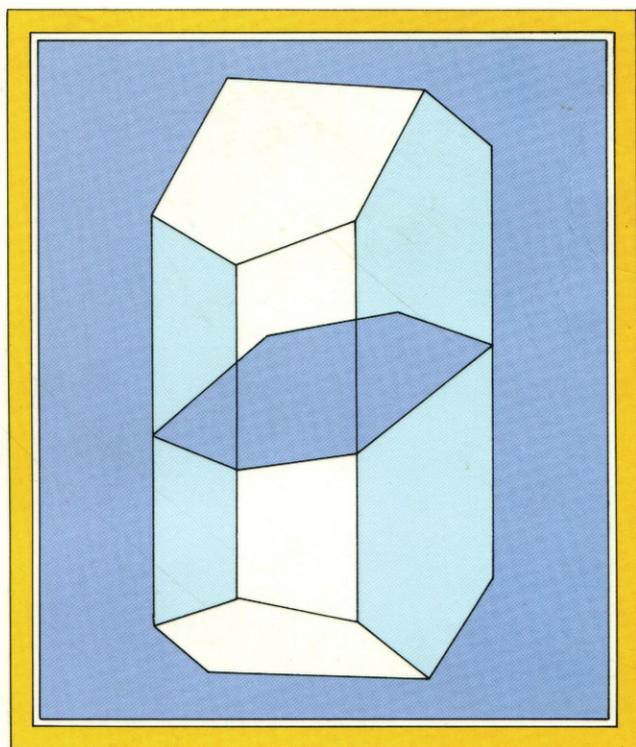


A Practical Introduction to Optical Mineralogy



C.D. Gribble A.J. Hall

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A Practical Introduction to Optical Mineralogy

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Preface

Microscopy is a servant of all the sciences, and the microscopic examination of minerals is an important technique which should be mastered by all students of geology early in their careers. Advanced modern textbooks on both optics and mineralogy are available, and our intention is not that this new textbook should replace these but that it should serve as an introductory text or a first stepping-stone to the study of optical mineralogy. The present text has been written with full awareness that it will probably be used as a laboratory handbook, serving as a quick reference to the properties of minerals, but nevertheless care has been taken to present a systematic explanation of the use of the microscope as well as theoretical aspects of optical mineralogy. The book is therefore suitable for the novice either studying as an individual or participating in classwork.

Both transmitted-light microscopy and reflected-light microscopy are dealt with, the former involving examination of transparent minerals in thin section and the latter involving examination of opaque minerals in polished section. Reflected-light microscopy is increasing in importance in undergraduate courses on ore mineralisation, but the main reason for combining the two aspects of microscopy is that it is no longer acceptable to neglect opaque minerals in the systematic petrographic study of rocks. Dual purpose microscopes incorporating transmitted- and reflected-light modes are readily available, and these are ideal for the study of polished thin sections. The technique of preparing polished thin sections has been perfected for use in the electron microprobe analyser, which permits analysis of points of the order of one micron diameter on the polished surface of the section. Reflected-light study of polished thin sections is a prerequisite of electron microprobe analysis, so an ability to characterise minerals in reflected light is of obvious advantage. Reflected-light microscopy is described with consideration of the possibility that experienced transmitted-light microscopists may wish to use this book as an introduction to the reflected-light technique.

This book therefore introduces students to the use of both the transmitted- and reflected-light microscope and to the study of minerals using both methods (Ch. 1). The descriptive section on minerals is subdivided for ease of presentation: the silicates (which are studied using transmitted light) are described in Chapter 2, and are followed in Chapter 3 by the non-silicates (which are studied using either transmitted or reflected light). The minerals are presented in alphabetical order but, to save duplicating descriptions, closely related minerals have been presented together. The best way to locate the description of a given mineral is therefore to look up the required mineral in the index, where minerals appear in alphabetical order. Although important, a detailed understanding of optical theory is not essential to mineral identification.

Accounts of transmitted-light optical crystallography and reflected-light theory are therefore placed after the main descriptions of minerals, in Chapters 4 and 5 respectively. The appendices include systematic lists of the optical properties of minerals for use in identification.

This book is intended to be an aid to the identification of minerals under the microscope, but not to the description or interpretation of mineral relationships. We both hope that the text fills its intended slot, and that students find it helpful and enjoyable to use.

