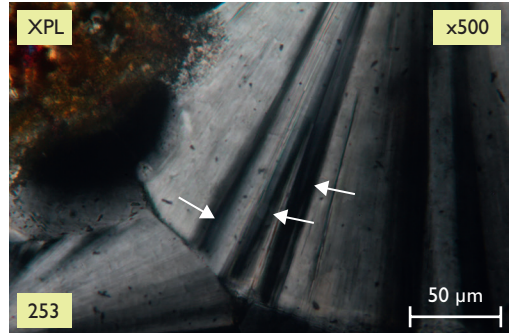
- 14 Moderate relief 15
Low relief 26

MODERATE RELIEF

- 15 Isotropic or v.dark to mid grey 1st order interf. colours (close to isotropic);
 $\delta = 0.000-0.004$. 16
1st order mid grey/white, or higher order birefringence 20
- 16 Fibrous or acicular form (6a): **ZEOLITE Gp. (e.g. MESOLITE)**

Note: Mod. -ve relief, bordering on low -ve relief; RI = 1.505-1.512; $\delta = 0.001$.

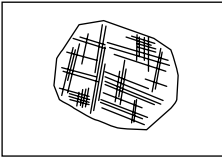
Mesolite needles (1st order very dark grey $\delta = 0.001$), interspersed amongst radiating needles of thomsonite/natrolite (1st order light grey to white) as part of vesicle infill, in amygdaloidal basalt; Spray, Oregon, USA.



Not fibrous/acicular

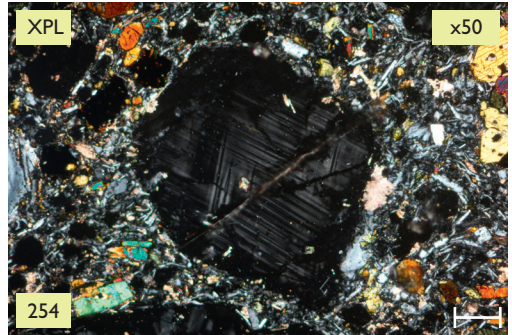
17

- 17 Complex cross-hatched twinning (6c). Hexagonal, or trapezohedral shape; RI = 1.508-1.511, therefore bordering low/mod -ve relief; $\delta = 0.001$. **LEUCITE**



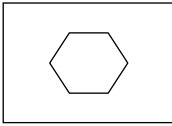
(6c)

Leucite in leucite tephrite; Vesuvius, Italy.



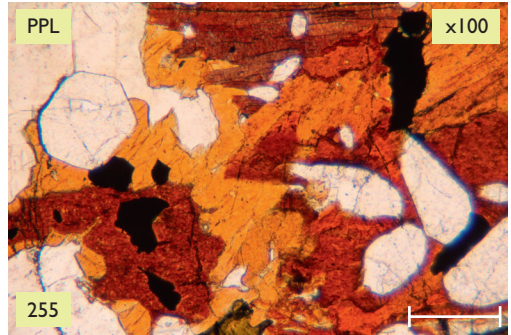
Lacks cross-hatched twinning. May be rounded, hexagonal, trapezohedral or short rods/prisms. 18

- 18 “Bright” relative to other colourless minerals; hexagon (6d)/granular/short rod/prism). Med. to high relief (RI = 1.63–1.655); $\delta = 0.001\text{--}0.007$. **APATITE**



(6d)

Apatite in Larvikite; Dalheim, Larvik, Norway.

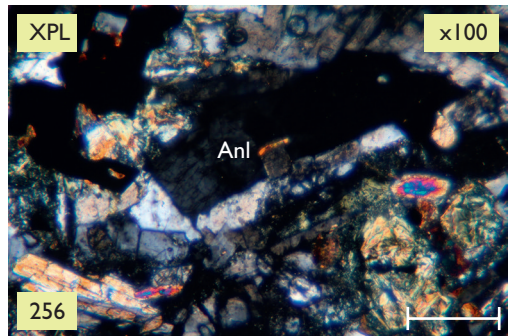


Dull or no different from other c'less minerals.

19

- 19 Isotropic (cubic system), but some crystals are weakly anisotropic $\delta = 0.000\text{--}0.001$. Trapezohedral, hexagonal or granular. May show lamellar twinning. Mafic rock: vesicle-fill or interstitial. **ANALCITE**

Analcite in teschenite; Salisbury Crags, Edinburgh, Scotland.



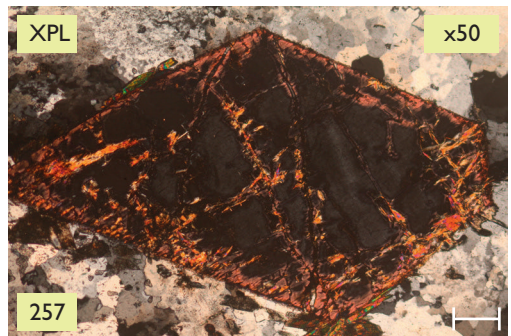
Anisotropic (δ generally >0.002). Hexagonal crystals or prisms/rods. Uniaxial interference figure. Granite/granite pegmatite.

Uniaxial -ve ($\delta = 0.004\text{--}0.009$)

Uniaxial +ve ($\delta = 0.000\text{--}0.010$)

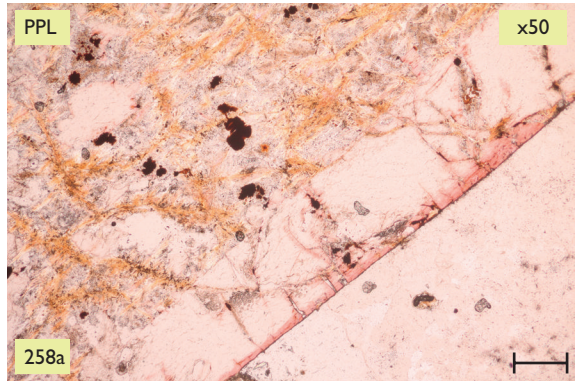
BERYL (■)
EUDIALYTE (■)

Eudialyte phenocryst in alkali granite; Mt. Yukspor, Kola, Russia.

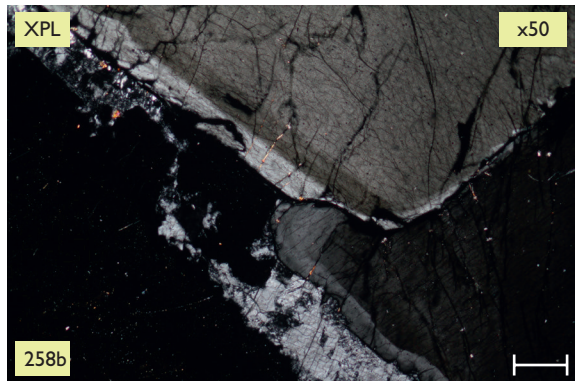


- 20 1st order grey/white to yellow/orange ($\delta = 0.004\text{--}0.015$) interf. colours. 21
 2nd or 3rd ord. interf. colours; $\delta > 0.020$. 24
- 21 Prismatic or columnar crystals in granites or granite pegmatites (usually isolated individual crystals). 22
 Fibrous/acicular or very elongate blades (aggregates); mafic rocks, vesicle fill, or high-T calc-silicate skarns of contact metamorphism. 23
- 22 Max. 1st order white. **EUDIALYTE(■), or BERYL(■)**

(258a) Eudialyte phenocryst in alkali granite; Mt. Yukspor, Kola, Russia;



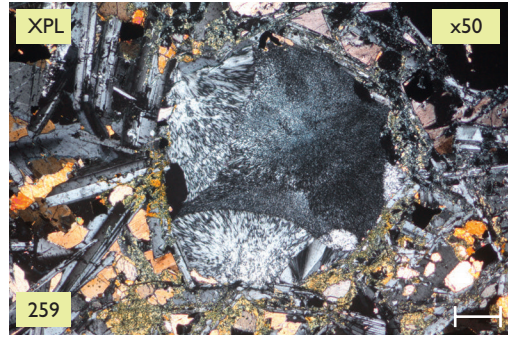
(258b) Eudialyte in sodalite-bearing syenite; Greenland.



Max. 1st order yellow.

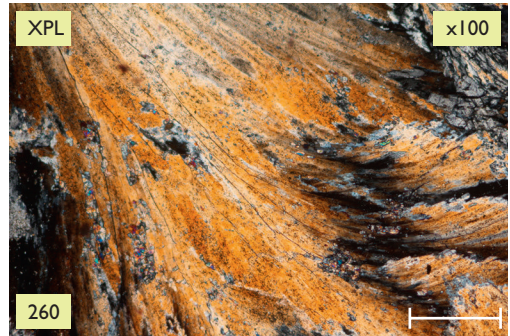
TOPAZ(■)

- 23 Fibrous/acicular (mafic rock, vesicle-fill or interstitial). Grey to 1st ord. yell. max. interf. colours.
ZEOLITE (eg Natrolite, Laumontite)



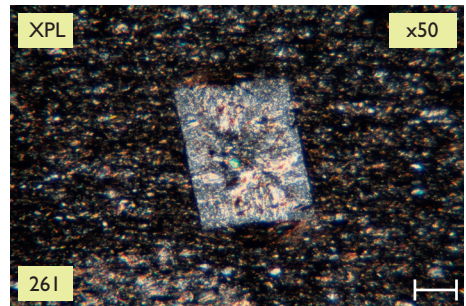
Zeolite amygdale in Tertiary dolerite dyke; Croagh Patrick, Mayo, Ireland.

- Acicular/elongate rods/blades. (Calc-silicate rocks, high T metamorphism) 1st ord. yell./orange $\delta = 0.014-0.015$.
WOLLASTONITE



Wollastonite in calc-silicate rock in the contact aureole of the Dartmoor Granite; Meldon, Devon, England. Note the N-S oriented crystals (left) and E-W oriented crystals (centre right) showing straight extinction.

- 24 Low 2nd ord. (bright blue to blue-grn.) interf. colours; $\delta = 0.021-0.025$
ILLITE, SMECTITE (Clay minerals) or GIBBSITE

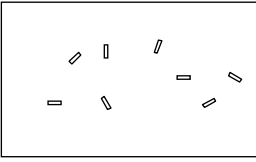


Andalusite porphyroblast pseudomorphed to an aggregate of clay minerals and sericite in andalusite slate; contact aureole of Skiddaw Granite, Lake District, England.

Note: True birefringence for these minerals is usually higher (illite $\delta = 0.030$; smectite $\delta = 0.010-0.040$), but thin crystals ($< 30 \mu\text{m}$) in fine grained aggregates will give lower interference colours. X-ray diffraction will be needed to confidently identify the clay minerals (and other minerals) present in such fine grained assemblages. Gibbsite is a common mineral in laterites and bauxite.

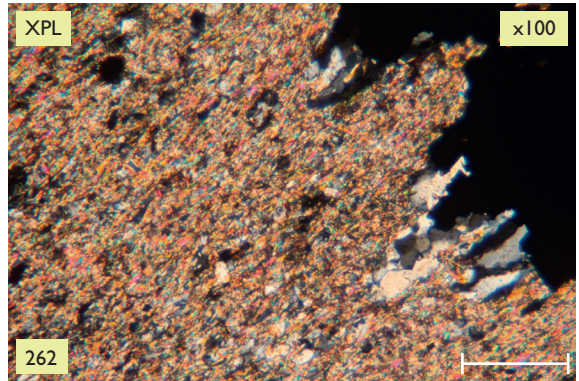
- Mid 2nd ord. (yellow) to low 3rd ord. (blue) interf. colours; $\delta = 0.026-0.040$. 25

25 Laths (or may seem nearly acicular if fine) (6e)

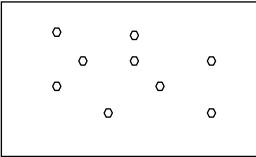
MUSCOVITE**(6e)**

Muscovite (fine-grained indistinct cleavage) in pyrite slate; locality unknown.

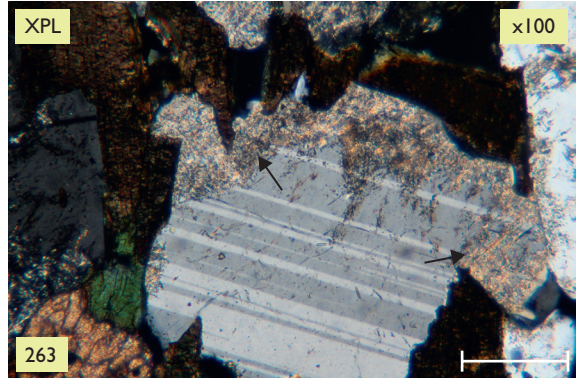
Note: In fine-grained aggregates the optical properties needed to enable distinction between muscovite, paragonite and pyrophyllite will probably not be present. Muscovite is the commonest of these three minerals. It is advisable to use X-ray diffraction techniques, scanning-electron microscopy or an electron microprobe to confirm the identity of minerals in fine-grained aggregates.



Minutely crystalline fine-grained aggregate (alteration product) (6f).

SERICITE (or Illite)**(6f)**

Sericite alteration arrowed of plagioclase giving a fine “dusting” across the feldspar in augen gneiss; Bettyhill, Tongue, Scotland.

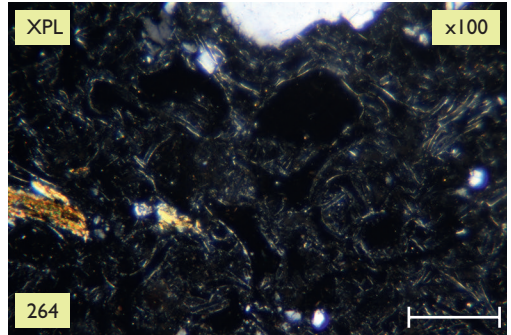


LOW RELIEF

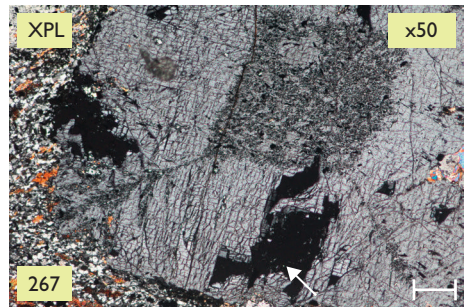
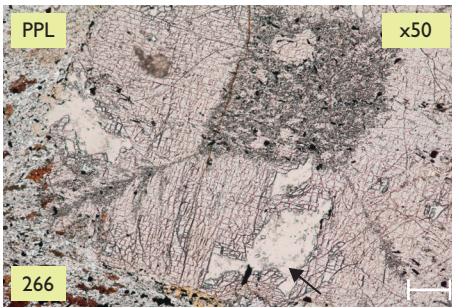
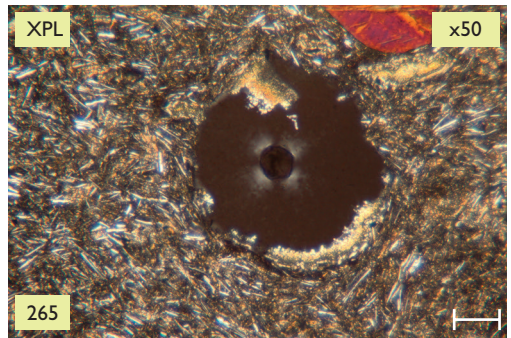
26 Isotropic:

VOLCANIC GLASS (or hole in slide!)

