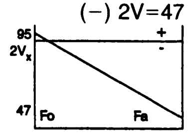
Appendix A

Optical Properties of Common Rock-Forming Minerals

Optical Properties of Common Rock-Forming Minerals

J. B. Lyons, S. A. Morse, and R. E. Stoiber

Mineral	Chemical Composition	Xl. System and Best Cleavage	Sign, 2V	Indices and Relief	Birefringence and Color	Distinguishing Characteristics [a]Characteristically parallel, but see Fig. 13-3.
			A. High Positive Relief			
Zircon	$ZrSiO_4$	Tet.	(+)	ω=1.940	High biref. (.055)	Small euhedral grains show parallel[a] extinction; may cause pleochroic haloes if enclosed in other minerals
Sphene (Titanite)	$CaTiSiO_5$	Mon. (110)	(+) 30–50	β=1.895 to 1.935	High biref. (0.108–.135) Often brownish in color	Wedge-shaped grains; may show (110) cleavage or (100) or (221) parting; $Z \wedge c = 51°$; very high relief; $r>v$ extreme.
Garnet	$A_3B_2(SiO_4)_3$ where $A = R^{2+}$ and $B = R^{3+}$	Iso.		High 1.7–1.9	Grandite often weakly birefracting.	Very pale pink commonest color; inclusions common. Indices vary widely with composition. Crystals often euhedral. Uvarovite green, very rare.
Staurolite	$H_2FeAl_4Si_2O_{12}$ (approximately)	Orth. (010)	(+) 2V = 87	β=1.750	Low biref. (.012)	Pleochroic colorless to golden yellow; one good cleavage; twins cruciform or oblique; metamorphic.
Olivine Series	Mg_2SiO_4 to Fe_2SiO_4	Orth. / Orth.	(+) 2V=85 / (−) 2V=47 	β=1.651 to β=1.865	High biref. (.035) High biref. (.051)	Colorless (Fo) to yellow or pale brown (Fa); high relief. Shagreen (mottled) surface; often cracked and altered to serpentine. Poor (010) and (100) cleavages. Extinction parallel.[a]

Tourmaline	$Na(Mg,Fe,Mn,Li,Al)_3$-$[Si_6O_{18}](BO_3)_3$-$(OH,F)_4$	Hex.	(−)	ω=1.636 to 1.698	Mod. biref. (.020)	Generally pleochroic; *maximum absorption across the length*. Colors chiefly brown, green, blue. Triangular outline on basal section.
Amphibole		(110)				Characteristic 124°–56° cleavage. Generally pleochroic.
Anthophyllite-Gedrite Cummingtonite	$(MgFe)_7(SiAl)_8O_{22}(OH)_2$ + Na in gedrite Same but no Na	Orth. Mon.	(+) and (−) 2V=80± same	β=1.605–1.689 1.65–71	Biref. mod. to low (.013 to .026)	Z=*c*; Y=*b*; may be pleochroic in tans; found only in metamorphic rocks; parallel[a] extinction.
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$	Mon.	(−) 2V = 85	β=1.615	Biref. mod. to low (.026)	Z∧*c*=20°; colorless; a metamorphic mineral.
Actinolite	$Ca_2(MgFe)_5Si_8O_{22}(OH)_2$	Mon.	(−) 2V = 75	β=1.642	Mod. (.020)	Z∧*c*=15°; pleochroic yellow to green.
Hornblende	Complex Al amphibole	Mon.	(−) 2V near 80	β=1.63–1.7	Mod. (.020)	Z∧*c*=15°–25°; pleochroic yellow, green, brown.
Arfvedsonite	Soda-rich amphibole	Mon.	2V large, (−)	β=1.69–1.70	Low (.005)	X∧*c*=20°; strong pleochroism in blues and greens; found chiefly in sodic igneous rocks.
Glaucophane	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$	Mon.	(−) 2V = 45	β=1.638	Mod. (.018)	Z∧*c*=5°; distinct lavender blue to blue-black pleochroism. A metamorphic mineral.
Sillimanite	Al_2SiO_5	Orth. (010)	(+) 2V = 30 r>v	β=1.658–1.670	Mod. (.020)	Y ⊥ single perfect cleavage; Z=c; may be in interlacing needles (fibrolite). Metamorphic rocks. End section:
Calcite	$CaCO_3$	Hex. $(10\bar{1}1)$	(−)	ω=1.658 ϵ=1.486	Extreme (.172)	Differential relief on stage rotation; one index far above 1.54, other below; rhombohedral cleavage; *often twinned*; told from dolomite etc. only by index.