Acknowledgements

The sections dealing with transmitted light have been written by C. D. Gribble. He acknowledges the debt owed to Kerr (1977), whose format has generally been employed in Chapter 2, and to Deer *et al.* (1966), whose sections on physical properties and mineral paragenesis have often been the basis of the RI values and occurrences given in this text. Other authors and papers have been employed, in particular Smith (1974) on the feldspars and Wahlstrom (1959) on optical crystallography.

Descriptions of the opaque minerals by A. J. Hall are based on data in many texts. However, they are taken mainly from the tables of Uytendogaardt and Burke (1971), the classic text *Dana's system of mineralogy* edited by Palache *et al.* (1962), the unsurpassed description of the textures of the ore minerals by Ramdohr (1969), and the atlas by Picot and Johan (1977). The textbook on the microscopic study of minerals by Galopin and Henry (1972), and course notes and publications of Cervelle, form the basis of the section on theoretical aspects of reflected-light microscopy.

The Michel-Levy chart on the back cover is reproduced with the kind permission of Carl Zeiss of Oberkochen, Federal Republic of Germany.

We are grateful for support and suggestions by our colleagues in the Universities of Glasgow and Strathclyde. A special thanks is due to the typists Janette Forbes, Irene Wells, Dorothy Rae, Irene Elder and Mary Fortune.

Also, we are particularly grateful to John Wadsworth and Fergus Gibb for their comments and reviews of the original manuscript, and to Brian Goodale for his comments on Chapter 4.

Any errors or inaccuracies are, however, ours.

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List of symbols and abbreviations used in the text

Crystallographic properties of minerals

$a b c$ or $XY Z$	crystallographic axes
hkl	Miller's indices, which refer to crystallographic orientation
(111)	a single plane or face
{111}	a form; all planes with same geometric relationship to axes
[111]	zone axis; planes parallel to axis belong to zone
β	angle between a and c in the monoclinic system
α, β, γ	angles between b and c , a and c , and a and b in the triclinic system

Light

λ	wavelength
A	amplitude
PPL	plane or linearly polarised light

Microscopy

N, S, E, W	north (up), south (down), east (right), west (left) in image or in relation to crosswires
NA	numerical aperture
XPOLS, XP, CP	crossed polars (analyser inserted)

Optical properties

n or RI	refractive index of mineral
N	refractive index of immersion medium
n_o	RI of ordinary ray
n_e	RI of extraordinary ray
n_α	minor RI
n_β	intermediate
n_γ	major RI
o	ordinary ray vibration direction of uniaxial mineral
e	extraordinary ray vibration direction of uniaxial mineral
α, β, γ	principal vibration directions of general optical indicatrix
δ	maximum birefringence ($n_e - n_o$ or $n_\gamma - n_\alpha$)
$2V$	optic axial angle
$2V_\alpha$	optic axial angle bisected by α
$2V_\gamma$	optic axial angle bisected by γ
Bx_α	acute bisectrix (an acute optic axial angle)
Bx_o	obtuse bisectrix (an obtuse optic axial angle)
OAP	optic axial plane
$\gamma^{\wedge}cl$	angle between γ (slow component) and cleavage
$\alpha^{\wedge}cl$	angle between α (fast component) and cleavage
k	absorption coefficient
R	reflectance (usually expressed as a percentage, R%)
R_{\min}	minimum reflectance of a polished section of a bireflecting mineral grain
R_{\max}	maximum reflectance of a polished section of a bireflecting mineral grain

SYMBOLS AND ABBREVIATIONS

R_o	principal reflectance corresponding to ordinary ray vibration direction of a uniaxial mineral
R_e	principal reflectance corresponding to extraordinary ray vibration direction of a uniaxial mineral
ΔR	bireflectance ($R_{\max} - R_{\min}$) referring to individual section or maximum for mineral

