ORE MINERALOGY

Oskar A. Thalhammer
University of Leoben, Austria

Aberra Mogessie
University of Graz, Austria

Keywords: ore minerals, ore deposits, elements, sulfides, oxides, epigenetic, syngenetic, vein, hydrothermal, magmatic, placer, skarn, reflected microscopy

Contents

Summary

This article is divided into two parts. The first part (Sections 1–4) deals with the theory of ore mineralogy and the practical aspects of reflected light ore microscopy. The theoretical part includes a discussion of the common optical properties of elements, oxides, and sulfides under the reflected light microscope. The second part (Section 5) deals with a brief overview of mineral deposits and their classification. Although there are a large number of mineral deposits, this article takes into consideration only a few general themes as type examples. The mineral deposits outlined and discussed are hydrothermal, syngenetic, epigenetic (vein, porphyry), skarn, magmatic, and placer.

1. Introduction to Ore Mineralogy

An ore is a naturally occurring rock or material composed of a mineral or minerals of economic value that can be extracted at a reasonable profit. This section focuses particularly on the types of ore minerals and the microscopic investigation of metalliferous materials. We do not refer to industrial minerals such as carbonates, micas, and feldspars, which will be discussed in Chapter 6 of the Encyclopedia. Ore minerals generally show a high density and a metallic luster, compared with semimetallic and nonmetallic minerals. Therefore, ore minerals are not transparent and thus cannot be investigated microscopically under transmitted light. During the first part of the eighteenth century, scientists (e.g., Lieberkühn) invented another method of microscopic investigation, namely the "reflected light microscopy." The necessity of such an investigation technique is simply based on the fact that the minerals under consideration are of economic value, representing the raw material for numerous final metalliferous products. The microscopic investigation of these ore minerals is thus of high priority for anybody involved in the prospecting of ore-mineral deposits, the extraction of these minerals (i.e., the mining industry), in their refractory and metallurgical treatment, and for those responsible for the final products. From 1920 ore microscopy received a real impetus, mainly due to the very detailed systematic work of Paul Ramdohr. In the times when mineralogists had no electron microprobe or scanning electron microscope available, Paul Ramdohr was able to identify several hundreds of ore-mineral phases under the reflected-light microscope qualitatively with the additional use of etching techniques. These systematic studies resulted in the publication of the first edition of *Die Erzmineralien und ihre Verwachsungen* [*The Ore Minerals and their Intergrowths*] in 1950.

2. Characteristic Physical Properties of Ore Minerals

In this section we briefly discuss the most common characteristic properties of ore minerals that are used to distinguish them in reflected light.

2.1. Hardness

There are numerous ways of estimating hardness in polished surfaces. The relative hardness of minerals can be estimated by the depth and the width of existing scratches from the grinding and polishing procedure (Figure 3a). With some experience a relative hardness estimate can also be made by carefully observing grain boundaries of

coexisting minerals. When a specimen is polished, obviously the harder minerals will be cut less than the softer and thus stand in positive relief with respect to the softer. The boundary between the two minerals appears then as a coarse, thick contour.

Another possibility of relative determination of hardness is the Kalb hardness. At the junction of a hard and soft grain, there tends to be a slight departure from flatness. This effect can be observed by a white line, the Schneiderhöhn line, which is analogous to the Becke line. As the distance between the objective lens and the polished section is increased (i.e., the stage is lowered) the white line will move into the softer mineral.

The hardness can also be measured quantitatively by a microhardness tester. One objective of the microscope is replaced by a diamond octahedron oriented downward. A shutter release applies the load of the diamond. The fall of the diamond onto the grain leaves a square indentation on the section. The volume or the diameter of the square is measured and compared with a series of tables of known hardness of minerals. This hardness is the Vickers hardness.

