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ROCK-FORMING MINERALS

1.1 Introduction

This book is intended to be a reference for the advanced undergraduate and beyond. Depending on your skill level, it may be a primary guide or used to refresh your knowledge. This book does not replace a proper mineralogy course or textbook; it does not replace an optical petrography course or textbook. It is intended to be used in conjunction with such courses and to be a long-term reference after the completion of such courses. You should be learning or already know how to use an optical microscope. You may already know, or be learning, how to recognize and determine the distinctive properties of the most common igneous and metamorphic rock-forming minerals. This includes:

- descriptive matter: crystal shape/habit, twinning, alteration, etc.
- color
- pleochroism
- anisotropy
- crystal systems and uniaxial (tetragonal, hexagonal) versus biaxial (orthorhombic, monoclinic, triclinic) character
- optic signs as positive (+) or negative (–)
- birefringence ($1^\circ < 0.018$, $2^\circ < 0.036$, $3^\circ < 0.055$) and use of the Michel-Levy color chart
- relief (high, moderate, low)
- cleavage (1, 2 or >2, and how to determine the angle between them)
- extinction (parallel, inclined, symmetrical, undulose) and the angle of extinction.

The recognition and characterization of minerals and textures of igneous and metamorphic rocks is the primary purpose of this book. A person with little experienced can follow the steps outlined in Fig. 1.1 to identify unknown minerals in thin-section. These steps define a systematic method for mineral identification. The information obtained is then used in conjunction with the overview of mineral characteristics given in Table 1.1. We use a simplified approach to mineral classification based primarily on the Michel-Levy color chart (Fig. 1.2) and birefringence. The Michel-Levy color chart provides a quantified visual reference of mineral birefringence in which lower-order colors are more vibrant, and higher-order colors become increasingly pastel (Fig. 1.2). The minerals in Table 1.1 are listed in order of increasing birefringence. Once the birefringence of a mineral is determined, Table 1.1 is used to narrow the range of possible choices. Other characteristics – such as relief, cleavage, pleochroism, and optic sign – may be needed for final identification of the mineral.

The use of Table 1.1 assumes that thin-sections have the "correct" thickness (30 µm) for the accurate determination of birefringence. This is not always the case: Thinner sections will produce lower interference colors and thicker sections will result in higher interference colors than those of the ideal 30 µm thickness. The more experienced person will recognize whether a thin-section is the correct thickness by assessing, for example, the interference colors of common minerals such as quartz or plagioclase. If you are more experienced, you can proceed directly to the overview of mineral characteristics (Table 1.1). Mineral abbreviations follow the recommendations of Whitney and Evans (2010) (Table 1.2).

