

INTERNAL GEODYNAMICS

(ENDOGENOUS PROCESSES OF THE EARTH)

İÇ JEODİNAMİK

(DÜNYANIN ENDOJEN OLAYLARI)

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Lesson 4:

The Minerals and Rocks of the Earth

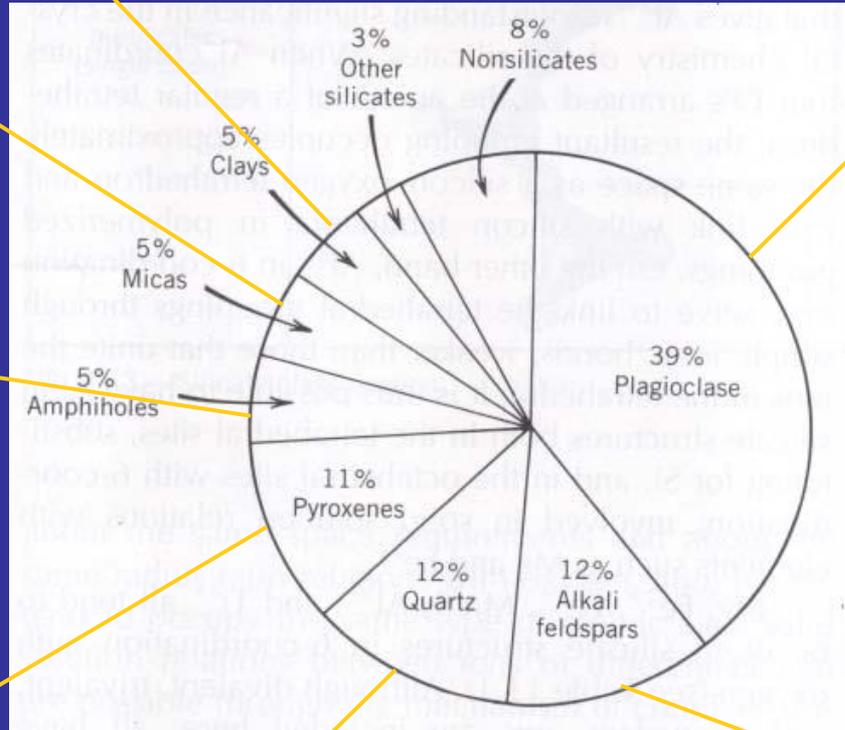
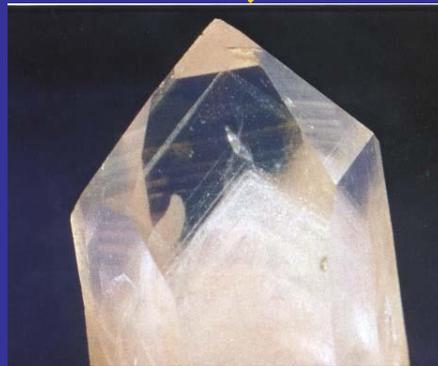
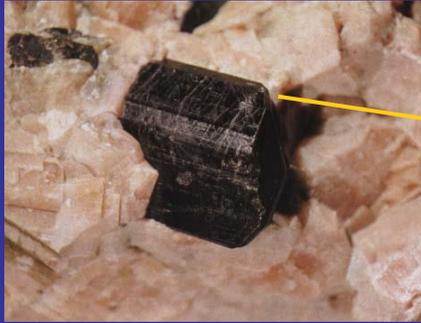
*Part IIIa: The minerals- special
mineralogy*

Because minerals show much greater variability in terms of their chemical composition than in terms of their crystal structure, it has been customary to classify them primarily according to chemical composition. The following classes have been recognised on the basis of the **dominant anion** or **groups of anions**:

1. Native elements
2. Sulfides
3. Sulfosalts
4. Oxides
5. Halides
6. Carbonates
7. Nitrates
8. Borates
9. Phosphates
10. Sulfates
11. Tungstates
12. Silicates

Of all these classes of minerals only the silicates and the carbonates are really important as rock-makers. All other minerals occur only as small contributors to the building of the earth's crust or mantle. Only in the core, Fe-alloys assume a critical rôle.

