CHAPTER 4 THE PHYSICAL PROPERTIES OF MINERALS

142 parallel-fibrous aggregates, such as asbestos and some varieties of gypsum, are said to have silky luster. Transparent minerals with layer-lattice structures and accompanying perfect lamellar cleavage have characteristically pearly luster produced by reflection from successive cleavage surfaces; examples are talc, the micas, and coarsely crystallized gypsum. Porous aggregates of a mineral, such as the clays, scatter incident light so completely that they seem to be without luster and are described as dull or earthy. It can be shown that a mineral's refractive index and light absorption, and thus its reflectivity (luster), can be roughly correlated with its predominant bonding as follows: the indices of refraction are high, moderately high, and low for materials with predominantly metallic, covalent, and ionic bonding, respectively; the absorption of light is high, moderately low, and low for materials with these bonds, also respectively; consequently, the luster tends to be high, moderate,



Figure 4-3. The electromagnetic spectrum (to right), with colors of the visible light portion shown on the expanded section (to left). the brownish red color of some feldspars is very likely due to the presence of submicroscopic hematite, probably produced by exsolution of ferric iron that replaced aluminum in the feldspar structure when it first crystallized.

11. Interference of light that is macroscopically observable is essentially restricted to minerals containing thin films of air in cracks (e.g., "iris quartz") and minerals exhibiting surface tarnish (e.g., chalcopyrite and bornite). The colors seen, which are often compared to the iridescent films produced by oil on water, depend on the thickness of the film, the refractive index of the film material, and the character of the incident light.

12. Diffraction of light causes the colors perceived for some opal and labradorite. The principle involved is that which accounts for the combined scattering and interference of electromagnetic waves by diffraction gratings with appropriate spacings. Thus, the spacing of the domains, whatever their character and origin, that constitute the effective grating and the angle of observation are responsible for the color(s) perceived.

Several minerals not belonging to the isometric crystal system selectively absorb visible wavelengths differently in different directions. The result is that these minerals exhibit different colors when light is transmitted through them along different directions. This phenomenon, which is called *pleochroism*, is generally seen during microscopic examination using polarized light. Nonetheless, pleochroism can be observed in some mineral specimens by using only sunlight or common tungsten light bulbs. For example, cordierite (also called dichroite because of this feature) can be seen to transmit purple light when viewed in one direction and light yellow when viewed at right angles to that direction. It appears, in fact, that the Vikings recognized this property and used grains of cordierite and its reaction to

sunlight, which is partially plane-polarized, as a navigation aid.

Some colors of some minerals are changed when the minerals are submitted to heat treatment or atomic bombardment (e.g., exposure to X-rays, gamma rays, or neutron beams). Examples of such changes include the heating of brown zircons to render them blue, the heating of yellow topaz to change it to pink, and the atomic bombardment of off-color diamonds to make them light green or bluish. (The change in diamonds is generally restricted to an outer zone that is only a few tens of microns thick.) Heat treatments presumably cause the addition of sufficient energy to exceed that necessary for holding electrons in vacancy defects. In some cases, the original colors, either natural or artificially induced, can be restored by another of these processes. A general rule of thumb is that heat treatment will reverse results of atomic bombardment and vice versa. For example, smoky guartz can be made colorless by heating, and topaz that has been made pink by heating may be "reyellowed" by gammaray bombardment.

As with other properties of minerals, color and investigations relating to color have many applications. Several of these deal with gemstones and were determined on the basis of empirical observations and experimentation long before the pertinent theories were even hypotheses; the fundamental explanations of some of these applications are not well understood even today. Applications include several diverse things other than the heat treatments and atomic bombardment we just mentioned: Some minerals, because of their pleochroism, have to be cut according to a certain crystallographic orientation to exhibit their desired colors; for example, rubies with their table facets perpendicular to c exhibit their preferred purplish-red color, whereas rubies cut parallel to c are orange-red. Porous varieties of some minerals can be stained; for example, most brightly colored agates and turquois pieces have been soaked in solutions that have deposited pigments within their pores. There are, of course, several other diverse uses of mineral pig147

156 though not in all cases, means a hardness of 6 or more.

Since the bonding of a crystal structure is typically different in different directions, the hardness of a mineral may be expected to differ somewhat with crystallographic direction. Such variation is generally quite small, but in a few minerals, it is considerable. Thus, on the {100} cleavage surface of kyanite, the hardness is $4\frac{1}{2}$ in the direction of the c axis (i.e., parallel to the chains of silica tetrahedra) and $6\frac{1}{2}$ in the direction of the b axis (i.e., perpendicular to the chains). Also, on c{0001}, calcite has a hardness of $2\frac{1}{2}$, whereas on $r\{10\overline{1}1\}$, its hardness is 3. Such differential hardness in the case of diamond is of great practical importance; the {111} surface in a diamond crystal is the hardest surface known to man. This fact, coupled with diamond's {111} cleavage, enables diamond dust to be used to abrade all but octahedral planes of other diamonds.