Quantitative colour

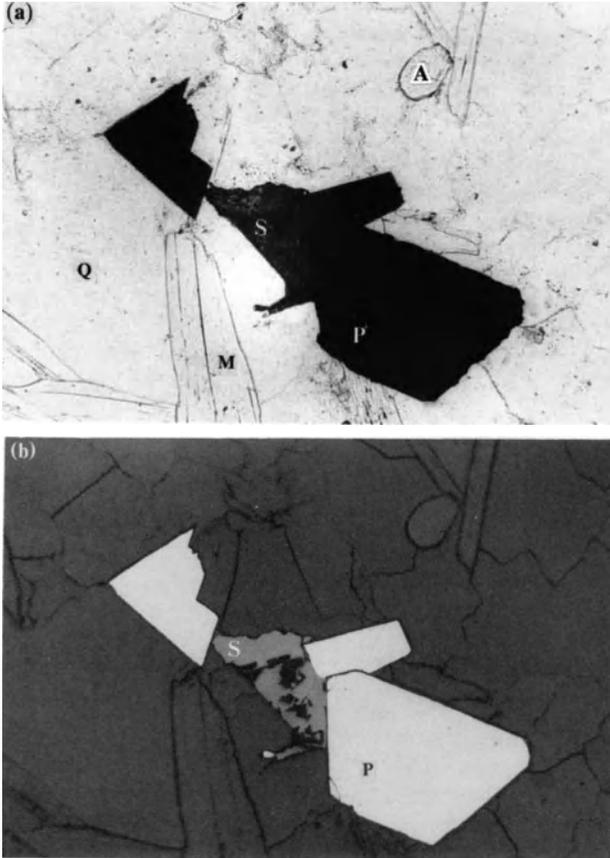
$Y\%$	visual brightness
λ_d	dominant wavelength
$P_e\%$	saturation
x, y	chromaticity co-ordinates

Mineral properties

VHN	Vickers hardness number
H	hardness on Moh's scale
D	density
SG	specific gravity

General

P	pressure
T	temperature
XRD	X-ray diffraction
REE	rare earth elements
nm	nanometre
μm	micrometre or micron
mm	millimetre
cm	centimetre
d	distance or length
\AA	angstroms
cl	cleavage
kb	kilobar
>	greater than
<	less than
\geq	greater than or equal to
\leq	less than or equal to
\sim	approximately
\approx	approximately equal to
\perp	perpendicular to
\parallel	parallel to
4+	four or greater
3D	three dimensional
Zn + Fe + S	association of elements in ternary chemical system
Zn - Fe - S	association of elements



Frontispiece Photomicrographs, taken using (a) transmitted light and (b) reflected light, of the same area of a polished thin section of quartzite containing pyrite (P), sphalerite (S), muscovite (M), apatite (A) and abundant quartz (Q).

The features illustrated in transmitted light are: (i) opacity – pyrite is the only opaque phase, sphalerite is semi-opaque, and the others are transparent; (ii) relief – very high (sphalerite, $n \approx 2.4$), moderate (apatite, $n \approx 1.65$), moderate (muscovite, $n \approx 1.60$), and low (quartz, $n \approx 1.55$); (iii) cleavage – perfect in muscovite (n is the refractive index of the mineral).

The feature illustrated in reflected light is reflectance: 54% (pyrite, white – true colour slightly yellowish white), 17% (sphalerite, grey), 6% (apatite, dark grey), 5% (muscovite, dark grey), and 5% (quartz, dark grey) (reflectance is the percentage of incident light reflected by the mineral).

Note that opaque grains, grain boundaries and cleavage traces appear black in transmitted light, whereas pits (holes), grain boundaries and cleavage traces appear black in reflected light.

1 Introduction to the microscopic study of minerals

1.1 Introduction

Microscopes vary in their design, not only in their appearance but also in the positioning and operation of the various essential components. These components are present in all microscopes and are described briefly below. Although dual purpose microscopes incorporating both transmitted- and reflected-light options are now available (Fig. 1.1), it is more convenient to describe the two techniques separately. More details on the design and nature of the components can be obtained in textbooks on microscope optics.

