

Figure 12.75. A mineralogical example of $^{[010]c}$ in diopside with the Mg (i.e., M1 sites) removed, the Ca atoms (i.e., M2 sites) shown as spheres, and portions of two tetrahedral chains. Recall $^{[010]c}$ is composed of a mirror plane perpendicular to b with a $1/2$ translation in the c direction. The image on the left is a perspective view and shows how the Ca atoms are related to one another with a translation parallel to c and then a reflection across the gray plane (which represents $^{[010]c}$). The view on the right is projected perpendicular to the glide plane and shows the Ca atoms alternately above and below the glide plane and translated parallel to c .

The glides are named for the direction and amount of translation. Finally, in Table 12.9 is a list of the glide planes.

Space Groups

With the addition of screw axes and glide planes, we now have the full complement of symmetry operations that exist in 3-D, so we can mix and match them to create all 230 of their possible combinations, which are called **space groups**. Each of these has its own symbol and number, from 1 to 230. The 230 space groups are listed by crystal system and point group in Table 11.9.

To start, let's look at the anatomy of a space group symbol. The space group symbols are a combination of the lattice type and one of the 32 point groups. The possible number of space groups grows as we allow for the translational symmetry that creates screw axes and glide planes. Consider the space groups $P2/m 2/m 2/m$ (Figure 12.79a) and $P2_1/b 2_1/a 2/m$ (Figure 12.79b). Both of these are orthorhombic and have a P lattice (the letter representing the lattice type always precedes the symmetry operators). $P2/m 2/m 2/m$ contains only point group operations while $P2_1/b 2_1/a 2/m$ contains both point and space group operations.

A bias in the nomenclature has evolved for use of space group symbols. Crystallographers often abbreviate space group symbols, as well as point group symbols discussed above. For instance, $P2/m 2/m 2/m$ is abbreviated as $Pmmm$ and $P2_1/b 2_1/a 2/m$ as $Pbam$. Although a crystallographer would understand these abbreviations, we will avoid abbreviations of space groups in this text. The amount of time saved in making such abbreviations is an order of magnitude less than the confusion they have caused! Table 11.9 lists the

230 space groups associated with the 32 point groups and six crystal systems. It's our challenge now to briefly discuss these space groups to see how they are created, so we can use them in Chapter 14 to represent crystal structures. (By the way, one of us (M.E.G.) had an entire semester course on space groups as a graduate student, so this is really a *brief* overview!)

Triclinic system. We'll develop space groups from lowest to highest symmetry, and begin with the triclinic system. Recall that there are only two

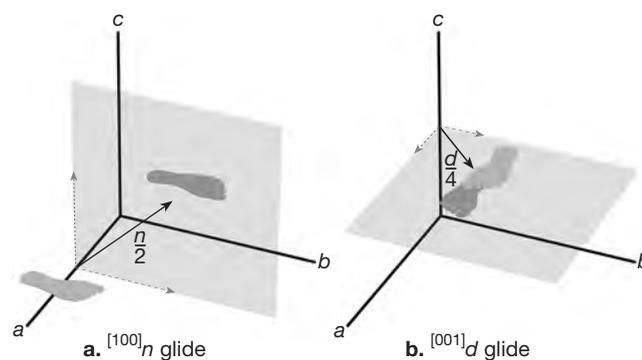


Figure 12.76. Examples of a diagonal (n) glide and diamond (d) glide. Both of these glides have translations in two, rather than one direction, as for the axial glides. **a.** Diagonal (n) glides have two $1/2$ glide translations parallel to the two crystallographic axes in the plane; the end result of this is a "diagonal" translation (with respect to the two axes) across the plane. The vector 3 in Figure 12.73 would be the result of a $1/2$ translation parallel to a and a $1/2$ translation parallel to b . Thus, a $^{[100]n}$ would have $1/2$ translation in b and $1/2$ in c and transform the right foot into a left foot as above. **b.** A diamond (d) glide is similar to an n glide, except that the translations are only $1/4$ in both directions instead of $1/2$. So a $^{[001]d}$ would be similar to a $^{[001]n}$, though the length of the diagonal translation is less. Thus the $^{[001]d}$ would translate $1/4$ in a and $1/4$ in b and transform the right foot into the left foot as above.

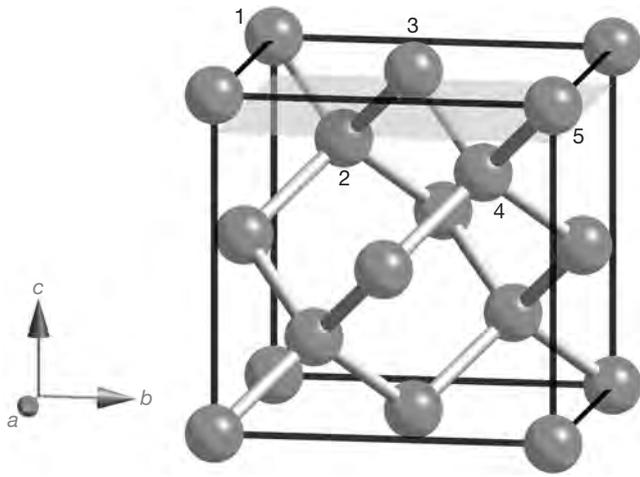


Figure 12.77. An example of a diamond glide in diamond. The $[001]_d$ causes the C atoms to be translated by $\frac{1}{4}a$ and $\frac{1}{4}b$ before being reflected across a plane parallel to (001). The $[001]_d$ is shown on the upper portion of the unit cell of diamond. Atom 1 is related to 2 by the operation of the $[001]_d$, as is atom 2 to 3, 3 to 4, and 4 to 5.

