APPLIED MINERALOGY AND THE INDUSTRIAL USE OF MINERALS

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Keywords: applied mineralogy, technical mineralogy, mineral deposits, mineral processing, materials, materials development, materials science, materials properties, ceramics, phase analysis, chemical analysis

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Summary

Applied mineralogy as addressed in this chapter is the mineralogical materials science. It concentrates on anorganic non-metal materials and comprises all aspects of their analysis, sampling, preparation, synthesis, property determination and evaluation. Applied mineralogy overlaps with the appropriate sections of other physico-chemical, technical and life sciences.

Many important technical products of industry come from the use of natural occurring minerals, the use of some of the most common is reviewed here.

1. Introduction

The terms “applied” and “technical mineralogy” are makeshift expressions which address a number of historically grown fields of mineralogy. The very root of mineralogy comes from the Greek word "*mina*" (shaft), and points to the fact that the first reason to have a closer look at types of naturally occurring more or less homogeneous solid matter (a rough definition of minerals) was to be able to use them.

Even though in some countries the name "technical mineralogy" has some tradition, it is avoided in this article because it gives the nonspecialist the impression of a subject only concerned with technical problems of mineral handling, and without its own basic natural science aspects and foundations.

Mineralogy is highly tied to the development of suitable methods to analyze solids (see *Modern XRD Methods in Mineralogy* and *Analytical Techniques for Elemental Analysis of Minerals*), which enable the mineralogist to investigate the chemical composition and the atomic structure of matter, to categorize the natural phase assemblages ("paragenesis"), and to infer the processes and conditions (chemistry, temperature, pressure) that gave the matter its specific character.

Therefore basic mineralogical methods are applied, for example to rocks in petrology or to single crystals in crystallography. The methodological aspects make mineralogists from basic research directly useful for work in an industrial context. But this is usually not meant when speaking of applied or technical mineralogy.

The methodological basis of mineralogy is also responsible for the extension of mineralogy to non- natural solid matters. Synthetic mineral-like solids have come to be included in the practical use of the term "mineral," and nowadays nearly nobody worries about calling SiC, for example, a mineral, even though the natural occurrence as "moissianite" is limited to extremely rare cases in some sediments and meteorites, while the worldwide annual production capacity of this product is in the range of a million tonnes.

Several fields in mineralogy are applied in the meaning "directly concerned with economical or ecological processes or matter":

1. the science of ores and mineral deposits
2. environmental mineralogy
3. mineralogical materials science and processing

From these areas of applied mineralogy in the wide sense, only the last one is addressed as applied mineralogy in the narrow sense, or technical mineralogy. Before the role of mineralogists in materials science and materials processing is explained, there follows a short introduction on the industrial use of more common natural minerals.

2. The Industrial Use of Natural Non-Ore Minerals

A huge range of products used in industrialized societies is mineralic or mineral-based, from clays and sands for buildings to metals and semiconductors, which ultimately come from ores or mineral deposits. The production of the most common industrial minerals (clays, sand, gravel, limestone, silica) is so vast, ranging to billions of tonnes annually, that secure world data are not available. Table 1 lists important non-ore minerals and their major applications, which are outlined in more detail below.

Mineral	**Million tonnes**	**Major use**
Barite	6	Drill fluids, television glass
Borate minerals	4	Glass
Feldspar	9	Glass, pottery
Fluorspar	4	Metallurgical use
Magnesite	3	Refractories
Potash	26	Fertilizers
Talc	9	Ceramics, paint
Rutile/Ilmenite	9	Paper, paint, steel
Zircon	1	High-tech, nuclear

Source: after the US Geological Survey.

Table 1. Annual rounded world production figures and major uses of some common minerals in 2000. Source: after the US Geological Survey.

This list is by no means complete. Each of the approximately 4000 known minerals is potentially of economic value, if it is found in sufficient quantities and purities. And the listing is biased by the choice of non-ore minerals, because ores are also the source for many nonmetal products. Bauxite is for example a naturally occurring heterogeneous material composed primarily of aluminum hydroxide minerals, and more then 100 million tonnes are mined each year. Even though a major portion of the ore is used to produce aluminum, the same material is also converted to alumina (Al_2O_3), which is one of the most important materials found in refractories, as an abrasive, a catalyst, and in many other ceramic applications.

A very useful source of information for the industrial use and the consumption of minerals is the website of the US Geological Survey (http://minerals.usgs.gov/minerals).

In the following, an overview is given of the use of major non-ore minerals in industry, and the processes mineralogists have to control. Useful reference books and detailed information may be gained through www.mineralnet.co.uk. Material about the processing routes is often found in the literature on chemical technology.

Apart from its direct use in drilling fluids, barite ($BaSO_4$) is a mineral, which is mined to become converted by reaction with coal to the water soluble BaS, which in turn is reacted with CO_2 or carbonate to yield $BaCO_3$, a raw material for television glasses. Other uses are in the structural clay industry or the manufacture of magnetic ferrites. An increasing market for the dielectric/piezoelectric $BaTiO_3$ is likely.

Borate minerals like tincal ($Na_2O \cdot 2B_2O_3 \cdot 5H_2O$) and ulexite ($Na_2O$ $2CaO$ $5B_2O_3$ $16H_2O$) are mined and transformed into refined borates such as boric acid H_3BO_3, which are in demand because they are ingredients for a variety of vitreous products, such as fiberglass, laboratory glasses, glazes, and enamels.

Diamond, pure cubic carbon, is certainly known for its use as jewelry. However, the gems make up only a minor part of its usage compared to its application as an abrasive. Synthetic diamonds (see below) are increasingly displacing their natural counterparts, which already account for only 10% of the amount in industrial use. None the less the world mining efforts yielded about 58 million carats (11.6 tonnes) in the year 2000.

