

# BUILDING CRYSTAL STRUCTURE BALL MODELS USING PRE-DRILLED TEMPLATES: SHEET STRUCTURES, TRIDYMITE, AND CRISTOBALITE

**Kurt Hollocher**

Geology Department  
Union College  
Schenectady, NY 12308  
hollochk@gar.union.edu

## OVERVIEW<sup>1</sup>

Ball models have long been used as teaching tools in Mineralogy to illustrate molecular and crystal structures. At Union College, Mineralogy students construct crystal structure ball models to help them better understand the concepts of crystalline order, relative atomic size, atomic coordination, crystal chemistry, and crystal symmetry. We have used two methods for this:

- 1) The students each choose a mineral (an ionic compound) to work on during the second half of the term. They research the mineral origin, occurrence, chemistry, properties, and structure, and write a report. Part of the report is a model of one or more unit cells of the mineral, built using glued together 1/8" to 1" diameter metal and plastic balls (everything from ball bearings to marbles to tennis balls can be successfully used, provided they can be firmly stuck together). The students must choose ball sizes so that they properly fit into the various sites using the radius ratio concept for ionic coordination polyhedra. This type of project has been reasonably successful, but the ball models do not always work out well.

The first problem is that many structures are too difficult for most undergraduates (or me) to build. Garnet and quartz, for example, are two that may look easy, but turn out to be very difficult to build. A related problem is that most silicate and oxide structures are not simple arrays of atoms, like the intersections of lines on graph paper. Small differences between ball radii and the effective (scaled) ionic radii of the real atoms, or small displacements of the balls from atomic positions in the real structures, often result in grossly distorted models. For example, the isometric spinel minerals can be thought of as being based on a cubic closest packed array of oxygens, with the oxygen layers perpendicular to a unit cell body diagonal. In principal, all one should have to do is make the oxygen layers, adding cations in the appropriate places as you go. However, all of the spinel models that have come from these student projects are trigonal.

Several different methods have been used to glue the spheres in the proper places: rulers, clay supports, tape supports, graph paper grids, custom ruled grids, computer drawings, constructing simple subunits of the structures and then combining them, and others. In most cases these methods do not work well since they are not accurate enough or cannot be applied accurately enough. I thought that using pre-drilled templates would allow the straight-forward construction of a limited set of structures, but structures that at least could be successfully built. Since the object is to learn about crystal structures, rather than about model construction techniques, I thought the tradeoff was reasonable.

---

<sup>1</sup> Sources of the materials we use are given in the Appendix.

- 2) I had two kinds of templates machined: a packed hexagonal array (Figure 1) used for making octahedral layers with “ ” spheres as oxygens or hydroxyls, and an extended hexagonal array (Figure 2) for making corner-sharing tetrahedral layers with “ ” spheres as oxygens. In one 3-hour lab session students use the templates to build various sheet silicate components. The models are then used with sheet mineral hand samples and other props to show the origin of strong pleochroism, the systematics of stacking polytypes, and the reasons for differences in hardness. The models are useful for teaching principles of X-ray diffraction, because the sheets can be stacked and measured to show why the basal spacings of the sheet structures differ. The sheet components that the students make are brucite, serpentine, and talc. These can make brucite, serpentine, talc, biotite (requires some loose K atoms), chlorite, and various clays. Offsets of the paired hydroxyls in the octahedral layers of talc or biotite make it easy to show sheet stacking vectors and the ordering of stacking polytypes. Stacking polytypes can also be demonstrated with oriented layers of Plexiglas® hexagons (Figure 3).

The models are fully extended hexagonal sheets, not the less extended trigonal sheets that are so common in nature. Trigonal templates are much harder to design and machine. All of the octahedral layers we make are trioctahedral, since the octahedral vacancies of dioctahedral sheets make the final models too fragile for routine classroom use.

Using templates to make sheet silicate models is easy, accurate, fast, and reliable. Three years of Mineralogy students, working in groups of two, have successfully built their one or two model components in one lab session, with time to spare for discussion of crystal structure, stacking, and using mineral specimens as examples of how properties change with structure (note that each group needs its own templates, so make plenty). The only serious problem has been with excess glue dripping down and cementing the model to the template. This problem can be solved by making the templates of plastic that is resistant to Duco® cement, such as polyethylene or polypropylene, instead of Plexiglas®. Wood has been tried as a template material, but it is too difficult to make sharp, clean edges on the holes, and so ball locations are not accurate enough. Hot-melt glue guns, for gluing the balls together, have been found by others to work well. Glue guns do not have potentially toxic solvents and the glue cures in seconds, but minor burns are possible. Some glue guns are quite inexpensive.

As the years go by, sheet silicate models accumulate. The individual sheet components are not very useful or instructive, so I do not give them away to the students who made them (although giving away colorful models to students may be good advertising for geology programs). Instead, I keep some model sets for use outside of Mineralogy. Scout troops, for example, love them during mineral demonstrations. I gave away one set (two of each kind of sheet) to a high school earth science teacher, and that is probably what I will continue to do.

What else can the templates be used for? In principal they can be used for any structure that can be approximated by hexagonal arrays of oxygens and/or by fully extended hexagonal tetrahedral layers. Two examples that I include below are tridymite and cristobalite, which are easily made using only the tetrahedral layer template. Reasonably accurate ilmenite and hematite models can easily be made using the octahedral template, although the distorted octahedra will not be distorted in quite the right way. Olivine, spinel, and most other structures based on closest packed arrays of oxygens usually cannot be properly made with these templates. This is because the template octahedra are extended in a plane parallel to the layer to fit the fully extended hexagonal tetrahedral layers in sheet silicates. As a result, the octahedra are strongly flattened perpendicular to the layers. If you want to make olivine and spinel, drill an octahedral template like

that shown in Figure 1, but make the line spacings 0.380" instead of 0.433" for " balls. You will also have to use six-coordinated spheres that have diameters of 5/16" rather than the 7/16" spheres used here for the sheet silicates.

### Crystal and Structural Chemistry of Common Sheet Silicates

All of the common sheet silicates and related minerals are based on two principal components: tetrahedral layers and octahedral layers.

#### Tetrahedral layers

The tetrahedral layers are nominally hexagonal arrays of corner-sharing  $\text{SiO}_4$  tetrahedra. In most natural sheet silicates, small rotations of the Si-O-Si bonds result in arrays that have trigonal symmetry. The shared oxygens in the layer are called "bridging oxygens", since they are the bridges that link adjacent  $\text{SiO}_4$  tetrahedra. The other oxygens are called "apex oxygens", since they occupy the 'free' apex of each tetrahedron. Apex oxygens are all shared with cations in the octahedral layer. In talc and some other sheet silicates,  $\text{Si}^{4+}$  occupies all of the tetrahedral sites. In other sheet silicates  $\text{Al}^{3+}$  replaces usually  $\frac{1}{3}$  but up to  $\frac{2}{3}$  of the  $\text{Si}^{4+}$  ions.

#### Octahedral layers

The octahedral layers are composed of edge-sharing octahedra, and the layers come in two varieties. In trioctahedral layers all octahedra are occupied, usually by divalent cations such as  $\text{Mg}^{2+}$ . In dioctahedral layers only  $\frac{2}{3}$  of the octahedra are occupied, usually by  $\text{Al}^{3+}$ .

#### Connected octahedral and tetrahedral layers

Octahedral layers can be bare, can be attached to a tetrahedral layer on one side, or can be sandwiched between two tetrahedral layers. Bare octahedral layers are obviously not silicates, but since they are layer structures related to and in some cases combined with other layer types, they are included here. In bare octahedral layers, such as brucite, all of the anions are hydroxyls rather than oxygens to maintain charge balance. Each 6-coordinated cation is bonded to 6 hydroxyls. We will ignore the hydrogens of the hydroxyls in our models. The stacking sequence for pure octahedral layer minerals is  $\text{O} \sim \text{O} \sim \text{O} \sim \text{O}$ , where O represents octahedral sheets stacked up parallel to  $c$ , and ' $\sim$ ' represents weak hydrogen bonds between the sheets.

If the octahedral layer is connected to one tetrahedral layer, as in the 2-layer sheet silicate serpentine, then  $\frac{2}{3}$  of the hydroxyls on *one* side of the octahedral layer are replaced by oxygens. These are the apex oxygens of the tetrahedral layer that are shared between the tetrahedral and octahedral layers. Each 6-coordinated cation is bonded to 2 oxygens and 4 hydroxyls. The stacking sequence for 2-layer silicates is  $\text{T-O} \sim \text{T-O} \sim \text{T-O} \sim \text{T-O}$ , in which T represents tetrahedral layers, O represents octahedral layers, '-' represents strong bonds within the sheets, and ' $\sim$ ' represents weak hydrogen bonds between the sheets.

If the octahedral layer is sandwiched between two tetrahedral layers, as in the 3-layer sheet silicates talc, then  $\frac{2}{3}$  of the hydroxyls (as in brucite) on *both* sides of the octahedral layer are replaced by tetrahedral layer apex oxygens. Each octahedral cation is then bonded to two hydroxyls and four oxygens. Again, the oxygens are shared between the octahedral and tetrahedral layers. The stacking sequence for 3-layer sheet silicates is  $\text{T-O-T} \sim \text{T-O-T} \sim \text{T-O-T}$ , with the symbols as defined above, except that ' $\sim$ ' here represents weak Van der Waals bonds in talc or stronger ionic bonds in micas where K, Na, or Ca occupy the interlayer sites.

### Systematic crystal structural chemistry

The table below summarizes the common sheet silicates and related minerals, as distinguished by layer type, layer stacking, and layer composition. The A-site is the 10 to 12 coordinated site nested between the 6-sided rings of facing tetrahedral layers. The A-site may contain  $K^+$ ,  $Na^+$ ,  $Ca^{2+}$ , and other large low-charge ions, and o (vacancies).

Stack	Layers	A-site	Diocahedral	Triocahedral
~O~	1-layer	None	Gibbsite $\{Al_2\}\{OH\}_6$	Brucite $\{Mg_3\}(OH)_6$
~O-T~	2-layer	None	Kaolinite $\{Al_2\}\{Si_2O_5\}(OH)_4$	Serpentine $\{Mg_3\}[Si_2O_5](OH)_4$
~T-O-T~	3-layer	□	Pyrophyllite $\square\{Al_2\}\{Si_4O_{10}\}(OH)_2$	Talc $\square\{Mg_3\}[Si_4O_{10}](OH)_2$
~T-O-T~	3-layer mica	$K^+$	Muscovite $K\{Al_2\}\{AlSi_3O_{10}\}(OH)_2$	Biotite (Phlogopite) $K\{Mg_3\}[AlSi_3O_{10}](OH)_2$
~T-O-T~O~	4-layer	None	None?	Chlorite $\{Mg_3\}[Si_4O_{10}](OH)_2 \cdot \{Mg_3\}(OH)_6$

T = Tetrahedral layer in the stack.

O = Octahedral layer in the stack.

{ } = Octahedral layer cations in the formulae.

[ ] = Tetrahedral layers in the formulae.

The coupled substitution  $3^{[6]}M^{2+} \Leftrightarrow 2^{[6]}Al^{3+} + [6]\square$  controls the composition difference between dioctahedral and trioctahedral structures. The coupled substitution  $^{[12]}\square + [4]Si^{4+} \Leftrightarrow [^{12}]K^+ + [4]Al^{3+}$  controls the composition difference between 3-layer sheet structures having empty (e.g., talc) vs. occupied (e.g., biotite) A-sites.  $Na^+$ , and  $Ca^{2+}$  are major A-site ions in some micas. A common substitution in micas, chlorite, and some serpentines is the coupled substitution  $^{[6]}Mg^{2+} + [4]Si^{4+} \Leftrightarrow [^{6}]Al^{3+} + [4]Al^{3+}$  (the Tschermak substitution), which makes most micas and chlorite more Al-rich than the basic formulae. Many medium-size ions can substitute in the octahedral sites, including  $Fe^{2+}$  (almost universal),  $Ni^{2+}$ ,  $Co^{2+}$ ,  $Fe^{3+}$ ,  $V^{3+}$ ,  $Cr^{3+}$ ,  $Li^+$ , and  $Ti^{4+}$ . Obviously some substitutions are simple and some are coupled, depending on the ion and the sheet silicate into which it is substituting. No ions other than  $Si^{4+}$  and  $Al^{3+}$  are abundant in tetrahedral sites.

### Stacking polytypes

Despite the nominally hexagonal shape of the sheets, sheet silicates do not generally have hexagonal symmetry. First, tetrahedral layers must usually shrink a little to fit the more rigid octahedral layers. Tetrahedral layers do this by slight rotations of Si-O-Si bridging oxygen bonds, becoming trigonal in the process. Second, paired hydroxyls and tetrahedral layers on either side of each octahedral layer in micas and talc are offset from one another (Figure 4). Each sheet, therefore, has an intrinsic polarity known as the stacking vector (Figure 5). The vectors of stacked sheets may all point in the same direction in a crystal, or they may point in different directions in a repeating pattern or randomly up the stack (the c axis; Figure 6). Sheet silicates that are identical but for the stacking vector repeat pattern are polymorphs, but are referred to as polytypes since they are physically almost identical to one another. X-ray diffraction, however, can spot the characteristic repeat spacing of the stacking vector. There are six simple types of stacking vector repeats, presented in the table below and in Figure 6.