2.2. Texture

Some opaque minerals exhibit special textures of the polished surface, such as the intersection of orthogonal cleavages in galena (PbS), which gives rise to prominent triangular pits. There are numerous other textural features such as the shape of the mineral, cleavage, zonation, specific exsolution textures, and so on that are beyond the scope of this section and should be the main target for the more advanced stage of ore microscopy.

2.3. Optical Properties

2.3.1. Reflectivity

Reflectivity is defined as the ratio of the intensity of the light reflected by a mineral to the intensity of the light incident upon it, expressed in percent with a variation from below 10% to nearly 100% in opaque substances. The qualitative degree of reflectivity is judged in comparison with a known mineral. It must be considered that the visual impression of the reflectivity is influenced markedly by the effect of contrast to neighboring crystals with higher or lower reflectivity. In an environment of highly reflecting crystals, a moderately reflecting crystal appears oppressed and pale or, conversely, will seem brighter than would correspond to its real reflectivity.

For example, consider a polished specimen of quartzose gangue with molybdenite (reflectivity R = 20.9–40.0%) and arsenopyrite (R = up to 52.0%). The molybdenite appears bright against the gangue, but when there is arsenopyrite in the field, the molybdenite is so dull that it hardly appears to be the same mineral as before. In general, the brightest crystal present in the field of vision determines the impression of brightness of the others. Oxides exhibit a reflectivity between 10% and 26%; sulfides lie in the range of 20–58%, and elements above 60%, as a rough estimate.

2.3.2. Reflectance Color

a. Microphotograph of chromite (Cr) irregularly rimmed by ferritchromite (FCr).
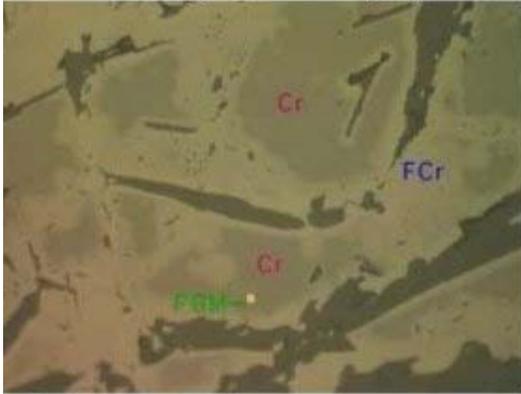
b. Microphotograph of a massive, gold-bearing sulfide ore.
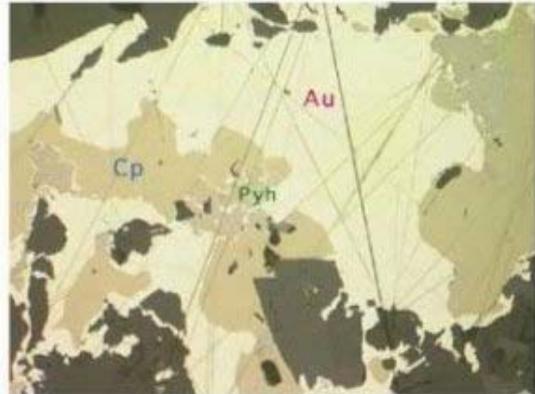
c. Microphotograph of magnetite (Magn) and ilmenite (Ilm).
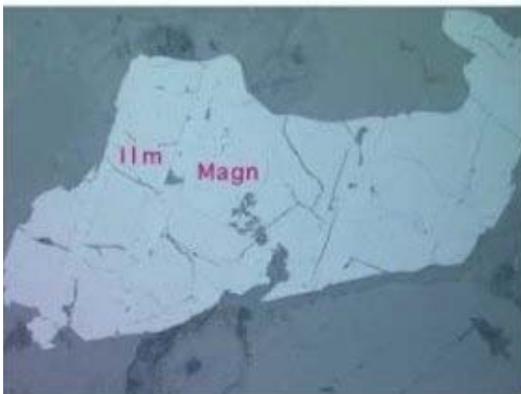
d. Microphotograph of a typical magmatic ore association, composed of pyrrhotite (Pht) with exsolved inclusions of pentlandite (Pent) and zoned magnetite (Mgt).