triclinic point groups: 1 and $\bar{1}$. To make space groups from these point groups, we need to associate each of them with a Bravais lattice (Figures

12.48 to 12.51). For the triclinic system, only P lattice can occur. Thus, we add the “ P ” to each of our point groups and arrive at $P1$ and $P\bar{1}$ space groups. Are there other types of symmetry elements that could exist within the triclinic system if we allowed for the addition of translational components (i.e., any screw axes or glide planes)? The answer is no, because there are no mirror planes in this systems and there is no such thing as a 1-fold screw axis.

Monoclinic system. This system contains 13 space groups, and there are more minerals from them than from any of the others (Table 11.9). There are two lattice types (Figures 12.48 and 12.50) that can occur in this system, P and C , where C is a side-centered lattice with an extra lattice point on the (001) face. Recall there are three point groups in this system: 2, m , and $2/m$. So we add a P and C lattice type to each of these three space groups to arrive at $P2$, $C2$, Pm , Cm , $P2/m$, and $C2/m$.

Next we need to consider what types of screw axes and glide planes might occur in this system. A 2-fold axis with a $\frac{1}{2}$ translation would be a 2_1 screw (more precisely here a $[010]2_1$), so we could form $P2_1$ and $P2_1/m$. There is no $C2_1$ because a $[010]2_1$ and C -centered lattice are not compatible

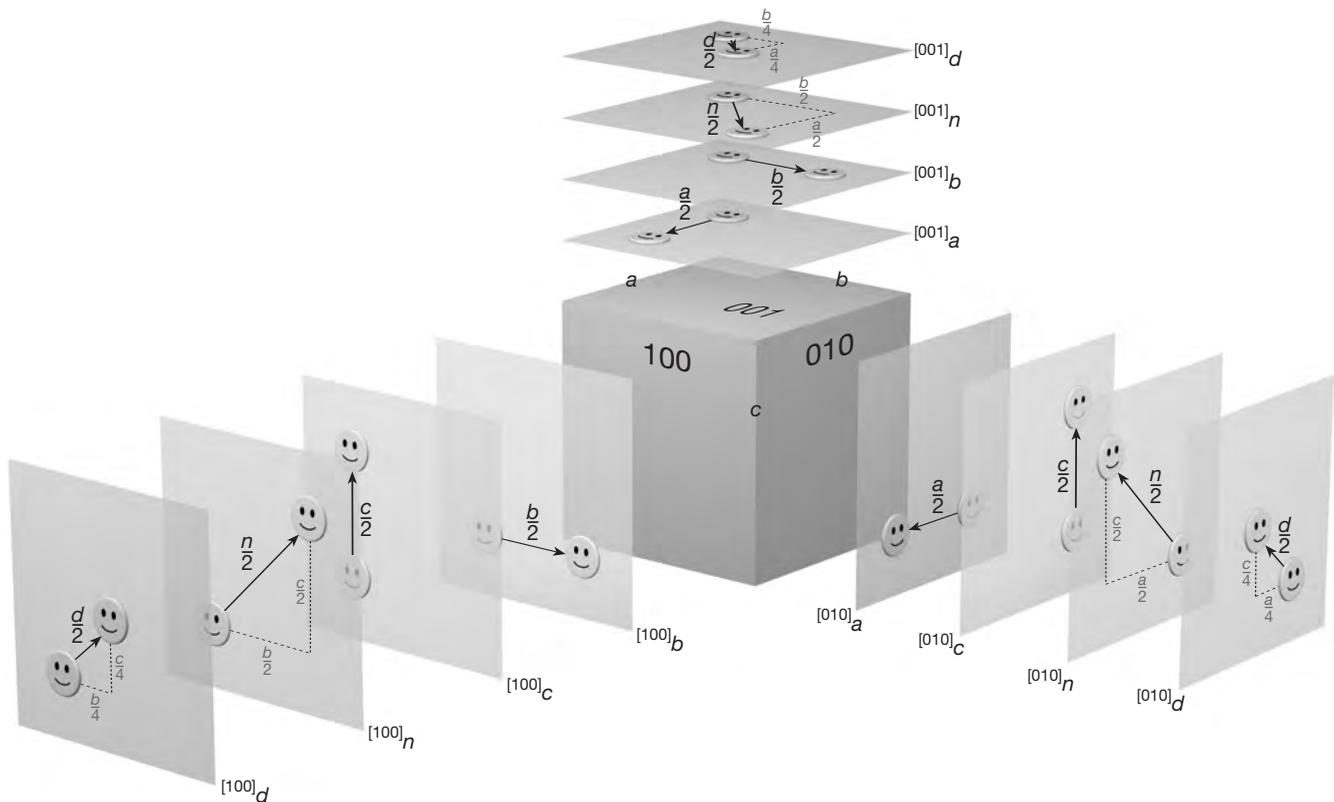


Figure 12.78. A summary of the different types of glide planes and how they are symmetry-constrained to the (100), (010), and (001) faces. As shown, there are four possible glide planes for each of the three faces: two axials, a diagonal, and a diamond glide. Adapted from Bloss (Figure 7.9, page 170, 1994).