Let us remember the contribution of various minerals to the make-up of the earth's crust:



The composition of the earth's crust (after Ronov and Yaroshevsky, 1969; from Klein, 2002)

The crust makes up about 0.03839 of the total earth mass

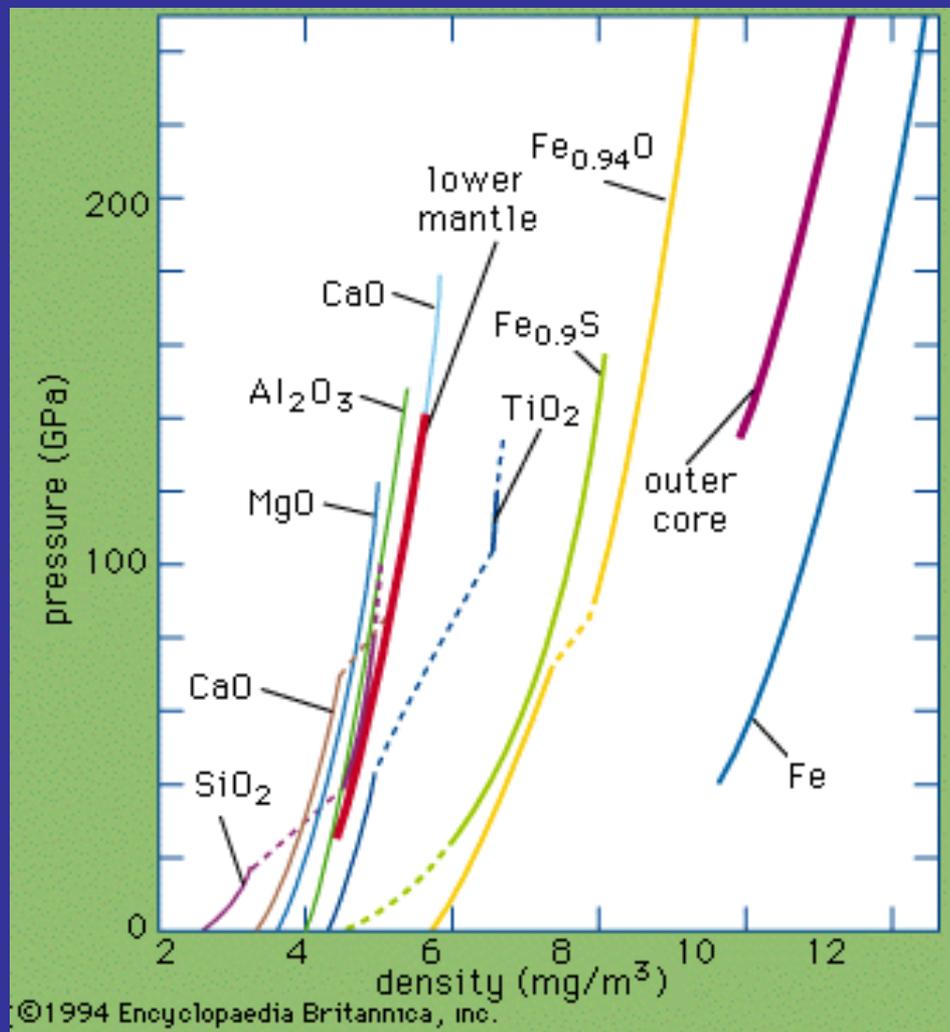
Important message: The **silicates** are the most important minerals for our understanding of by far most of the geological phenomena. Of the silicates, the **feldspars** are the most important minerals for our understanding of the earth's crust (both continental and oceanic). Therefore we must know them well. Some important feldspar references for this class:

Janecke, S. U. and Evans, J. P., 1988, Feldspar-influenced rock rheologies: *Geology*, v. 16, pp. 1064-1067

The earth's mantle is unavailable for direct sampling except in:

- 1) Ophiolite nappes and in ophiirags of ultramafic composition
- 2) Subcontinental ultramafic nappes in orogenic belts
- 3) Ultramafic nodules brought up by volcanoes (including kimberlites)
- 4) Diamonds bearing ferropericlase, $(\text{Fe},\text{Mg})\text{O}$, inclusions (São Luiz, Brazil and Guinea, W. Africa)

All these, except 4, sample the uppermost mantle. The rest of the mantle is unknown from direct observation except that it contains ferropericlase. We infer its composition from 1) seismic velocities, 2) from ultra-high pressure petrologic experiments, and 3) from the composition of meteorites.