e. Microphotograph of chromite (Cr) patches
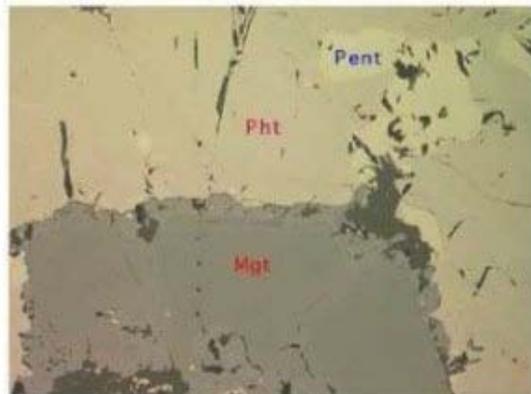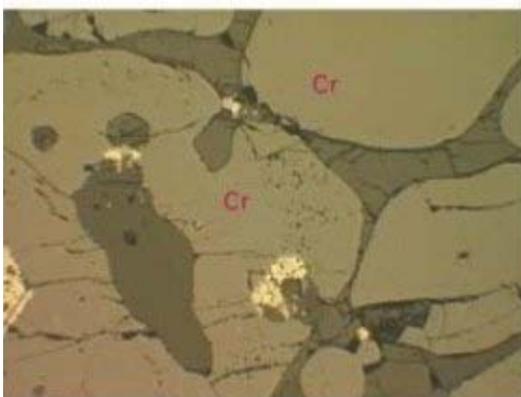
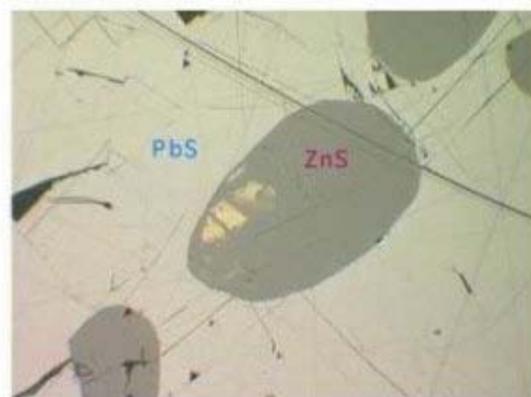f. Microphotograph of coarse-grained Pb-Zn-ore.

Figure 1. Microphotographs.

a. Microphotograph of chromite (Cr) irregularly rimmed by ferritchromite (FCr). In the lower part is a tiny little inclusion of a platinum-group mineral (PGM), in this case a laurite (RuS$_2$), visible. Note the higher reflectance of ferritchromite compared to chromite. Photograph taken under reflected light, parallel nicols, magnification × 500. Sample from a chromitite of the Kraubath ultramafic massif, eastern Alps, Austria.

b. Microphotograph of a massive, gold-bearing sulfide ore. Native gold (Au) closely intergrown with chalcopyrite (Cp) and pyrrhotite (Pyh). Note the very high reflectance of gold and its softness displayed by deep scratches. Photograph taken under reflected light, parallel nicols, magnification × 100. Sample from Rotgülden, eastern Alps, Austria.

c. Microphotograph of magnetite (Magn) and ilmenite (Ilm). Ilmenite forms parallel exsolution lamellae in magnetite. Note the apparent high reflectance of both oxides due to the dark surrounding of silicate phases (dark gray). Photograph taken under reflected light, blue filter, parallel nicols, magnification × 200. Sample from a granodioritic intrusion in northwestern New South Wales, Australia.

d. Microphotograph of a typical magmatic ore association, composed of pyrrhotite (Pht) with exsolved inclusions of pentlandite (Pent) and zoned magnetite (Mgt). Note the gray reflectance color of magnetite in association with distinctly higher reflecting sulfides. Photograph taken under reflected light, parallel nicols, magnification × 100. Sample from the komatiite-type Raglan Ni-deposit in northern Quebec, Canada.