Polytype name	Sheets/ repeat	Crystal system	Stacking vector rotation/layer	Symmetry element    c
1M	1	Monoclinic	none	mirror.
2M <sub>1</sub>	2	Monoclinic	60°	c glide.
2M <sub>2</sub>	2	Monoclinic	120°	c glide.
2O	2	Orthorhombic	180°	c glide.
3T	3	Trigonal	120°	3 <sub>1</sub> screw axis
6H	6	Hexagonal	60°	6 <sub>1</sub> screw axis
M <sub>a</sub>	Disordered	Monoclinic	Disordered	mirror

Look in a mineralogy text to see which minerals commonly have which stacking polytypes.

### Building the Models: Instructions to Students

#### Sheet silicates

Sheet silicates are among the easiest silicate models to make. Most sheet silicates do not have perfect hexagonal arrays, but rather are slightly distorted with trigonal symmetry. Even in the rare sheet silicates with perfectly hexagonal arrays (e.g., the Fe-rich biotite annite), the sheets stack to yield monoclinic, trigonal, orthorhombic, or hexagonal crystals. Our models will have completely extended, perfectly hexagonal arrays since it makes no difference to the symmetry of the final crystals, and it makes the models easier to build.

You will work in teams of two building parts for a variety of trioctahedral sheet structures. It is not difficult to build accurate models, since most of the atoms will be located using precisely machined templates. The glue tends to be a bit of a mess. Do your best to keep glue off the templates, and keep paper towels handy to wipe up excess glue. Each team will build parts of various sheet structures, including 3-layer talc sheets, 2-layer serpentine sheets, and 1-layer brucite sheets. Using these components, and unglued K<sup>+</sup> ions, we will be able to construct a variety of mica, clay, and hydroxide structures. Dioctahedral sheet silicates are easy to build in principle, but in practice the models are too fragile.

Gluing is the hardest part of making ball models. The best way to do it is to put a ball in place first to see where it makes contact with others. Then remove the ball, put small blobs of glue at the contact points, and fit it back together. Make sure the glue is at the contact points, and leave the glue to dry. Don't let the glue drip down onto the template.

Atoms and the balls that represent them are shown in Figure 7. For talc, follow the instructions in Figures 8 to 12. For serpentine, follow the instructions in Figures 8, 13, and 14. For brucite, follow the instructions in Figures 13 and 15.

In the serpentine and talc models one tetrahedral layer is completely removable from the octahedral layer. This allows you to see how oxygens are shared between layers, and to see the 6-coordinated ions that are otherwise hidden. A-site vacancies of talc can be filled with loose K<sup>+</sup> ions to make biotite.

## Tridymite and Cristobalite

Tridymite and cristobalite are polymorphs of silica,  $\text{SiO}_2$ . They are two of the nine known thermodynamically stable, condensed silica phases (Figure 16):  $\alpha$  and  $\beta$  quartz,  $\alpha$  and  $\beta$  tridymite,  $\alpha$  and  $\beta$  cristobalite, coesite, stishovite, and liquid. Other low-temperature phases that have limited or no true stability fields are moganite and keatite. A new silica polymorph, structurally similar to baddeleyite ( $\text{ZrO}_2$ ), has been predicted on theoretical grounds to be the stable silica polymorph at deep mantle pressures (Belonoshko, et al., 1996).

In their stability fields tridymite and cristobalite can both undergo displacive phase transformations: tridymite from the low temperature trigonal  $\alpha$  form to the high-temperature hexagonal  $\beta$  form, and cristobalite from the low temperature tetragonal  $\alpha$  form to the high temperature isometric  $\beta$  form. Tridymite also undergoes several metastable polymorphic transformations at temperatures below those of its stability field (Heaney et al., 1994).

The tridymite structure is based on the stacking of alternating layers of corner-sharing silica tetrahedra. Within each layer up- and down-pointing tetrahedra alternate. The layers are stacked so that up-pointing tetrahedra in one layer share oxygens with the down-pointing tetrahedra in the layer above. The layers are arranged to form hexagonal channels parallel to the  $c$  crystallographic axis. If you look down the  $c$  axis of the structure (Figure 17A), down-pointing tetrahedra of one layer completely hide the up-pointing tetrahedra in the layer below; all the tetrahedral bases are oriented the same way. The structure of hexagonal  $\beta$  tridymite is related to that of lonsdaleite, the hexagonal polymorph of diamond<sup>2</sup>. Silicon in tridymite occupies the same positions as carbon in lonsdaleite, and the oxygens occupy positions corresponding to the C-C bonds.

The cristobalite structure is related to that of tridymite. It, too, is built up of layers of corner-sharing silica tetrahedra, and in each layer up- and down-pointing tetrahedra alternate. However, in cristobalite the layers have three possible positions rather than two, and the hexagonal channels seen in tridymite are blocked. If viewed perpendicular to the layers (Figure 17B), the tetrahedra in one layer are rotated  $60^\circ$  from tetrahedra to which they are linked in the underlying layer. Unlike tridymite, the overlying tetrahedra do not completely hide underlying tetrahedra. Isometric  $\beta$  tridymite has a structure related to that of diamond: silicons occupy the same positions as carbon in diamond, and oxygens occupy positions corresponding to the C-C bonds.

For tridymite, follow the directions in Figures 18 and 19. For cristobalite, follow the directions in Figures 20 to 23. The high-symmetry  $\beta$  polymorphs are made here since templates for them are much easier to design and machine than those for the lower symmetry  $\alpha$  polymorphs.

---

<sup>2</sup> Lonsdaleite and diamond have structures identical to wurtzite and sphalerite, respectively, if you pretend that all of the atoms in the sulfides are carbon.

### General References

- Bailey, S.W., Editor (1984) Micas. *Reviews in Mineralogy*, v. 13.  
Bailey, S.W., Editor (1988) Hydrous Phyllosilicates (Exclusive of Micas). *Reviews in Mineralogy*, v. 19.

### References Cited

- Belonoshko, A.B., Dubrovinsky, L.S. and Dubrovinsky, N.A. (1996) A new high-pressure silica phase obtained by molecular dynamics. *American Mineralogist*, v. 81, p. 785-788.  
Klein, C. and Hurlbut, C.S. Jr. (1993) *Manual of Mineralogy*, 21<sup>st</sup> Edition. John Wiley and Sons, Inc., New York.  
Heaney, P.J., Prewitt, C.T. and Gibbs, G.V. (1994) Silica: Physical Behavior, Geochemistry, and Materials Applications. *Reviews in Mineralogy*, v. 29, 606 p.  
Thompson, J.B., Jr. (1981) An introduction to the mineralogy and petrology of the biopyriboles. In Veblen, D.R., Editor, *Amphiboles and Other Hydrous Pyriboles—Mineralogy*, *Reviews in Mineralogy*, v. 9A, p. 141-188.

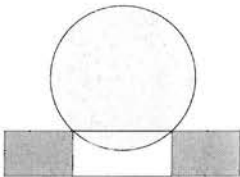
### APPENDIX: Sources for Materials

<b>Plastic sheeting:</b>	<b>Plastic spheres:</b>
United States Plastic Corp.	Ace Plastics, Inc.
1390 Neubrecht Rd.	26 North Ave.
Lima, Ohio 45801	Garwood, NJ 07027
800-537-9724.	800-695-4223

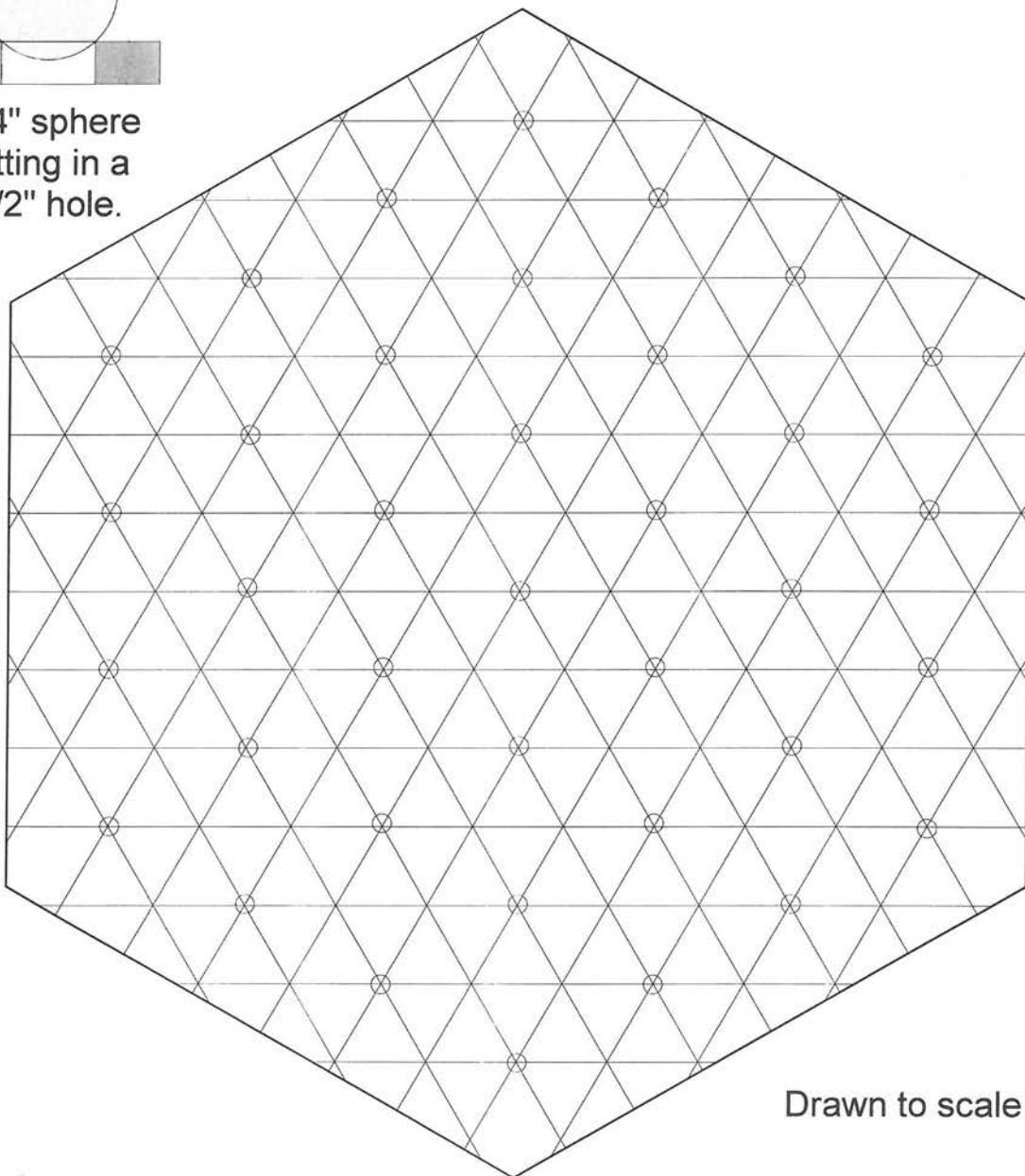
**Figure 1. Octahedral layer template for 3/4" spheres.**

Material should be 1/4" plastic, preferably polyethylene or polypropylene, or some other plastic to which Duco® Cement does not stick. Plexiglas® works, but models may stick and may be damaged when removed.

1/2" holes should be drilled all the way through the plastic at the positions marked with circles. The lines marking the drill positions are 0.433" apart, and the lines are at 60° angles to one another.



3/4" sphere  
sitting in a  
1/2" hole.