Mineral	Chemical Composition	Xl. System and Best Cleavage	Sign, 2V	Indices and Relief	Birefringence and Color	Distinguishing Characteristics
Chloritoid	$H_2FeAl_2SiO_7$	Mon. (110)	(+) 2V 36–68	β=1.720–1.770	Low (.007–.016)	Pleochroic in greenish-black to gray. Epidote has better cleavage. X parallel to (010) parting.
Zoisite	$HCa_2Al_3Si_3O_{13}$	Orth. (010)	(+) 2V = 30±, r<v	β=1.700	Low (.006)	Abnormal blue interference colors; one cleavage; parallel[a] extinction; colorless.
Epidote	$H(CaFe)_2Al_3Si_3O_{13}$	Mon. (001)	(−) 2V = 75	β=1.753–1.763	High (.033–to .051)	Abnormal interference colors; Z∧cleavage= 14°–24°; weakly pleochroic in pistachio greens; usually in fine aggregates.
Kyanite	Al_2SiO_5	Tri.	(−) 2V = 83	β=1.722	Low (.012)	High relief; 2 good cleavages, best is (100); Z∧*c*=30°; alters to sericite; nice colorless blades.
Pyroxene		(110) 93–87°				Cleavage characteristic; cf. amphibole.
Enstatite	$MgSiO_3$	Orth. (210)	(+) 2V = 55	β=1.652–1.670	Low biref.	Parallel[a] extinction. Colorless.
Hypersthene	$(MgFe)SiO_3$	Orth. (210)	(−) 2V = 75	β=1.680–1.702	Low biref.	Parallel[a] extinction; faint pink to green pleochroism distinctive.
Pigeonite	$(MgFe)SiO_3 + CaSiO_3$	Mon. (110)	(+) 2V = 0 − 20	β=1.654–1.660	Low biref.	Colorless; Z∧*c*=22°–45°; low 2V diagnostic.
Diopside	$CaMgSi_2O_6$	Mon. (110)	(+) 2V = 60	β=1.672	Mod. biref.	Z∧*c*=38°; colorless; pure form common chiefly in contact metamorphic rocks.

Continued

(*Pyroxene*, cont.)

Augite	$Ca(MgFe)Si_2O_6$	Mon. (110)	(+) 2V = 60	β=1.676–1.745	Mod. biref.	Z∧*c*=48°–54°; may twin on (100) or (001); light colored in thin section, but reddish or violet when Ti is abundant.
Aegirinaugite	$Ca(MgFe)Si_2O_6$ – $NaFeSi_2O_6$	Mon. (110)	(+) 2V = 65	β=1.680–1.720	Mod. biref. Green	Z∧*c*=65°–75°; pleochroic in greens; may show inclined dispersion; common in alkalic rocks.
Apatite	$Ca_5(F,Cl)(PO_4)_3$	Hex.	(−)	ω=1.632–1.648	Low (.004)	Small hexagonal prisms; shagreen surface; colorless. Small inclusions common.
Andalusite	Al_2SiO_5	Orth. (110)	(−) 2V = 85	β=1.640	Low (.011)	*Faint pink pleochroism*; X=c; carbonaceous inclusions; alters to sericite.
			B. *Intermediate Positive Relief*			
Micas		(001)				Perfect basal cleavage
Muscovite	$KAl_2[AlSi_3]O_{10}(OH)_2$	Mon.	(−) 2V = 45±	β=1.582–1.610	High biref.	High index parallels cleavage; colorless.
Sericite						Fine grained muscovite.
Biotite	$K(Mg,Fe)_3[AlSi_3]O_{10}(OH)_2$	Mon.	(−) 2V = 0 − 10	β=1.564–1.690	High biref. Green, brown	Pleochroic; max. absorption and high index parallel cleavage; pleochroic haloes around inclusions; green ferric, brown titanian.
Paragonite	$NaAl_2[AlSi_3]O_{10}(OH)_2$	Mon.	Na analog of muscovite, with which it may be intergrown in schists; X-ray or probe needed to identify.			
Chlorite	$(Mg,Al,Fe)_6[Al,Si]_4O_{10}(OH)_8$	Mon. (001)	(+) or (−) small-zero	β=1.570–1.65	Very low B; pleochroic in greens	Perf. (001) cleavage; may show abnormal interference colors; max. absorption parallel to cleavage; high index parallel or normal to cleavage.