Volcanic glass shards in Miocene ignimbrite; Bonifacio, Corsica, France.



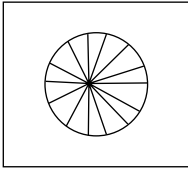
Vesicle in boninite; Japan.



Hole in slide (arrowed) where a small fragment of andalusite has been plucked out during the thin-section making process. Andalusite (end-section) in crd-and slate; Connemara, Ireland.

Non-isotropic

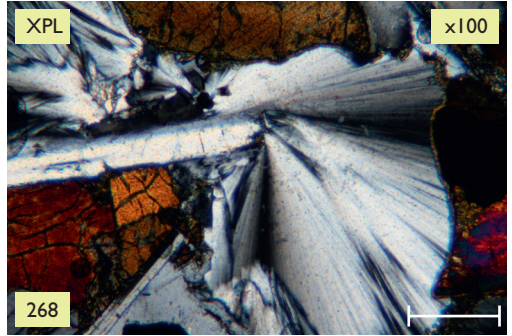
- | | | |
|----|--|----|
| 27 | 1 st order dk.grey/grey/white interf. colours | 28 |
| | 1 st order yellow/orange interf. colours | 38 |
| 28 | Fibrous/acicular crystals (6a, 4c), or thin blades; often radiating. | 29 |
| | Not fibrous/acicular or thin blades. | 30 |
| 29 | Vesicle fill or cavity fill (6g): | |



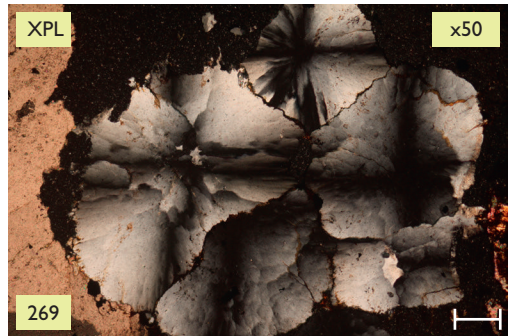
(6g)

Zeolite cavity-fill alteration after plagioclase in dolerite; Scawt, Antrim, N.Ireland.

ZEOLITE (eg Thomsonite)



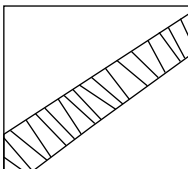
or CHALCEDONY



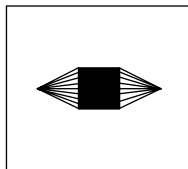
Chalcedony in basaltic andesite from lower pillow lavas; Troodos Ophiolite, Cyprus.

Vein mineral (6h) or in strain shadow (6i) (low T metamorphic conditions):

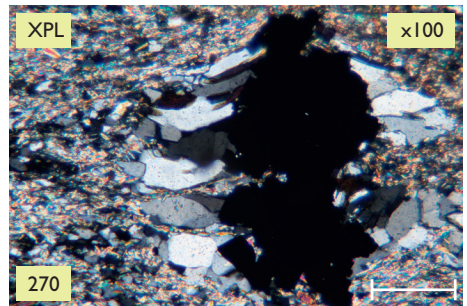
fibrous QUARTZ



(6h)



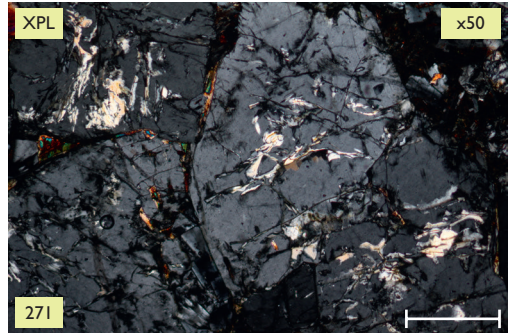
(6i)



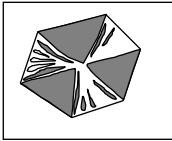
Fibrous quartz in strain shadow of pyrite crystals in pyrite slate; locality unknown.

- 30 Phenocryst, porphyroblast, porphyroclast or clast. 31
 Groundmass, matrix, inclusions, vein-fill, alteration product. 35
- 31 Rectangular (qtz-absent undersaturated Na-rich ig.rock). **NEPHELINE**

Nepheline in nephelinite; Bohemia, Czech Republic.

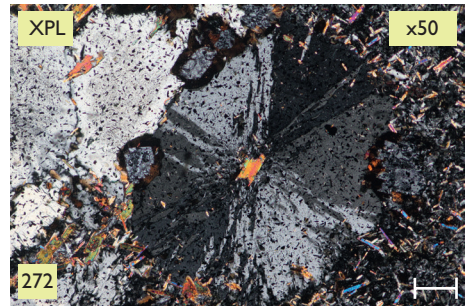


- Not rectangular 32
- 32 Sector-trilling/zoning or cross-hatched twinning. 33
 No sector trilling/zoning or cross-hatched twins. 34
- 33 Sector-trilling/sector zoning (6j). Max. interf. colours to 1st Order white or pale yellow ($\delta = 0.007-0.011$). **CORDIERITE**



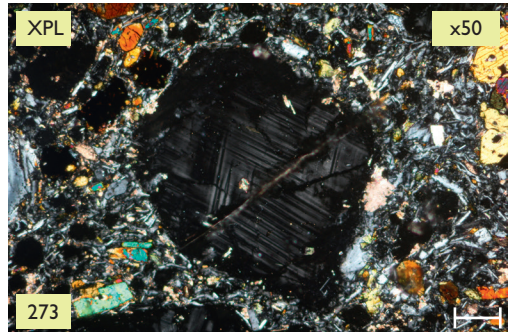
(6j)

Cordierite showing sector twinning in crd- and hornfels, Connemara, Ireland (see start of Section 6 for an enlargement of this image).



- Complex cross-hatched twinning (6c). 1st Ord. dk.grey interf. colours ($\delta = 0.001$). **LEUCITE**

Leucite in leucite tephrite; Vesuvius, Italy.



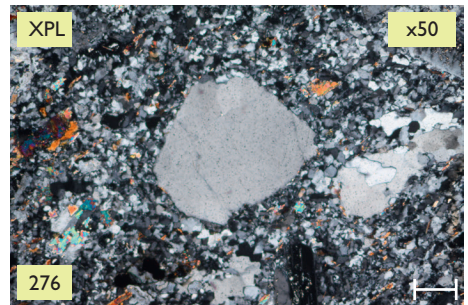
34 Biaxial, high 2V (abundant inclusions, altered). **PLAGIOCLASE(...)/CORDIERITE****Plagioclase (albite)**

Plagioclase with abundant clinozoisite inclusions in ab-czo-act mafic hornfels; locality unknown.

Cordierite

Cordierite in cordierite-andalusite hornfels, Connemara, Ireland.

Uniaxial +ve (no/few inclusions, no retrogression).

QUARTZ

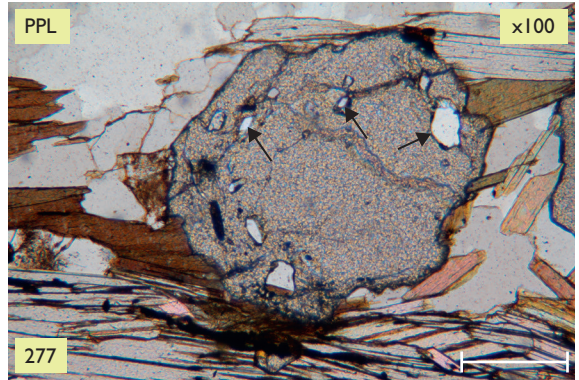
Quartz phenocryst in recrystallised felsic dyke/sill in the vicinity of Corvock Granite, S.Mayo, Ireland.

Note: Although plagioclase is a cleaved mineral, with biaxial interference figure, these characteristics are not always obvious in regional metamorphic rocks. Plagioclase formed in rocks with significant shear stress generally lack twinning or just show a simple twin. This makes it difficult to distinguish from cordierite and quartz. Abundant inclusions in both plagioclase and cordierite of many metamorphic rocks generally makes it impossible to obtain an interference figure. It is worth bearing in mind that quartz does not occur as porphyroblasts and that whilst both plagioclase and cordierite may show alteration to sericite, only plagioclase is likely to have abundant epidote/clinozoisite inclusions.

35 Inclusion:

QUARTZ

Low relief quartz inclusions (arrowed) in high relief garnet porphyroblast in garnet mica-schist; Ross of Mull, Scotland.



Not an inclusion:

36

36 Felted mass of fine platy crystals (6e, 6f).

KAOLINITE (clay)

Clay minerals (and sericite) forming a pseudomorph after andalusite porphyroblasts in chialstolite slate; Skiddaw Granite aureole, Lake District, England.

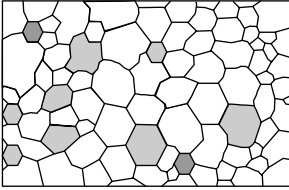


Granular, polygonal, or prismatic (rectangular or rhombic) crystals.

37

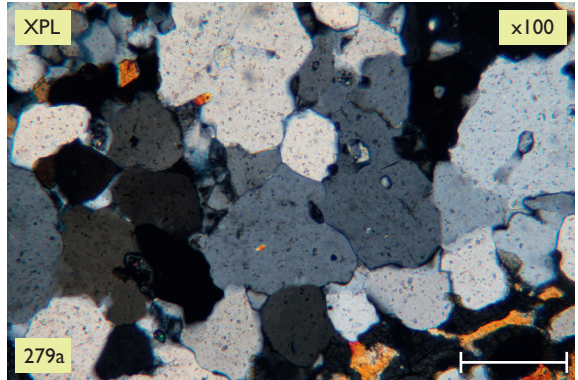
37 Granular (6b) or polygonal aggregate (6k) of largely equidimensional crystals.

QUARTZ

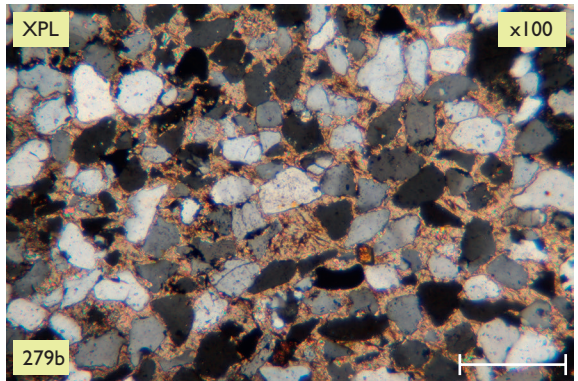


(6k)

(a) Polygonal aggregate of quartz in semi-pelitic schist; Mangkuma-Ketempe, Ghana.

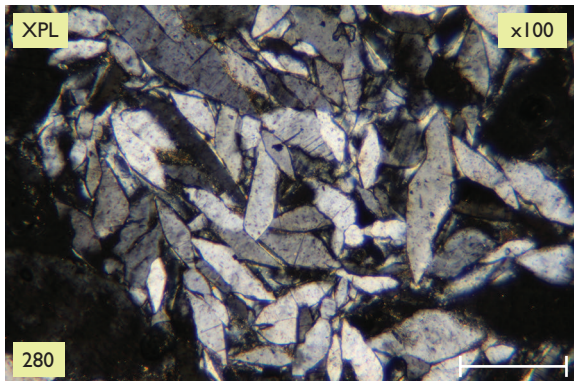


(b) Detrital quartz grains surrounded by a calcite cement in sandstone. Hook Quarry, West Hoathly, Sussex, England.



Prismatic (rectangular to rhombic/diamond-shaped) elongate crystals. **GYPSUM**

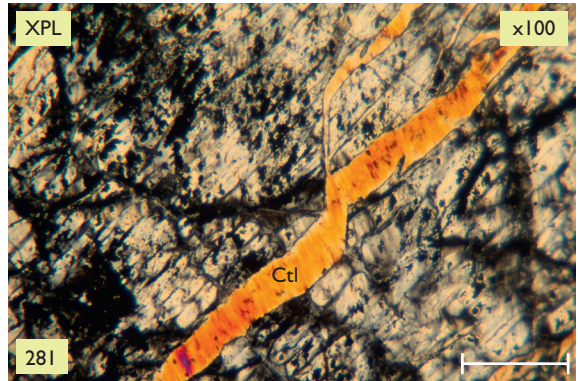
Gypsum in evaporite; Kirkby Thore, Cumbria, England.



38 Fibrous veinlets (ultramafic rock).

CHRYSOTILE

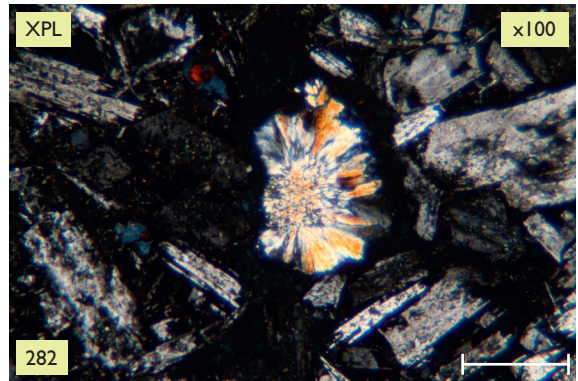
Serpentine (chrysotile) micro-veinlet in serpentinite; Ballantrae, Scotland.