Drawn to scale

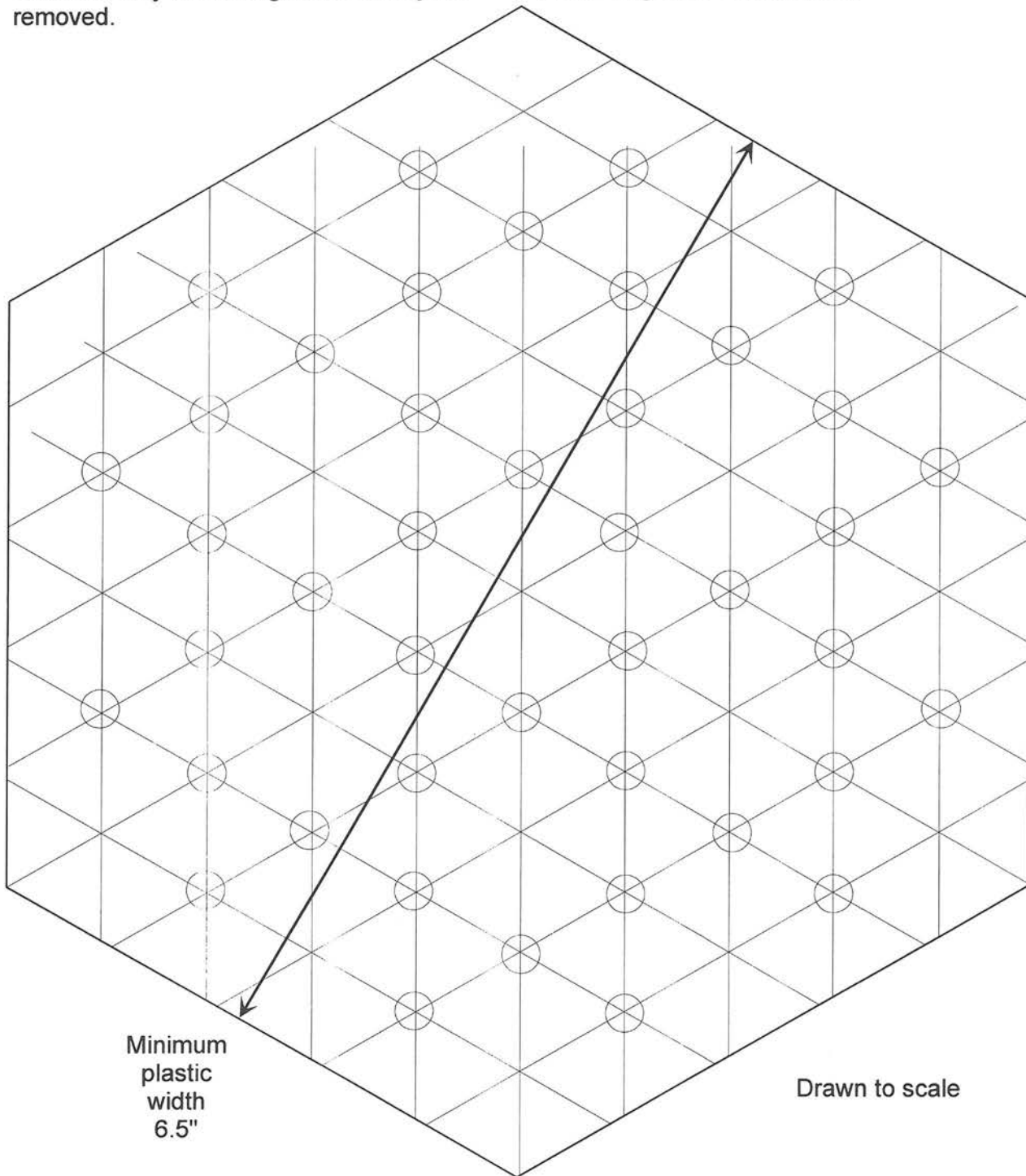
←—————→  
Minimum plastic width 5.5"



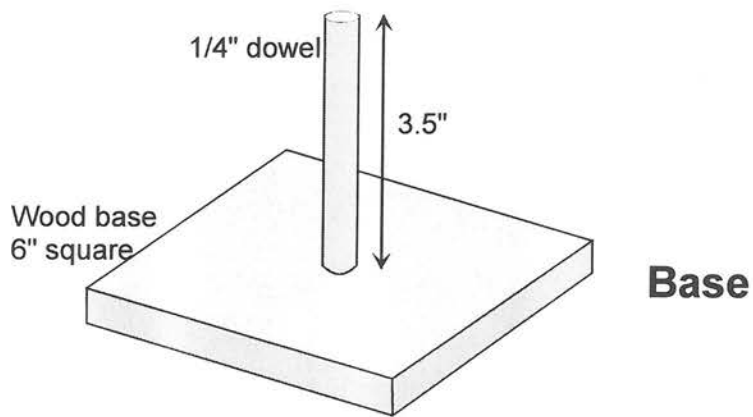
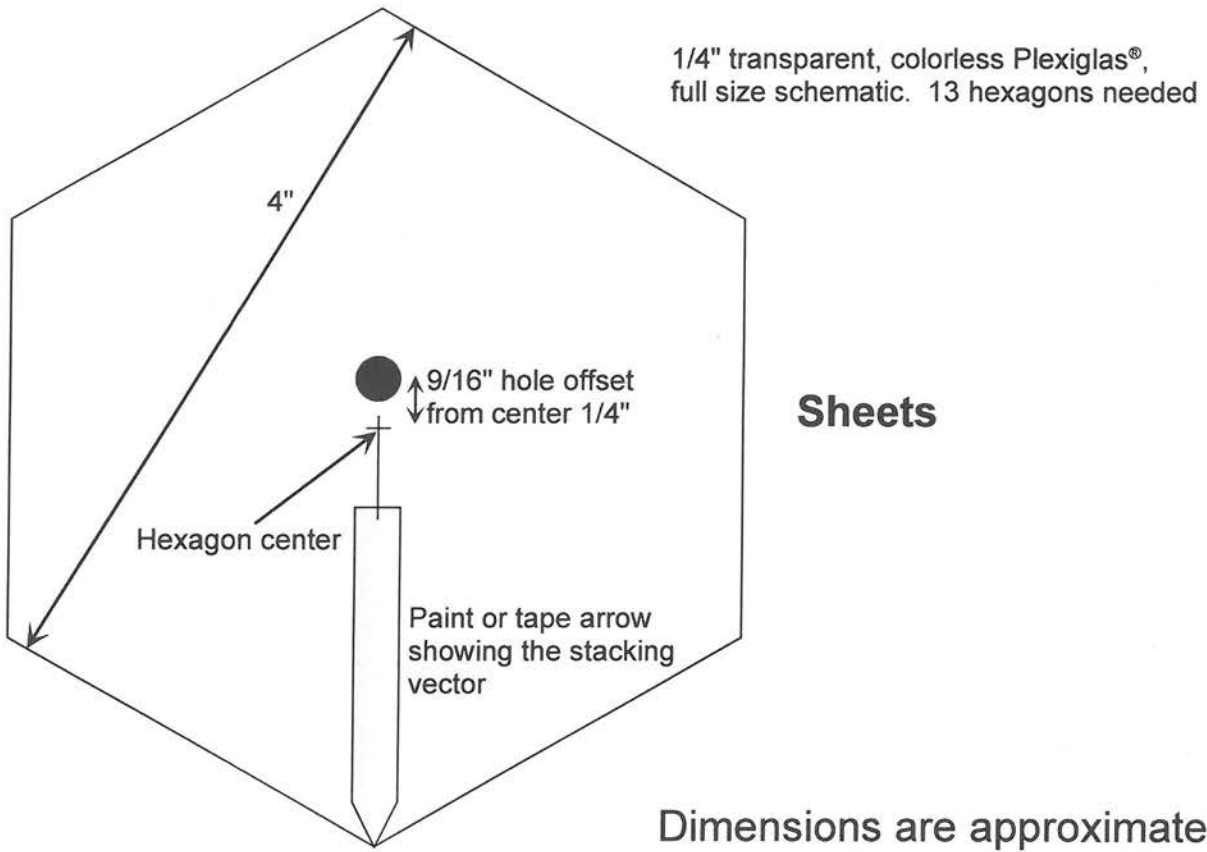
## Figure 2. Tetrahedral layer template for 3/4" spheres.

Material should be 1/4" plastic, preferably polyethylene or polypropylene, or some other plastic to which Duco® Cement does not stick. Plexiglas® works, but models may stick and may be damaged when they are removed.

1/2" holes should be drilled all the way through the plastic at the positions marked with circles. The lines marking the drill positions are 0.650" apart, and the lines are at 60° angles to one another.



**Figure 3. Stacking polytypes demonstration model.**



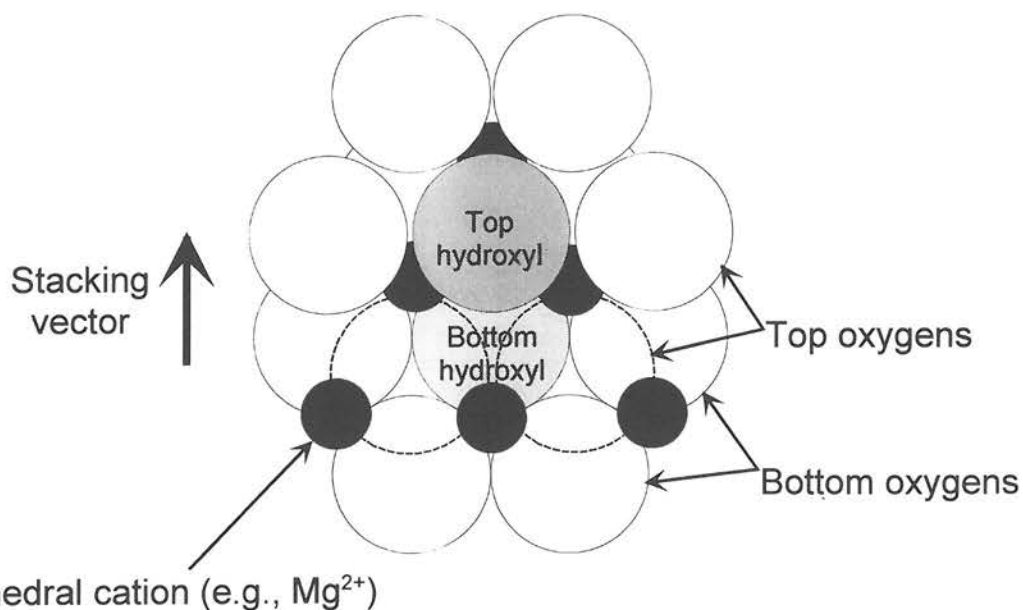


Figure 4. Portion of an octahedral layer in a three layer sheet, showing locations of the hydroxyl pairs. The stacking vector most easily visualized by students is the projection of an arrow that passes from the bottom hydroxyl to the top hydroxyl, as shown.

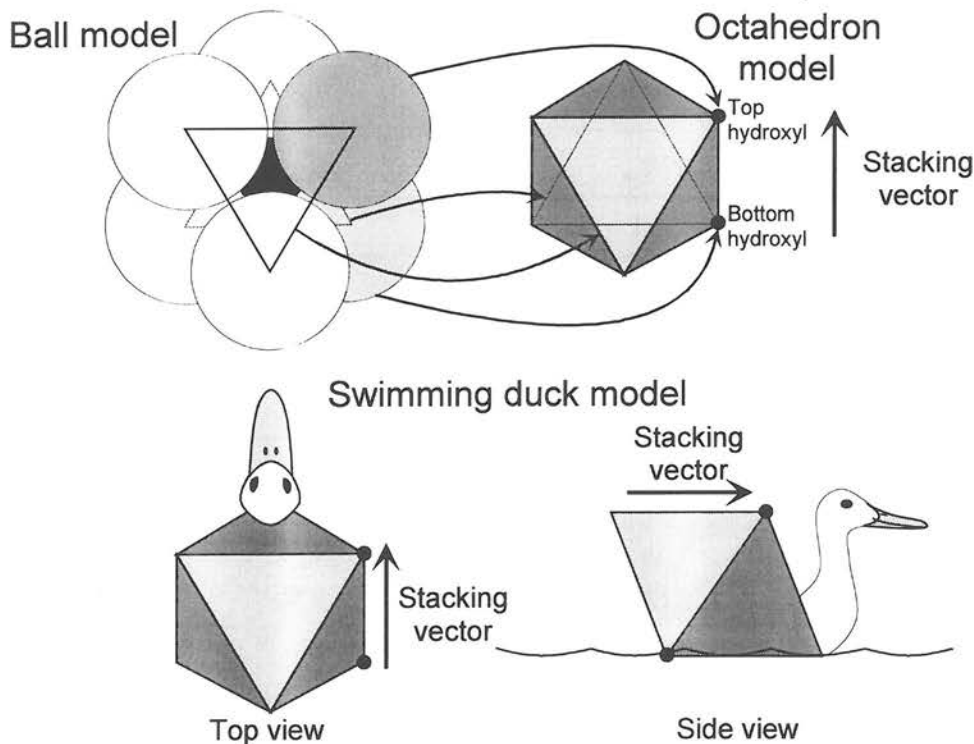
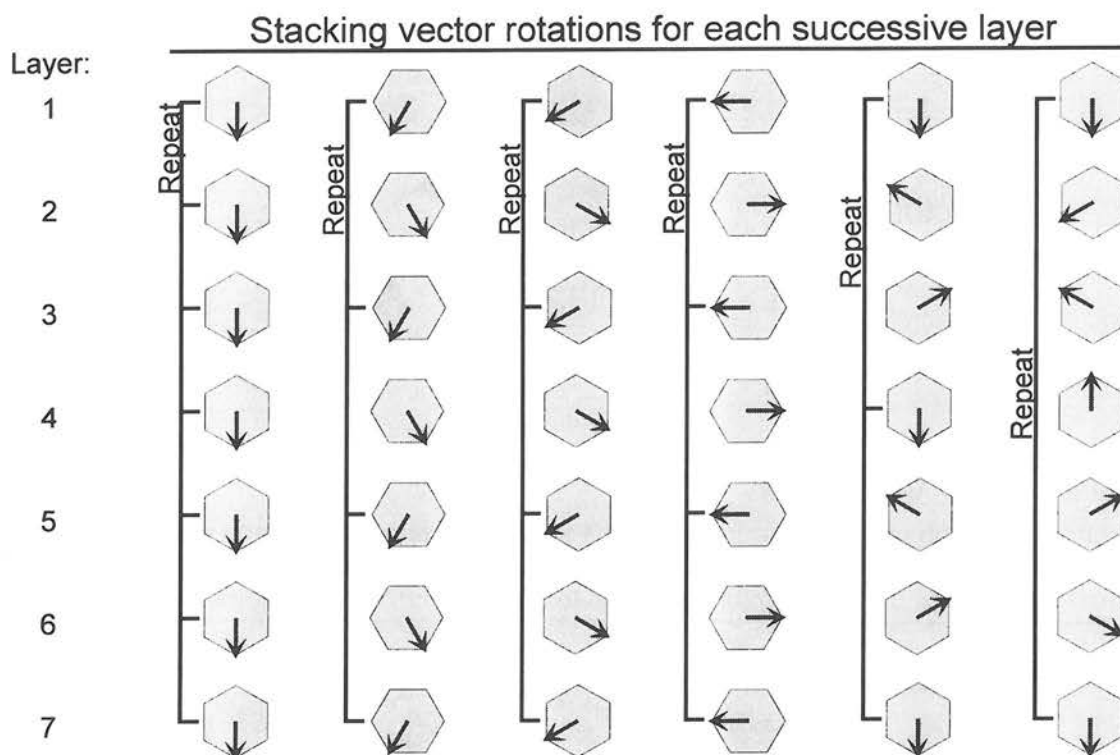


Figure 5. Illustrations of one octahedron in the octahedral layers of three-layer sheets (from the left side of Figure 4). The corners of the octahedron are defined by the atom centers in the ball model. The swimming duck model is a device used to remember the stacking vector orientation based on the hydroxyl offsets (ducks modified after Thompson, 1981).