Mineral	Chemical Composition	Xl. System and Best Cleavage	Sign, 2V	Indices and Relief	Birefringence and Color	Distinguishing Characteristics
Serpentine	$Mg_6Si_4O_{10}(OH)_8$	Mon.	(−)	n=1.55±	Very low B	Colorless to green; fibrous or radial; often alters from olivine.
Talc	$Mg_3Si_4O_{10}(OH)_2$	Mon. (001)	(−)2V= 0–30	β=1.59	High biref. (.03–.05)	Difficult to distinguish from muscovite except by its association and slightly lower indices and 2V.
		C. *Low Relief (Positive and Negative)*				
Feldspar		(001) (010) (100)			Colorless	Variously twinned.
Orthoclase	$KAlSi_3O_8$	Mon. (001) (010)	(−) 2V = 30–60	β=1.523	Low (.006)	Index lower than 1.54; 2 good cleavages; no polysynthetic twinning.
Sanidine	$KAlSi_3O_8$		(−)2V 0–40	β=1.523	Low	High temperature polymorph of orthoclase.
Microcline	$KAlSi_3O_8$	Tri. (001) (010)	(−) 2V=83	β=1.522	Low (.007)	Cross-hatch (plaid) twinning distinctive.
Anorthoclase	$(Na,K)AlSi_3O_8$	Tri.	(−) 2V=50	β=1.528	Low (.006)	Cross-hatch twinning; uncommon.
Plagioclase Albite	$NaAlSi_3O_8$, An = 0–10 Plagioclase end member	Tri. (001) (010) (100)	(+) 2V=70	β=1.529	Low (.010)	Albite twinning characteristic. All other plagioclase has *n* > 1.54.
Oligoclase	An 10–30	-do-	(−) 2V=86			May be antiperthitic (with exsolution of Or). May be iridescent (peristerite).
Andesine	An 30-50	-do-	(+) 2V=87			May be antiperthitic up to about An 40.
Labradorite	An 50-70	-do-	(+) 2V=78			May be iridescent when slowly cooled.

Continued

Bytownite	An 70-90	-do-	(−) 2V=83			Fine lamellar exsolution common.
Anorthite	$CaAl_2Si_2O_8$, An 90–100 Plagioclase end member	-do-	(−) 2V=77	β=1.583		Metamorphic and arc volcanic rocks.
Quartz	SiO_2	Hex.	(+)	ϵ=1.553 ω=1.544	Low (.009)	No color, cleavage, or alteration. Often has inclusions; undulatory extinction common.
Nepheline	$NaAlSiO_4$	Hex.	(−)	ω=1.536–1.549	Low (.005)	Resembles quartz, but sign negative. Told from orthoclase by higher index and uniaxial character; often altered to cancrinite or sodalite (blue).
Cordierite	$Mg_2Al_4Si_5O_{18}$	Orth.	(−) 2V 40–80	β=1.543	Low (.011)	Often confused with quartz but biaxial; also may show inclusions of sillimanite, yellow pleochroic haloes, and characteristic twins.
Scapolite	Marialite ~Ab + NaCl Meionite ~An + $CaCO_3$	Tet.	(−)	ω=1.539–1.596	(.002–.039) often *zoned* int. colors	Alteration of plagioclase, mostly contact-metamorphic. Zoned interference colors characteristic.
			D. *Moderate Negative Relief*			
Leucite	$KAlSi_2O_6$	Iso.		n=1.508		Generally weakly birefracting; inclusions common; trapezohedral crystals.
Analcite	$NaAlSi_2O_6 \cdot H_2O$	Iso.		n=1.489		Trapezohedral form; generally lacks inclusions.