Feldspars belong to the group known as "rock-forming minerals," and as such they are found in enormous abundance on Earth's surface. They are solid solutions, usually primarily composed of $NaAlSi_3O_8$ (albite), $KAlSi_3O_8$ (potassium feldspar), and $CaAl_2Si_2O_8$ (anorthite); minable deposits are often in pegmatitic veins or in sands. Feldspars are a major component in glasses and pottery and other large-volume ceramic products such as tiles.

Fluorspar or fluorite (CaF_2) is found in veins and dykes, and is the main source for the production of hydrofluoric acid (HF), which is in turn the major source for virtually all fluorine-containing chemicals. Metallurgical important fluxes like AlF_3 are also made from fluorite.

Magnesite ($MgCO_3$) along with brucite ($Mg(OH)_2$) and dolomite ($CaMg(CO_3)_2$) are the economically important minerals that serve as raw material for magnesia (MgO) production. Magnesite is one of the major components of refractories for kilns, furnaces, and electric insulation. Alternative sources for MgO are seawater and brines.

The so-called "potash" (K_2O) resources are salt deposits (for example, sylvine KCl or langbeinite $K_2Mg_2(SO_4)_3$). Potash-containing minerals such as these chlorides, nitrates, and sulfates are major components of fertilizers.

Talc ($Mg_6[Si_8O_{20}](OH)_4$) as a soft mineral formed from ultrabasic rocks under hydrothermal conditions, or in metamorphic siliceous dolomites. It is used in many applications as an additive in ceramics, paper, roofing, and cosmetics.

The titanium oxides rutile (TiO_2) and ilmenite ($FeTiO_3$) are important raw materials for metal production, but other uses such as opacifier in enamels and paints are also of economic importance.

Zircon ($ZrSiO_4$) and baddeleyite (ZrO_2) are mined as byproducts of Ti-mineral mining. Their main use is as ceramics, opacifiers, refractories, or foundry applications.

These are a few examples of the very large-scale industrial use of natural non-ore minerals. There are many others, and some of the minerals used in smaller quantities are of strategic importance. Useful minerals have to be in reach of mining efforts; in other words, they should not be buried too deep in the Earth. To judge whether a mineral containing a certain element as a major phase is rare and of high price, it is useful to have a look at the average abundance of minor elements in Earth's crust to minable depth (Table 2). But this is not sufficient: the distribution and occurrence of suitable concentrated deposits has to be considered as well.

Element	**Parts per million (ppm)**	**Element**	**Parts per million (ppm)**
Fluorine	625	Cobalt	25
Strontium	375	Niobium	20
Sulfur	260	Lead	13
Carbon	200	Tin	2
Zirconium	165	Uranium	1.8
Vanadium	135	Molybdenum	1.5
Chlorine	130	Tungsten	1.5
Chromium	100	Mercury	0.08
Nickel	75	Silver	0.07
Zinc	70	Platinum	0.01
Copper	55	Gold	0.004

Table 2. Estimated average chemical contents of selected minor elements in the minable part of Earth's crust

3. Mineralogical Materials Science and Processing

The first issue to be covered here is the mineralogist's own strength, which is the broad analytic capabilities every mineralogical education will convey. The techniques in detail are discussed elsewhere in this encyclopedia. Here we only want to show the context related to applied mineralogy.

In most cases the mined mineral is not ready for use. Before it can be converted into a consumer product it has to be treated to become a saleable product. During these processes many mineralogists are active in the processing plants to ensure the quality of the processes and hence of the product.But it is not only the processing of natural minerals a mineralogist may work on. In several subdivisions we describe a number of steps from the mined mineral towards a saleable product—sampling, preparation, raw material production, ceramic processing—which are sometimes summarized under the heading "processing." Subsequently, the characterization of mineral properties and their use for the development of materials is addressed.

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Biographical Sketch

Klaus G. Nickel was born 1953 in Langen/Hessen (Germany). He had school and industrial education (chemical laboratory assistant) in Frankfurt and its vicinity before starting to study geology from 1975–1979 at the Johannes-Gutenberg University, Mainz. He obtained a Dipl.-Geol.) with the thesis: "Geological and petrologic investigations in the area of the Nahe valley between Norheim and Staudernheim with particular reference to the intermediate magmatites." Concentrating on petrologic problems, he received his Ph.D. working on experimental petrology under the supervision of D.H. Green (1979–1983) in the Faculty for Geosciences at the University of Tasmania, Hobart, Australia. His research was on "Petrogenesis of garnet and spinel peridotites. A study with particular reference to the role of chromium in geothermometry and geobarometry," with a strong focus on thermodynamic reasoning and modeling of phase relations.
From 1983–1986 he continued experimental work on geothermobarometry at the Max Planck Institute for Chemistry, Mainz, before changing subject to apply these methods to materials science. At the Max Planck Institute for Metals Research in Stuttgart, he participated in the development of Si_3N_4- and SiC-based materials for high temperature engineering applications from 1986–1991.
Specializing in thermal analysis with a main thrust on oxidation and corrosion-related problems, he became Professor for Applied Mineralogy at the Eberhard Karls University in Tübingen in 1991. Even though his work on corrosion problems still forms a major subject, his interests have substantially broadened to include work on dental and SOFC materials, carbon and silicon, processing, synthesis, and properties, with a balance between more applied (for example, Grain shape measurement) and more fundamental (for example, non-hydrostatic phase transformations) aspects.
He is a member of the coordination committee for advanced ceramics and the chairman of the working group "Corrosion of ceramic materials" of the German Ceramic Society and the German Society for Materials Research, and is the director of the mineralogical institute.