**Figure 6. Sheet silicate stacking polytypes.**



Stacking polytype	1M	2M <sub>1</sub>	2M <sub>2</sub>	2O	3T	6H
Layer spacing	10Å	10Å	10Å	10Å	10Å	10Å
Rotation/layer	0°	60°	120°	180°	120°	60°
Layers/repeat	1	2	2	2	3	6
Repeat distance	10Å	20Å	20Å	20Å	30Å	60Å
Nominal X-ray diffraction d-spacings						
{001}	<u>10Å</u>	20Å	20Å	20Å	30Å	60Å
{002}	5Å	<u>10Å</u>	<u>10Å</u>	<u>10Å</u>	15Å	30Å
{003}	3.33Å	6.67Å	6.67Å	6.67Å	<u>10Å</u>	20Å
{004}	2.5Å	5Å	5Å	5Å	7.5Å	15Å
{005}	2Å	4Å	4Å	4Å	6Å	12Å
{006}	1.67Å	3.33Å	3.33Å	3.33Å	5Å	<u>10Å</u>

**Figure 7. Types of atoms used in the sheet silicate. models.**

- 5/32" steel:  $\text{Si}^{4+}$  or  $\text{Al}^{3+}$  in tetrahedral sites
- 7/16" blue plastic:  $\text{Mg}^{2+}$  in octahedral sites
- 3/4" colorless plastic: Oxygen in tetrahedral or octahedral sheets
- 3/4" orange plastic: Hydroxyls in octahedral sheets
- 1" colorless plastic:  $\text{K}^+$  in interlayer sites

**Ball counts for each sheet**

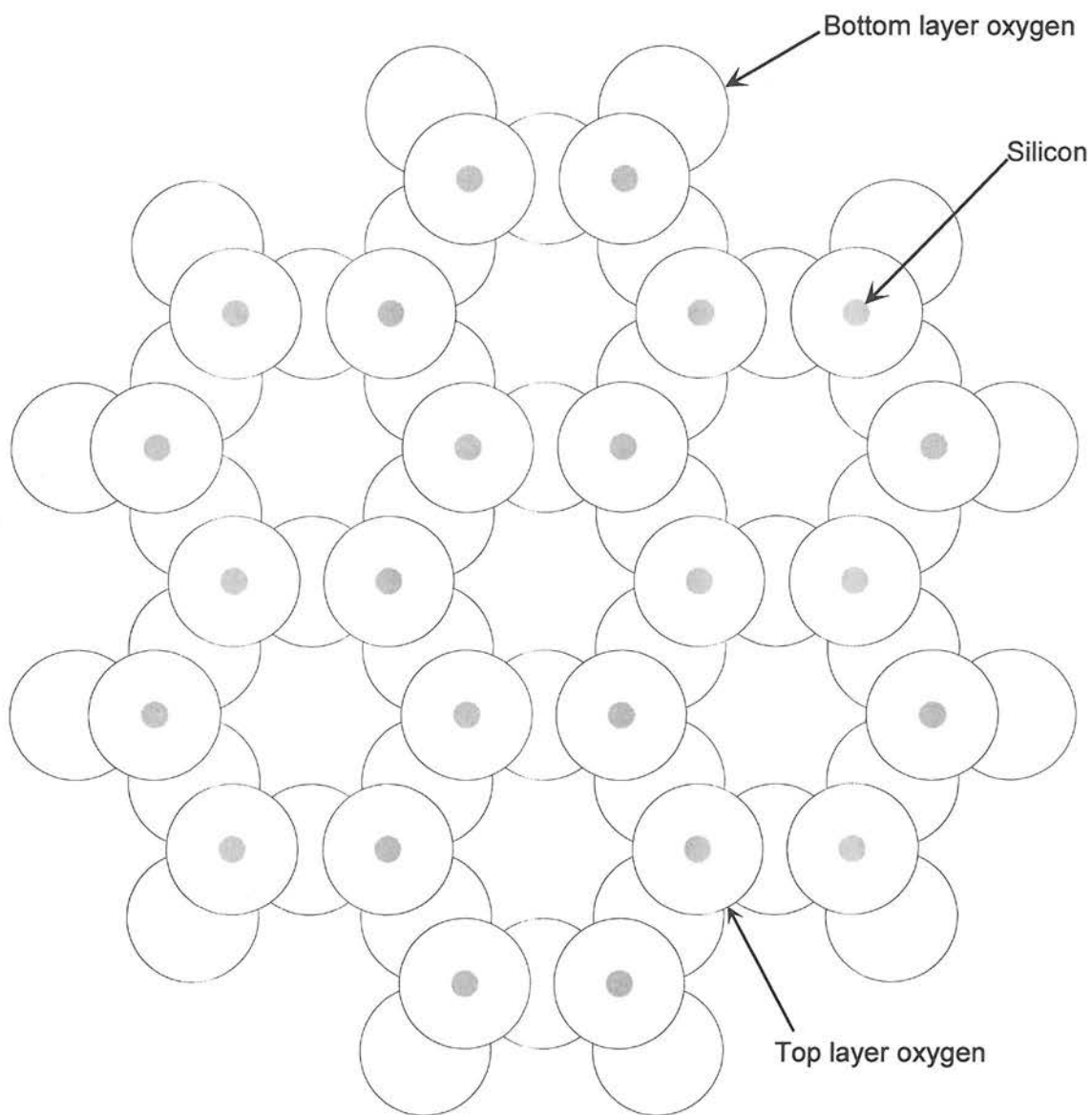
Brucite requires 73 OH and 36 Mg

Serpentine requires 66 O, 24 Si, 50 OH, and 36 Mg

Talc requires 132 O, 48 Si, 26 OH, and 36 Mg

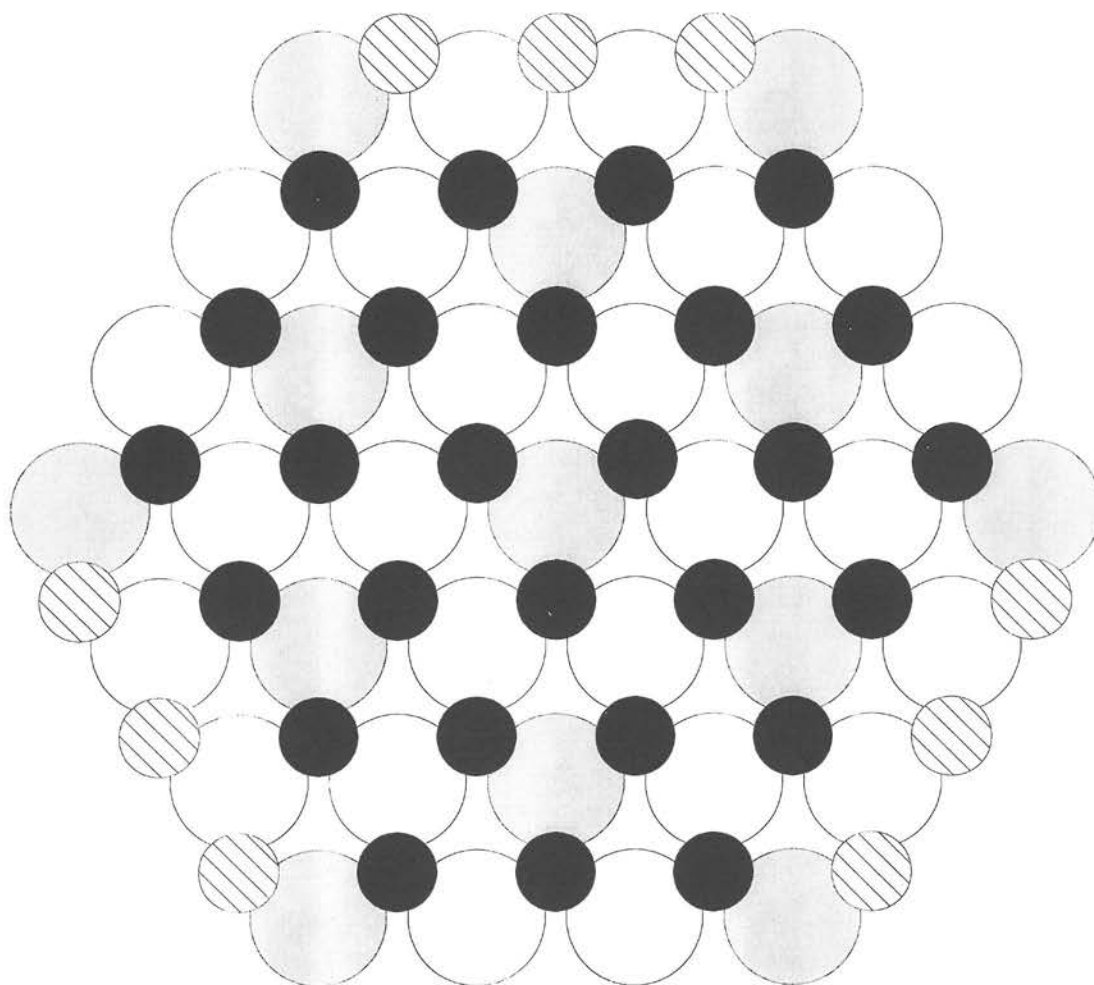
Biotite requires a talc sheet plus 7 K atoms