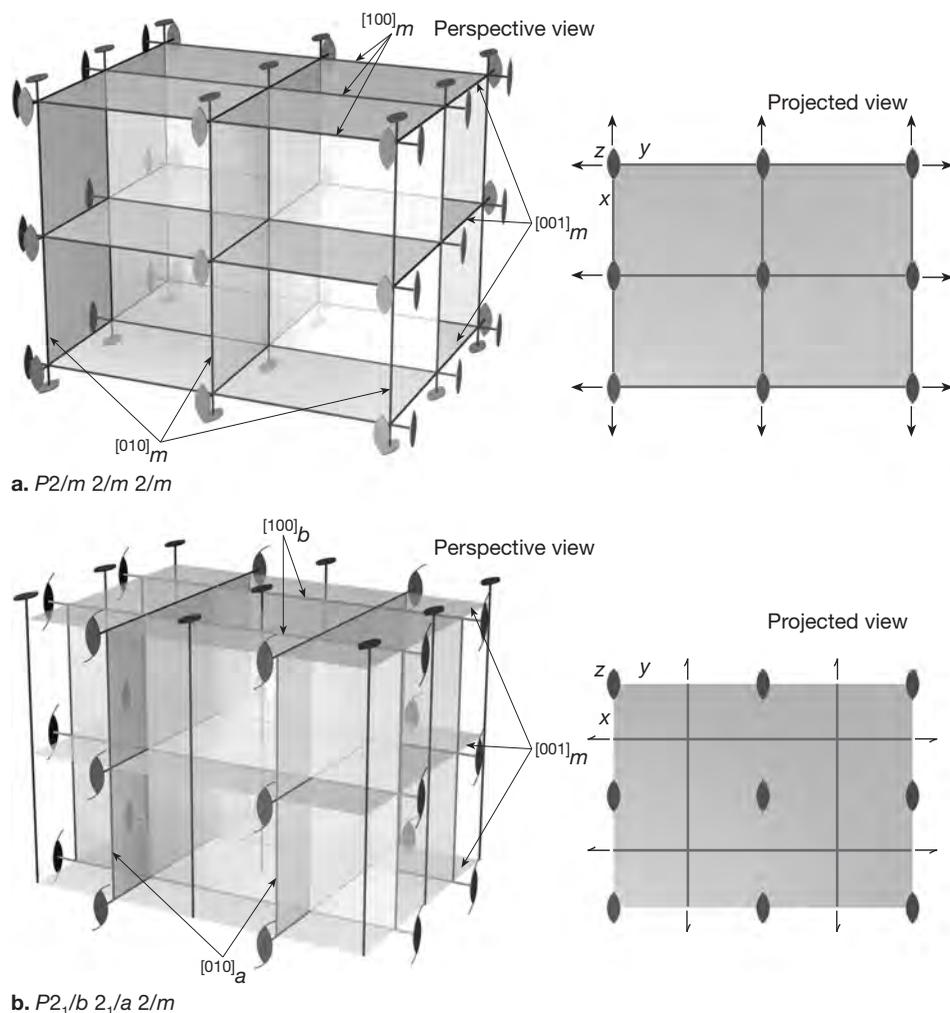


Figure 12.79. Examples of orthorhombic space groups both in a perspective and projected views. See Tables 12.3 and 12.9 for the meaning of the symbols **a**. The space group $P\ 2/m\ 2/m\ 2/m$ would have 2-fold axes and mirrors coinciding with, and perpendicular to, all three crystallographic axes. **b**. The space group $P2_1/b\ 2_1/a\ 2/m$ is similar to $P\ 2/m\ 2/m\ 2/m$, except two of the 2-fold axes are now 2_1 screws and two of the mirror planes are now axial glide planes.

(i.e., the two symmetry types cannot exist at the same time.) What kind of glide planes can occur in the monoclinic system? Recall that we have a $[010]m$, which can have glide components in either a or c (Figure 12.80). Because of the monoclinic symmetry, the glide direction can only be in c (Figure 12.80a). By adding the c glide, we create Cc , $P2/c$, $P2_1/c$, and $C2/c$. So we have created the thirteen monoclinic space groups from the symmetry-allowed permutations of the three point groups, two lattice types, and screw axes and glide planes (i.e., the $[010]2_1$ and $[010]c$).