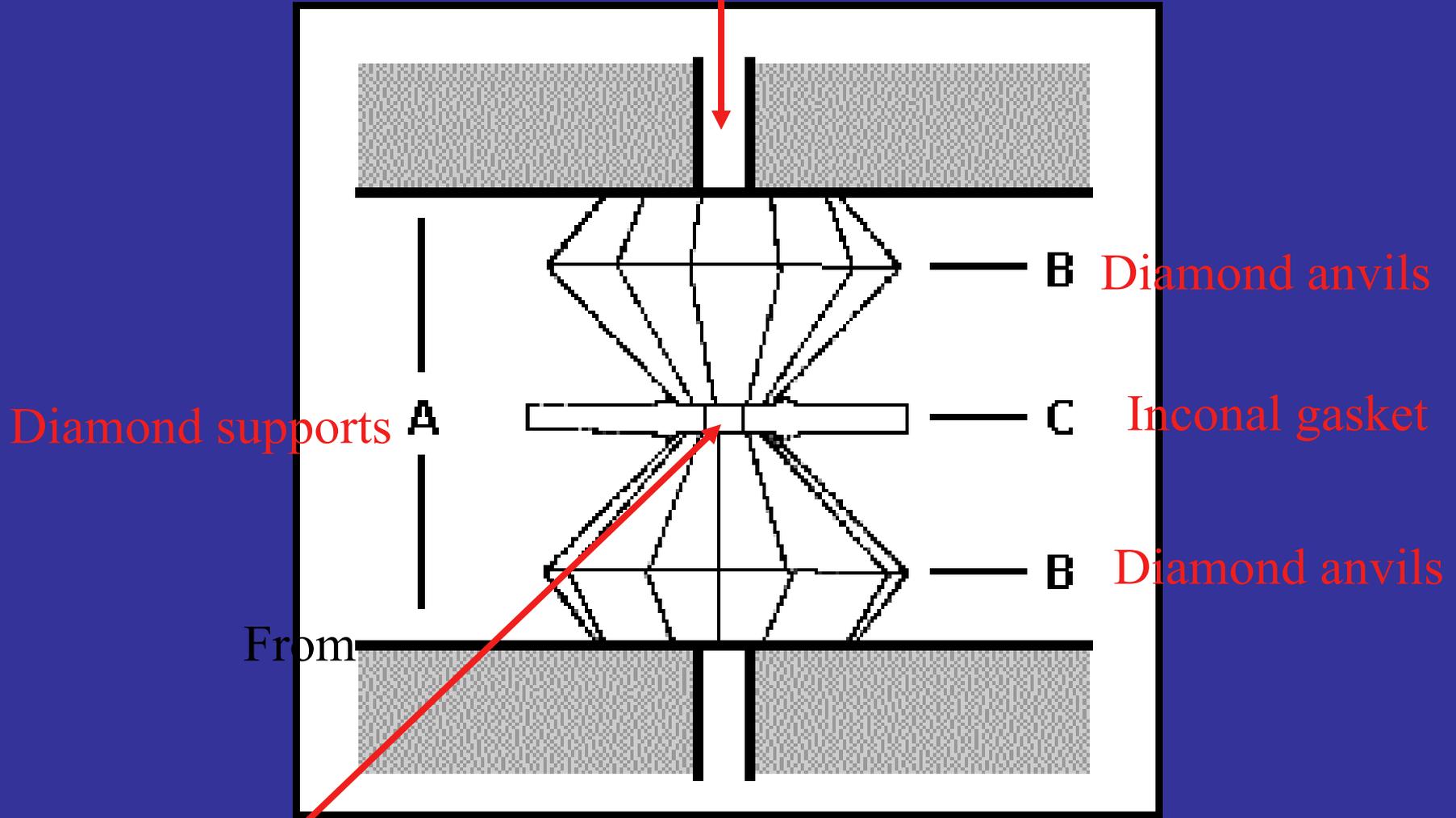
This diagram shows a range of compositions possible at the pressures and densities indicated. The pressure is easily calculated from depth and density. The density is inferred from the seismic velocities.