Chlorite requires one talc and one brucite sheet



**Figure 8. Complete tetrahedral layer for talc or serpentine.**

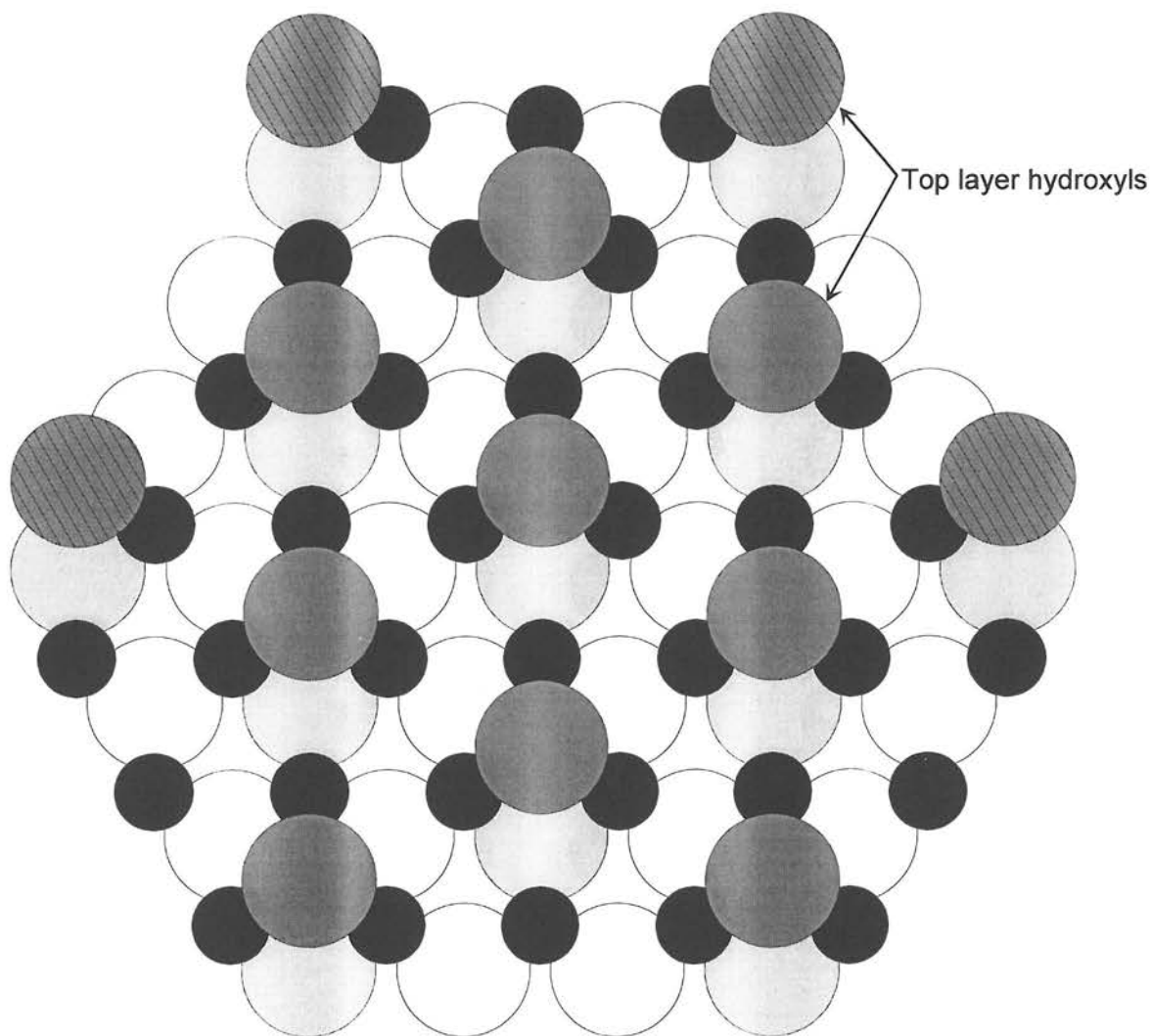
On the tetrahedral template put an oxygen in each position, gluing them together as you go. Then put a silicon over each oxygen triangle. Finally, glue an oxygen over each silicon. This layer is finished.



**Figure 9. Partial octahedral layer in talc.**

On the octahedral template put an oxygen or hydroxyl in each position, as shown. Glue on the Mg<sup>2+</sup> ions to hold the layer together. Nine Mg<sup>2+</sup> ions (hatch pattern) on two edges will have to wait until the glue is dry.

When the glue is dry, flip this layer over onto a flat surface. Glue the remaining nine Mg<sup>2+</sup> ions into place as shown.

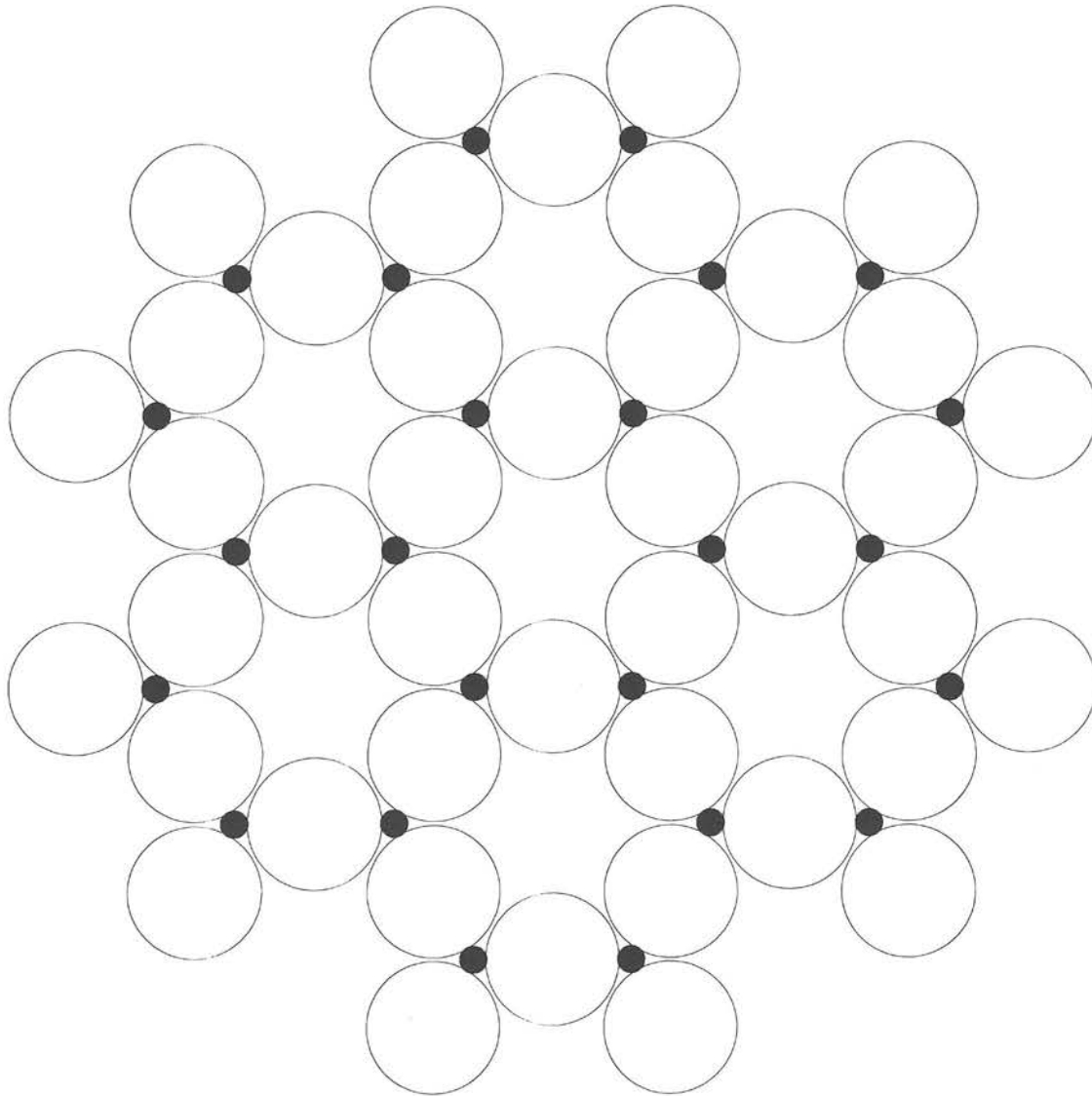


**Figure 10. Top layer hydroxyls for the octahedral layer in talc.**

Start with the partial octahedral layer from Figure 9. Nine top layer hydroxyls fit nicely between the triangles of  $Mg^{2+}$  ions without rolling away. These make the hydroxyl pairs. Glue these in place. Four hydroxyls (hatch pattern) must wait until the glue on the other nine is dry.

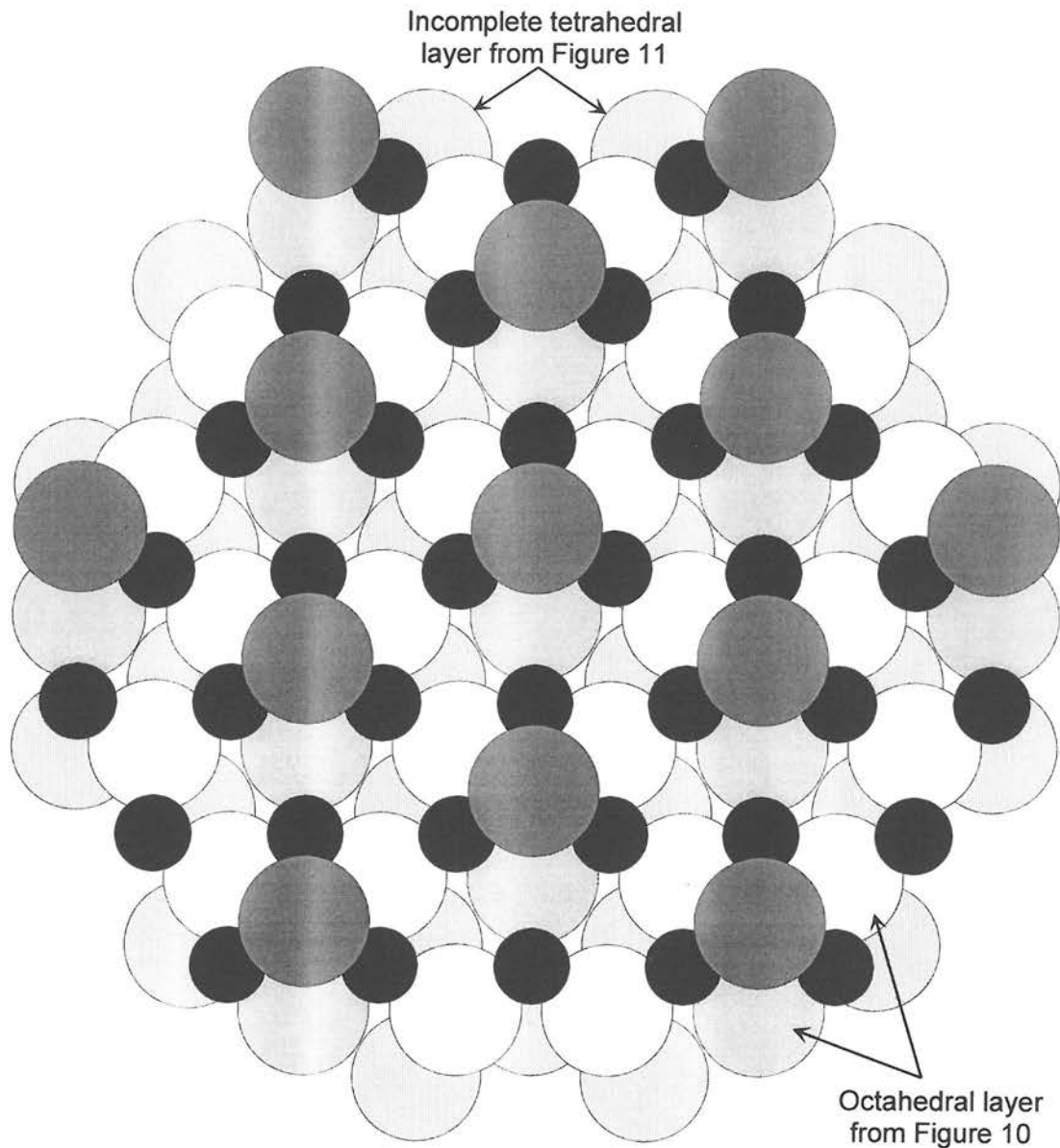
When the glue is dry, flip the layer over onto an octahedral template. Fit the remaining four hydroxyls in place and glue them. You may have to support each with a bit of paper to make sure they touch and glue firmly to the adjacent atoms.





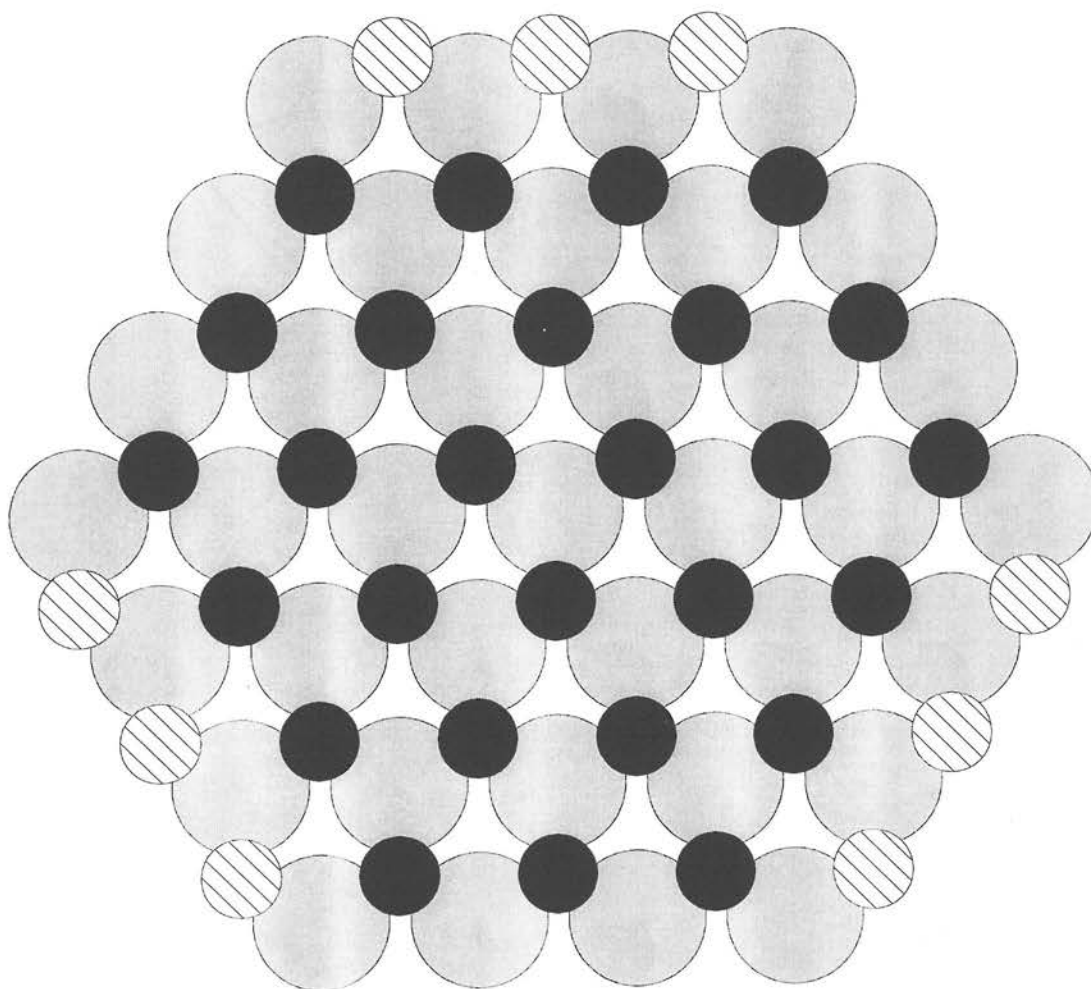
**Figure 11. Incomplete tetrahedral layer for talc.**

On a tetrahedral template put an oxygen in each position, gluing them together as you go. Put a silicon over each oxygen triangle, but do not glue them. These silicons will be covered by oxygens in the octahedral layer from Figure 10, as shown in Figure 12.