Some of the space groups in Table 12.10 have a “*” next to them. These are the so-called “non-standard” space groups and they occur because some researchers have chosen different orientations for the symmetry elements and crystallographic axes. There are at least ten non-standard space groups for the triclinic case, 30 for monoclinic, and a whopping 165 for the orthorhombic systems (fortunately, none for the other systems because none of the other crystal systems has these non-standard space groups; they are more

symmetry-constrained and the choice of symmetry directions cannot be varied). Several of these non-standard space groups are used to describe the feldspars and are extremely common in minerals (Table 12.10). We’ll turn our attention to the non-standard space groups after the discussion of space groups is completed.

Orthorhombic system. Because we are using permutations of symmetry elements to compose the space groups, the numbers of possibilities grows with the number of symmetry elements and lattice types. The orthorhombic system only has three point groups (222 , $mm2$, and $2/m\ 2/m\ 2/m$), there are four possible lattice types (Figures 12.48 to 12.51). So we start with twelve space groups before considering screw axes and glide planes. When we add them in, we gain an addition 38 new space groups (Table 11.9). Unlike the monoclinic case, we can have glide planes along (100), (010), and (001) because the crystallographic axes in the orthorhombic system are mutually perpendicular. Also, there are a , b , c , and even n glides. What’s more, past researchers have selected different ori-

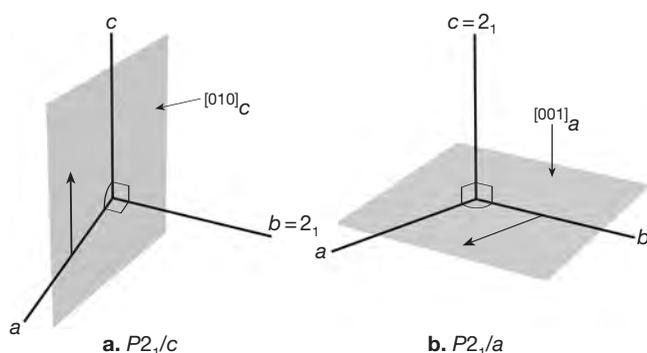


Figure 12.80. Different choices of axes will result in different space groups. For instance, in the monoclinic minerals either the b or c axis can be chosen to correspond to the sole symmetry direction. **a.** The commonly-chosen second setting for monoclinic minerals, where b is selected as the symmetry direction, results in the standard space group $P2_1/c$, where the $^{[010]}m$ is converted into a $^{[010]}c$ glide by translation parallel to c . **b.** In the so-called first setting, where c is selected to coincide with the sole symmetry axis, the $P2_1/c$ shown in Figure 12.80a would become $P2_1/a$, because the $^{[001]}m$ would change to $^{[001]}a$ with the glide parallel to a (as indicated by the arrow). In Figure 12.80a, (the second setting) $\alpha = \gamma = 90^\circ$ and $\beta \neq 90^\circ$, while for the first setting, $\alpha = \beta = 90^\circ$ and $\gamma \neq 90^\circ$. The crystal structures of the minerals are not changing, but we are just choosing different basic vector sets to describe them.

entations for some of the symmetry operations, creating 165 non-standard space groups (Table 12.10, which will be discussed later.)

Tetragonal system. There are seven point groups in this system but only two lattice types, P and I , which gives us 14 space groups to start. Another 52 space groups are created by the addition of screw axes and glide planes (Table 11.9).

Hexagonal system. Again there are only two lattice types in this system, P and R . The R lattice type can only occur in minerals with a 3- or $\bar{3}$ -fold axis parallel to c , of which there are five point groups. Incorporation of the P and R lattice types with the space symmetry operations yields 25 point groups. There is some overlap between these space groups, as pointed out in Figure 12.53 where corundum was generated based on either an R or P lattice. The seven point groups that start with a 6 or $\bar{6}$ can only have P lattices. The addition of translations then yields the 27 space groups shown in Table 11.9.

Isometric system. This system has 3-fold axes that coincide with the $[111]$ direction, making five point groups. Three possible lattice types can occur for this system, P , I , and F . Combinations of the five point groups and three lattice types with translational symmetries result in the 36 remaining space groups (Table 11.9).

Table 12.10 lists the top 20 (of the 230) space groups in terms of the numbers of known minerals to form in each. Interestingly, the sum of these 20 is 53%, so only 9% of the space groups contain over half the known minerals! $P\bar{1}$ occurs in the most minerals, followed by four monoclinic space groups. The space group systems in this table follow fairly closely those shown in Table 12.8, except that triclinic system now comes in second instead of third. But also notice that all (two) of the triclinic space groups are in the top 20 and not far from where the orthorhombic ones are.

Non-standard space groups. As we mentioned above, there are non-standard space groups in the triclinic, monoclinic, and orthorhombic systems. Fortunately, there are no non-standard space groups in the systems with higher symmetry because the symmetry axes are constrained to conform to the crystallographic axes in a fixed manner (i.e., the 4-fold and 6-fold axes of the tetragonal and hexagonal systems always coincide with c , while the 3-fold axes of the isometric systems always coincide with $[111]$).