1.2 The transmitted-light microscope

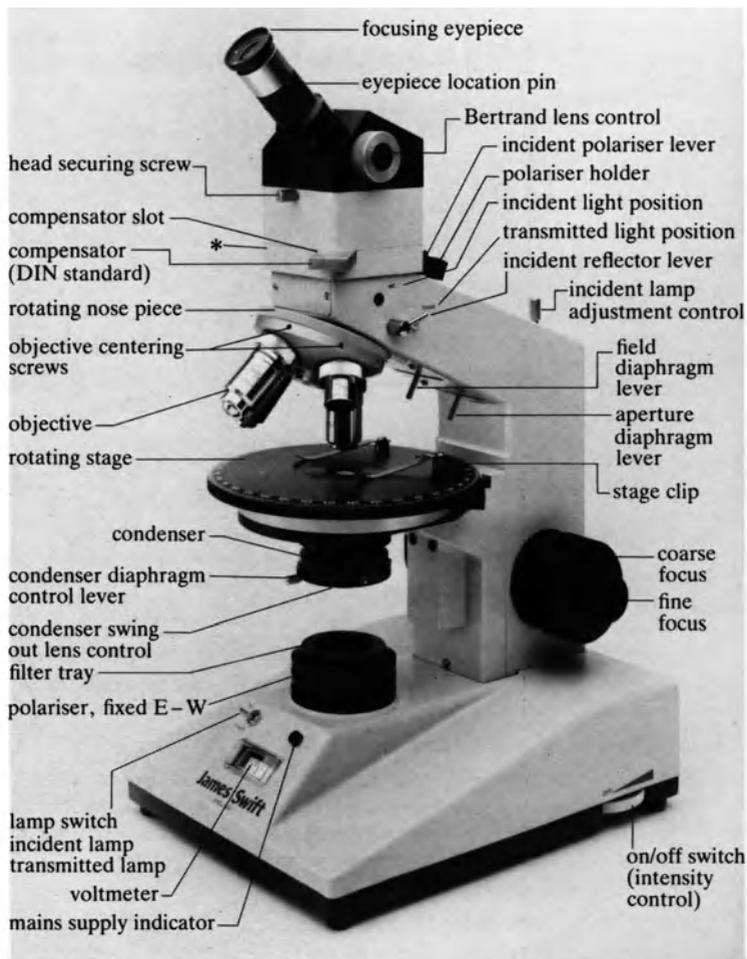
The light source

In transmitted-light studies a lamp is commonly built into the microscope base (Fig. 1.2). The typical bulb used has a tungsten filament (A source) which gives the field of view a yellowish tint. A blue filter can be inserted immediately above the light source to change the light colour to that of daylight (C source).

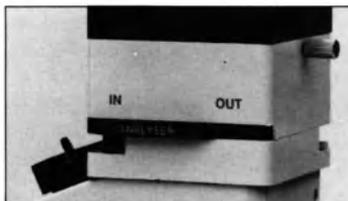
In older microscopes the light source is quite separate from the microscope and is usually contained in a hooded metal box to which can be added a blue glass screen for daylight coloured light. A small movable circular mirror, one side of which is flat and the other concave, is attached to the base of the microscope barrel. The mirror is used to direct the light through the rock thin section on the microscope stage, and the flat side of the mirror should be used when a condenser is present.

The polariser

The assumption is that light consists of electromagnetic vibrations. These vibrations move outwards in every direction from a point source of 'white' light, such as a microscope light. A polarising film (the polariser) is held within a lens system located below the stage of the microscope, and this is usually inserted into the optical path. On passing through the polariser the light is 'polarised' and now vibrates in a single



Model MP 3502M



*** Analyser**

The analyser is located on the left-hand side of the head mounting block on all MP3500 microscope models

Figure 1.1 The Swift Student polarising microscope (photo courtesy of Swift Ltd).

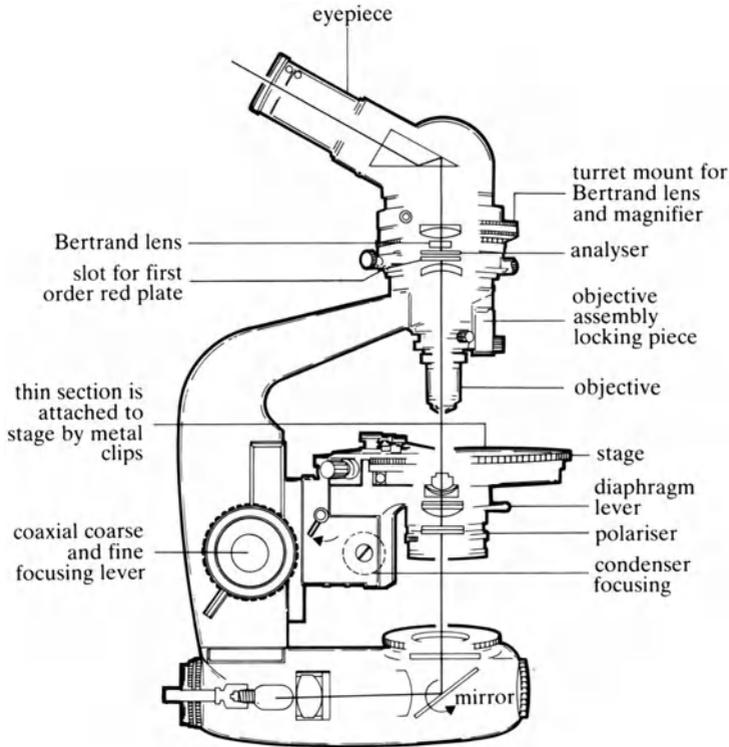


Figure 1.2 Modern transmitted light microscope. Older models may focus by moving the upper barrel of the microscope (not the stage as in the illustration), and may use an external light source. The illustration is based on a Nikon model POH-2 polarising microscope.

plane. This is called *plane polarised light* (PPL). In most UK microscopes the polariser is oriented to give E–W vibrating incident light (see also Ch. 4).