e. Microphotograph of chromite (Cr) patches. This shape of chromite aggregates is typical for podiform chromitites. The dark gray inclusions in chromite are olivine and orthopyroxe. The interstitial space between the chromites is formed by serpentinized olivine. Photograph taken under reflected light, parallel nicols, magnification × 100. Sample from the Kempirsai massif, Kazakhstan.

f. Microphotograph of coarse-grained Pb-Zn-ore. Sphalerite (ZnS), ovally shaped, is closely intergrown with galena (PbS). Note the very obvious internal reflections of sphalerite in yellowish color. Photograph taken under reflected light, parallel nicols, magnification × 200. Sample from an unknown locality in the eastern Alps, Austria.

The colors of ore minerals, which range from pure white to gray, are one of their most characteristic and useful properties. As color is a function of the character of the human eye, each observer must make his or her own descriptions of the colors of minerals and must not be disconcerted if the pale cream mineral they have just observed is described as light yellow by someone else, for instance.

It is important to note that a difference in reflectivity can affect the eye, and where two minerals have a similar color but different reflectivity, the one of higher reflectivity appears the clearer because of its greater brightness. The color of a mineral is strongly influenced by the color of neighboring crystals—mutual color interference. For example, chalcopyrite (CuFeS$_2$) by itself has a characteristic and easily recognizable yellow color. Inside sphalerite (ZnS), it appears a very clear yellow, but in contrast with native gold, it appears a dull greenish yellow (Figure 1b). In addition, color is a function of the index

of refraction (RI) of the immersion medium—the medium comprising the space between the objective and the surface of the mineral. Covellite (CuS) in air (RI = 1.00) is deep blue, in cedar oil (RI = 1.515) red violet, and in methelene iodide (RI = 1.74) orange red.

2.3.3. Bireflectance and Reflection Pleochroism

Isometric minerals—for example, pyrite (FeS_2), galena (PbS), and pentlandite ((Ni, Fe)$_9S_8$)—remain unchanged in color and brightness as the stage of the microscope is turned. Many minerals of the other crystal systems (i.e., anisotropic minerals), however, show distinct changes in brightness or color, or both, with rotation of the stage, and grains of differing orientation side by side in a section differ in color or brightness. The effects are analogous in appearance to the pleochroism shown by transparent minerals in transmitted light. Bireflectance or bireflexion is the change in intensity of the light reflected from a mineral as it is rotated on the microscope stage. Reflection pleochroism is the variation in tint of a colored mineral observed as it is rotated on the microscope stage. A pleochroic mineral is by necessity also bireflectant.

The bireflectance depends on the difference between the two reflectivities whereas the pleochroism depends on the differences between the dispersions of the two reflectivities. It must be remembered that for a given mineral, the intensity of the bireflectance varies with the orientation of the section and that the highest bireflectance observed for the mineral in a polished section is not necessarily the maximum for the mineral. For example, only a vertical section of a uniaxial mineral (//C) will show the maximum bireflectance for the mineral.

2.3.4. Anisotropy and Polarization Colors

To observe these phenomena, the analyzer and polarizer must be crossed. When the stage of the microscope is rotated with the polars crossed, it is noticeable that certain ore grains remain dark; these are referred to as "uniradial sections" (monoreflecting) and are either isometric minerals or else basal sections of some uniaxial mineral. These basal sections can be recognized as such because different sections of the same mineral are bireflecting.