The non-standard space groups in the triclinic system result from the choice of a different lattice type. Table 12.11 lists the ten non-standard space groups for the triclinic system, which show all the different lattice types except R . These differ-

Table 12.10.
The "top 20" space groups and the number and percent of the minerals they contain.
(Data from Dana's New Mineralogy (Gaines et al., 1997)).

Space group	# minerals	%
$P\bar{1}$ (2)	221	6.9
$C2/m$ (12)	217	6.8
$C2/c$ (15)	138	4.3
$P2_1/c$ (14)	132	4.1
$P2_1/a$ (14)*	124	3.9
$R\bar{3}2/m$ (166)	101	3.2
$P1$ (1)	90	2.8
$F4_1/d\bar{3}2/m$ (227)	81	2.5
$P2_1/n$ (14)*	80	2.5
$P2_1/m$ (11)	75	2.3
$P6_3/m2/m2/c$ (194)	66	2.1
$F4/m\bar{3}2/m$ (225)	58	1.8
$P2_1$ (4)	44	1.4
$P2_12_12_1$ (19)	42	1.3
$P6_3/m$ (176)	42	1.3
$P2_1/b2_1/n2_1/m$ (62)*	41	1.3
$R\bar{3}$ (148)	38	1.2
$R3m$ (160)	37	1.2
$P2_1/b2_1/c2_1/a$ (61)	32	1.0
$P2_1/a3$ (205)	30	0.9

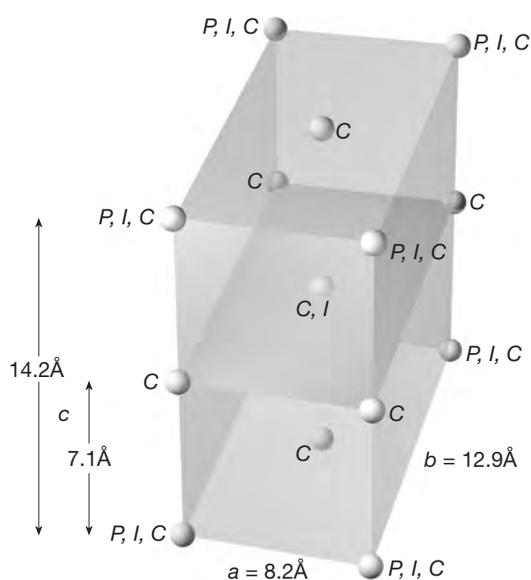


Figure 12.81. Above three different lattice types are drawn on a unit cell of a feldspar. Three letters are used (P, I, C) to mark the different cells, with the letters representing the lattice corners, face, and/or center. Again notice how the P lattice repeat in c is twice that of the C lattice. (Modified from Figure R.12, Ribbe, 1975.) For the triclinic system, there are non-standard space groups that result from choosing lattices other than P. For instance, the standard space group $P\bar{1}$ is often used to describe feldspars, though past researchers have (unfortunately) chosen other related lattice types, such as $I\bar{1}$ or $C\bar{1}$. Note that as in the case of a P lattice for enstatite (Figure 12.55b) and a C lattice for diopside (Figure 12.55a), the a repeat is twice as long for P as for C. The same condition holds here for the C triclinic lattice as compared to the P lattice.

ent lattice types occur by changing the size of the unit cell. For instance, $P\bar{1}$, $I\bar{1}$, and $C\bar{1}$ lattice types have all been used to describe feldspars (Figure 12.81). While $P\bar{1}$ would work to describe all of the structures for the feldspars, earlier researchers unfortunately picked these other types of space groups. Because we often want to compare current structures to those done earlier, we have adopted some of these non-standard space groups. The remaining eight non-standard space groups could be described similarly based on changing the size of the unit cell to incorporate different lattice points.

In the monoclinic system, non-standard space groups result from selection of different symmetry axes and non-standard lattice types. For instance, $P2_1/c$ could be represented by the non-standard space group $P2_1/a$ (Figure 12.80) by choosing a different axis set (i.e., the former has b as the symmetry axis while the latter has c). Different non-standard lattice types can also be chosen. Table 12.11 shows the 27 non-standard monoclinic space groups that result from select-

ing c instead of b as the sole symmetry axis, and allowing for other lattice types.

Because there are six permutations of how to fit the three mutually perpendicular symmetry operation directions with the three mutually perpendicular crystallographic axes, there are 156 possible non-standard space groups in the orthorhombic system! Table 12.11 lists six entries for each of the 57 orthorhombic space groups that result from permutations of the a , b , and c axes. Consider space group number 41. The point group for this space group is $mmm2$. Thus we can expect to have mirror planes or glide planes in the first two entries that correspond to the a and b directions and a 2-fold or 2_1 screw in the last (or c) direction. The standard setting for this space group creates $Aba2$, which we could write as $A_{[100]b}^{[100]c} [010]a [001]2$. Notice that there are five other possible ways that a , b , and c could fit to this symmetry if we choose the axes differently. For example, if we write $C_{[100]c}^{[100]a} [010]2$, it would imply that c and b have changed places; this is (hopefully) apparent because the position of the "2" was changed.