Substage diaphragms

One or two diaphragms may be located below the stage. The field diaphragm, often omitted on simple student microscopes, is used to reduce the area of light entering the thin section, and should be in focus at the same position as the thin section; it should be opened until it just disappears from view. The aperture diaphragm is closed to increase resolution; it can be seen when the Bertrand lens is inserted.

The condenser or convergent lens

A small circular lens (the condenser) is attached to a swivel bar, so that it can be inserted into the optical train when required. It serves to direct a cone of light on to the thin section and give optimum resolution for the

objectives used. The entire lens system below the microscope stage, including polariser, aperture diaphragm and condenser, can often be racked upwards or downwards in order to optimise the quality of illumination. Some microscopes, however, do not possess a separate convergent lens and, when a convergent lens is needed, the substage lens system is racked upwards until it is just below the surface of the microscope stage.

Stage

The microscope stage is flat and can be rotated. It is marked in degrees, and a side vernier enables angles of rotation to be accurately measured. The stage can usually be locked in place at any position. The rock thin section is attached to the centre of the stage by metal spring clips.

Objectives

Objectives are magnifying lenses with the power of magnification inscribed on each lens (e.g. $\times 5$, $\times 30$). An objective of very high power (e.g. $\times 100$) usually requires an immersion oil between the objective lens and the thin section.

Eyepiece

The eyepiece (or ocular) contains crosswires which can be independently focused by rotating its uppermost lens. Eyepieces of different magnification are available. Monocular heads are standard on student microscopes. Binocular heads may be used and, if correctly adjusted, reduce eye fatigue.

The analyser

The analyser is similar to the polariser; it is also made of polarising film but oriented in a N-S direction, i.e. at right angles to the polariser. When the analyser is inserted into the optical train, it receives light vibrating in an E-W direction from the polariser and cannot transmit this; thus the field of view is dark and the microscope is said to have *crossed polars* (CP, XPOLS or XP). With the analyser out, the polariser only is in position; plane polarised light is being used and the field of view appears bright.

The Bertrand lens

This lens is used to examine interference figures (see Section 1.3.2). When it is inserted into the upper microscope tube an interference figure can be produced which fills the field of view, provided that the convergent lens is also inserted into the optical path train.

The accessory slot

Below the analyser is a slot into which accessory plates, e.g. quartz wedge, or first order red, can be inserted. The slot is oriented so that

accessory plates are inserted at 45° to the crosswires. In some microscopes the slot may be rotatable.

Focusing

The microscope is focused either by moving the microscope stage up or down (newer models) or by moving the upper microscope tube up or down (older models). Both coarse and fine adjusting knobs are present.

1.3 Systematic description of minerals in thin section using transmitted light

Descriptions of transparent minerals are given in a particular manner in Chapters 2 and 3, and the terms used are explained below. The optical properties of each mineral include some which are determined in plane polarised light, and others which are determined with crossed polars. For most properties a low power objective is used (up to $\times 10$).

1.3.1 Properties in plane polarised light

The analyser is taken out of the optical path to give a bright image (see Frontispiece).

Colour

Minerals show a wide range of colour (by which we mean the natural or 'body' colour of a mineral), from colourless minerals (such as quartz and feldspars) to coloured minerals (brown biotite, yellow staurolite and green hornblende). Colour is related to the wavelength of visible light, which ranges from violet (wavelength $\lambda = 0.00039$ mm or 390 nm) to red ($\lambda = 760$ nm). White light consists of all the wavelengths between these two extremes. With colourless minerals in thin section (e.g. quartz) white light passes unaffected through the mineral and none of its wavelengths is absorbed, whereas with opaque minerals (such as metallic ores) all wavelengths are absorbed and the mineral appears black. With coloured minerals, selective absorption of wavelengths take place and the colour seen represents a combination of wavelengths of light transmitted by the mineral.