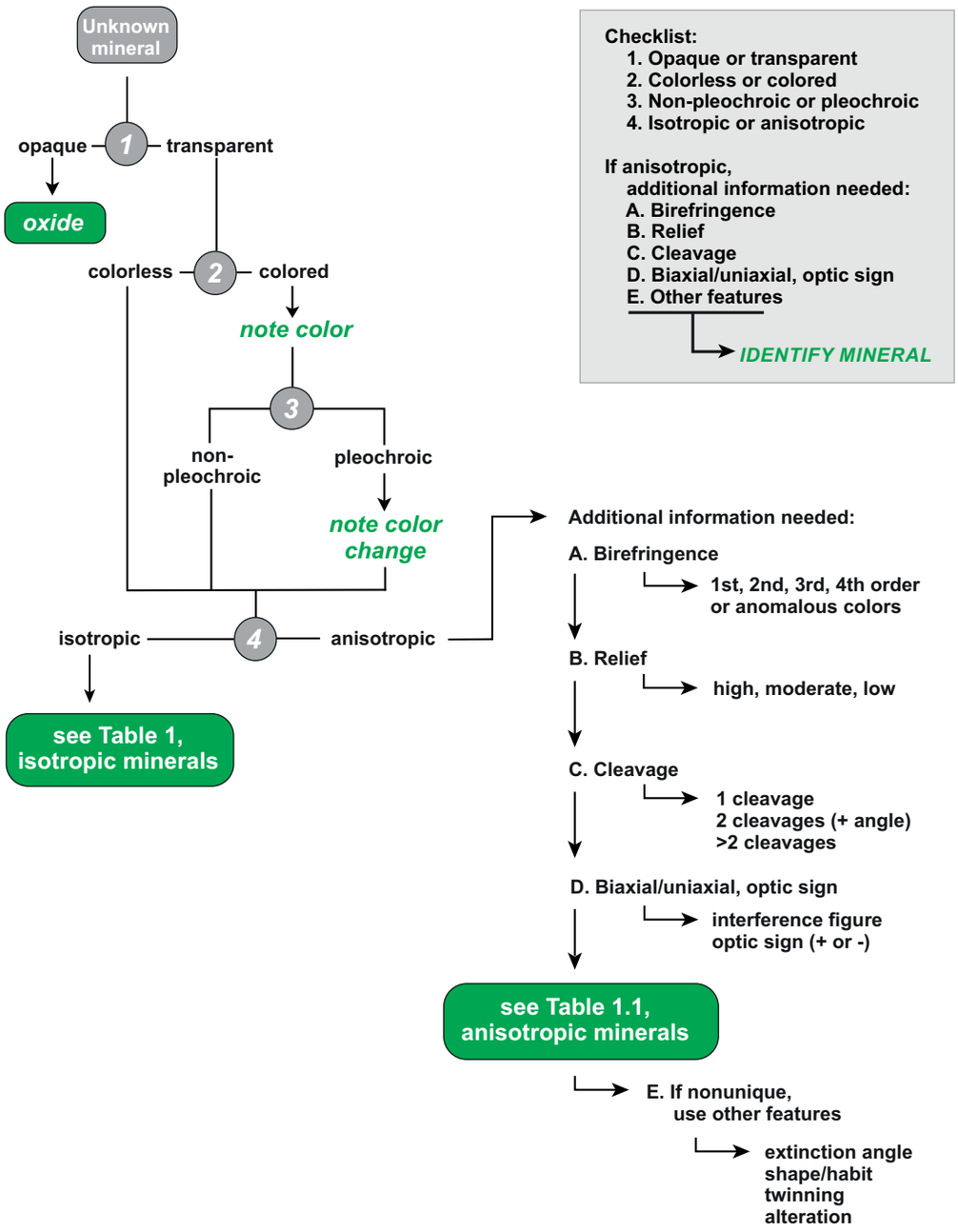

Figure 1.1 Flow chart for the identification of a mineral in thin-section using a petrographic microscope. Follow the numbered steps from the upper-left to the lower-right. At each number, a decision is made regarding whether to stop or continue. At step 4, additional information may be needed, as specified by letters A–E. Final identification can be made with cross-reference to Table 1.1.

Table 1.1 Overview of common rock-forming minerals and their distinguishing characteristics

Birefringence	Mineral	Relief	Cleavage	Pleochroic	U	B	+	–
Isotropic minerals								
1.433	Fluorite	H–	*					
1.479–1.493	Analcime	M–						
1.483–1.490	Sodalite	M–						
1.508–1.511	Leucite	L–						
1.71–1.89	Garnet	H						
1.719–2.74	Spinel	H						
2.30–2.38	Perovskite	H						
Anisotropic minerals								
0.00–0.01 (avg.)	Chlorite	M	*	*		*		*
0.001–0.005	Chabazite	M–				*	*	*
0.001–0.007	Apatite	M		*	*			*
0.001–0.013	Melilite	M	*	*		*	*	*
0.002–0.004	Tridymite (α)	M–				*	*	
0.003 (approx.)	Cristobalite (α)	M–				*	*	
0.003–0.005	Nepheline	L–				*	*	*
0.003–0.008	Zoisite	H	*			*	*	
0.003–0.009	Heulandite	M–	*			*	*	*
0.003–0.010	Phillipsite	M–				*	*	
0.004–0.005	Na-scapolite (marialite)	L	**		*			*
0.004–0.007	Antigorite	L	*			*		*
0.004–0.009	Beryl	L			*			*
0.004–0.015	Clinozoisite	H	*			*	*	
0.005–0.006	Kalsilite	L–				*		*
0.005–0.009	Sapphirine	H	*	*		*	*	*
0.005–0.022	Chloritoid	L	*	*	*		*	
0.006	Coesite	M				*		*
0.006–0.008	Lizardite	L	*			*		*
0.006–0.010	K-spar, Na-spar	L	**			*		*
0.006–0.016	Riebeckite	H	**	*		*	*	*
0.006–0.021	Jadeite	H	**			*	*	
0.007–0.016	Enstatite	H	**	*		*		*
0.007–0.021	Katophorite	H	**	*		*		*
0.008 (approx.)	Microcline	L	**			*		*
0.008 (approx.)	Åkermanite	M			*		*	
0.008–0.009	Corundum	H		*	*			*