Mineral	Chemical Composition	Xl. System and Best Cleavage	Sign, 2V	Indices and Relief	Birefringence and Color	Distinguishing Characteristics
Calcite	$CaCO_3$	Hex. $(10\bar{1}1)$	(−)	$\omega=1.658$ $\epsilon=1.484$	Extreme biref. (.172)	Differential relief on rotation of stage; one index below 1.54, other far above; rhombohedral cleavage; often twinned; told from other rhombohedral carbonates only by index.
Cristobalite	SiO_2	Tet.	(−)	$\omega=1.487$ $\epsilon=1.484$	Low	Often looks isotropic; multiple twinning; generally in fibrous balls in cavities; negative relief.
Tridymite	SiO_2	Orth.	(+) 2V=35	$\beta=1.469$	Low	Lath-shaped forms; negative elongation; wedge-shaped grains; slight pinkish color; negative relief.
Zeolites	Complex hydrous Na,Ca,Al silicate	Orth.	(+) or rarely (−)		Low-Mod.	Generally low index, weak biref.; rarely colored; often fibrous. See tables for more data.
Fluorite	CaF_2	Iso. (111)		n=1.4339		Often in euhedral octahedra. Common accessory in some granites.

[a]Characteristically parallel, but see Fig. 13-3.

Appendix B
Identification of Fibrous Asbestos

The most common asbestos minerals are two types of amphibole (riebeckite and grunerite) and the serpentine mineral chrysotile. The amphibole fibers are particularly hazardous to health, and the list of fibrous minerals regulated by the U.S. Environmental Protection Agency also includes the amphiboles tremolite, actinolite, and anthophyllite. Details of the mineralogy and health effects of asbestos minerals are given by Skinner et al. (1988).

Blue amphibole asbestos (riebeckite, also called crocidolite) was heavily used in coating pipes and bulkheads in warships during World War II. Its use in later applications was more limited, but for a long time amphibole fibers were routinely mixed in with chrysotile, so many fiber-bearing materials contain some of both minerals. Typical applications during the mid-century are found in insulation, and the manufacture of floor and ceiling tiles used in public buildings. "Management in place" is often recommended where the material involved is unlikely to release fibers in everyday situations. In other situations, removal is often practiced whether or not it might be warranted by the mineralogy and etiology of the fibers.

It is of clear importance to public health and risk management to identify correctly the minerals present in any fibrous product to which people may be routinely exposed. Optical examination offers a low-cost means of crystal identification and fiber counting, especially as a precursor to more specialized methods of examination such as electron microscopy.

The names and properties of the three most common asbestos minerals are listed in Table B-1. All are monoclinic. Amosite is another name for grunerite. The amphiboles are chain silicates with fiber axes parallel to the *c* crystallographic axis. Chrysotile is a septechlorite sheet silicate in which fibers are rolled-up sheets elongate parallel to the *a* crystallographic axis, but along which the indicatrix axis may be either Z or X. The so-called Z fibers may be the more common.

Measurement of refractive index furnishes definitive information leading to the identification of asbestos minerals. This is done by the immersion method using standard refractive index liquids. If white light is used for illumination, the criterion of match in oblique illumination is the orange-red ("pylon") color described in Chapter 3 (see Fig. 3-15 or Fig. 17-3). Dispersion staining is used in many industrial laboratories to enhance the appearance of asbestos fibers and determine their refractive index. If dispersion staining is used with central screening (Chapter 3; McCrone, 1987; McCrone et al. 1977), the color indicating the condition of match is deep violet (Fleischer et al., 1984, Table 1). Other colors may be interpreted, according to the method used, by reference to either of these figures or the table. Either method leads to the correct result.

The two amphiboles have high refractive index, near 1.7, whereas chrysotile has a moderate refractive index near 1.5; this distinction provides a fundamental and rapid basis for identification. If the unknown fiber sample is immersed in a liquid of n = 1.56 and shows low relief or color fringes it cannot be one of the amphiboles. Conversely, if the sample is immersed in a liquid of n = 1.7 any amphiboles present will have low relief or show color fringes, whereas any chrysotile present will have high negative relief.