When the axis directions are changed relative to the symmetry directions, the other symmetry types change (Figure 12.82). Here, we are changing only the coordinate system we use to describe the minerals. We start with a , b , and c as the three symmetry directions to arrive at $Aba2$. Next, we change the orientation of the symmetry elements to the order c , a , b to arrive at $Cc2a$. This says that the symmetry along a for $Aba2$ is along c for $Cc2a$, the symmetry that was along b for $Aba2$ is along a for $Cc2a$, and the symmetry along c for $Aba2$ is along b for $Cc2a$. Yes, this is very confusing! This is why crystallographers have worked to standardize all these orientations. However, we have included these older, non-standard space groups here just in case you ever need to refer to the earlier crystallographic work.

Summary

This chapter had the task of exploring the subject of symmetry at a higher level than Chapter 11. As stated at the start, we really deal with two kinds of symmetry in mineralogy: external, which relates to mineral shapes and internal, which relates to atomic arrangement. External morphology was studied first, before analytical methods were developed that allowed us to explore internal atomic arrangements. Because of this history, some of the nomenclature developed to understand external symmetry has been carried over to internal symmetry. However we now emphasize

Table 12.11.
Non-standard space groups based on different axes choices and orientations.

Triclinic: $A1$ (1), $A\bar{1}(2)$, $B1$ (1), $B\bar{1}$ (2), $C1$ (1), $C\bar{1}$ (2), $I1$ (1), $I\bar{1}$ (2), $F1$ (1), $F\bar{1}$ (2)

Monoclinic: Pn (7), Pa (7), $P2/n$ (13), $P2/a$ (13), $P2/b$ (13), $P2_1/n$ (14), $P2_1/a$ (14), $P2_1/b$ (14), $A2$ (5), Aa (7), An (9), $A2/m$ (12), $A2/a$ (13), $A2_1/a$ (14), $A2/n$ (15), $B2$ (5), Bm (8), Bn (9), $B2/m$ (12), $B2/n$ (15), $I2$ (5), Im (8), Ia (9), Ib (9), $I2/m$ (12), $I2/a$ (15), $I2/b$ (15)