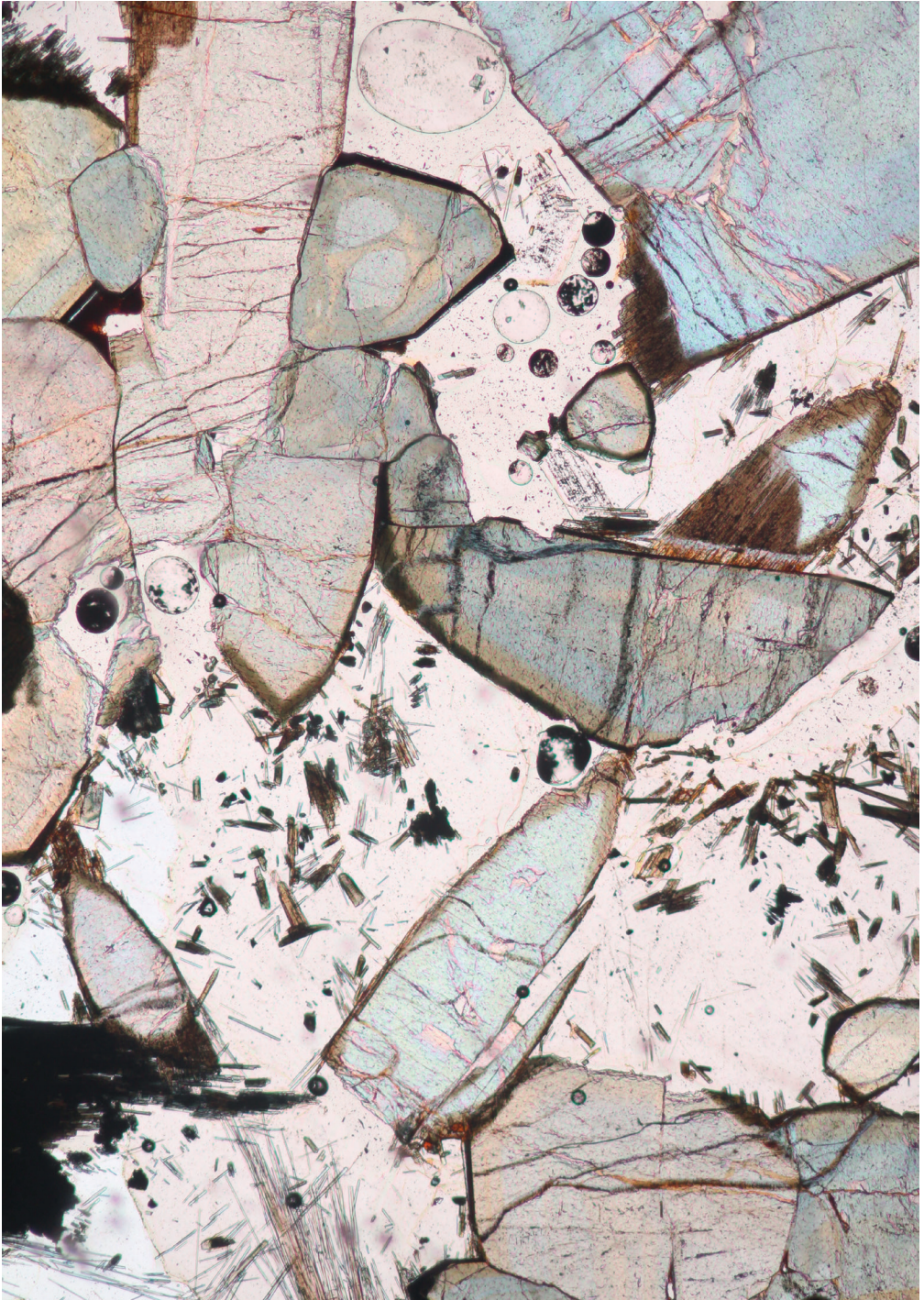
Vesicle-fill (mafic rocks, especially basalts); $\delta = 0.010-0.012$.

ZEOLITE (eg Laumontite)

Zeolite (e.g. laumontite) in meta-dolerite/diorite; locality unknown.

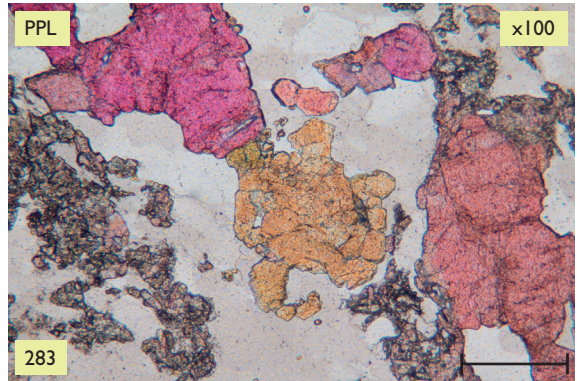


0 Cleavage traces, coloured



1 Extreme red to violet to yellow pleochroism.

PIEMONTE



Piemontite. Pennsylvania, USA.

Not intense red to violet to yellow pleochroism.

2

2 Blue, or colourless to pale blue/blue pleochroism

3

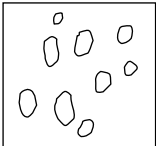
Not blue.

6

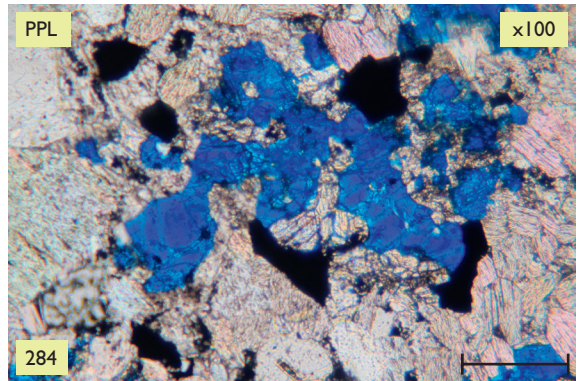
BLUE

3 Isotropic. Medium -ve relief; anhedral or granular (7a).

SODALITE Gp. (e.g Sodalite, Lazurite)



(7a)



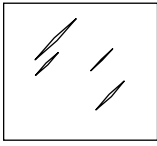
Lazurite (sodalite group) in metasomatised marble; locality unknown.

Anisotropic.

4

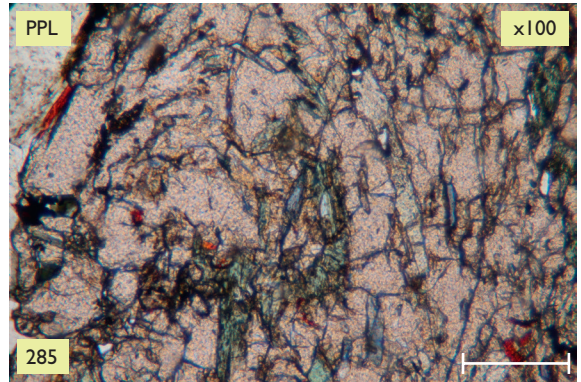
4 High relief

5

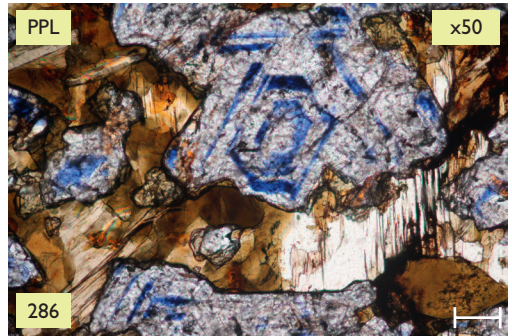
Moderate relief. ($\delta = 0.009-0.022$); small needles (7b).

(7b)

Glauco-phane (needles) as inclu-sions in garnet within glaucophane-garnet schist (blueschist); Ile de Groix, Brittany, France.

**GLAUCOPHANE(...)**5 1st order grey/white interf. colours ($\delta = 0.005-0.008$). Granulite facies metamorphism.**SAPPHIRINE**

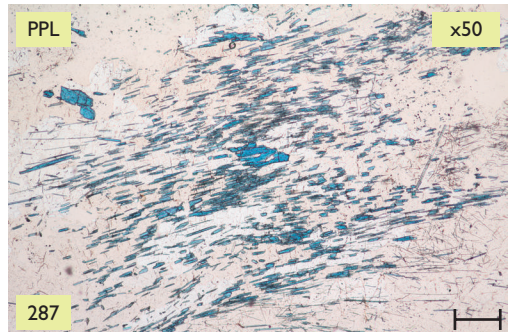
Sapphirine in sapphirine-biotite rock; locality unknown.



Top 1st ord./ low 2nd ord. interf. colours ($\delta = 0.011-0.020$).

DUMORTIERITE

Dumortierite in dumortierite-qtz rock; locality unknown (also see Image 198, and an enlargement of this image at the start of Section 4).

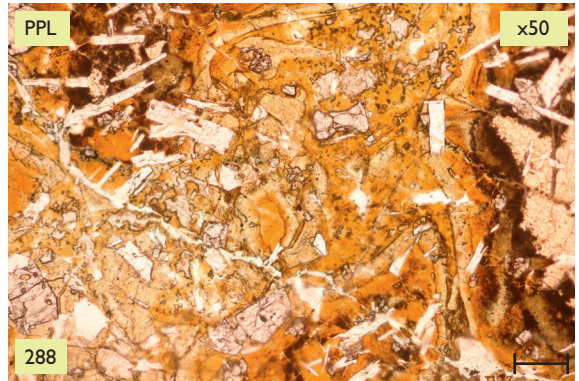


- 6 Yellow, orangy-yell., or c'less to yellow or yell.-grn. pleochroism. 7
 Green, brown, pink/red, red-brn. or orange-brn. 11

YELLOW (or yellow-green, or orange)

- 7 Low to medium relief; fine grained aggregate.

PALAGONITE/ SMECTITE (a clay mineral)



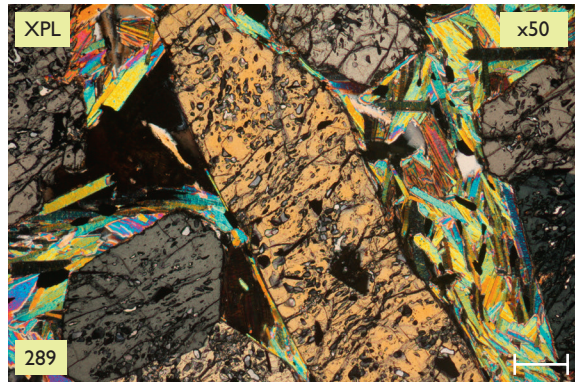
Palagonite in palagonite tuff; Portree, Skye, Scotland.

Medium to high relief

8

- 8 Max. 1st ord. yell./orange interf. colours ($\delta = 0.011-0.014$), high relief (metapelite); colourless to yellow pleochroism.

STAUROLITE



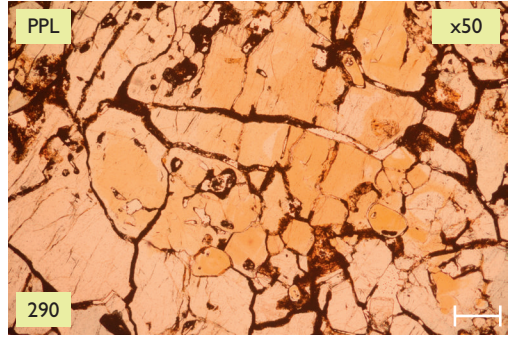
Staurolite in stt-bt-schist; Glen Esk, Scotland (see Images 193 and 212 for staurolite in PPL).

2nd/3rd order interference colours

9

9 Max. low/mid 2nd ord. interf. colours ($\delta = 0.021-0.029$).

TOURMALINE (Dravite)



Tourmaline (Dravite); locality unknown.

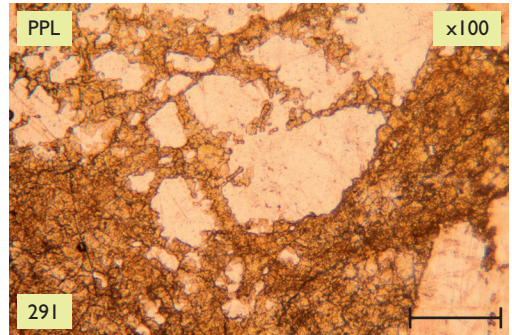
Max. 3rd ord. interf. colours.

10

10 Yellow to yellow-green, colourless to yellow-green pleochroism, ($\delta = 0.015-0.051$). High relief. Biaxial -ve, high $2V = 90-116^\circ$. Common mineral, especially in metabasites and alteration zones.

EPIDOTE

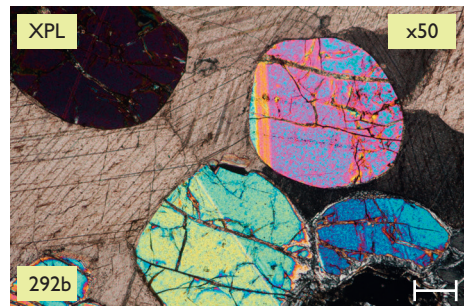
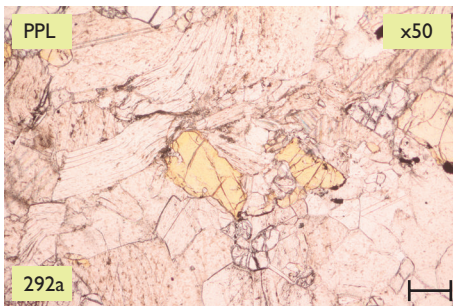
Note: Strength of colour in epidote increases with increased Fe^{3+} in epidote (= pistacite content).



Epidote in epidotised granite; Ghana.

Yell.-orangy yell. or c'less/pale yellow pleochroism, ($\delta = 0.026-0.041$). Moderate to high relief. Biaxial +ve, $2V$ c. $50-80^\circ$. Rather uncommon mineral of certain calc-silicate rocks and skarns in mineralised areas.

HUMITE Gp. (eg Humite, Clinohumite, Chondrodite)



Chondrodite in mineralised skarn; Ottawa, Canada. Note: Clinohumite and chondrodite may show lamellar twinning.

- 11 Green to blue-grn. 12
 Brown, red-brn., pink/red, orange-brn. or yell.-brn. 18

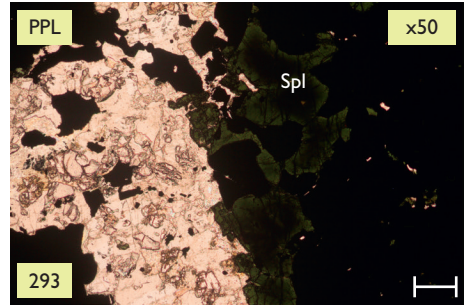
GREEN or BLUE-GREEN

- 12 High relief 13
 Low or moderate relief 15

- 13 Isotropic:

SPINEL

Note: **SPINEL** sensu stricto is the Mg end-member of the Spinel series, and **HERCYNITE** the Fe end-member. However, Spinel sensu lato shows a significant amount of Fe²⁺ substitution for Mg. This mineral is called **PLEONASTE** (dark green), and is associated with high temperature metamorphism.

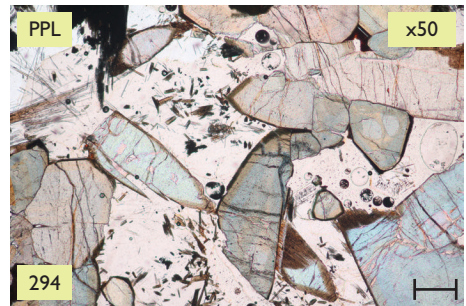


Spinel (pleonaste) in crn-spl-mag rock; locality unknown.

Non-isotropic

14

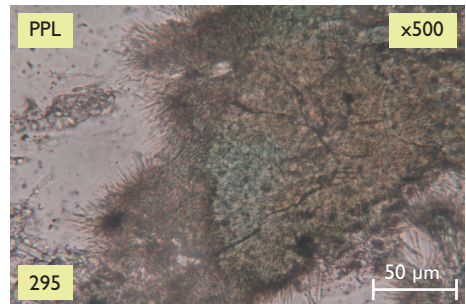
- 14 Mid/upper 2nd order interf. colours, strong pleochroism (± colour zonation), // extinction. Yell.-grn-green-blue-grn. pleochroism. **TOURMALINE (Schorl)**



Tourmaline (schorl) in quartz-tourmaline rock near granite intrusion; Roche, Cornwall, England (see start of Section 7 for an enlargement of this image”).

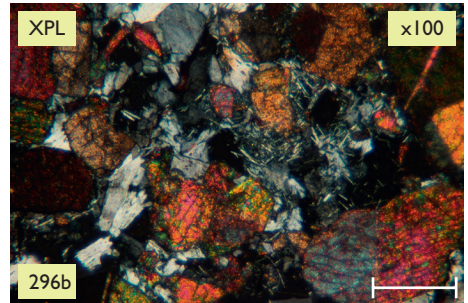
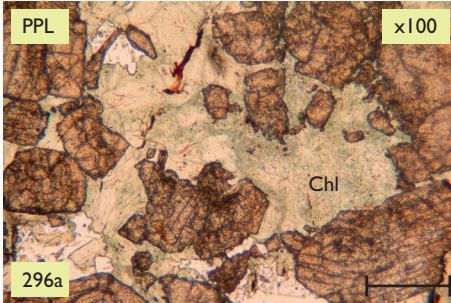
- Upper 1st order (or anomalous) interf. colours, weak or moderate c'less-yell.grn.-yell.-brn.-blue-grn. pleochroism.