How do we know which composition is possible at a given pressure? We conduct **petrologic experiments** at very high pressures and temperatures. The present **diamon-anvil-cell techniques** enable us to achieve pressures in excess of those prevailing at the centre of the earth ($> 5 \times 10^6$ bars)! Laser heating techniques make it possible to reach temperatures as high as 6000°K ($=5727^\circ\text{C}$). Remember that the temperature at the inner core is estimated to be in excess of 7000°K .



A diamond-anvil-cell device for achieving very high experimental pressures. The pipes are for the water of the cooling system.

Observation



Diamond supports

B Diamond anvils

C Inconel gasket

B Diamond anvils

From

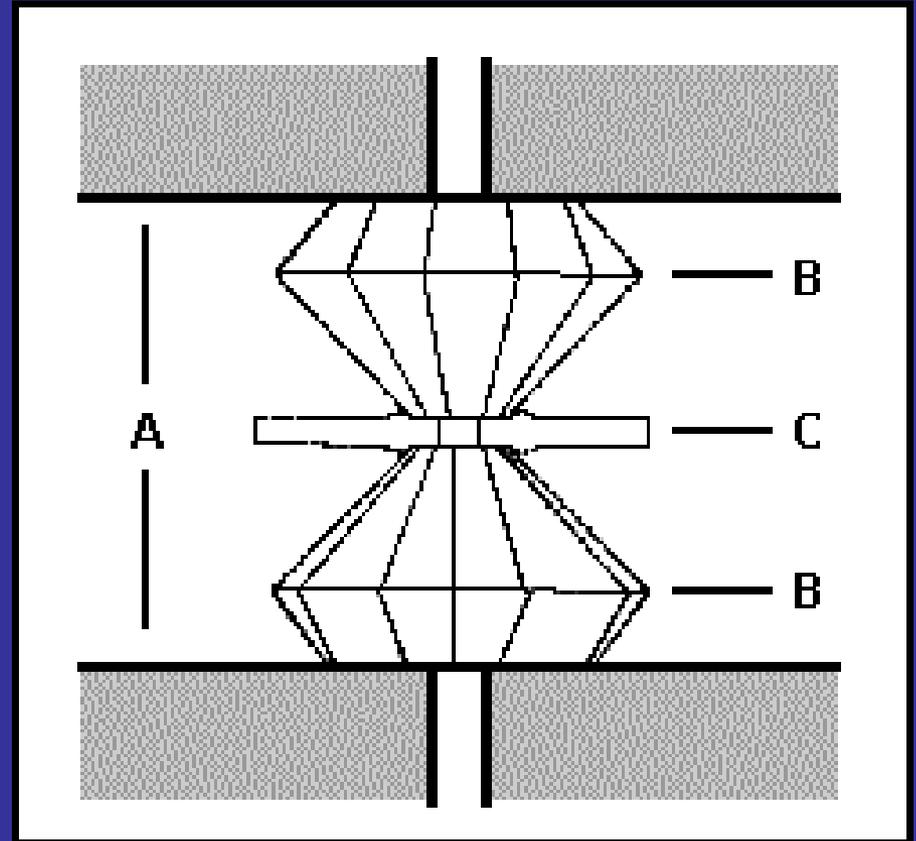
Sample goes here

From <http://www.hpdo.com/intro.html>

The development of diamond anvil cell (DAC) technology in the US National Bureau of Standards in the 1950's has resulted in tremendous development in understanding of the behavior of matter under a wide range of pressures. In geology, laboratory experiments utilizing high pressure and temperature offer one of the means to infer the conditions of deep planetary interiors. Fundamental questions about phase transformations, crystal structure and the nature of atomic bonding can be answered using high-pressure techniques.

Diamond, in addition to being recognized as the hardest and least compressible material, has the important property of being transparent to most of the spectrum of electromagnetic radiation, including γ -ray, X-ray, portions of ultraviolet, visible, and most of the infrared region.

The DAC is based upon the opposed-diamond configuration, in which a sample is placed between the polished culets of two diamonds and is contained on the sides by a metal gasket. In this configuration, very little force is required to create extremely large pressures in the sample chamber, and, because of the transparency of diamond, the sample may be examined *in situ* (while at elevated pressure) by optical microscope, spectroscope (Raman, infrared, Brillouin), and diffraction techniques.