Orthorhombic: $P22_12$ (17), $P2_122$ (17), $P22_121$ (18), $P2_122_1$ (18), $Pm2m$ (25), $P2mm$ (25), $Pcm2_1$ (26), $Pb2_1m$ (26), $Pm2_1b$ (26), $P2_1am$ (26), $P2_1ma$ (26), $Pb2b$ (27), $P2aa$ (27), $Pbm2$ (28), $Pc2m$ (28), $Pm2a$ (28), $P2cm$ (28), $P2mb$ (28), $Pbc2_1$ (29), $Pb2_1a$ (29), $Pc2_b$ (29), $P2_ab$ (29), $P2_ca$ (29), $Pcn2(30)$, $Pn2b$ (30), $Pb2n$ (30), $P2na$ (30), $P2an$ (30), $Pnm2_1$ (31), $Pm2_1n$ (31), $Pn2_1m$ (31), $P2_1mn$ (31), $P2_1nm$ (31), $Pc2a$ (32), $P2cb$ (32), $Pbn2_1$ (33), $Pn2_1a$ (33), $Pc2_1n$ (33), $P2_1nb$ (33), $P2_1cn$ (33), $Pn2n$ (34), $P2nn$ (34), $P2/b$ $2/m$ $2/b$ (49), $P2/m$ $2/a$ $2/a$ (49), $P2/c$ $2/n$ $2/a$ (50), $P2/n$ $2/c$ $2/b$ (50), $P2/m$ $2_1/m$ $2/b$ (51), $P2_1/m$ $2/a$ $2/m$ (51), $P2/m$ $2/c$ $2_1/m$ (51), $P2/b$ $2_1/m$ $2/m$ (51), $P2/c$ $2/m$ $2_1/m$ (51), $P2_1/n$ $2/n$ $2/b$ (52), $P2/n$ $2/a$ $2_1/n$ (52), $P2_1/n$ $2/c$ $2/n$ (52), $P2/b$ $2/n$ $2_1/n$ (52), $P2/c$ $2_1/n$ $2/n$ (52), $P2/n$ $2/m$ $2_1/b$ (53), $P2/m$ $2_1/a$ $2/n$ (53), $P2/n$ $2_1/c$ $2/m$ (53), $P2_1/b$ $2/m$ $2/n$ (53), $P2_1/c$ $2/n$ $2/m$ (53), $P2/c$ $2_1/c$ $2/b$ (54), $P2_1/b$ $2/a$ $2/b$ (54), $P2/b$ $2/c$ $2_1/b$ (54), $P2/b$ $2_1/a$ $2/a$ (54), $P2/c$ $2/a$ $2_1/a$ (54), $P2_1/c$ $2/m$ $2_1/a$ (55), $P2/m$ $2_1/c$ $2_1/b$ (55), $P2_1/b$ $2/n$ $2_1/b$ (56), $P2/n$ $2_1/a$ $2_1/a$ (56), $P2_1/c$ $2/a$ $2_1/m$ (57), $P2/c$ $2_1/m$ $2_1/b$ (57), $P2_1/b$ $2_1/m$ $2/a$ (57), $P2_1/m$ $2/c$ $2_1/a$ (57), $P2_1/m$ $2_1/a$ $2/b$ (57), $P2_1/n$ $2/m$ $2_1/n$ (58), $P2/m$ $2_1/n$ $2_1/n$ (58), $P2_1/m$ $2/n$ $2_1/m$ (59), $P2/n$ $2_1/m$ $2_1/m$ (59), $P2/c$ $2_1/a$ $2_1/n$ (60), $P2_1/c$ $2_1/n$ $2/b$ (60), $P2/b$ $2_1/n$ $2_1/a$ (60), $P2_1/n$ $2_1/c$ $2/a$ (60), $P2_1/n$ $2/a$ $2_1/b$ (60), $P2_1/c$ $2_1/a$ $2_1/b$ (61), $P2_1/m$ $2_1/n$ $2_1/b$ (62), $P2_1/n$ $2_1/a$ $2_1/m$ (62), $P2_1/m$ $2_1/c$ $2_1/n$ (62), $P2_1/b$ $2_1/n$ $2_1/m$ (62), $P2_1/c$ $2_1/m$ $2_1/n$ (62), $A2_122$ (20), $A2mm$ (35), $A2_1ma$ (36), $A2_1am$ (36), $A2aa$ (37), $Am2m$ (38), $Ac2m$ (39), $Am2a$ (40), $Ac2a$ (41), $A2_1/m$ $2/m$ $2/a$ (63), $A2_1/m$ $2/a$ $2/m$ (63), $A2_1/b$ $2/m$ $2/a$ (64), $A2_1/c$ $2/a$ $2/m$ (64), $A2/m$ $2/m$ $2/m$ (65), $A2/m$ $2/a$ $2/a$ (66), $A2/b$ $2/m$ $2/m$ (67), $A2/c$ $2/m$ $2/m$ (67), $A2/b$ $2/a$ $2/a$ (68), $A2/c$ $2/a$ $2/a$ (68), $B2212$ (20), $Bm2m$ (35), $Bm21b$ (36), $Bb21m$ (36), $Bb2b$ (37), $Bmm2$ (38), $B2mm$ (38), $Bma2$ (39), $B2cm$ (39), $Bbm2$ (40), $B2mb$ (40), $Bba2$ (41), $B2cb$ (41), $B2/m$ $2_1/m$ $2/b$ (63), $B2/b$ $2_1/m$ $2/m$ (63), $B2/m$ $2_1/a$ $2/b$ (64), $B2/b$ $2_1/c$ $2/m$ (64), $B2/m$ $2/m$ $2/m$ (65), $B2/b$ $2/m$ $2/b$ (66), $B2/m$ $2/a$ $2/m$ (67), $B2/m$ $2/c$ $2/m$ (67), $B2/b$ $2/a$ $2/b$ (68), $B2/b$ $2/c$ $2/b$ (68), $Ccm2_1$ (36), $Cm2m$ (38), $C2mm$ (38), $Cm2a$ (39), $C2mb$ (39), $Cc2m$ (40), $C2cm$ (40), $Cc2a$ (41), $C2cb$ (41), $C2/c$ $2/m$ $2_1/m$ (63), $C2/c$ $2/m$ $2_1/b$ (64), $C2/m$ $2/m$ $2/b$ (67), $C2/c$ $2/c$ $2/b$ (68), $Im2m$ (44), $I2mm$ (44), $Ic2a$ (45), $I2cb$ (45), $Ibm2$ (46), $Im2a$ (46), $Ic2m$ (46), $I2mb$ (46), $I2cm$ (46), $I2/c$ $2/m$ $2/a$ (72), $I2/m$ $2/c$ $2/b$ (72), $I2_1/m$ $2_1/m$ $2_1/b$ (74), $I2_1/m$ $2_1/a$ $2_1/m$ (74), $I2_1/m$ $2_1/c$ $2_1/m$ (74), $I2_1/b$ $2_1/m$ $2_1/m$ (74), $I2_1/c$ $2_1/m$ $2_1/m$ (74), $Fm2m$ (42), $F2mm$ (42), $Fd2d$ (43), $F2dd$ (43)

internal symmetry because of the plethora of analytical methods we have to study it. Point group symmetry leads to an understating of external morphology, followed by the development of space group symmetry which has its basis in

point groups, but allows translations which are critical to form the internal arrangement of atoms.