PUMPELLYITE



Pumpellyite (highly magnified) in sub-greenschist facies metavolcanic rock; Rose-land, Cornwall, England.

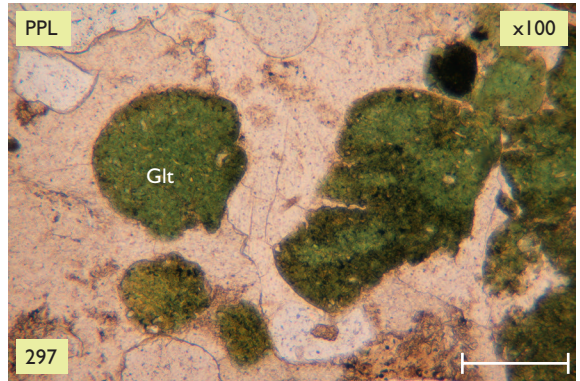
- 15 Moderate relief 16
 Low relief 17
- 16 Colourless to green or pale/dark green pleochroism, 1st order grey (or anomalous) interf. colours: **CHLORITE**



Chlorite (with and without obvious cleavage) in cassiterite-rich vein rock within granite; East Pool and Agar Mine, Cornwall, England.

Note: The subhedral high relief brown crystals (PPL) are the tin ore mineral, cassiterite.

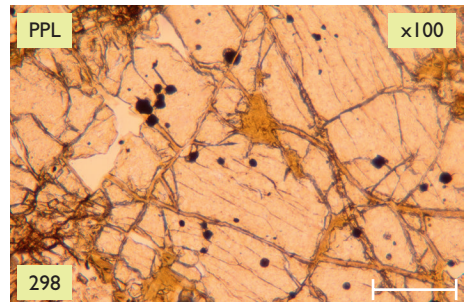
Strongly coloured, sometimes yell-green to deep green pleochroism; top 1st order/ mid 2nd order interf. colours, but generally masked by the strong colour of the mineral (sandstone/greensand/impure limestone). **GLAUCONITE**



Glaucoune in Cretaceous greensand; Folkestone, Kent, England.

- 17 Alteration of olivine (mafic/ultramafic rock or marble).

SERPENTINE (e.g. *Antigorite*)

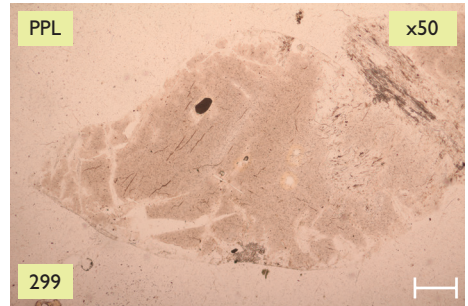


Serpentine micro-veinlets formed as part of olivine alteration in picrodolerite; Duntulm, Skye, Scotland.

Alteration of cordierite (metasediment/high T met. rock).

'PINITE'

Note: Pinite is a microcrystalline aggregate principally of muscovite (sericite) and chlorite, which gives the green colour.

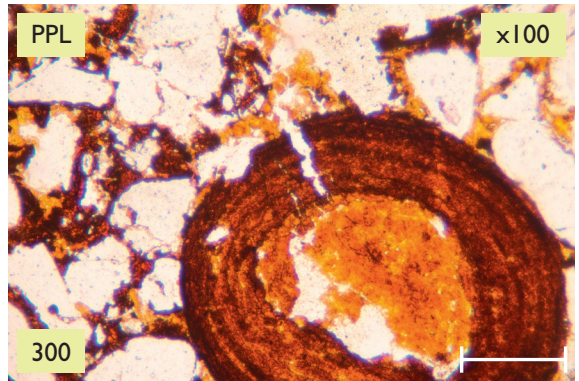


Pinnitised cordierite in cordierite-bearing quartzite; Kragerö, Norway.

BROWN/ RED/ PINK/ORANGE-BRN./ YELL.-BRN.

- | | | |
|----|---|-----------------|
| 18 | High/very high relief | 19 |
| | Low or Moderate relief | 29 |
| 19 | Isotropic (or appearing to be) | 20 |
| | Anisotropic | 24 |
| 20 | Well defined grains, often with good crystal form | 21 |
| | Fine grained or amorphous mass | LIMONITE |

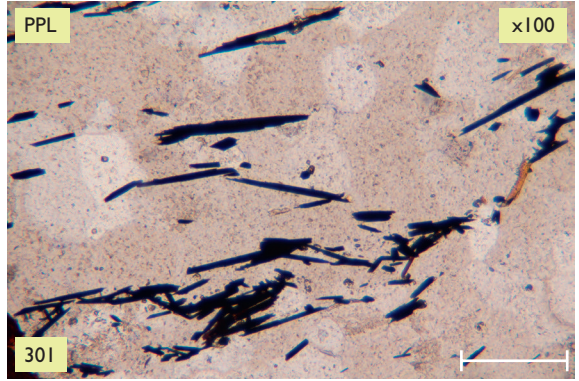
Note: Limonite (yellow, yell.-brn. to orange in PPL) is a cryptocrystalline mix of Fe-oxides/hydroxides (goethite, lepidocrocite, ± haematite).



Limonite in oolitic limestone; Abbotsbury, Dorset, England.

- 21 Needle-like or rodded crystals 22
 Anhedral, rounded, hexagonal, square or other form 23
- 22 Appears almost black in PPL, due to strong absorption, but thin crystal edges are brown to dk. brown (blueschist facies meta-ironstone). **DEERITE**

Deerite in stilpnomelane-rich siliceous meta-ironstone; Laytonville Quarry, CA, USA.

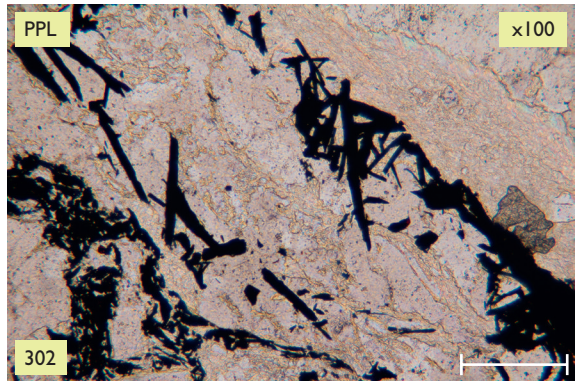


Essentially opaque in thin-section, but very thin edges of crystals may show bright red in PPL.

HAEMATITE (Specular Haematite)

Note: Specular haematite has a "scaly" or "micaceous" crystal form. Cross-sections of such thin platy crystals exhibit needle-like or square-ended rod form in thin-section

Specular haematite in haematite-quartz-sericite vein; Cap de la Hague, Normandy, France.

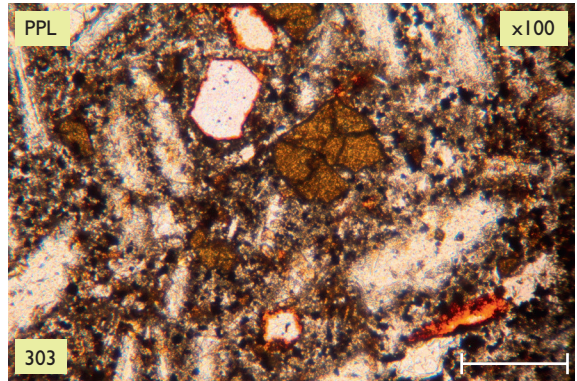


23 Brown to dark brown (igneous rocks)

PEROVSKITE

Note: *Ti-garnets (Melanite and Schorlomite) of certain alkaline igneous rocks are also brown in thin-section. Also check out AENIGMATITE, which is v.dark brown, pleochroic, but can appear isotropic.*

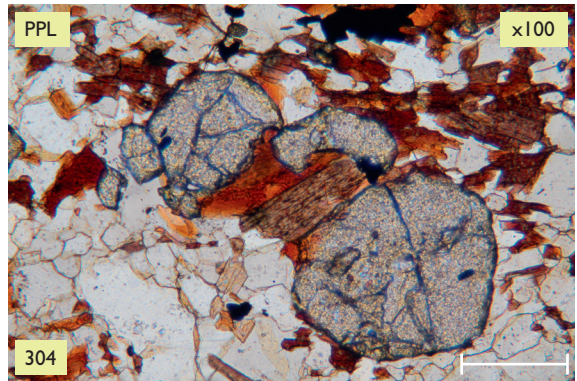
Perovskite in olivine melilitite; Katunga, Burundi.



Pale pinkish/pale brownish

ALMANDINE (garnet)

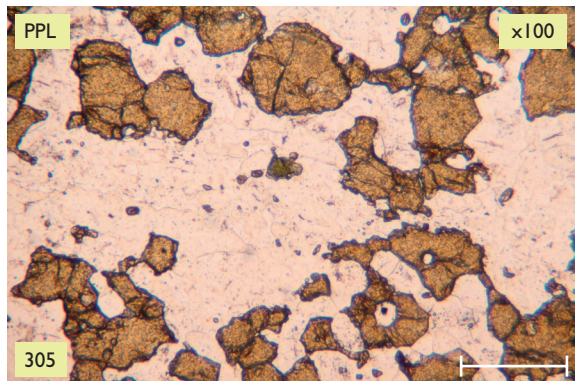
Garnet (almandine-rich; c. Alm_{70%}) in regional metamorphic garnet mica-schist; Garve, Scotland.



Pale brown

SPESSARTINE (garnet)

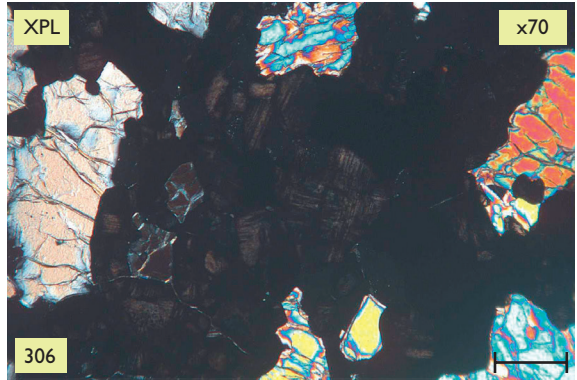
Spessartine garnet in hydrothermally altered quartzo-feldspathic metavolcanic rock; Nisserdal region, Telemark, Norway (also see Images 87–88).



- 24 Very weak birefringence ($\delta = 0.000-0.002$) 1st Ord. dark grey to black. Larger crystals may show complex (cross-hatched) twinning. **PEROVSKITE**

Note: Also check out AENIGMATITE, which is v. dark brown, pleochroic, and despite high birefringence ($\delta = 0.070-0.080$), this is masked by strong background colour so impossible to determine.

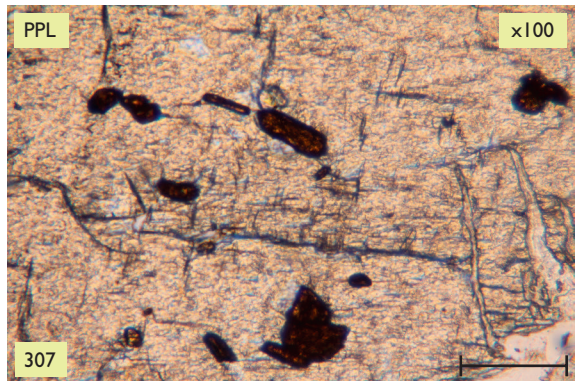
Perovskite (showing very low first-order interference colours and complex twinning) with olivine in peridotite; Africanda, Kola Peninsula, Russia. (photo courtesy of Giles Droop).



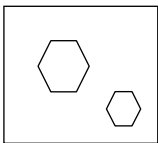
Birefringence > 0.003 (1st Ord mid grey or higher). Twinning rare and, if present, is simple. 25

- 25 Needle-like (7b) or rodded crystals (and granular) with strong red-brown colour. V. high relief. **RUTILE**

Rutile (small rods) included in kyanite, within kyanite schist; Loch Assapol, Mull, Scotland.

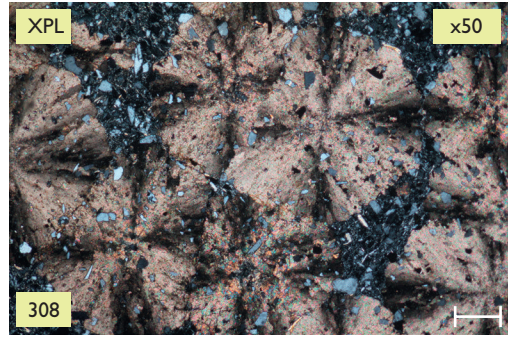


Granular rounded/oval (7a), or hexagonal (7c), or polygonal, diamond-shaped or amorphous, or sphaerulitic aggregates. 26



(7c)

- 26 Relief varies on rotation (5a) (moderate to high to v.high). May occur as sphaerulitic aggregates: **SIDERITE**

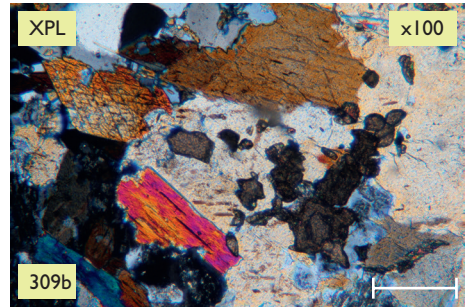
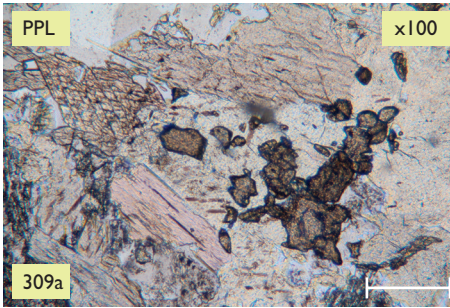


Siderite (sphaerulitic form) in Jurassic sideritic sandstone; Yorkshire, England.

Relief stays constant on rotation

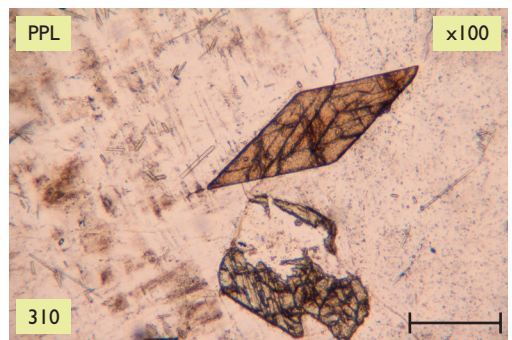
27

- 27 Pale brn.- yell.brn., 4th/5th ord. pastel interf. colours: **TITANITE (=Sphene)**



Titanite in actinolite skarn; Loch Leuh, Donegal, Ireland.

Diamond-shaped crystal of titanite (=sphene) with adjacent crystal of spodumene set in a background of microcline. Spodumene granite; Leinster, Ireland.