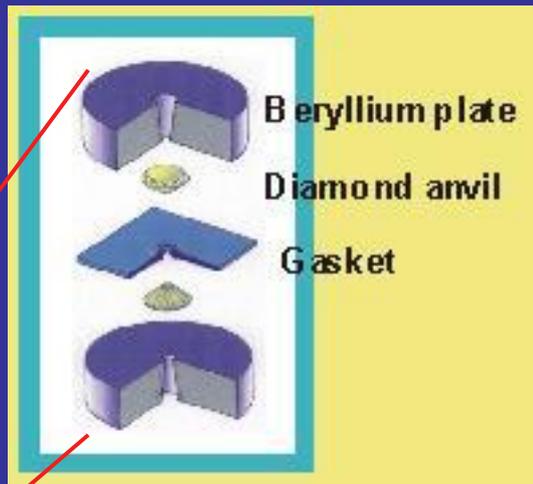
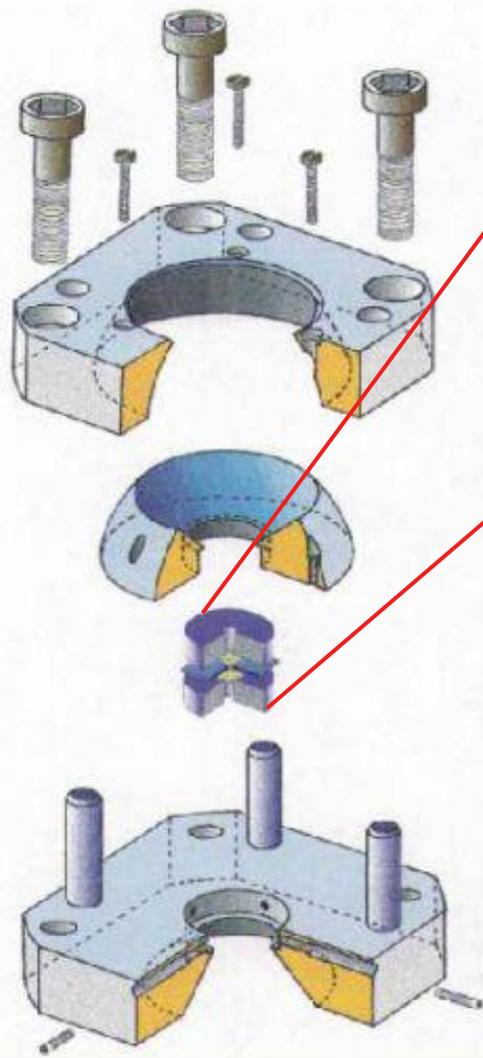


The diamond anvils are skillfully cut from natural, gem quality stones to have 16 pavilion facets, a 70% table, and a working surface (culet). The anvils are cut to correct crystallographic orientation [table and culet parallel to the (100) diamond plane] and care is taken to insure parallelism of the table and culet.

The culet of the diamond anvil is typically 0.6 mm in diameter. This size insures that pressures of up to 20 GPa (GPa = 10 kbar = 10,000 bar = 9,870 atm) can be achieved (depending upon the choice of DAC). To perform studies to higher pressures, diamonds cut with smaller, beveled culets are recommended.

The selection of diamond type and culet size should be based upon the experimental techniques which are to be employed and the maximum pressure to be achieved.

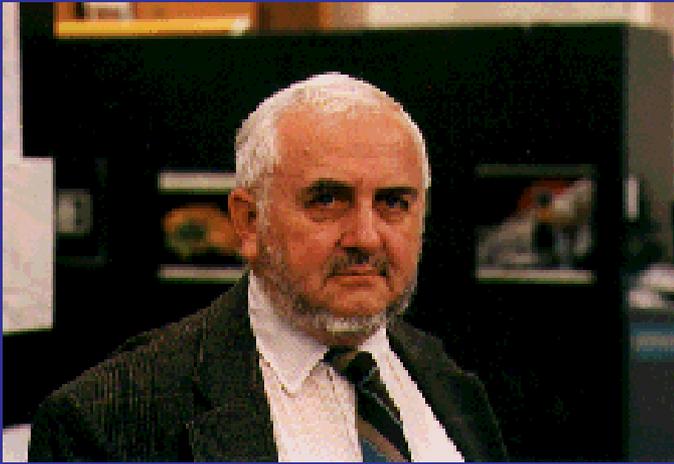
From: <http://www.hpdo.com/intro.html>



Inside of a diamond anvil cell
(Virginia Tech Crystallography Laboratory, USA)