Table 1.1 (*cont.*)

Birefringence	Mineral	Relief	Cleavage	Pleochroic	U	B	+	–
0.008–0.011	Topaz	M	*			*	*	
0.008–0.018	Cordierite	L	*	*		*		*
0.009	Quartz (α)	L				*		*
0.009–0.010	Stilbite	L–	*			*		*
0.009–0.012	Andalusite	M	*			*		*
0.01 (approx.)	Albite (Na-Pl)	L	**			*	*	*
0.010–0.012	Arfvedsonite	H	**	*		*		*
0.010–0.020	Pumpellyite	H	**	*		*	*	*
0.011 (approx.)	Gehlenite	H			*			*
0.011–0.014	Staurolite	H	*	*		*	*	
0.012 (approx.)	Barite	M	**			*		*
0.012 (approx.)	Natrolite	M	*			*	*	
0.012–0.016	Kyanite	H	*	*		*		*
0.012–0.028	Omphacite	H	**	*		*	*	
0.013 (approx.)	Anorthite (Ca-Pl)	M	**			*		*
0.013–0.014	Wollastonite	M	**			*		*
0.013–0.017	Chrysotile	L				*		*
0.013–0.020	Eckermannite	H	**	*		*		*
0.013–0.021	Anthophyllite	M	**			*	*	*
0.013–0.036	Allanite	H		*		*	*	*
0.014–0.017	Ca,Mg-olivine (monticellite)	M		*		*		*
0.014–0.020	Brucite	M	*		*		*	
0.015–0.022	Mg-richterite	H	**	*		*		*
0.015–0.051	Epidote	H	*	*		*		*
0.016–0.022	Ferrosilite	H	**	*		*		*
0.017–0.021	Li-tourmaline (elbaite)	M		*	*			*
0.017–0.032	Ferroactinolite	H	**	*		*		*
0.018–0.022	Sillimanite	H	*	*		*	*	
0.018–0.025	Augite	H	**	*		*	*	
0.019–0.021	Lawsonite	H	**			*	*	
0.02 (approx.)	Hornblende	H	**	*		*	*	*
0.020–0.032	Cummingtonite	H	**			*	*	
0.021–0.029	Gedrite	H	**	*		*	*	*
0.021–0.029	Mg-tourmaline (dravite)	M		*	*			*
0.022–0.027	Tremolite	M	**			*		*
0.022–0.029	Fe-richterite	H	**	*		*		*

Table 1.1 (*cont.*)

Birefringence	Mineral	Relief	Cleavage	Pleochroic	U	B	+	–
0.022–0.051	Prehnite	M	*			*	*	
0.018–0.020	Glaucophane	M	**	*		*		*
0.023–0.029	Pigeonite	H	**	*		*	*	
0.024–0.034	Ca-scapolite (meionite)	L			*			*
0.025–0.033	Ferroaugite	H	**			*	*	
0.025–0.035	Fe-tourmaline (schorl)	H		*	*			*
0.025–0.073	Piemontite	H	*	*		*	*	
0.024–0.028	Hedenbergite	H	**	*		*	*	
0.028–0.047	Kaersutite	H	**	*		*	*	
0.028–0.07	Biotite	M	*	*		*		*
0.03–0.11	Stilpnomelane	H	*	*		*		*
0.030–0.045	Aegirine–augite	H	**	*		*	*	*
0.032–0.045	Grunerite	H	**	*		*		*
0.028–0.034	Diopside	H	**			*	*	
0.035	Mg-olivine (forsterite)	H				*	*	
0.035–0.042	Muscovite	M	*		*			*
0.036–0.054	Sericite	L,M				*		*
0.040–0.060	Aegirine	H	**	*		*		*
0.042–0.065	Zircon	H			*		*	
0.045–0.075	Monazite	H	*			*	*	
0.050 (approx.)	Pyrophyllite	M	*			*		*
0.050 (approx.)	Talc	M	*			*		*
0.052	Fe-olivine (fayalite)	H		*		*		*
0.080	Perovskite	VH	*			*	*	
0.096	Xenotime	VH	*	*	*		*	
0.096–0.098	Cassiterite	H			*		*	
0.100–0.192	Titanite	H	*	*		*	*	
0.155–0.156	Aragonite	L,H	*			*		*
0.172–0.190	Calcite	L,H	*		*			*
0.179–0.185	Dolomite	L,H	*		*			*
0.0190–0.218	Magnesite	L,H	*		*			*
0.207–0.242	Siderite	H	*		*			*
0.286–0.296	Rutile	VH	*		*		*	

L, low; M, moderate; H, high; VH, very high.