To link (literally and figuratively) the material presented in the chapter, Figure 12.83 shows a concept map of the relationships between point sym-

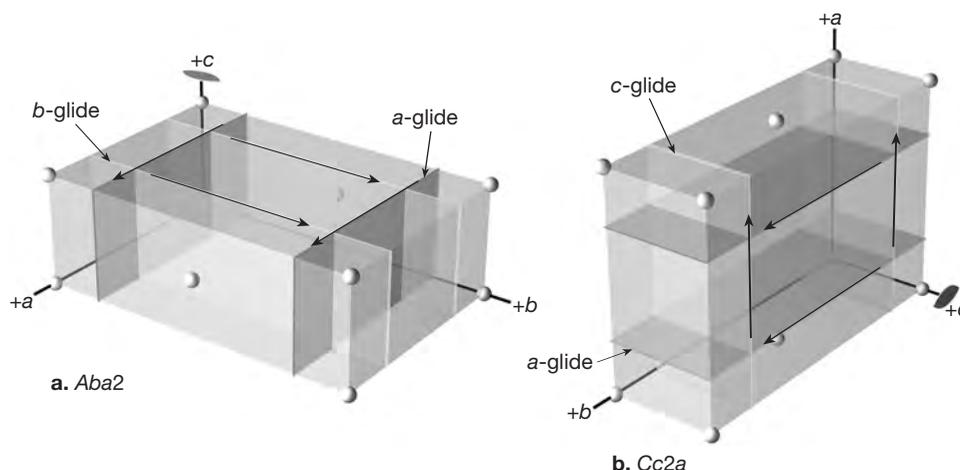


Figure 12.82. An example of a non-standard space group for the system. (Modified from Figure 13.34, Bloss, 1994.) **a.** A sketch of the unit cell and major symmetry elements for the standard space group $Aba2$ (#41). This space group is derived from the point group $mm2$ and has an A side-centered lattice. The orientation of the symmetry elements for $Aba2$ could be written explicitly as $A^{[100]}b^{[010]}a^{[001]}2$, which is the accepted convention for orthorhombic minerals (Table 12.7 and Figure 12.33). **b.** The non-standard space group $Cc2a$ results from a different axis choice. In fact, there are six permutations ($= 3!$) for assigning the three mutually-perpendicular symmetry operations to the three mutually-perpendicular crystallographic axes. In Figure 12.82a, the symmetry directions were assigned in the order a, b, c . For $Cc2a$, they are assigned in the order b, c, a .

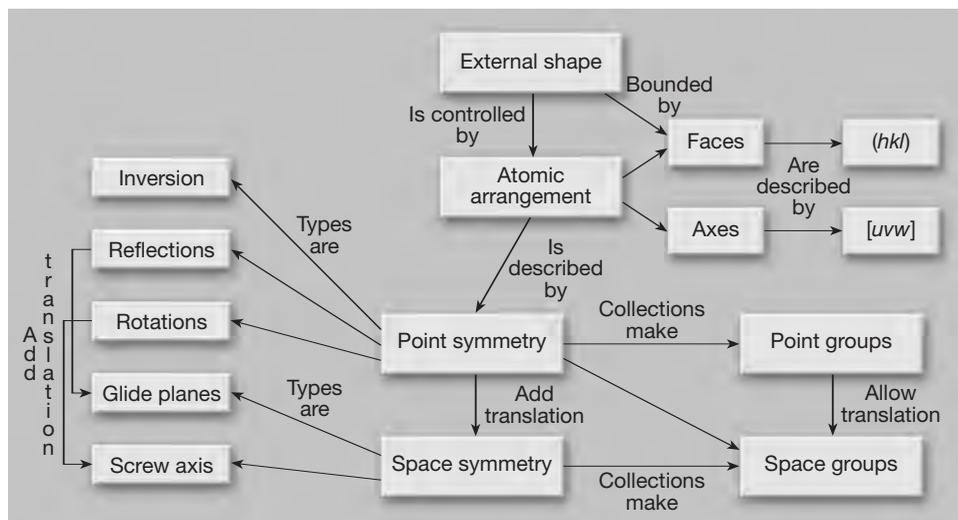


Figure 12.83. A concept map that relates the crystallographic nomenclature that we have developed in this chapter. From an historical perspective it is important to remember that all of this nomenclature has roots in the external shape of a mineral, because this was the first things observed by humans.

metry, crystal systems, point groups, Bravais lattices, (hkl) 's, $[uvw]$'s, space group symmetry, and space groups. It has taken centuries for crystallographers to arrive at the crystal systems, point and space groups and all the nomenclature necessary to describe the crystalline state. The effort you spend trying to comprehend this material now will reward you many fold (pun intended) as you pursue your career in geology. While this material may make your head hurt, it will teach you to envision and manipulate 3-D objects in your mind! And this will make you a better geologist!

References

- Buerger, M. (1978) Elementary crystallography. MIT Press, Cambridge, Mass., 528 pp.
- Bloss, F.D. (1994) Crystallography and crystal chemistry. Mineralogical Society of America, Washington D.C., 545 pp.
- Gaines, R.V., Skinner, H.C.W., Foord, E.E., Manson, B., and Rosenweig, A. (1997) Dana's New Mineralogy, 8th Edition. John Wiley and Sons, Inc., 1819 pp.
- Gibbs, G.V. (1997) The metrical matrix in teaching mineralogy. In Teaching Mineralogy, editors J.B. Brady, D.W. Mogk, and D. Perkins, III, 201–212.
- Hahn, T. (1995) International table for crystallography, volume A, space-group symmetry. Kluwer Academic Publishers, Dordrecht, Holland, 878 pp.