**Figure 12. Gluing the incomplete tetrahedral layer to the octahedral layer for talc.**

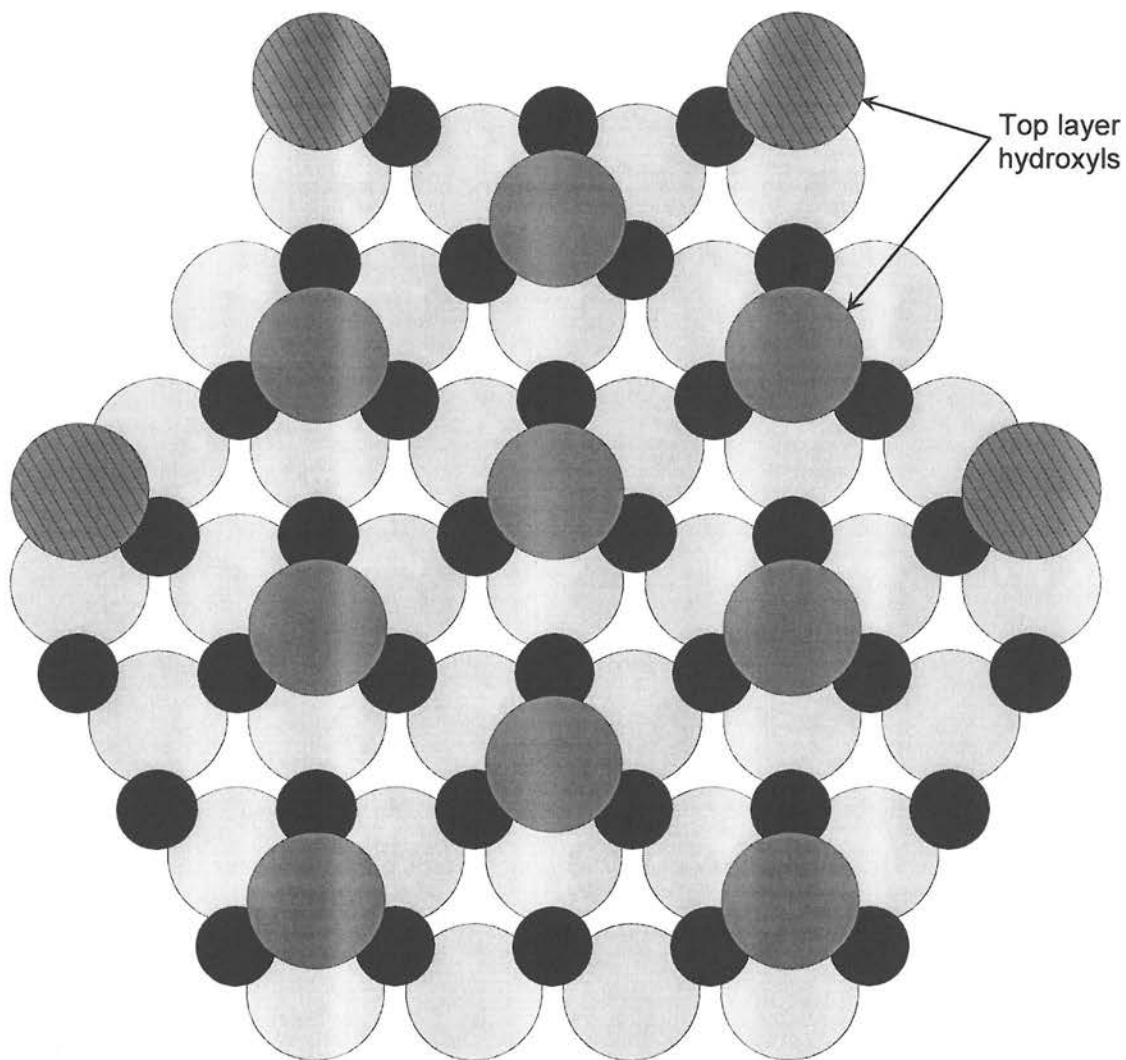
Take the incomplete tetrahedral layer from Figure 11 (stippled above) and on top of it lay the octahedral layer from Figure 10. Orient the octahedral layer so that its oxygens rest exactly over all of the silicons on the incomplete tetrahedral layer. Once you see how the octahedral layer fits, remove the octahedral layer, put glue on appropriate spots on the incomplete tetrahedral layer oxygens, and replace the octahedral layer. Let the glue dry and this structure is finished.



**Figure 13. Bottom layer hydroxyls for the octahedral layer of serpentine and brucite.**

On an octahedral template put an hydroxyl in each position. Then glue on  $Mg^{2+}$  ions to hold the layer together. Nine of the  $Mg^{2+}$  ions on the edges (hatched pattern) will have to wait until this layer dries.

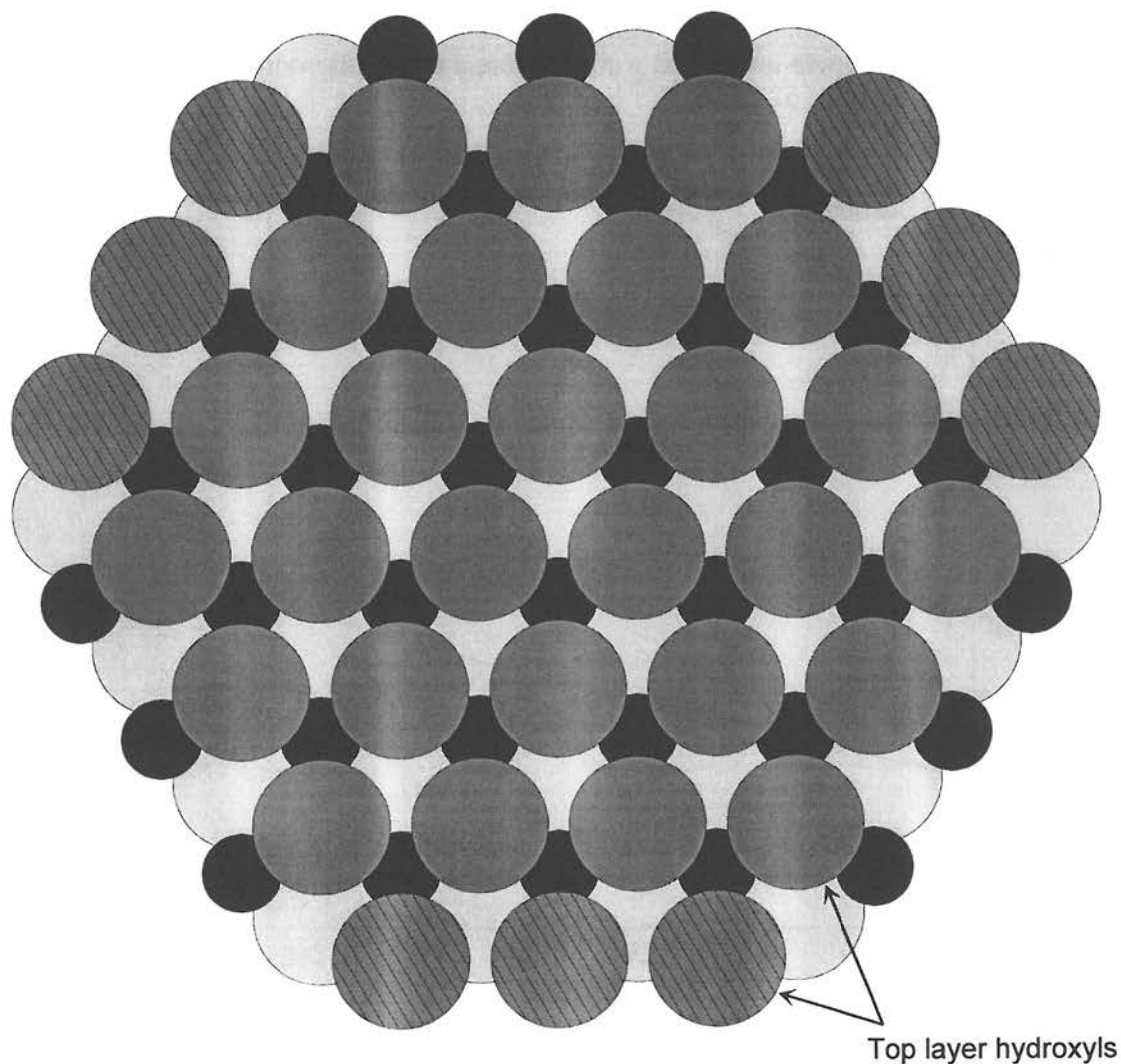
When dry, flip this layer over onto a flat surface. Then glue on the remaining nine  $Mg^{2+}$  ions in place.



**Figure 14 Top layer hydroxyls for the octahedral layer in serpentine.**

Take the octahedral layer from Figure 13. Nine hydroxyls fit nicely between the triangles of  $Mg^{2+}$  ions without rolling away. Glue these in place. Four hydroxyls (hatch pattern) must wait until the glue on the other nine is dry.

When the glue is dry, flip the layer over onto an octahedral template. Fit the remaining four hydroxyls into place and glue them. You may have to support each with a bit of paper to make sure that they touch and glue firmly to adjacent atoms.



**Figure 15. Top layer hydroxyls in the octahedral brucite layer.**

Take the octahedral layer from Figure 13. Most of the top layer hydroxyls fit nicely between  $Mg^{2+}$  triangles without rolling away. Glue these in place. Nine hydroxyls (hatch pattern) on the edges will have to wait until the glue is dry.

When the glue is dry, flip the octahedral sheet upside down onto a flat surface. Glue the remaining nine hydroxyls into place as shown. When the glue is dry, this structure is done.

Figure 16. Phase diagram showing the P-T stability fields of the silica polymorphs. The stability fields of  $\alpha$  and  $\beta$  tridymite and  $\alpha$  and  $\beta$  cristobalite are not differentiated. Modified after Klein and Hurlbut (1993, p. 527).