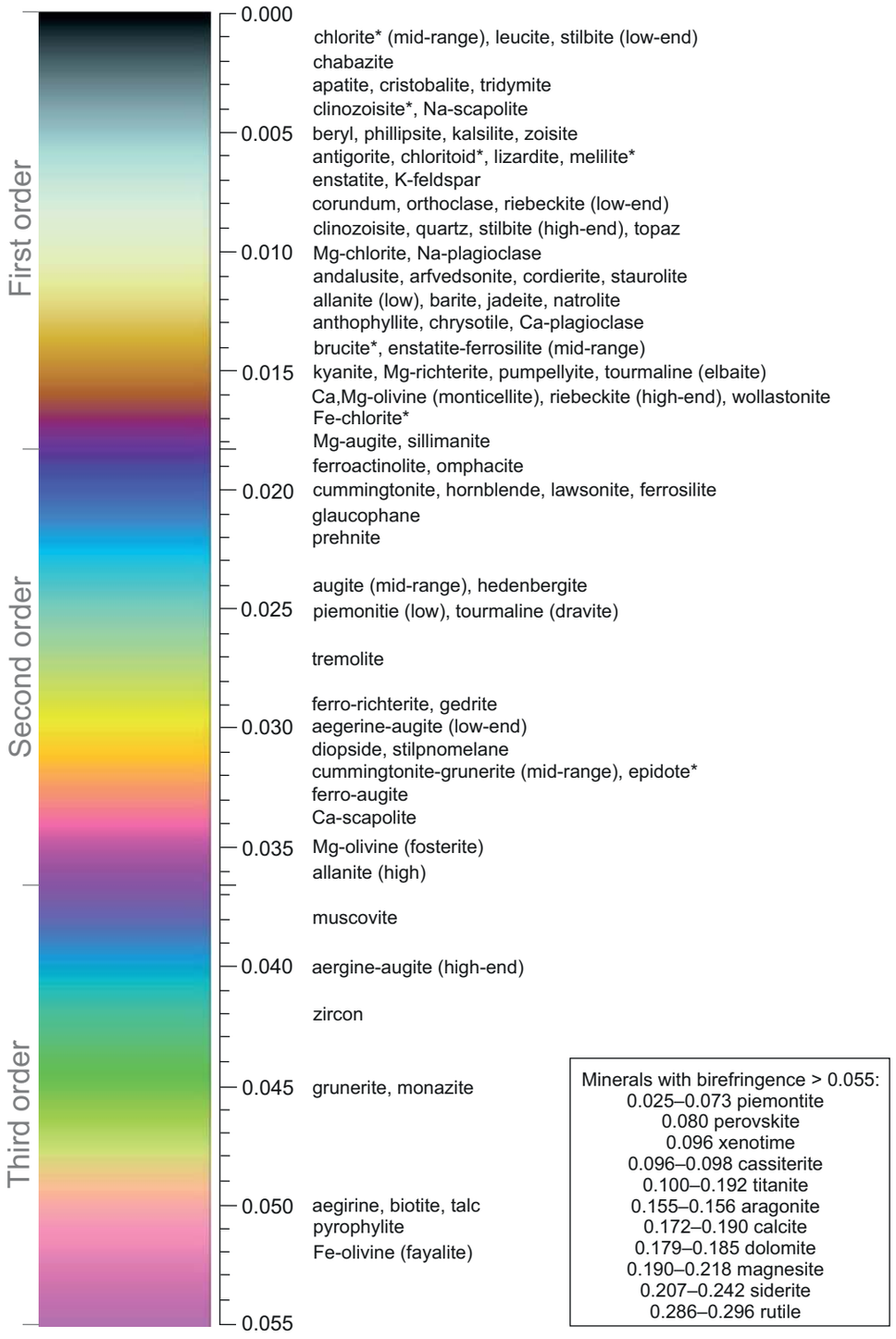

Figure 1.2 Michel-Levy birefringence chart for mineral identification (after Kato, 2001). Uses a 30 μm thin-section to determine birefringence. Cross-reference the birefringence to Table 1.1 and compare the properties of minerals with similar birefringence in order to make the final mineral identification. Note that minerals with an asterisk (*) can show anomalous colors.