Under crossed polars an anisotropic mineral will show a change in intensity of illumination or color of illumination, or both, as the stage is rotated. The observed colors are referred to as polarization colors and are often highly characteristic and useful in mineral identification. If the nicols are exactly crossed, then in general in a 360° rotation of the stage there will be four positions of maximum darkness—extinction positions—90° apart, alternating with four positions of maximum illumination lying at about 45° to the positions of darkness. Examples of distinctly anisotropic minerals are pyrrhotite (FeS), molybdenite (MoS_2), and arsenopyrite (FeAsS). Weakly anisotropic minerals such as chalcopyrite ($CuFeS_2$) should be viewed very carefully in strong light. In many cases it is best to view adjacent grains while rotating the stage of the microscope, rather than try to see light and dark positions in a single grain.

2.3.5. Internal Reflections

Many ore specimens—for example, sphalerite (ZnS)—are sufficiently translucent or transparent to admit incident light to substantial depths below the surface of the specimen. If this light is reflected back up through the tube of the microscope by a cleavage crack, grain boundary, or some other subsurface feature, it will assume the color of the mineral in transmitted light. Most internal reflections are in the range from red to brown to yellow (e.g., hematite (Fe_2O_3) shows red, sphalerite yellow internal reflections) (Figure 1f). It is mostly not the color of internal reflections of different minerals that is useful in the determination of minerals, but rather the presence or absence of internal reflections and, where present, their frequency and intensity.

3. Reflected-Light Microscopy

3.1. Theory

The theory of reflected light is very complex compared to that of transmitted light, due to the fact that light reflected from a polished surface obeys, generally, the law of specular reflection, but some light is still diffused. However, an understanding of the theory of reflected light is much less relevant in the identification of ore-mineral phases when compared to mineral identification under transmitted light; therefore only a few basic principles will be discussed here, as they are important for the practical application of ore microscopy.

3.1.1. The Reflectance of Opaque Mineral Phases

When light passes through a transparent medium, only a very small amount of the light is absorbed. These media have an absorption coefficient $k = 10^{-4}$. If k is in the order of 10^{-1}, almost no light can pass through this medium and it is termed "not transparent" or "opaque." When light is sent onto the polished surface of an opaque mineral, most of the light will be reflected. The amount of light reflected depends on the refractive index n of the mineral and on its absorption coefficient k. The reflectance R is thus given by the modified Fresnel equation:

$$R = \frac{(n - n_0)^2 + k^2}{(n + n_0)^2 + k^2} \tag{1}$$

where n_0 is the refraction index of the immersion medium (i.e., the surrounding of the particular medium) and n is the refraction index of the mineral of interest. To consider the refraction index n_0 of the surrounding medium is a very important factor and has to be kept in mind when investigating opaque mineral phases under the reflected light. This implies that the surrounding medium determines the general impression of brightness of a particular opaque phase. Magnetite, for instance, has a reflectance of 20.7% and shows a reflectance color of gray when occurring together with sulfides with an average reflectance between 45% and 50%. However, magnetite being surrounded by very low reflecting silicates (e.g., having an average reflectance of less than 10%) appears almost white.

Eq. (1) applies to all cubic minerals. For uniaxial and biaxial minerals the same principal relationship holds, but due to two and three different crystallographic directions, respectively, maximum and minimum reflections are obtained:

$$R_1 = \frac{(n_1 - n_0)^2 + k_1^2}{(n_1 + n_0)^2 + k_1^2} \qquad R_2 = \frac{(n_2 - n_0)^2 + k_2^2}{(n_2 + n_0)^2 + k_2^2} \qquad (2)$$

Maximum and minimum reflections (i.e., the bireflection) will only be obtained when the vibrating direction of the incident light coincides with one or the other principal direction. Sections cut parallel to the crystallographic c-axis show the maximum bireflection of a uniaxial mineral. For minerals of lower symmetry there is only one section exhibiting the maximum bireflection. In practice, in a polished section a particular mineral may not exhibit the maximum bireflection because it is cut variably. The reflectance of an opaque mineral can be measured quantitatively. The first attempts go back to 1930 when Leitz put the first visual photometer on the market. Computerized photomultiplier-tube photometers are now in use for measuring the reflectivity of even small mineral grains (i.e., down to 1 μm in diameter), as well as for studying coal constituents.