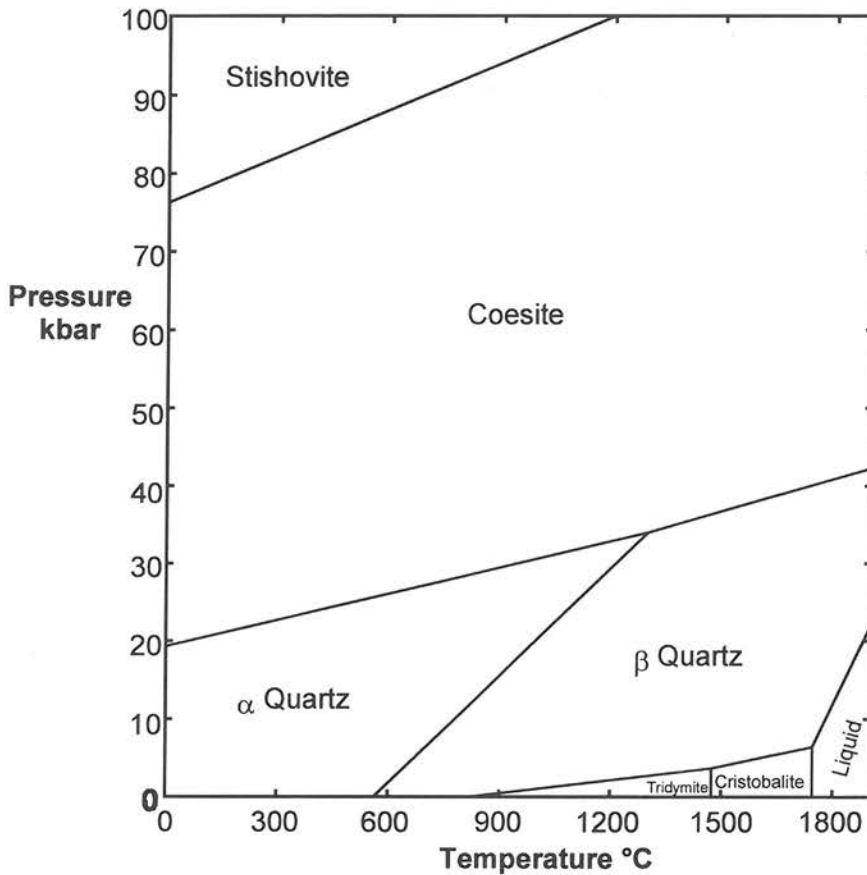
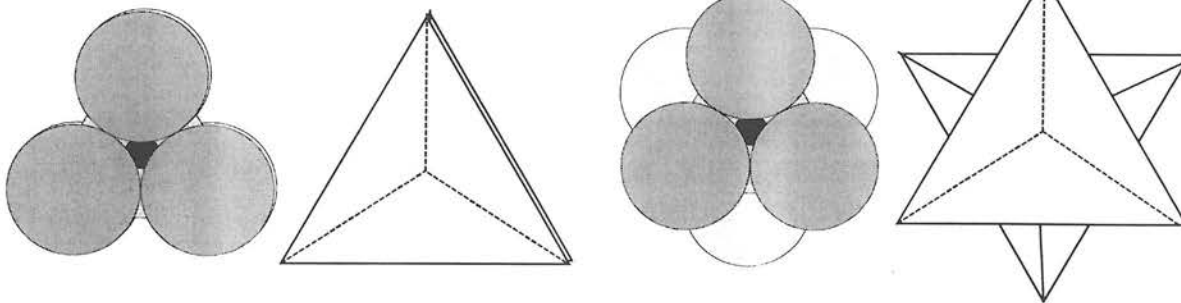
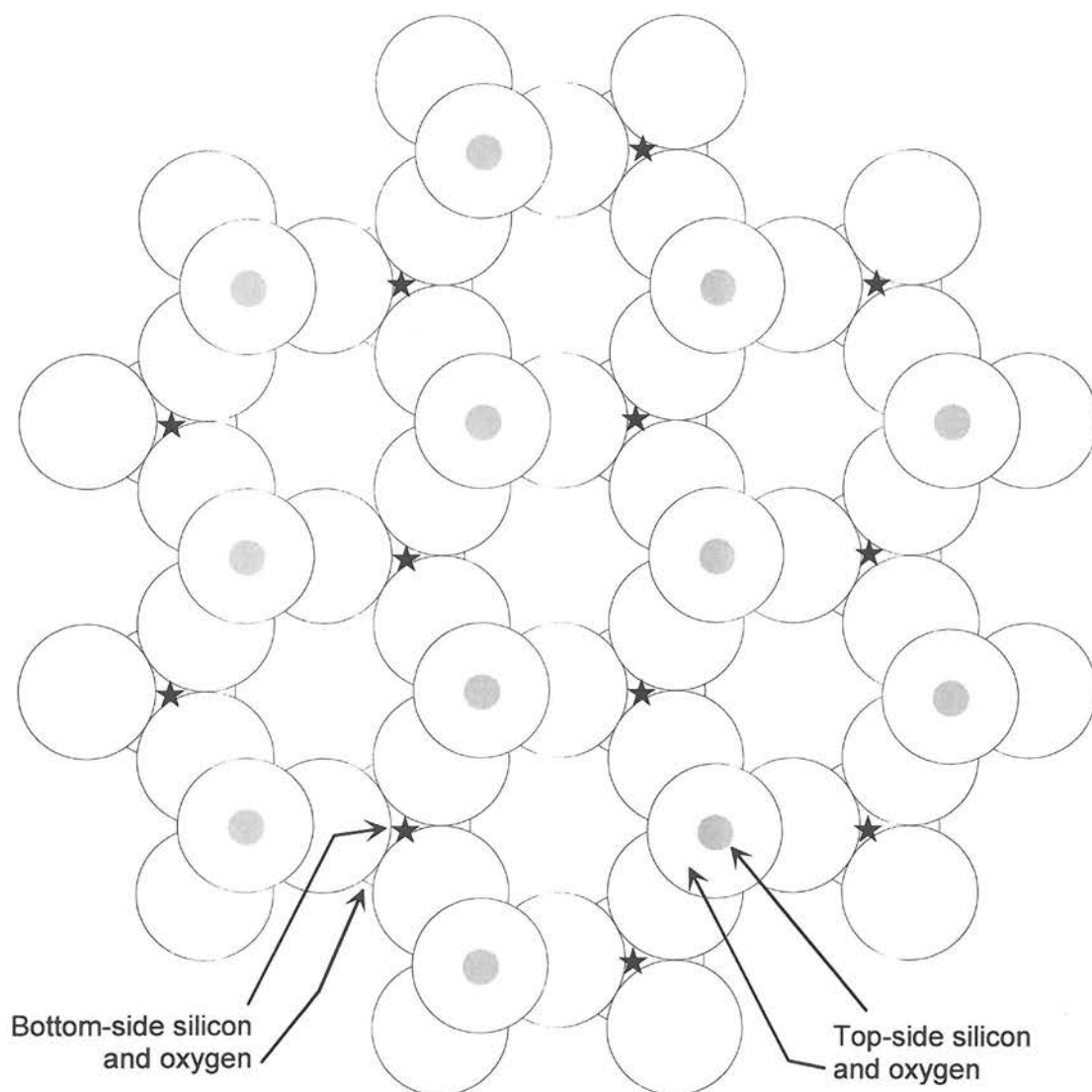


Figure 17 Views of adjacent corner-sharing silicon-oxygen tetrahedra in tridymite (A) and cristobalite (B) as viewed perpendicular to the construction sheets. This view is down the  $c$  axis in tridymite, and down one of the bar-3 axes in cristobalite. In tridymite, overlying tetrahedra are oriented the same way as, and so exactly cover, underlying tetrahedra. In cristobalite, overlying tetrahedra are rotated  $60^\circ$  with respect to underlying tetrahedra, and so are partly in view.

A. Tridymite: underlying tetrahedron is hidden.

B. Cristobalite: underlying tetrahedron is visible.



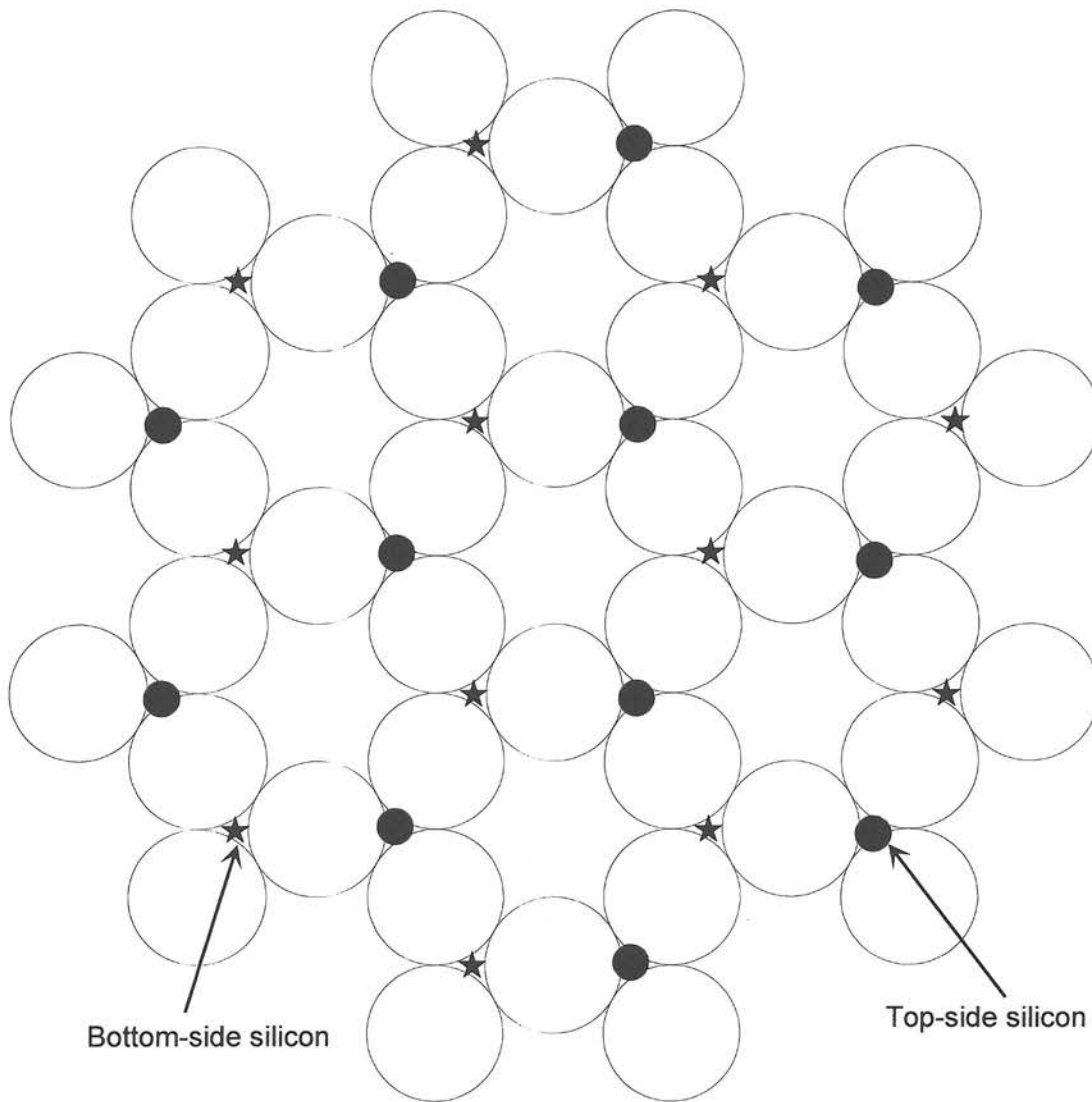


**Figure 18. Tridymite layers 1 and 3. Make 2.**

The whole model takes 174 O and 72 Si.

On a tetrahedral template put one layer of oxygens in each position, gluing them together as you go. Then put a top-side silicon over half of the oxygen triangles, as shown, and glue an oxygen above each silicon. Let this structure dry.

When dry, remove the structure from the template and flip it over onto a flat surface. Then put a bottom-side silicon over the other half of the oxygen triangles, and glue an oxygen above each of these silicons.



**Figure 19. Tridymite layer 2 and final assembly. Make 1.**

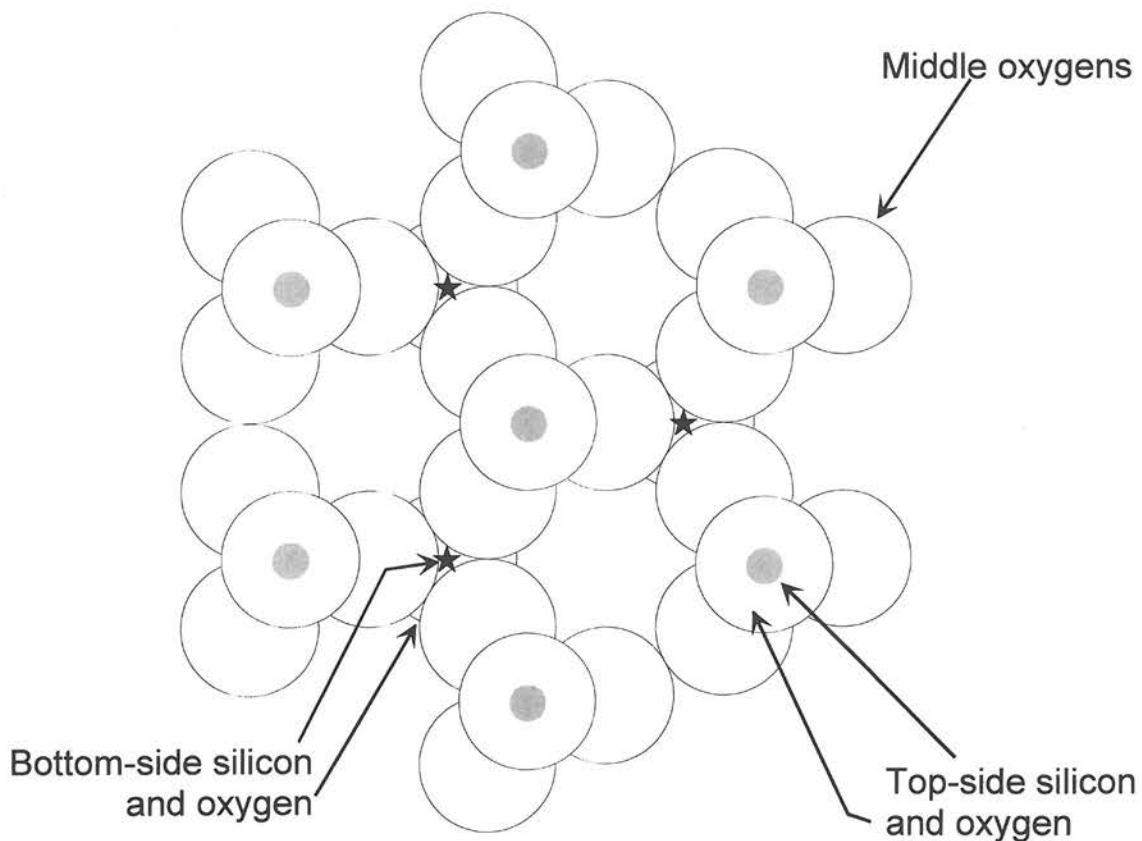
On a tetrahedral template put an oxygen in each position, gluing them together as you go. Put a top-side silicon in half the oxygen triangles, as shown, but do not glue them.