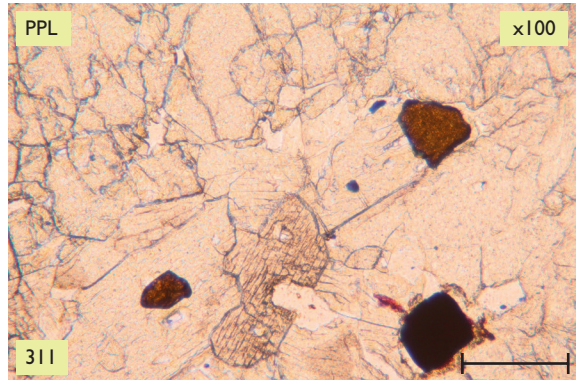


Deep brown, red-brown or red.

28

28 Individual granular, round/oval crystals (7b). v.high relief (RI = 2.61-2.90).

RUTILE

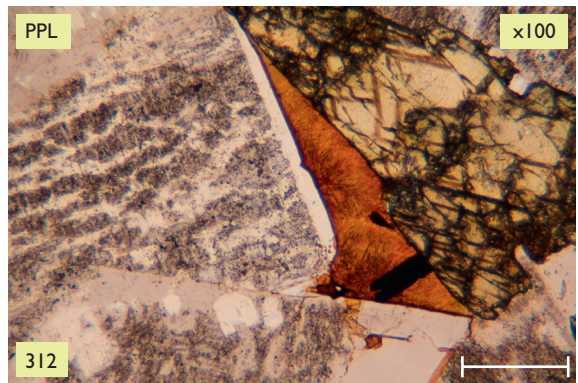


Rutile in kyanite eclogite; Qinling Belt, Dabie Shan, China.

Amorphous mass (alteration of olivine, especially in basalt):

IDDINGSITE

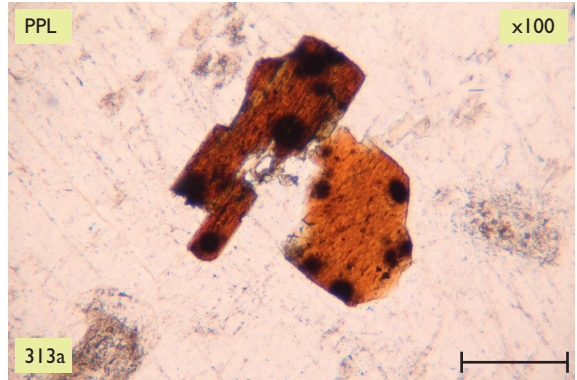
Note: Iddingsite is a fine grained mix of smectite, chlorite and goethite/haematite.



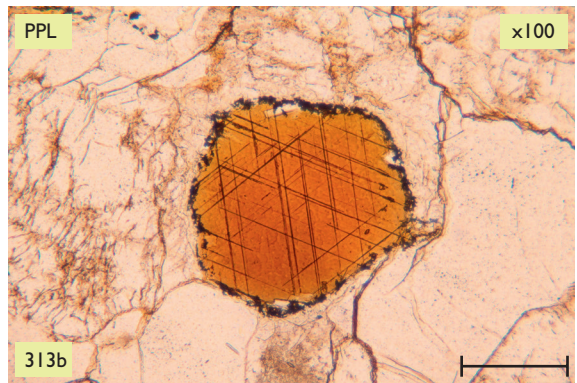
Iddingsite in ekerite; Drammen, Norway.

- 29 Moderate relief, roughly hexagonal (7c) or subhedral. Dk.brown or red-brn (non-pleochroic), birefr. nil, low or masked. **BIOTITE(■)**

(a) Biotite end-section (hexagonal no pleochroism, no cleavage) and more typical side-section (sub-rectangular pleochroic lath with cleavage) in granite; St.Jacut, Brittany, France. The biotite crystals also display dark pleochroic haloes around minute zircon inclusions (see Image 251).



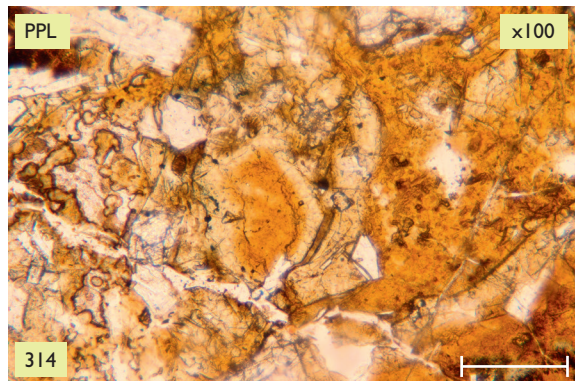
(b) Biotite end-section (in granite) showing miniscule needles of rutile with a crystallographically-controlled arrangement to give a pattern at 60° angles in a fine 'Widmanstätten-type' exsolution texture (see Spry, 1969, pg.98). This does not represent intersecting cleavages.; St. Jacut, Brittany, France.



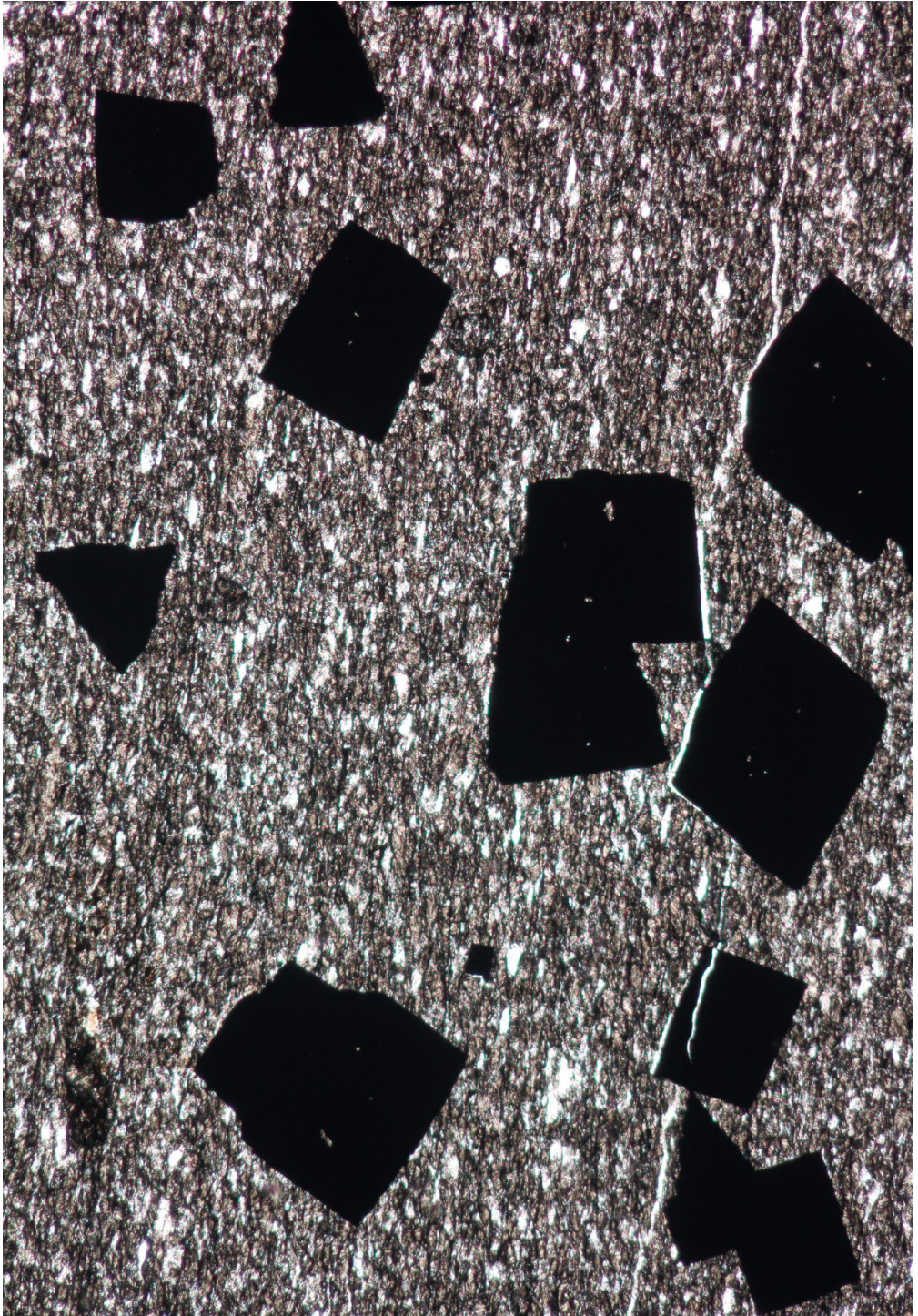
Low or mod. relief. Amorphous yellow-orange/yell.-brn. alteration product.

PALAGONITE/SMECTITE

Palagonite in palagonite tuff; Portree, Skye, Scotland (also see Image 288).



Opaque minerals



OPAQUE MINERALS

As the present key is designed for examination of standard 30µm thin-sections with a glass cover slip, using a transmitted light petrological microscope, it is not suited to the detailed identification of opaque minerals. For accurate identification of such phases, it is advisable to use thicker, polished thin-section (without cover slip) and to study using a metallurgical reflected light microscope. For further detail on the identification of such phases, refer to an ore mineralogy text (e.g. Craig & Vaughan, 1994, or Ixer, 1990).

Despite the limitations of opaque mineral identification when not using a reflected light microscope, it is still possible to make some reasonable mineral interpretations in a standard thin-section based on shape, form and associated minerals. This final Section provides a key to some of the commonest opaque minerals, seen as accessory phases in igneous, metamorphic and sedimentary rocks, and also as common vein or matrix phases in rocks of mineralised districts.

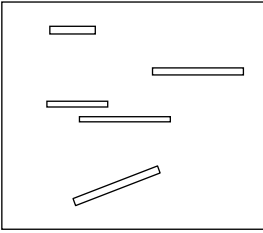
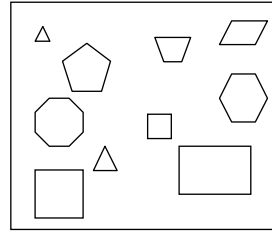
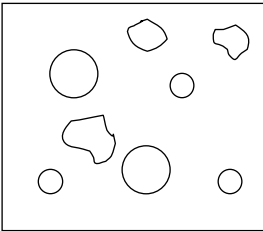
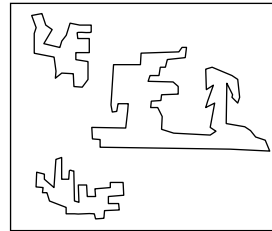
As with previous Sections of this key, the emphasis is on features seen during standard transmitted light microscopy, but colours in reflected light (RL) are also mentioned for those who wish to undertake more thorough examination. If the microscope you are using has a reflected light option, you could divert or turn off the transmitted light and switch to reflected light mode, to see the basic RL colour for the mineral of interest. If the crystals of interest are of reasonable grain size, studying the thin-section in good light with a hand lens will prove very useful. Alternatively, a standard binocular microscope used for hand specimen work or biological samples is very effective. The observations are best made with an oblique reflected light source.

All images shown below were taken either using transmitted light (PPL or XPL) with a standard petrological microscope, or else with the transmitted light source turned off and an oblique reflected light source simply positioned to one side of the microscope stage and shone from above at about 45° to the specimen.

The full range of opaque minerals associated with mineralised areas is outside the scope of this key, but it is hoped that the approach suggested above, and the images presented below, will prove helpful in enabling some of the common opaque minerals that occur as accessory phases in many rocks to be recognised.

OPAQUE MINERALS

- | | |
|--|---|
| 1 Euhedral, subhedral, anhedral or skeletal | 2 |
| Fine grained, cryptocrystalline or amorphous | 8 |
| 2 Acicular/rodded, or elongate laths (cross-sections through platy/scaly crystals) (8a). | 3 |
| Squares, rhombs, diamonds, pentagons, hexagons, triangles, and/or octahedra (8b), or anhedral/rounded (8c) or skeletal (8d). | 4 |

**(8a)****(8b)****(8c)****(8d)**

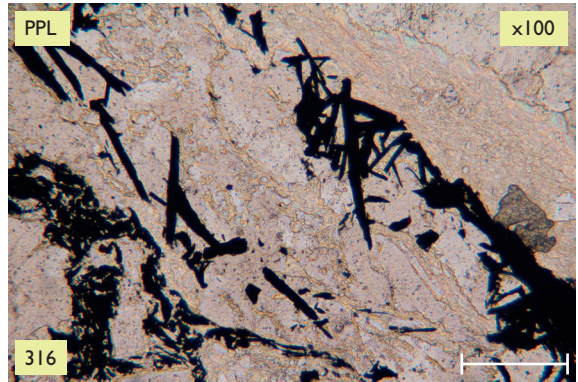
- 3 Elongate laths (8a). Thin edges may be brown in PPL. V.high relief (RI = c.2.70). RL = Brown with pink/violet tint (darker than haematite). Very common in regional metamorphic rocks.

ILMENITE

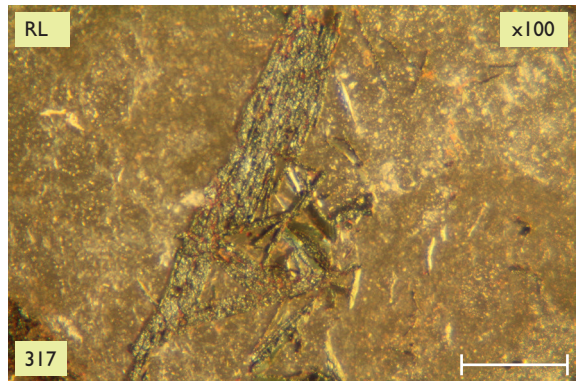
Ilmenite in granoblastic crd-bt-ilm rock; locality unknown.

Elongate laths (8a) and needles. Thin margins may be dark red in PPL. V.high relief (RI = 2.87–3.22). RL = Grey-white, (with blueish tint).

SPECULAR HAEMATITE

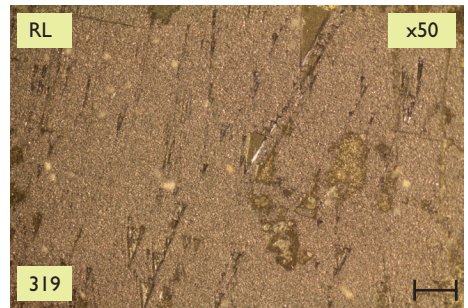
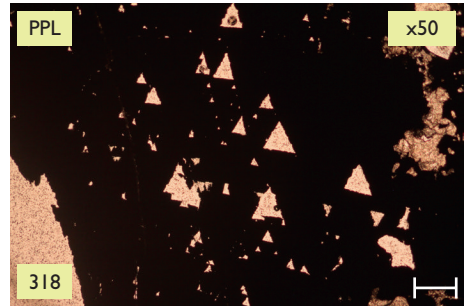


Specular haematite in haematite-quartz-sericite vein; Cap de la Hague, Normandy, France.



Specular haematite in haematite-quartz-sericite vein; Cap de la Hague, Normandy, France.