The sign of the elongation is diagnostic between the amphiboles, being positive in grunerite and negative in riebeckite (the terms length-slow and length-fast, respectively, are also in common use). Birefringence, hence interference color, is also diagnostic, being much larger in grunerite. The most spectacular diagnostic feature is the blue color of riebeckite, easily recognized in fibers only a few micrometers thick. The woolly material is pale blue to the naked eye, and unprocessed fibers are dark blue.

The high refractive index along the length of grunerite is about the same as the low refractive index along the length of riebeckite. A 1.698 oil is effective in seeking a color fringe to identify these minerals because it is more stable than the common 1.7+ oils and hence needs less frequent calibration.

The dispersion method affords a rapid means of establishing quantitatively the diagnostic refractive index of fibrous asbestos. It is used according to the methods described in Chapter 16.

Values of the dispersion, $n_F - n_C$, were determined at the University of Massachusetts from standard samples of the three mineral groups, with the results shown in Table B-1. Fibers were matched at varying wavelengths of light in different oils, and the results regressed in Hartmann space. A binder present in the grunerite sample was removed by dissolution in water, followed by rinsing in acetone and drying in air. Results were easily obtained for grunerite and chrysotile, but the high color of riebeckite makes the recognition of color fringes and shadows difficult. To enhance the use of the oblique illumination stop inserted from the NW, the polarizer

Table B-1
Properties of Common Asbestos Minerals

	Amphibole		Serpentine
	Grunerite (Amosite)	Riebeckite (Crocidolite)	Chrysotile
Approximate chemical composition	$Fe_7Si_8O_{22}(OH)_2$	$Na_2Fe_3(Al,Fe)_2$ $Si_8O_{22}(OH)_2$	$Mg_6Si_4O_{10}(OH)_8$
Crystal System	Monoclinic	Monoclinic	Monoclinic
Fiber axis	*c*	*c*	*a*
Elongation	+ (length slow)	− (length fast)	+ (Z fiber) or − (X fiber)
n along fiber	γ' ≈ 1.70	α' ≈ 1.70	γ' (Z); α' (X) ≈ 1.56; ≈ 1.55
Reported range	1.679–1.719	1.685–1.700	1.545–61 (Z) 1.538–60 (X)
Standard sample (UMass)	1.6995	1.6995	1.559 (Z)
Birefringence	strong, 0.04	weak, 0.004	weak, < 0.008
$n_F - n_C$	0.012	0.019	0.010
Color of fibers	Colorless to pale yellow	Dark blue to greenish yellow	Colorless
At matching refractive index:			
Color fringe in oblique illumination	Orange-red	Orange-red (may be obscured)	Orange-red
Dispersion color (central screen)	Deep violet	Deep violet (may be obscured)	Deep violet
Diagnostic features	+ elong, B, γ' near 1.7	Blue color, α' near 1.7	low n, ± elong colorless

and the fiber were oriented NE, so the shadow appeared evenly along the length of the fiber. Slight misorientation is of no concern because of the low birefringence. The refractive indices n_D found for γ' of grunerite and α' of riebeckite were both 1.6995. The chrysotile sample was determined to have $\gamma' = 1.559 \pm 0.001$, the relatively large error bracket being due mainly to demonstrably real variation among the fibers rather than uncertainty in the wavelength of match.

Other possibly fibrous minerals that may occur in asbestos samples are talc (*n* along fiber 1.59), brucite (1.56), tremolite (1.63), actinolite

(1.67), anthophyllite (1.63), and wollastonite (1.63). Of these, only brucite is likely to be confused with any of the major three asbestos minerals, and it can be distinguished by its high birefringence and low hardness. Talc is also distinguished by its very high birefringence and very low hardness. The other minerals in the "1.6" group can be identified by the immersion method using all relevant optical properties and reference to standard tables. A single mount will often serve to determine the refractive index of tremolite, actinolite, or anthophyllite by the dispersion method (Su, 1993).

Synthetic and natural organic fibers may also occur in asbestos samples, and most can be distinguished by their low refractive indices. A comprehensive treatment of these is given by McCrone (1987).

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Index