Table 1.2 Mineral abbreviations (after Whitney & Evans, 2010)

Ab, Albite	Cst, Cassiterite	Hul, Heulandite series
Act, Actinolite	Ctl, Chrysotile	
Adr, Andradite	Cum, Cummingtonite	Ilt, Illite series
Aeg, Aegirine	Czo, Clinozoisite	Ilm, Ilmenite
Afs, Alkali feldspar		
Agt, Aegirine–augite	Di, Diopside	Jd, Jadeite
Ak, Åkermanite	Dol, Dolomite	
Alm, Almandine		Kfs, K-feldspar
Aln, Allanite	Eck, Eckermannite	Kls, Kalsilite
Amp, Amphibole supergroup	En, Enstatite	Krs, Kaersutite
An, Anorthite	Ep, Epidote	Ktp, Katophorite
And, Andalusite		Ky, Kyanite
Anl, Analcime	Fa, Fayalite	
Ano, Anorthoclase	Fac, Ferro-actinolite	Lct, Leucite
Ap, Apatite	Fi, Fibrolite (fibrous sillimanite)	Lmt, Laumontite
Arf, Arfvedsonite	Fkrs, Ferro-kaersutite	Lpd, Lepidolite
Arg, Aragonite	Fl, Fluorite	Lws, Lawsonite
Atg, Antigorite	Fo, Forsterite	Lz, Lizardite
Ath, Anthophyllite	Fprg, Ferro-pargasite	
Aug, Augite	Frct, Ferro-richterite	Mag, Magnetite
	Fs, Ferrosilite	Marf, Magnesio-arfvedsonite
Bdy, Baddeleyite	Fsp, Feldspar	Mc, Microcline
Brc, Brucite		Mgh, Maghemite
Brl, Beryl	Ged, Gedrite	Mgs, Magnesite
Brt, Barite	Gh, Gehlenite	Mll, Melilite series
Bt, Biotite	Gln, Glaucophane	Mnz, Monazite
	Glt, Glauconite	Mor, Mordenite
Cal, Calcite	Gn, Galena	Mrbk, Magnesio-riebeckite
Cbz, Chabazite	Grs, Grossular	Ms, Muscovite
Ccp, Chalcopyrite	Grt, Garnet supergroup	Mtc, Monticellite
Chl, Chlorite	Gru, Grunerite	Mw, Merwinite
Chr, Chromite	Gth, Goethite	
Cld, Chloritoid		Nph, Nepheline
Coe, Coesite	Hbl, Hornblende series	Nsn, Nosean
Cpx, Clinopyroxene	Hd, Hedenbergite	Ntr, Natrolite
Crd, Cordierite	Hem, Hematite	
Crn, Corundum	Hgr, Hydrogrossular	Ol, Olivine group
Crs, Cristobalite	Hst, Hastingsite	Omp, Omphacite

Table 1.2 (*cont.*)

Opl, Opal	Qz, Quartz	Thr, Thorite
Opq, Opaque mineral		Tlc, Talc
Opx, Orthopyroxene	Rbk, Riebeckite	Tpz, Topaz
Or, Orthoclase	Rct, Richterite	Tr, Tremolite
	Rdn, Rhodonite	Trd, Tridymite
Pcl, Pyrochlore	Rt, Rutile	Ttn, Titanite
Per, Periclase		Tur, Tourmaline supergroup
Pg, Paragonite	Sa, Sanidine	
Pgt, Pigeonite	Sch, Scheelite	Urn, Uraninite
Ph, Phengite series	Scp, Scapolite	Usp, Ulvöspinel, Ulvospinel
Phl, Phlogopite	Sd, Siderite	Uv, Uvarovite
Php, Phillipsite	Sdl, Sodalite	
Pl, Plagioclase series	Ser, Sericite	Vtr, Vaterite
Pmp, Pumpellyite	Sp, Sphalerite	
Pmt, Piemontite	Spd, Spodumene	Wo, Wollastonite
Po, Pyrrhotite	Spl, Spinel	Wrk, Wairakite
Prh, Prehnite	Spr, Sapphirine	
Prg, Pargasite	Sps, Spessartine	Xtm, Xenotime-(Y)
Prl, Pyrophyllite	Srp, Serpentine	
Prp, Pyrope	St, Staurolite	Zeo, Zeolite family
Prv, Perovskite	Stb, Stilbite series	Zo, Zoisite
Psb, Pseudobrookite	Sti, Stishovite	Zrn, Zircon
Px, Pyroxene supergroup	Stp, Stilpnomelane	
Py, Pyrite		