- 4 Crystals exhibit elongate triangular pits. Occurs as anhedral crystals or euhedral cubes. RL = white (but usually mid grey when viewed with cover slip on thin-section in oblique RL). Associated with Pb-mineralised areas. **GALENA**

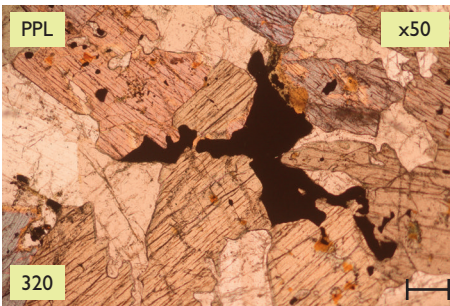


Galena in a Zn-mineralised siliceous rock; Minera, Wrexham, Wales. The triangular pits form where material has been plucked out in thin-section preparation. These elongate triangles are picking out cleavage of this cubic mineral.

Crystals do not exhibit elongate triangular pits

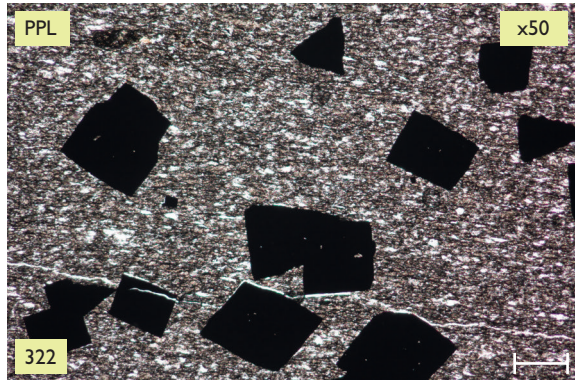
- 5 Euhedral or subhedral crystals (8b), or round (8c)
Skeletal crystals (8d)

ILMENITE (or Ilmenomagnetite)

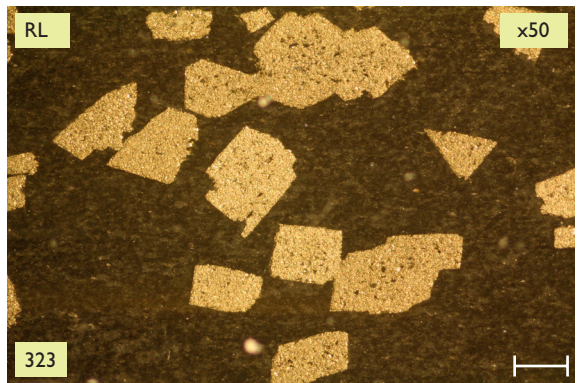


Ilmenite (or ilmenomagnetite) in gabbro; Beinn Bheag, Mull, Scotland. Skeletal ilmenite crystals are common in mafic igneous rocks. Thin edges may be brown in PPL. V.high relief ($RI = c.2.70$).

- 6 Squares, rhombs, hexagons, triangles. RL = pale yellow (will look brassy or golden when thin-section viewed with hand lens). **PYRITE**



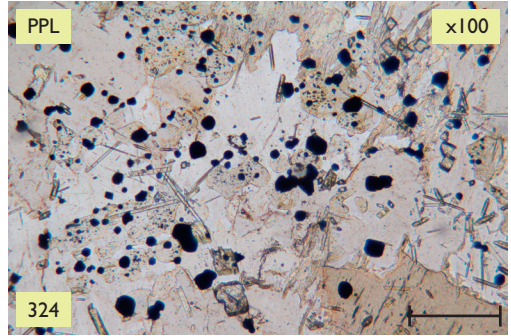
Pyrite in slate; locality unknown (see start of Section 8 for an enlargement of this image).



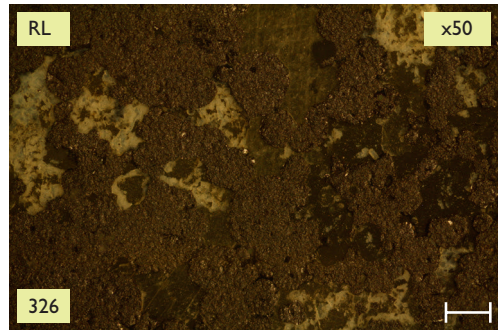
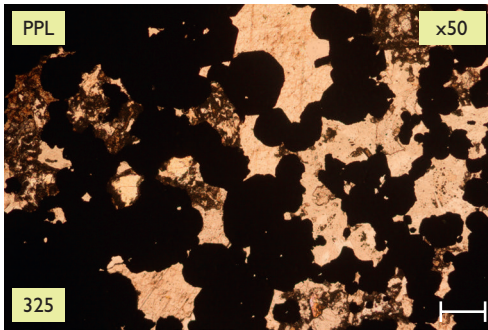
Pyrite in slate; locality unknown. Pyrite looks brassy or golden when thin-section is held up to light and viewed through a hand lens. In RL (polished sections), pyrite is pale yellow.

Round, octagonal, diamond-shaped, square, or hexagonal. RL = dk.grey to black (will look black or steely metallic dark grey with hand lens). 7

- 7 Magnetic. If abundant in the thin-section it has a strong magnetic effect. To test this, place a compass on a flat surface and glide the thin-section slowly over it. If magnetic, the compass needle will be deflected. Magnetite appears steely metallic dk. grey when observed through a hand lens in oblique reflected light. RL = dk. grey with brown tint. Common accessory mineral in many igneous and metamorphic rocks and a detrital mineral in sedimentary rocks. **MAGNETITE**



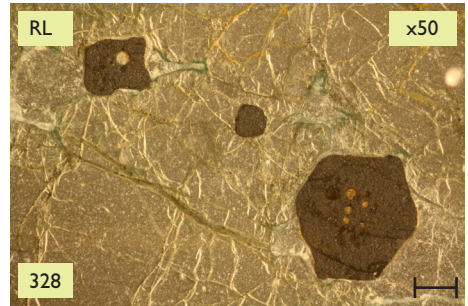
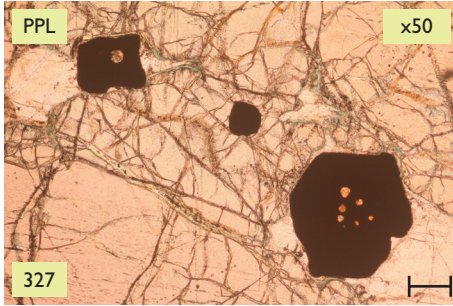
Magnetite in sil-bt-kfs-mag hornfels; Weets, Grampian, Scotland.



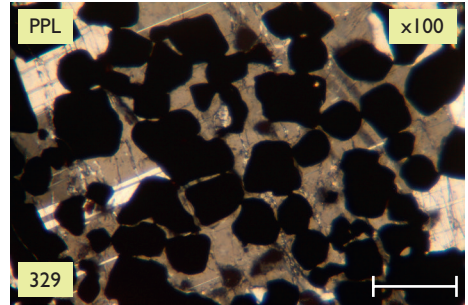
(325-326) Magnetite in monticellite-magnetite skarn; Camas Malag, Skye, Scotland. Being a magnetic mineral, high concentrations, such as this example, are strongly magnetic.

Non-magnetic. High concentrations of chromite will not deflect a compass needle in the manner described above for magnetite. RL = Dark grey to brownish grey. Associated with ultramafic igneous rocks (e.g. peridotites), metamorphosed ultramafic rocks (e.g. serpentinites). Appears dk.grey to black through the hand lens.

CHROMITE



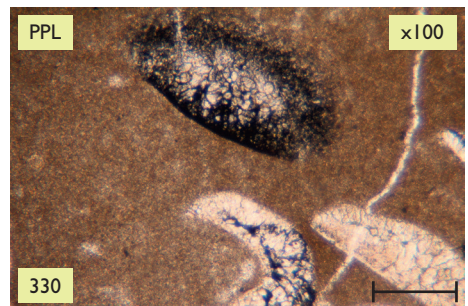
Chromite in olivine-rich ultrabasic rock of cumulate sequence; Rhum, Scotland.



Chromite in 1cm thick chromitite layer with anorthitic plagioclase making up the background; within ultramafic cumulate sequence, Rhum, Scotland.

- 8 Fine grained cryptocrystalline or amorphous opaques cannot be identified with confidence in thin-section by standard transmitted light microscopy. To correctly identify these minerals, reflected light microscopy and electron microprobe analysis or scanning-electron microscopy will be needed. In many mudrocks and carbonates/calc-pelites, finely disseminated carbonaceous material is usually present. When metamorphosed (e.g. schists, marbles), the fine carbon develops a more defined mineral structure as it recrystallises to graphite. However, even this is only aggregates of fine specks. RL = Brn.-gry to dk.grey-black bireflectance pleochroism.

GRAPHITE



Carbonaceous material in biomicrite limestone; Purbeck, Dorset, England.

Appendix I: Birefringence value (δ) and corresponding interference colours for a 30 μm rock thin-section. The “phase difference” or “retardation value” (in nm) marking the top of each order is given in the first column.

			δ
Isotropic		black	0.000
1st Order 550nm	Low	grey (or 'Berlin blue')	0.003–0.005
		pale grey/white	0.006–0.008
	Mid	pale yellow/yellow	0.009–0.012
		orange	0.013–0.015
	Top	red/deep red	0.016–0.018
2nd Order 1101nm	Low	violet/blue	0.019–0.021
		blue-green	0.021–0.023
		green/yell.grn	0.023–0.025
	Mid	yellow	0.025–0.027
		orange	0.027–0.031
		red	0.031–0.034
	Top	purple/violet	0.034–0.037
3rd Order 1652nm	Low	violet/blue/blue-grn	0.037–0.038
		green	0.038–0.043
		yellow-peach	0.043–0.047
	High	pink/pale pink	0.047–0.055
4th Order 2203nm	Low	pale green	0.055–0.064
		pale cream/peach	0.064–0.068
	High	v.pale pink	0.068–0.075
5th Order+		v.pale pastel shades, cream, pearl grey to milky white	0.075–0.200

Appendix 2: Birefringence table of minerals in order of δ values (based on data in Deer *et al.*, 1992, 2013, and Kerr, 1977)

Fluorite	Isotropic
Spinel (e.g. Pleonaste)	Isotropic
Garnet (Almandine)	Isotropic
Garnet (Pyrope)	Isotropic
Volcanic glass, and glass (hole in slide)	Isotropic
Lazurite	Isotropic
Limonite	Isotropic
Periclase	Isotropic
Sodalite Group (Sodalite, Nosean, Haiüyne)	Isotropic
Sphalerite	Isotropic
Spinel	Isotropic
Analcite	Isotropic (to 0.001 in some cases)
Garnet (Spessartine)	Isotropic (to 0.001 in some cases)
Garnet (Andradite)	Isotropic (to 0.005 in some cases)
Collophane	Isotropic (to 0.005 in some cases)
Garnet (Grossular)	Isotropic (to 0.008 in some cases)
Palagonite	0.000–0.001
Perovskite	0.000–0.002
Zeolite	0.000–0.015
Mesolite	0.001
Leucite	0.001
Apatite	0.001–0.007
Vesuvianite (Idocrase)	0.001–0.009
Chlorite	0.001–0.010
Melilite	0.001–0.013
Chabazite	0.002–0.010
Nepheline	0.003–0.005
Zoisite	0.003–0.008
Eudialyte	0.003–0.022
Serpentine (Antigorite)	0.004–0.007
Beryl	0.004–0.009
Clinozoisite	0.004–0.015
Scapolite (Na-rich [Marialite], Me_0 – Me_{50})	0.004–0.020
Sapphirine	0.005–0.009

Chloritoid	0.005–0.022
Clay (Kaolinite Gp.)	0.006
Stilbite	0.006–0.008
Orthoclase	0.006–0.010
Microcline	0.006–0.010
Antiperthite	0.006–0.010
Anorthoclase	0.006–0.010
Sanidine	0.006–0.010
Perthite (Microperthite)	0.006–0.010
Thomsonite	0.006–0.012
Riebeckite	0.006–0.016
Jadeite	0.006–0.021
Heulandite	0.007
Scolecite	0.007
Plagioclase (Albite-Labradorite)	0.007–0.010
Adularia	0.008
Corundum	0.008–0.009
Topaz	0.008–0.011
Enstatite	0.008–0.014
Cordierite	0.008–0.018
Crossite	0.008–0.020
Quartz	0.009
Celestine	0.009
Chalcedony	0.009
Andalusite	0.009–0.012
Plagioclase (Bytownite)	0.009–0.012
Axinite	0.009–0.016
Gypsum	0.010
Arfvedsonite	0.010–0.012
Hypersthene	0.010–0.016
Pumpellyite	0.010–0.020
Clay (Smectite Gp.)	0.010–0.040
Staurolite	0.011–0.014
Dumortierite	0.011–0.020
Barytes	0.012
Laumontite	0.012
Plagioclase (Anorthite)	0.012–0.013
Natrolite	0.012–0.013
Kyanite	0.012–0.016
Monticellite	0.012–0.020
Brucite	0.012–0.020
Tremolite	0.012–0.027
Omphacite	0.012–0.028
Wollastonite	0.013–0.014
Serpentine (Chrysotile)	0.013–0.017
Glaucophane	0.013–0.020
Anthophyllite	0.013–0.026

Allanite (<i>Orthite</i>)	0.013–0.036
Actinolite	0.014–0.026
Spodumene	0.014–0.027
Ferrosilite	0.015–0.022
Epidote	0.015–0.051
Hornblende	0.016–0.028
Cummingtonite	0.016–0.045
Grunerite	0.016–0.045
Sillimanite	0.018–0.022
Augite	0.018–0.033
Titanaugite	0.018–0.033
Lepidolite	0.018–0.038
Lawsonite	0.019–0.021
Glauconite	0.020–0.030
Scapolite (Ca-rich [Meionite], $Me_{50}-Me_{100}$)	0.020–0.038
Tourmaline (Dravite)	0.021–0.029
Prehnite	0.022–0.035
Hemimorphite	0.022–0.035
Pigeonite	0.023–0.029
Diopside	0.024–0.031
Cancrinite	0.025
Hedenbergite	0.025–0.034
Tourmaline (Schorl)	0.025–0.035
Piemontite	0.025–0.073
Yoderite	0.026
Chondrodite	0.028–0.034
Paragonite	0.028–0.038
Clinohumite	0.028–0.041
Kaersutite	0.028–0.047
Humite	0.029–0.031
Deerite	0.030
Clay (Illite)	0.030–0.035
Aegirine-Augite	0.030–0.050
Stilpnomelane	0.030–0.110
Biotite	0.033–0.059
Olivine (Forsterite)	0.035
Muscovite	0.036–0.049
Iddingsite	0.038–0.044
Anhydrite	0.040
Diaspore	0.040–0.050
Aegirine	0.040–0.060
Zircon	0.042–0.065
Phlogopite	0.044–0.047
Monazite	0.045–0.075
Talc	0.050
Pyrophyllite	0.050
Olivine (Fayalite)	0.052

Astrophyllite	0.060
Titanite (Sphene)	0.100–0.192
Goethite	0.138–0.140
Aragonite	0.155–0.156
Calcite	0.172–(0.190)
Dolomite	0.179–(0.185)
Ankerite	0.182–0.202
Magnesite	0.190–(0.218)
Rhodochrosite	(0.190)–0.219–(0.230)
Siderite	(0.207)–0.242
Rutile	0.286–0.296
Lepidocrocite	0.570

Appendix 3: Glossary

(based largely on Barker (1998), with additions and amendments)

2V angle The acute angle between optic axes of biaxial minerals (also referred to as the optic axial angle). This angle is bisected by the γ optic axis, which in this context is referred to as the acute bisectrix (see 1.4.6 and Fig. 1.27).