-
-
-

TO ACCESS ALL THE **37 PAGES** OF THIS CHAPTER,
Visit: http://www.eolss.net/Eolss-sampleAllChapter.aspx

Bibliography

Barnes J.W. (1988). *Ores and Minerals: Introducing Economic Geology*, 181 pp. Maidenhead, UK: Open University Press. [This presents introductory topics in an understandable manner.]

Charles S.H. (1987). *Sample Deposits and their Tectonic Setting*, 365 pp. Oxford:Macmillan Education Ltd. [This is an important reference for economic deposits related to different tectonic regimes.]

Criddle A.J. and Stanley C.J. (1986). *The Quantitative Data File for Ore Minerals of the Commission on Ore Microscopy of the International Mineralogical Association*, 420 pp. London: British Museum (Natural History). [This is a standard reference work, useful for the identification of ore minerals.]

Evans A.M. (1993). *Ore Geology and Industrial Minerals: An Introduction, Third Edition*, 389 pp. Oxford: Blackwell Scientific Publications Inc. [This is a standard reference book used by economic geology students and researchers on ore deposits and industrial minerals.]

Guilbert J.M. and Park C.F. Jr. (1986). *The Geology of Ore Deposits*, 985 pp. New York: W.H. Freeman and Co. [This presents a detailed description of ore deposits with a number of interesting examples.]

Harris D.C. and Cabri L.J. (1991). Nomenclature of platinum-group-element alloys: review and revision. *Canadian Mineralogist* **29**, 231–237. [This presents a review of platinum-group-element nomenclature from the authorities in this field.]

Kruger F.J. and Schoenberg R. (1998). Isotope evidence for the origin of PGE rich Bushveld Chromitites and the Merensky Reef by felsic magma mixing. *8th International Platinum Symposium Abstracts, The Geological Society of South Africa and the South African Institute of Mining and Metallurgy, Symposium Series S18*, pp. 185–188. [This presents some isotope data and discusses the origin of platinum-group-elements in the chromitites of the world-famous intrusion: the Bushveld Complex in South Africa.]

Kullerud G., Yund R.A., and Moh G.H. (1969). Phase relations in the Cu-Fe-S, Cu-Ni-S, and Fe-Ni-S systems. *Economic Geology Monograph* **4**: 323–343. [This presents phase petrologic data for sulfide bearing-Cu-Fe and Ni systems.]

McKinstry H.E. (1948). *Mining Geology*, 680 pp. Englewood Cliffs, NJ: Prentice Hall. [This presents an intensive discussion on theoretical and practical aspects of mining geology.]

Palache C., Berman H., and Frondel C. (1944). *Dana's System of Mineralogy, Seventh Edition*, Vol. I, 834 pp. New York: John Wiley and Sons. [This presents a comprehensive database of minerals.]

Peters W.C. (1978). *Exploration and Mining Geology*, 696 pp. New York: John Wiley and Sons Inc. [This is an extensive reference work for methods of mineral exploration and mining geology.]

Picot P. and Johan Z. (1982). *Atlas of Ore Minerals*, 458 pp. Orleans Cedex, France: BRGM, and Amsterdam: Elsevier. [This is a useful reference manual for the identification and description of ore minerals under reflected light microscopy.]

Ramdohr P. (1980). *The Ore Minerals and their Intergrowths*, 1205 pp. Oxford, UK: Pergamon Press. [This is one of the most important reference works on ore minerals and their textural relations, written by the authority in this field.]

Roberts R.G. and Sheahan P.A. (1988). *Ore Deposit Models: Geoscience Canada, Reprint Series 3*, 194 pp. St John's, Newfoundland: Geological Association of Canada. [This presents a summary of ore-deposit models in an understandable manner.]