There are, of course, several second-order generalizations; for example, the lesser the hardness, the lower the melting temperature. Also, with polymorphic pairs, but with exceptions, the ones formed at higher pressures tend to be denser and thus harder than the ones formed at lower pressures. And, hardness may increase with decreasing temperature; for example, the hardness of ice becomes approximately 6 at -40° C. In addition, a number of apparent anomalies are known; for example, hardness values for intermediate members of some solid-solution series are slightly greater than the hardness values for either end member.

Hardness, considered in conjunction with other properties related to strength, is important in gemology and also in the choice of minerals and other materials for use as abrasives, jewel bearings, and pressure equipment. Hardness is also important to several ore dressing considerations.

MAGNETIC PROPERTIES

Only a few minerals are attracted strongly by a simple bar or horseshoe magnet. Of these, the

most common are magnetite, Fe_3O_4 , pyrrhotite, $Fe_{1-x}S$, and maghemite, generally considered to be a polymorph of Fe_2O_3 . Some specimens of magnetite and maghemite are themselves natural magnets and thus will attract, for example, iron filings. When suspended, these specimens will orient themselves with their appropriate axes trending north-south; such specimens, generally called *lodestones*, were used in the earliest forms of compasses.

Actually, nearly all minerals are affected by a nonuniform magnetic field; that is, they react mechanically, to some greater or lesser extent, whenever they are placed in a magnetic field. Although it has been shown that there are five kinds of reactions—termed diamagnetism, paramagnetism, ferromagnetism, ferrimagnetism, and antiferromagnetism—only three different kinds are easily distinguished:

- Diamagnetism: The slight repulsion whereby a material moves, or tends to move, toward regions of weaker magnetic field strength; theoretically, this property is possessed by certain domains of all minerals.
- Paramagnetism: The slight attraction whereby material moves, or tends to move, toward regions of stronger magnetic field strength; this tendency varies directly with the strength of the applied magnetic field.
- Ferromagnetism: The strong attraction toward regions of strong magnetic field strength; these materials are also magnetic even outside a magnetic field, although most become more magnetic within such a field.

Macroscopically, ferrimagnetic materials react in the same way that ferromagnetic materials do, and antiferromagnetic materials exhibit no magnetism.

The understanding of magnetism in minerals and other crystalline materials is less than complete. Some of the especially pertinent aspects of magnetism follow:

1. Individual atoms are magnetic—both protons within nuclei and electrons in their surrounding orbital clouds are magnetic. The

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Figure 5-2. The system Ne-Tr (or Q)—i.e., NaAlSiO₄-SiO₂: (a) at 10 kb; (b) at 28 kb. Ne, nepheline; Jd, jadeite; Ab, albite; Q, quartz; Tr, tridymite; L, liquid (melt). (After Bell, P. M. and Roseboom, E. H. 1969, "Melting relationships of jadeite and albite to 45 kilobars with comments on melting diagrams of binary systems at high pressures." Mineralogical Society of America, Special Paper No. 2, 151–161.)

CaO; Na₂O, K₂O, and H₂O (C = 9), and its major phases are quartz, oligoclase-andesine, microcline, and hornblende (P = 4). As the phase rule implies, P does not exceed C. Furthermore, even if the common accessory minerals (sphene, apatite, and magnetite) and the required additional components (TiO₂ and P₂O₅) are added, there is still conformity with the rule (P = 7 < C = 11). As this example suggests, it is often true that the actual number of minerals (phases) is less than the maximum number allowable under the mineralogical phase rule. In fact, the definitions of both components and degrees of freedom are far from clear in many rock systems. For instance, even the minimum number of components can frequently be constituted in more than one way.

PHASE EQUILIBRIUM DIAGRAMS

As shown in the figures of this chapter, phase equilibrium diagrams identify the phases that exist for a given system under the conditions indicated; that is, the diagrams are graphic presentations of chemical systems, and they show how stability fields for diverse phases correlate with the given variables. Although some phase diagrams that pertain to minerals have been prepared on the basis of thermodynamic calculations, most represent results of laboratory investigations of systems equilibrated under carefully controlled temperatures, pressures, and compositions. If used with discretion, the information given in these diagrams can greatly aid mineralogists and petrologists in their interpretations of the geneses of minerals and rocks. (And, these diagrams, as well as phase diagrams for nongeological systems, also find important applications in ceramics and metallurgy.) A number of books outline the methods used in constructing and interpreting phase diagrams (e.g., Levin et al., 1964; Ehlers, 1972; and Ernst, 1976). The following sections will introduce you to some of the more frequently encountered relations shown on phase diagrams.

Unary Diagrams

Phase diagrams for one-component systems are exemplified by the diagram for SiO_2 (Figure 5-1).