Acicular A term used to describe crystals with needle-like form (see Fig. 1.3b).

Acute bisectrix (see 2V angle)

Amphibolite A metamorphosed basic igneous rock with a mineral assemblage comprised largely of amphibole and plagioclase, usually with quartz and epidote.

Amygdale A term for vesicles infilled by a secondary mineral (e.g. zeolites, calcite) (see Image 236a).

Anatexis The process of partial melting of high grade metamorphic rocks in the presence of H_2O . This process produces granitoid melts and typically operates in the middle and lower crust during orogeny.

Anhedral Crystals with irregular shape, lacking any of their characteristic faces (see Fig. 1.3d).

Anisotropic Minerals with different optical properties (e.g. refractive indices) in different directions are said to be optically anisotropic (opposite of isotropic). Anisotropic minerals show birefringence in cross-polarised light producing interference colours caused by anisotropy affecting how different light rays pass through the crystal.

Antiperthite A feldspar intergrowth comprising K-feldspar inclusions enclosed within plagioclase (the converse of perthite).

Becke line Best seen at high magnification (x400) with the sub-stage condenser raised and the diaphragm closed, the Becke Line is a bright line of light concentration at the boundary between minerals of different relief (relating to different refractive indices). As the microscope tube is raised (slightly defocused), the Becke line moves towards the higher relief mineral. Named after the German mineralogist F. Becke who first used the technique in 1893 (see Fig. 1.8).

Bertrand lens An accessory lens on the petrological microscope, situated between the objective and the eye-piece, used in conoscopic illumination to bring the interference figure on the surface of the objective lens into focus with the eye-piece.

Biaxial interference figure In conoscopic illumination, the light passing through a mineral specimen diverges on exit to produce a conical beam. In biaxial minerals (e.g. muscovite), cut perpendicular to the acute bisectrix, this beam gives an

interference figure on the surface of the objective lens, comprising two curved black lines (“isogyres”). By insertion of a Bertrand lens, the interference figure is projected to the eye-piece (see 1.4.6 and Fig. 1.26).

Birefringence (δ) A numerical value defined by the difference between maximum and minimum refractive indices for a particular mineral. These differences are consistent with specific crystallographic axes. The magnitude of birefringence is reflected by the interference colours produced in cross-polarised light (see 1.4.1, Fig. 1.14 and Appendices 1 & 2).

Blueschist A metamorphosed mafic rock indicative of high-P/low-T subduction-related metamorphism. It contains large quantities of sodic (blue) amphibole (glaucofan/crossite), and has a pronounced schistosity (see Image 196).

Calc-silicate rock A rock with a chemistry dominated by calcium and silica, consisting of hydrous or anhydrous calc-silicate minerals such as tremolite, diopside and grossular. Carbonate minerals are also commonly present (see Images 137 & 141).

Chemical Zoning Regular or abrupt changes in mineral chemistry from core to rim (see Fig. 1.18b).

Cleavage (of minerals) Crystallographically defined planes of preferred splitting, corresponding to planes of weaker bond-strength in the structure of the mineral. Their arrangement parallels particular crystal faces of the mineral, in turn related to the crystal system. In thin-section, cleavage traces appear as a series of parallel lines. Some minerals have no cleavage whilst others show one or more cleavages (see Fig. 1.5).

Conoscopic illumination Interference figures can only be produced in conoscopic illumination (= convergent polarised light). This is achieved by raising the sub-stage condenser to just below the microscope stage, then flipping the front lens of the sub-stage condenser “in”, to converge the light on a small central area of the thin-section. On leaving the thin-section the light diverges to give a slightly conical beam.

Contact aureole The zone of rocks surrounding a plutonic igneous intrusion which are thermally metamorphosed in response to the intrusion. The contact aureole can usually be sub-divided into a series of concentric zones of varying metamorphic grade based on mineral assemblages.

Contact metamorphism Thermal metamorphism associated with igneous intrusions, often accompanied by fluid infiltration. Such metamorphism produces a series of metamorphic reactions in the surrounding country rock to give a contact aureole.

Corona A monomineralic or polymineralic rim totally surrounding a core of another mineral phase. It represents an arrested reaction between the core phase and other components.

Cross-hatched twinning ‘Cross-hatched twinning’, ‘tartan pattern’ or ‘gridiron twinning’ is one of the most characteristic features of microcline. It results from the high-angle intersection of multiple albite and pericline twins (see Fig. 1.17c).

Crystallographic axes The reference axes used to define the three-dimensional geometry of minerals. The length and angular relationships between these axes vary according to their crystal system (see Fig.1.1). To avoid any confusion, please note that the present author has used the x,y,z notation for consistency with Deer et al. (1992, 2013), but in other texts (e.g. Kerr, 1977; Ehlers 1987a,b), the principal crystallographic axes are labelled a,b,c.

Deformation bands Distinct bands of deformation in crystals. Optically they are more sharply defined than undulose extinction, and represent higher strain. They can terminate either at grain boundaries or inside grains.

- Deformation lamellae** Sets of very narrow planar or tapered lenticular structures in quartz and many other silicates. They terminate inside grain boundaries, and show a variety of orientations, though are frequently perpendicular to bands of undulose extinction.
- Deformation twins** Twins developed in crystals in response to deformation. Especially common in calcite (Fig. 1.17d), plagioclase and pyroxene. Deformation twins terminating within the crystal have tapered ends.
- Dichotomous key** A key used to identify something (e.g. plant, animal, mineral) based on a series of steps (couplets) of dichotomous questions (i.e. questions for which there can be only one of two answers). The questions present a choice of distinguishing characters, and depending on the answer given, the user either progresses to the next question, or else is directed to another part of the key. The process continues until the identity is obtained.
- Disequilibrium** An incompatible association of mineral phases and/or a combination of textures and structures incompatible with prevailing conditions.
- Eclogite** A dense, high grade metamorphic rock of mafic composition with an essential assemblage of clinopyroxene (omphacite) and garnet.
- Epitaxial growth** The oriented growth of one mineral phase in optical continuity with another due to structural similarities between the two phases. (e.g. growth of secondary amphibole rims on earlier amphiboles of different composition).
- Equilibrium** That state of a rock system in which the phases present are in the most stable, low energy arrangement, and where all phases are compatible with the given P, T, and fluid conditions.
- Euhedral** Crystals with good shape, completely bounded by their characteristic faces (see Fig. 1.3a).
- Exsolution** The process whereby an initially homogeneous solid solution separates into two (or possibly more) distinct crystalline phases (typically during cooling) without the addition or removal of material (modified after Bates & Jackson, 1980).
- Extinction angle** For minerals with straight (=parallel) extinction, there is parallelism between the crystallographic axes and optic axes (vibration directions). However, minerals showing inclined extinction (e.g. clinopyroxenes, clinoamphiboles), have varying levels of angular difference between the optic axes and the crystallographic axes (see Fig. 1.20). The extinction angle of a crystal is obtained (in XPL) by measuring the angular difference between the long-axis of the crystal when aligned with N-S cross-wires, and the position oblique to this where the crystal goes into extinction (see Fig. 1.21-1.22). By convention, the angle quoted is the smaller value with respect to N-S (ie $< 45^\circ$).
- Fibrolite** A fine fibrous or hair-like variety of sillimanite common in amphibolite facies schists and gneisses (see Image 244). Often occurs in matted aggregates or knots termed *faserkiesel*.
- Fluid inclusion** A term for microscopic and sub-microscopic (and rarely macroscopic) inclusions of fluid trapped in minerals during primary crystallisation or fracture healing. They are typically $< 50 \mu\text{m}$ in size.
- Foliation** A set of closely-spaced planar surfaces produced in a rock as a result of deformation (e.g. schistosity, cleavage).
- Gneiss** A coarsely banded high grade metamorphic rock consisting of alternating, mineralogically distinct (usually felsic and mafic) layers.

- Granoblastic structure** An aggregate consisting of equidimensional crystals of approximately equal sizes. In many cases the crystals are rounded to anhedral, but granoblastic-polygonal aggregates are equally common. Granoblastic structure is especially characteristic of granulites, eclogites and many hornfelses.
- Granulite** A high grade metamorphic rock typically with granoblastic structure and with an essential assemblage of pyroxene (typically hypersthene) and anorthitic plagioclase (see Image 190).
- Greenschist** A low grade mafic rock with schistose texture and a mineral assemblage consisting largely of actinolite, chlorite, epidote, albite, quartz, and accessory sphene.
- Groundmass** The background, generally finer grained material, that constitutes the main bulk of a rock, and within which larger crystals or other objects may reside.
- Growth twin** Primary (or growth) twins represent twins present in a given crystal that formed at the time of crystal growth.
- Gypsum plate** The gypsum plate (retardation $\Delta = 550\text{nm}$), is one of several different accessory plates that can be inserted into the beam of cross-polarised light above the analyser, as an aid to determining the “fast” or “slow” direction of a mineral or its optic sign from an interference figure. (see 1.4.5 and Fig. 1.23)
- Hornfels** A hard, fine to medium grained granoblastic rock produced by high grade contact metamorphism.
- Hour-glass structure** A structure common in chloritoid (Fig. 1.18c) and certain other minerals, consisting of a dense mass of fine grained (usually opaque) inclusions arranged in the form of an ‘hour-glass’. It forms due to influence of the host crystal structure. Aegerine-augite crystals also commonly show an hour-glass structure, somewhat like sector-zoning, typically with a more augite-rich core progressing to a more aegerine-rich margin.
- Inclined extinction** Minerals showing inclined extinction (e.g. clinopyroxenes, clinoamphiboles), have varying levels of angular difference between the optic axes and the crystallographic axes. The extinction angle (maximum) of a mineral is defined as the maximum difference between the γ -axis (optical axis) and the z-axis (crystallographic axis) (see Figs. 1.20-1.22).
- Inclusion** A solid or fluid phase totally enclosed within a mineral (e.g. fluid inclusions in vein minerals, matrix phases in porphyroblasts (see Image 277), and melt within phenocrysts).
- Interference figure** In conoscopic illumination, the light passing through a mineral specimen diverges on exit to produce a conical beam. For favourable oriented crystals (with respect to optic axes), this beam produces an interference figure on the surface of the objective lens. The interference figure comprises a series of dark lines (“isogyres”), relating to the optic axes; a simple cross for uniaxial minerals and two curved black lines for biaxial minerals. By insertion of a Bertrand lens, the interference figure is projected to the eye-piece (see 1.4.6 and Figs. 1.25 & 1.26).
- Isogyres** The broad black bands (curves) marking areas of extinction in interference figures (see Figs. 1.25 & 1.26).
- Isotropic** Crystallographically and optically homogeneous crystals (i.e. minerals of the cubic system). Such minerals appear black in cross-polarised light (see Fluorite in Images 87-88). This is because the two perpendicular light rays created by the sub-stage polariser pass through isotropic crystals at the same velocity (same refractive index in all directions), and thus cancel when recombined when the analyser is inserted.

- Lamellar twinning** Repeated twinning of a crystal about a particular crystallographic plane (e.g. (010) in plagioclase), to produce an array of alternately arranged bands within the mineral, recognised by differences in extinction position (see Figs. 1.17b and 1.22).
- Length fast and length slow crystals** Polarised light hits the underside of the thin-section as a wave vibrating in a single plane. However, immediately on entering the crystal the light splits into two rays (ordinary ray and extraordinary ray), vibrating in separate planes at right-angles to each other. These rays move at different velocities as a function of the crystallographic structure and atomic arrangement. They are generally referred to as the “fast ray” and “slow ray”. Length-slow crystals are those which have the length of the crystal parallel to the slow ray, whilst for length fast crystals the reverse is true. Length slow rays always have a higher refractive index than the fast ray. The length “slow” or “fast” character can be determined with the use of accessory plates (mica plate, gypsum plate, quartz wedge) (see 1.4.5 and Figs. 1.23-1.24).
- Marble** A metamorphosed limestone, with a mineral assemblage dominated by calcite (see Fig. 1.9 and Image 91).
- Metamorphic facies** A metamorphic facies is a subdivision of metamorphic conditions in P-T space on the basis of diagnostic mineral assemblages which have been shown by experimental and field observations to characterise a specific range of P-T conditions for a particular compositional group of rocks (in association with H₂O fluid).
- Metamorphism** The mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions which have generally been imposed at depth below the surface zones of weathering and cementation, and which differ from the conditions under which the rocks in question originated (Bates & Jackson, 1980).
- Metapelite** A metamorphosed pelitic rock (see pelite).
- Metasomatism** Metamorphism involving modification of the bulk rock chemistry by influx or removal of chemical components via a fluid phase (e.g. widespread potassium metasomatism associated with granite intrusions).
- Mica ($\lambda/4$) plate** The mica ($\lambda/4$) plate (retardation $\Delta = 150\text{nm}$), is one of several different accessory plates that can be inserted into the beam of cross-polarised light above the analyser, as an aid to determining the “fast” or “slow” direction of a mineral, or its optic sign from an interference figure (see 1.4.5 and Fig. 1.23).
- Mica-fish** ‘Fish’- or ‘lozenge’-shaped mica porphyroclasts/ porphyroblasts aligned within a finer grained schistose matrix. They are characteristic of phyllonites and highly deformed schists, and can be used to determine shear-sense.
- Micropertthite** The microscopic intergrowth of plagioclase and K-feldspar, comprising exsolved fine plagioclase inclusions enclosed within K-feldspar (see Image 116a). Common in high grade metamorphic rocks and plutonic igneous rocks.
- Microstructure** The geometric arrangement and interrelationships between grains and internal features of grains.
- Migmatite** A coarse grained heterogeneous rock type characteristically with irregular and discontinuous interleaving of leucocratic granitoid material (leucosome) and residual high-grade metamorphic material (restite). Migmatites are often intensely folded and heavily veined. General opinion considers most migmatites to have developed by *in-situ* anatexis.