1.2 Framework Silicates

Plagioclase Feldspar $NaAlSi_3O_8 – CaAl_2Si_2O_8$

Optical Properties — THE FELDSPARS

Color in thin-section:	Colorless
Pleochroism:	Absent
Birefringence:	0.007–0.013
Relief:	Low
Cleavage:	Perfect {001} and {010} meeting at right-angle, poor {110}
Crystal system/optic sign:	Triclinic / Albite (+) or (–), Anorthite (–)
Other features:	Diagnostic polysynthetic twins parallel to prism faces; rarely albitic plagioclase in low-grade rocks lack twinning. Untwinned plagioclase can be confused with cordierite, but the latter may have yellowish alteration (pinite); distinguished from quartz by its biaxial nature and good cleavage; sericite alteration, sieve texture, and/or glass inclusions are common.

Paragenesis

Plagioclase is an abundant constituent of most igneous rocks, from ultrabasic–basic to acid, through intermediate and alkaline. It is scarce or absent only in some rare ultrabasic and alkaline rocks. Plagioclase is common in low- to high-grade (granulite facies) metamorphic rocks but becomes unstable at high P–T conditions (e.g. eclogite facies).

Igneous

Plagioclase is typically present in both extrusive and intrusive rocks, forming up to 50% of the total rock volume. In volcanic rocks, most plagioclase has disordered, high-temperature structure and occurs as phenocrysts and/or groundmass; phenocrysts are often compositionally zoned (Ca-rich cores with Na-rich rims). In plutonic rocks, slow cooling and diffusion erase compositional zoning. In layered mafic intrusions, plagioclase forms cumulate layers due to crystal settling processes.

Metamorphic

Plagioclase becomes more Ca-rich with increasing metamorphic grade. During low-grade regional metamorphism (chlorite and biotite zone) albite is stable, whereas oligoclase is more common in the garnet zone. The transition between amphibolite to granulite facies is marked by the reaction:

$$\underset{\textit{amphibole}}{Ca_2Mg_3Al_4Si_6O_{22}(OH)_2} + SiO_2 \rightarrow \underset{\textit{anorthite}}{2CaAl_2Si_2O_8} + \underset{\textit{orthopyroxene}}{3MgSiO_3} + H_2O$$

During contact metamorphism (e.g. the pyroxene hornfels facies), plagioclase can form via the breakdown of hornblende:

$$\underset{\textit{amphibole}}{NaCa_2Mg_3Fe^{3+}\ Al_3Si_6O_{22}(OH)_2} + 4SiO_2 \rightarrow \underset{\textit{plagioclase}}{CaAl_2Si_2O_8} +$$

$$NaAlSi_3O_8 + \underset{\textit{diopside}}{CaMgSi_2O_6} + \underset{\textit{orthopyroxene}}{Mg_2Fe^{2+}Si_3O_8} + H_2O$$

At eclogite facies, plagioclase is unstable and the anorthite component is taken up in omphacitic pyroxene and/or in garnet via the reactions:

$$\underset{\textit{albite}}{NaAlSi_3O_8} + \underset{\textit{olivine}}{(Mg,Fe)_2SiO_4} \rightarrow \underset{\textit{omphacite}}{NaAlSi_2O_6(Mg,Fe)SiO_3}\ \underset{\textit{anorthite}}{CaAl_2Si_2O_8} +$$

$$\underset{\textit{olivine}}{(Mg,Fe)_2SiO_4} \rightarrow \underset{\textit{garnet}}{Ca(Mg,Fe)_2Al_2Si_3O_{12}}$$

In numerous retrogressed eclogites, plagioclase commonly occurs as symplectic vermicular intergrowths with hornblende in kelyphitic rims around garnet.