#### **Final Assembly**

Take layer 1 from Figure 18 and glue it onto layer 2, above, so the bottom-side oxygens on layer 1 rest on top of the top-side silicons on layer 2. Wait for the glue to dry.

When dry, flip this assembly over and put bottom side silicons into the rest of the layer 2 oxygen triangles. Flip layer 3 over and glue it onto layer 2 so that, the apex oxygens cover the bottom side silicons. Tetrahedra in successive layers should lie directly above one another, hiding tetrahedra lying below and to make hexagonal channels parallel to  $c$ .



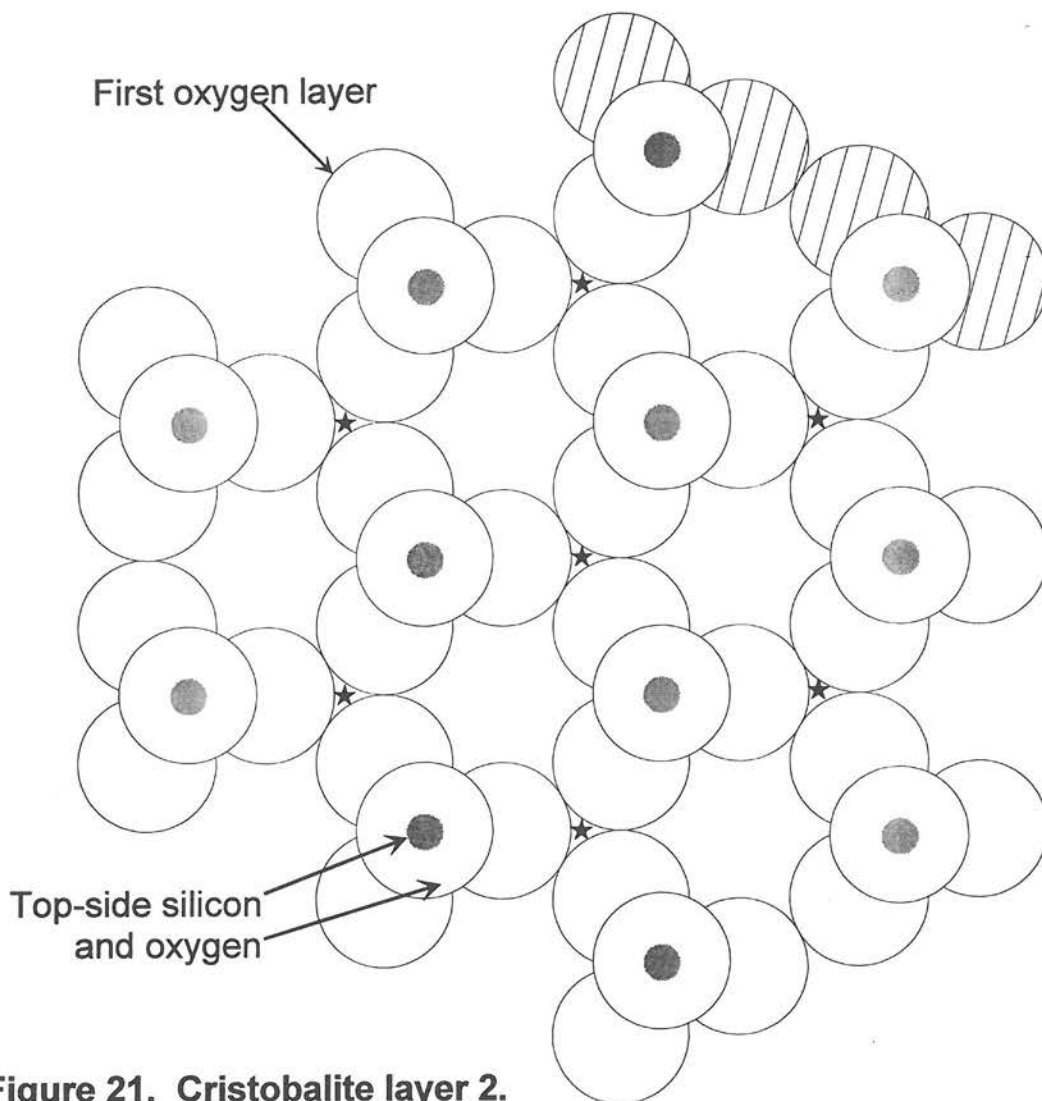


**Figure 20. Cristobalite layer 1.**

The whole model takes 164 O and 41 Si

On a tetrahedral template put an oxygen in each middle oxygen position shown, gluing them together as you go. Put a top-side silicon in seven of the oxygen triangles, as shown, and glue oxygens over the silicons. Wait for the glue to dry.

When dry, turn this layer over and put three bottom side silicons into the remaining oxygen triangles, and glue on the three bottom side oxygens.

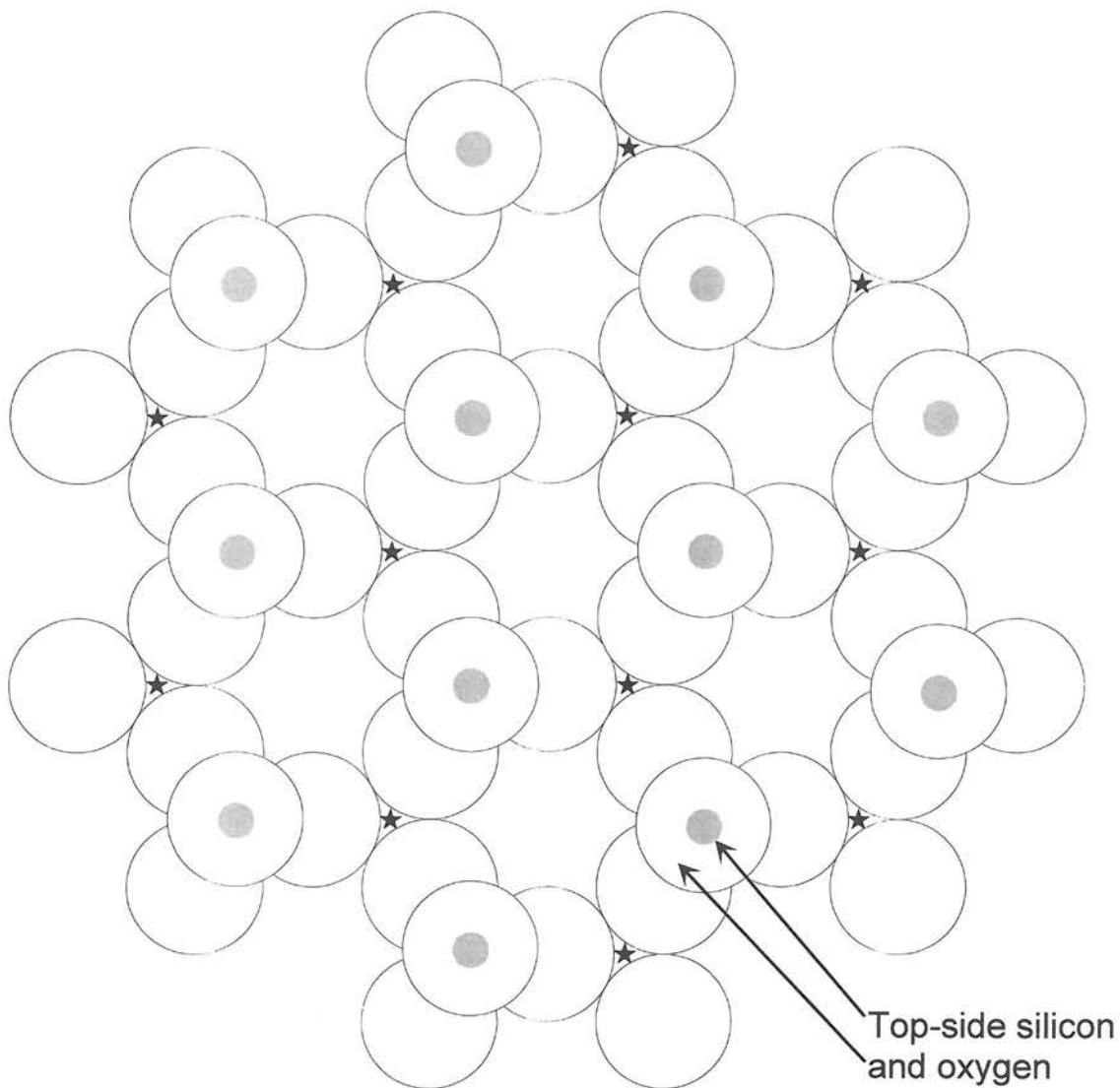


**Figure 21. Cristobalite layer 2.**

On a tetrahedral template make the first oxygen layer by putting oxygens in the positions shown, except those with the hatched pattern, gluing them together as you go. Four oxygens (hatched pattern) will not fit on a standard template, so on another template glue 4 oxygens in a row. Wait for the glue to dry.

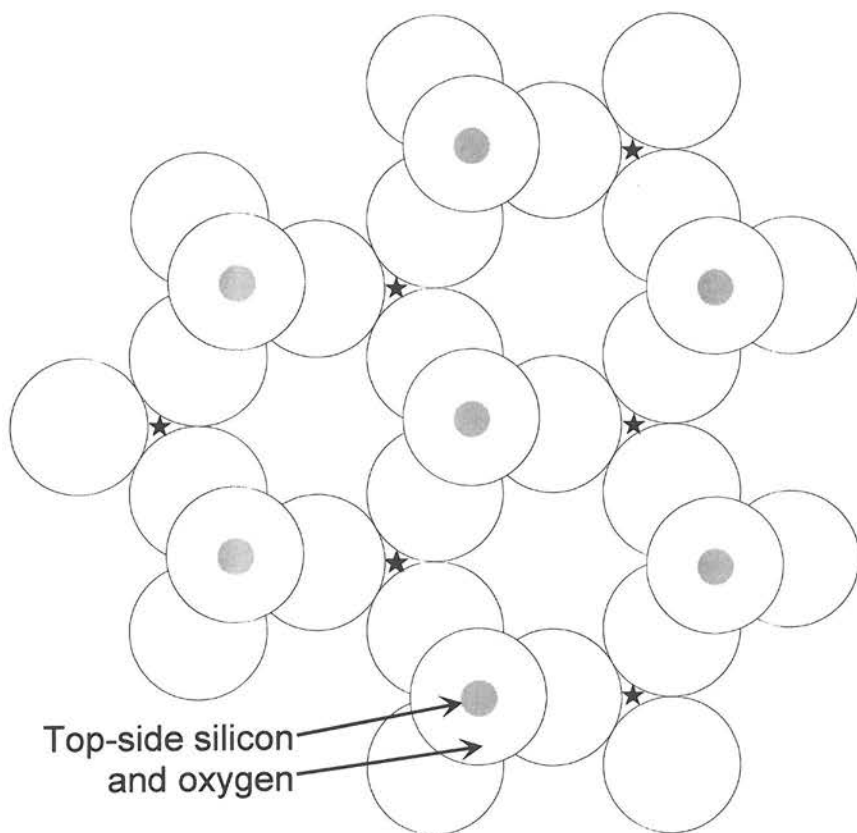
When dry, remove the two assemblies from their templates and put them on a flat surface. Glue the four oxygen assembly onto the larger assembly as shown. Wait for the glue to dry.

When dry, put a top-side silicon over half of the oxygen triangles, as shown, and glue an oxygen above each silicon.



**Figure 22. Cristobalite layer 3.**

On a tetrahedral template put one layer of oxygens in each position on the template as shown, gluing them together as you go. Then put a top-side silicon over half of the oxygen triangles, as shown, and glue an oxygen above each silicon.



**Figure 23. Cristobalite layer 4.**

On a tetrahedral template put an oxygen in each position shown, gluing them together as you go. Put a top-side silicon in seven of the oxygen triangles, as shown, and glue oxygens over the silicons.

### **Final assembly**

When the layers are dry, turn layer 4 upside down. Put silicons into the open oxygen triangles as indicated by the stars in Figure 23. Turn layer 3 upside down and glue it so that its apex oxygens exactly cover the loose silicons on layer 4. Then put silicons into the open oxygen triangles in layer 3, as indicated by the stars in Figure 22. Turn layer 2 upside down and glue it so that the oxygens exactly cover the loose silicons on layer 3. Lastly, put the 7 silicons onto the open oxygen triangles in layer 2, as shown by the stars in Figure 21. Turn layer 1 upside down and glue it so that the loose silicons on layer 2 are covered. When the glue is dry, the cristobalite model is finished.