- Multiple lamellar twinning** Multiple lamellar (or polysynthetic) twinning forms by repeat alternations of the crystal lattice about a particular plane in the crystal lattice (e.g. (010) in plagioclase). The regularity is such that alternate lamellae are identically oriented and thus have the same interference colour (see Figs. 1.17b, 1.22 and Image 136a).
- Myrmekite** A symplectic intergrowth of vermicular quartz and plagioclase resulting from the retrograde replacement of K-feldspar (see Image 116b).
- Omphacite** Sodium-rich variety of the clinopyroxene augite. An essential and characteristic mineral of eclogites (see Image 146a-b).
- Orthoscopic illumination** The standard arrangement when viewing a thin-section using a petrological microscope. This involves the various light rays moving in parallel paths upwards through the lens system of the microscope (and through the thin-section) up to the eye-piece where an image of the thin-section field of view is projected.
- Pegmatite** A very coarse grained (often granitic) igneous rock, usually with grain size > 3cm.
- Pelite** A rock of argillaceous composition with a mineral assemblage dominated by phyllosilicate minerals. Original sedimentary rocks are mudstones and siltstones, which when metamorphosed become slates, phyllites, schists etc.
- Peristerites** Sodic plagioclases consisting of microscopic and sub-microscopic intergrowths of albite and oligoclase. Such feldspars characterise the greenschist facies - amphibolite facies transition.
- Perthite** A feldspar intergrowth with plagioclase inclusions enclosed within K-feldspar. Common in high grade metamorphic rocks and plutonic igneous rocks (see Image 116a).
- Phenocryst** An igneous term used for larger crystals set within a finer grained groundmass (see Fig. 1.4a and Image 143).
- Pinnitisation** The retrogression, especially of cordierite, to an ultra fine grained green or yellow felty mixture of muscovite and chlorite (modified from Deer *et al*, 1992) (see Image 299).
- Pleochroism** The ability of an anisotropic crystal to differentially absorb various wavelengths of transmitted light in various crystallographic directions, and thus show different colours in different directions (see Fig. 1.6). As the microscope stage is rotated in plane-polarised light the mineral shows a colour change, and is said to be pleochroic (modified after Bates & Jackson, 1980).
- Poikilitic** An igneous term used to describe large crystals (phenocrysts) of one mineral enclosing numerous small crystals of one or more other minerals.
- Poikiloblastic** A metamorphic term used to describe porphyroblasts with abundant mineral inclusions (see Fig. 1.4c).
- Polygonal structure** A term for rocks containing crystals (usually equigranular) with polygonal shapes (commonly five or six-sided) and dominantly straight boundaries meeting at triple-points (modified from Spry, 1969). (see Image 279a, and accompanying diagram 6k).
- Polymorph** One of two or more crystallographic forms of the same chemical substance. For example, there are three common polymorphs of Al_2SiO_5 (i.e. andalusite, kyanite and sillimanite).
- Polysynthetic twinning** (see multiple lamellar twinning)
- Porphyritic** Igneous rock texture, comprising larger crystals (phenocrysts) in a finer grained groundmass.

- Porphyroblast** A metamorphic mineral that has grown to a much larger size than minerals of the surrounding matrix (see Fig. 1.10).
- Porphyroblastesis** The growth of porphyroblasts.
- Porphyroblastic** A term used to describe a metamorphic rock with large crystals (porphyroblasts) grown within a finer grained matrix.
- Porphyroclast** A large relict crystal, or crystal fragment in a fine grained matrix of a deformed rock.
- Porphyroclastic** A term used to describe rocks with abundant porphyroclasts (e.g. mylonites).
- Pressure shadow** (see Strain shadow)
- Primary twins** Twins developed during crystal growth (see 1.4.2).
- Pseudomorph** A mineral or aggregate of minerals having the form of another mineral phase being replaced. A pseudomorph is described as being “after” the mineral whose outward form it has (e.g. chlorite after garnet). Pseudomorphing is a gradual process such that at the arrested stage seen in thin-section the pseudomorph may be ‘partial’ or ‘complete’ (see Images 261 & 278).
- Quartz wedge** One of several different accessory plates that can be inserted into the beam of cross-polarised light above the analyser, as an aid to determining the “fast” or “slow” direction of a mineral, or its optic sign from an interference figure. The quartz wedge is a tapered wedge of a single large quartz crystal, cut and enclosed between two glass plates. It is inserted thin-end first, and produces progressively higher interference colours as thicker and thicker sections of the wedge are introduced.
- Reaction rim** A monomineralic or polyminerallc rim (commonly of hydrous phases) surrounding the core of another phase in the process of retrogression
- Regional (orogenic) metamorphism** Metamorphism affecting large areas of the Earth’s crust and commonly associated with collisional orogeny. Regional metamorphic rocks commonly exhibit complex interrelationships between mineral growth and deformation.
- Relief (of minerals)** The “relief” of a mineral describes the extent to which it stands out from the background when viewed in thin-section. Relief is directly related to the refractive index of the mineral concerned, and the difference in refractive index compared with surrounding minerals. The higher the refractive index of a mineral, the higher the relief (see 1.3.5, Table 1.2, Figs. 1.7 & 1.10).
- Retrograde metamorphism** Metamorphic changes in response to decreasing pressure and/or temperature conditions.
- Retrogression** Modification of the primary mineral assemblage due to waning P-T conditions and/or changing fluid chemistry. This process typically involves partial or complete replacement of high grade largely anhydrous phases by lower grade hydrous phases.
- Saussuritisation** The retrogressive replacement of anorthitic plagioclase in a fine grained aggregate of epidote group minerals and sericite (\pm calcite).
- Schist** Metamorphic rock, typically of pelitic or semi-pelitic composition, with a well developed schistosity (see Images 23, 81, 184, 202b).
- Schistosity** A planar structure defined by the alignment of inequant minerals such as micas and amphiboles and where individual minerals are discernable in hand

specimen. Rocks showing this structure are termed schists. Such a structure is common in regional metamorphic and blueschist facies metapelites and metabasites.

Secondary twins Twins that have formed subsequent to crystal growth. This includes *inversion twins* formed due to change in crystal habit as a result of instability of the initial structure with changing P-T, and *deformation twins* formed in response to deformation of the crystal lattice (see 1.17d).

Sector twinning (or sector-zoning) Geometrically arranged triangular, or wedge-shaped, crystallographically induced twins, characteristic of a small selection of minerals, especially cordierite (Fig. 1.18e). Although the sector-twinning (also termed “sector zoning”, “sector-trilling”) seen in cordierite of contact metamorphic aureoles was originally interpreted as a growth-twinning feature, it is now widely accepted as resulting from the transformation of metastable high-temperature hexagonal cordierite to stable low-temperature orthorhombic cordierite.

Sericitisation The alteration of a mineral or minerals to an aggregate of fine-grained white mica, known as sericite (see Image 263).

Serpentinite A retrogressed ultramafic rock with a mineral assemblage comprised largely of serpentine minerals.

Serpentinisation A process involving the conversion of high temperature minerals (especially olivine) to an aggregate of serpentine (see Image 298). This is common in retrogressed ultramafic rocks, and takes place at temperatures below 500°C and often <300°C in the presence of aqueous fluids.

Simple twin A mirroring of the crystal structure each side of a particular crystallographic plane as the crystal has grown. Because the two halves of the twin are differently oriented within the plane of the thin-section they are easily recognised in cross-polarised light due to different interference colours (see Fig. 1.17a).

Skarn A rock formed during contact metamorphism or regional metasomatism by reaction between carbonate rocks and fluids rich in elements such as iron and silica. Skarns have an assemblage dominated by calc-silicate minerals often in association with magnetite (see Image 325).

Skeletal crystals Individual crystals that have nucleated and grown between the grain boundaries of other crystals (particularly quartz) to form a skeletal or mesh-like network of thin interconnected strands (see Image 320).

Spherulitic A term describing a sub-spherical mass of acicular crystals radiating from a common point (see Image 308).

Steatitisation A process involving the retrogression of ultrabasic rocks to an assemblage comprised largely of talc.

Straight extinction For minerals with straight (=parallel) extinction, there is parallelism between the crystallographic axes and optic axes. The extinction angle of a crystal is obtained (in XPL) by measuring the angular difference between the long-axis of the crystal when aligned with N-S cross-wires, and the position where the crystal goes into extinction. In the case of straight extinction the angle is 0°, i.e. extinction is parallel with the N-S cross-wires (see Fig. 1.19).

Strain shadow A region of low strain immediately adjacent to a porphyroblast. It is located perpendicular to the principal axis (axes) of compression, and is largely protected from deformation by the higher rigidity (competence) of the porphyroblast (e.g. garnet, pyrite) relative to the matrix (e.g. quartz and phyllosilicates).

The porphyroblast and matrix may become detached along their contact, the space being filled with new crystals (e.g. quartz) showing fibrous growth forms in the direction of extension (if not recrystallized at higher temperatures). (see Image 270)

Sub-grains Sub-grains develop in deformed crystals, and are areas misoriented by a few degrees relative to the parent grain. They are picked out by standard optical microscopy since they pass into extinction at a slightly different position to the parent grain, although lacking sharply defined boundaries. Sub-grains are strain free, and form during recovery.

Subhedral A term used to describe metamorphic crystals (especially porphyroblasts) with moderately good form, and some well-formed crystal faces. (see Fig. 1.3c)

Symplectite Complex and intimate intergrowth of two or sometimes three simultaneously co-nucleating phases, one of which is usually vermicular or rodded in form. Such structures are especially common in retrogressed granulites.

Twin A polycrystalline unit composed of two or more homogenous portions of the same crystal species mutually oriented according to certain simple laws (see Fig. 1.17).

Twinkling By virtue of pronounced differences in refractive indices in different crystallographic orientations, some minerals, most notably carbonate minerals (e.g. calcite and dolomite) show marked change in relief when the microscope stage is rotated. This produces an effect known as “twinkling”, where the relief of individual crystals rises and falls as the stage is turned (see Fig. 1.9).

Ultramafic rock Igneous rocks dominated by ferromagnesium minerals (e.g. olivines, pyroxenes) (see Image 306).

Undulose extinction A term describing a property of deformed crystals (especially quartz) in which poorly defined zones of extinction are seen to sweep across individual crystals when the microscope stage is rotated. This feature is caused by deformation/distortion of the crystal lattice.

Uralitisation A process of alteration involving the pseudomorphic replacement of primary igneous pyroxenes by secondary metamorphic/hydrothermal amphiboles (often tremolite, actinolite or hornblende).

Vein A fracture or microfracture filled with crystalline material (see Fig. 1.12).

Vesicle Rounded, ellipsoidal or irregular small holes in lavas and near surface volcanic rocks, where volatiles have been exsolved from the magma during cooling and decompression (see Image 265). If filled with a secondary mineral they are termed amygdales.

Uniaxial interference figure In conoscopic illumination, the light passing through a mineral specimen diverges on exit to produce a conical beam. In uniaxial crystals (e.g. quartz) cut perpendicular to the z- crystallographic axis (\equiv c-axis), this beam produces an interference figure on the surface of the objective lens. By insertion of a Bertrand lens, the interference figure is projected to the eye-piece. The interference figure comprises a series of dark lines (“isogyres”), relating to the optic axes, and for uniaxial minerals produces a simple cross (see 1.4.6 and Fig. 1.25).

Vermicular A term for crystals with worm-like form (see Image 116b).

Appendix 4: Mineral abbreviations

The mineral abbreviations used throughout the present key are those given in Tables 2.12.1 and 2.12.2 of Fettes & Desmons (2007). In broad terms these abbreviations follow the widely accepted list of Kretz (1983), but with updates and revision. The fully revised list of Fettes & Desmons (2007) is that recommended by the Subcommittee on the Systematics of Metamorphic Rocks (SCMR), and a partial version of this list is given below. The abbreviations used by Bucher & Frey (1994) and Barker (1998) have a similar basis and show broad agreement.

Ab = albite	Chr = chromite
Act = actinolite	Chu = clinohumite
Aeg = aegirine	Cld = chloritoid
Afs = alkali feldspar	Cls = celestine
Agt = aegirine-augite	Coe = coesite
Alm = almandine	Cph = carpholite
Aln = allanite	Cpx = clinopyroxene
Als = aluminosilicate	Crd = cordierite
An = anorthite	Crn = corundum
And = andalusite	Crs = cristobalite
Anh = anhydrite	Cst = cassiterite
Ank = ankerite	Ctl = chrysotile
Anl = analcite (analcime)	Cum = cummingtonite
Ann = annite	Czo = clinozoisite
Ap = apatite	Dee = deerite
Arf = arfvedsonite	Di = diopside
Arg = aragonite	Dol = dolomite
Atg = antigorite	Drv = dravite
Ath = anthophyllite	Dsp = diaspore
Aug = augite	Elb = elbaite
Brc = brucite	En = enstatite
Brl = beryl	Ep = epidote
Brt = barite (barytes)	Fa = fayalite
Bt = biotite	Fl = fluorite
Cal = calcite	Fo = forsterite
Cbz = chabazite	Fs = ferrosilite
Ccn = cancrinite	Fsp = feldspar
Chl = chlorite	Gbs = gibbsite
Chn = chondrodite	Ged = gedrite

Gln = glaucophane	Per = periclase
Glt = glauconite	Pg = paragonite
Gn = galena	Pgt = pigeonite
Gp = gypsum	Phg = phengite
Gr = graphite	Phl = phlogopite
Grs = grossular	Pl = plagioclase
Grt = garnet	Pmp = pumpellyite
Hbl = hornblende	Prh = prehnite
Hc = hercynite	Prl = pyrophyllite
Hd = hedenbergite	Prp = pyrope
Hem = hematite (haematite)	Prv = perovskite
Hu = humite	Px = pyroxene
Hul = heulandite	Py = pyrite
Hyn = häüyne	Qtz = quartz
Ill = illite	Rbk = riebeckite
Ilm = ilmenite	Rds = rhodochrosite
Jd = jadeite	Rt = rutile
Kfs = K-feldspar	Sa = sanidine
Kln = kaolinite	Scp = scapolite
Krn = kornerupine	Sd = siderite
Krs = kaersutite	Sdl = sodalite
Ky = kyanite	Ser = sericite
Laz = lazulite (lazurite)	Sil = sillimanite
Lct = leucite	Sme = smectite
Lm = limonite	Sp = sphalerite
Lmt = laumontite	Spd = spodumene
Lpd = lepidolite	Spl = spinel
Lws = lawsonite	Spr = sapphirine
Lz = lizardite	Sps = spessartine
Mag = magnetite	Srl = schorl (schorlite)
Mar = mariolite	Srp = serpentine
Mc = microcline	St = staurolite
Mei = meionite	Stb = stilbite
Mel = melilite	Stp = stilpnomelane
Mgs = magnesite	Tlc = talc
Mnt = montmorillonite	Toz = topaz
Mnz = monazite	Tr = tremolite
Mrg = margarite	Trd = tridymite
Ms = muscovite	Ttn = titanite (sphene)
Mtc = monticellite	Tur = tourmaline
Mul = mullite	Uvt = uvarovite
Ne = nepheline	Ves = vesuvianite (idocrase)
Nsn = nosean	Wo = wollastonite
Ol = olivine	Wrk = wairakiite
Omp = omphacite	Zeo = zeolite
Op = opaque mineral	Zo = zoisite
Opx = orthopyroxene	Zrn = zircon
Or = orthoclase	Zwd = zinnwaldite
Osu = osumilite	

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Structured in the form of a dichotomous key, comparable to those widely used in botany, the mineral key provides an efficient and systematic approach to identifying rock-forming minerals in thin-section. This unique approach covers 150+ of the most commonly encountered rock-forming minerals, plus a few rarer but noteworthy ones. Illustrated in full colour, with 330+ high quality mineral photomicrographs from a worldwide collection of igneous, metamorphic, and sedimentary rocks, it also provides a comprehensive atlas of rock-forming minerals in thin-section.

Commencing with a brief introduction to mineral systems, and the properties of minerals in plane-polarised and cross-polarised light, the mineral key also includes line drawings, tables of mineral properties and an interference colour chart, to further aid mineral identification. To minimise the chance of misidentification, and enable less experienced petrologists to use the key with confidence, the key has been arranged to prioritise those properties that are most easily recognised.

Designed for simplicity and ease of use, it is primarily aimed at undergraduate and postgraduate students of mineralogy and petrology, but should also provide a valuable source of reference for all practising geologists dealing with rock thin-sections and their interpretation.