Pleochroism

Some coloured minerals change colour between two 'extremes' when the microscope stage is rotated. The two extremes in colour are each seen twice during a complete (360°) rotation. Such a mineral is said to be pleochroic, and ferromagnesian minerals such as the amphiboles, biotite and staurolite of the common rock-forming silicates possess this property.

Pleochroism is due to the unequal absorption of light by the mineral in different orientations. For example, in a longitudinal section of biotite, when plane polarised light from the polariser enters the mineral which has its cleavages parallel to the vibration direction of the light, considerable absorption of light occurs and the biotite appears dark brown. If the mineral section is then rotated through 90° so that the plane polarised light from the polariser enters the mineral with its cleavages now at right angles to the vibration direction, much less absorption of light occurs and the biotite appears pale yellow.

Habit

This refers to the shape that a particular mineral exhibits in different rock types. A mineral may appear euhedral, with well defined crystal faces, or anhedral, where the crystal has no crystal faces present, such as when it crystallises into gaps left between crystals formed earlier. Other descriptive terms include prismatic, when the crystal is elongate in one direction, or acicular, when the crystal is needle like, or fibrous, when the crystals resemble fibres. Flat, thin crystals are termed tabular or platy.

Cleavage

Most minerals can be cleaved along certain specific crystallographic directions which are related to planes of weakness in the mineral's atomic structure. These planes or cleavages which are straight, parallel and evenly spaced in the mineral are denoted by Miller's indices, which indicate their crystallographic orientation. Some minerals such as quartz and garnet possess no cleavages, whereas others may have one, two, three or four cleavages. When a cleavage is poorly developed it is called a parting. Partings are usually straight and parallel but *not* evenly spaced. The number of cleavages seen depends upon the orientation of the mineral section. Thus, for example, a prismatic mineral with a square cross section may have two prismatic cleavages. These cleavages are seen to intersect in a mineral section cut at right angles to the prism zone, but in a section cut parallel to the prism zone the traces of the two cleavages are parallel to each other and the mineral appears to possess only one cleavage (e.g. pyroxenes, andalusite).

Relief

All rock thin sections are trapped between two thin layers of resin (or cementing material) to which the glass slide and the cover slip are attached. The refractive index (RI) of the resin is 1.54. The surface relief of a mineral is essentially constant (except for carbonate minerals), and depends on the difference between the RI of the mineral and the RI of the enclosing resin. The greater the difference between the RI of the mineral and the resin, the rougher the appearance of the surface of the mineral. This is because the surfaces of the mineral in thin section are

made up of tiny elevations and depressions which reflect and refract the light.

If the RIs of the mineral and resin are similar the surface appears smooth. Thus, for example, the surfaces of garnet and olivine which have much higher RIs than the resin appear rough whereas the surface of quartz, which has the same RI as the resin (1.54) is smooth and virtually impossible to detect.

To obtain a more accurate estimate of the RI of a mineral (compared to 1.54) a mineral grain should be found at the edge of the thin section, where its edge is against the cement. The diaphragm of the microscope should be adjusted until the edge of the mineral is clearly defined by a thin, bright band of light which is exactly parallel to the mineral boundary. The microscope tube is then carefully racked upwards (or the stage lowered), and this thin band of light – the Becke line – will appear to move towards the medium with the higher RI. For example, if RI_{mineral} is greater than RI_{cement} the Becke line will appear to move into the mineral when the microscope tube is slowly racked upwards. If the RI of a mineral is close to that of the cement then the mineral surface will appear smooth and dispersion of the refractive index may result in slightly coloured Becke lines appearing in both media. The greater the difference between a mineral's RI and that of the enclosing cement, the rougher the surface of the mineral appears. An arbitrary scheme used in the section of mineral descriptions is as follows:

RI	Description of relief
1.40–1.50	moderate
1.50–1.58	low
1.58–1.67	moderate
1.67–1.76	high
>1.76	very high

The refractive indices of adjacent minerals in the thin section may be compared using the Becke line as explained.

Alteration

The most common cause of alteration is by water or CO_2 coming into contact with a mineral, chemically reacting with some of its elements, and producing a new, stable mineral phase(s). For example, water reacts with the feldspars and produces clay minerals. In thin section this alteration appears as an area of cloudiness within the transparent feldspar grain. The alteration may be so advanced that the mineral is completely replaced by a new mineral phase. For example, crystals of olivine may have completely altered to serpentine, but the area occupied by the serpentine still has the configuration of the original olivine crystal. The olivine is said to be pseudomorphed by serpentine.