Spry P.G. and Gedlinske B.L. (1987). *Tables for the Determination of Common Opaque Minerals*, 52 pp. Newhaven, CT: The Economic Geology Publishing Co. [This presents a list of important characteristics of ore minerals useful for identification purposes.]

Wuensch B.J. (1974). Sulfide crystal chemistry, sulfide mineralogy, *Reviews in Mineralogy* (ed. P.H. Ribbe), pp. 21–44. Chelsea, Michigan. [This presents review articles on sulfide crystal chemistry written by well-known authorities in this field.]

Zoltai T. and Stout J.H. (1984). *Mineralogy: Concepts and Principles*, 505 pp. Minneapolis, USA: Burgess Publishing Co. [This is an important reference work and textbook for mineralogy students and for those interested in understanding the concepts of mineralogy and petrology.]

Zussman J. (1967*). Physical Methods in Determinative Mineralogy*, 514 pp. London and New York: Academic Press. [This is a standard book with reference material for understanding the physical methods used in determinative mineralogy.]

Biographical Sketches

Oskar A.R. Thalhammer has held the position of Associate Professor of Mineralogy and Petrology at the Institute of Geological Sciences, Department of Mineralogy and Petrology, University of Leoben, Austria since 1995. He carried out his undergraduate studies at the Institute of Paleontology and Geology, Karl-Franzens University, Graz, Austria, and received a Ph.D. degree from the same institution in 1982. He occupied the positions of lecturer and senior lecturer in Economic Geology and Mineralogy at the Institute of Geological Sciences, University of Leoben from 1983 to 1987, and from 1990 to 1993. He worked as an Erwin Schrödinger Scholar and part-time lecturer at the Department of Geology, the University of Newcastle, NSW, Australia during 1988 and 1990, and as a guest professor at the

Department of Geology and Geophysics, the University of Adelaide, South Australia in 1994. Apart of that he has spent various short periods (2–4 months) on research visits at the Department of Geology, University of Oulu, Finland; Department of Geosciences, North Dakota State University, Fargo, USA; and IGEM, Academy of Sciences, Moscow, Russia.

His main research interests comprise mineralizations in mafic–ultramafic rocks (layered intrusions, ophiolites, and zoned massifs), with particular reference to precious metal and chromite deposits (mineralogy, geochemistry, petrology, and radioactive and stable isotopes); vein-type gold deposits hosted (structure of veins and host rocks, geochemistry, mineralogy, and isotopes); platinum-group element and Au mineralizations in black shales (mineralogy, geochemistry, and stable isotopes); as well as lead-zinc deposits hosted in carbonate sediments ("Bleiberg type"). Furthermore, his interests also include separation and concentration techniques of precious minerals and various ores (electric-pulse disintegration and hydro-separation technique).

He received the "Best Paper Award of *Mineralium Deposita*" for 1999 and 2000 in 2001 (together with F. Melcher, W. Grum, and T.V. Thalhammer). He has 19 years of experience in teaching various subjects of geological sciences (mineralogy, petrology, economic geology, structural geology, and geochemistry) in German and English, and the supervision of M.Sc. and Ph.D. projects. Oskar A. R. Thalhammer is a member of the editorial board of *Mineralium Deposita* and a member of numerous scientific institutions.

Aberra Mogessie is Editorial Advisory Board member of the *Journal of African Earth Sciences*, Fellow of the Society of Economic Geologists and a member of several national and international scientific associations, and reviewer of scientific articles for a number of international journals. He has several years of teaching experience (both in English and German) in different fields of earth sciences (mineralogy, petrology, geochemistry and ore mineralogy) at the University of Addis Ababa, Ethiopia, University of Innsbruck, Mining University of Leoben and the University of Graz in Austria and has advised several masters and Ph.D students. In addition to teaching and research activities, he has served as chair of the Institute of Mineralogy and Petrology, University of Graz, Austria.