(Virginia

LASER HEATING IN A DAC



William A. Bassett,
Cornell University

“1968 Taro Takahashi and I observed a phase transition that resulted from laser heating under pressure in a diamond anvil cell. Using a ruby laser, we successfully converted graphite to diamond. We soon realized that the ruby laser had such limited capabilities that

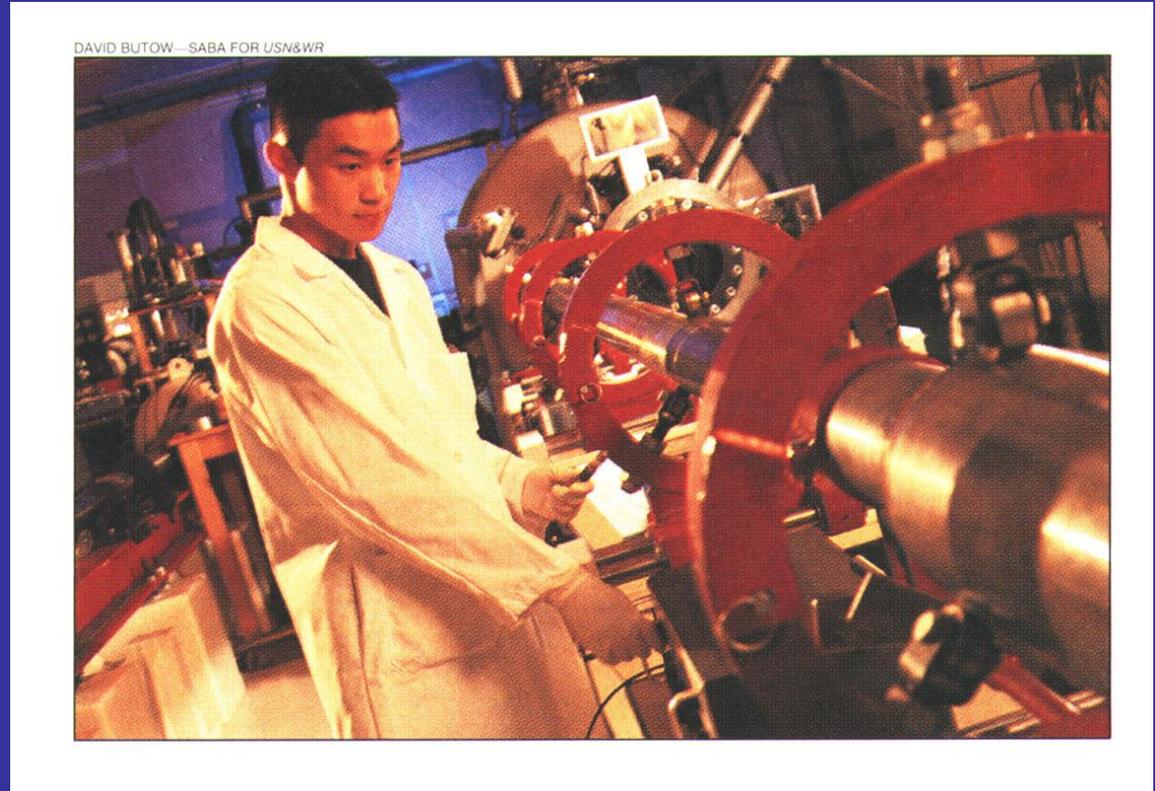
we acquired a yttrium–aluminum–garnet (YAG) laser that could be used in both continuous and pulsed modes. The road to successfully applying the technique was not without a few bumps. Thirty years later, these seem more amusing than they did at the time. It was with the YAG laser that Ming and Liu investigated a number of silicate phase transitions important to our understanding of the earth's mantle. Since then it has been gratifying to watch as others have adopted the technique and made many important contributions with it.”

from Review of Scientific Instruments, v. 72, pp. 1270-1272 (2001)

For obtaining very high pressures and temperatures, one can also use a gun!

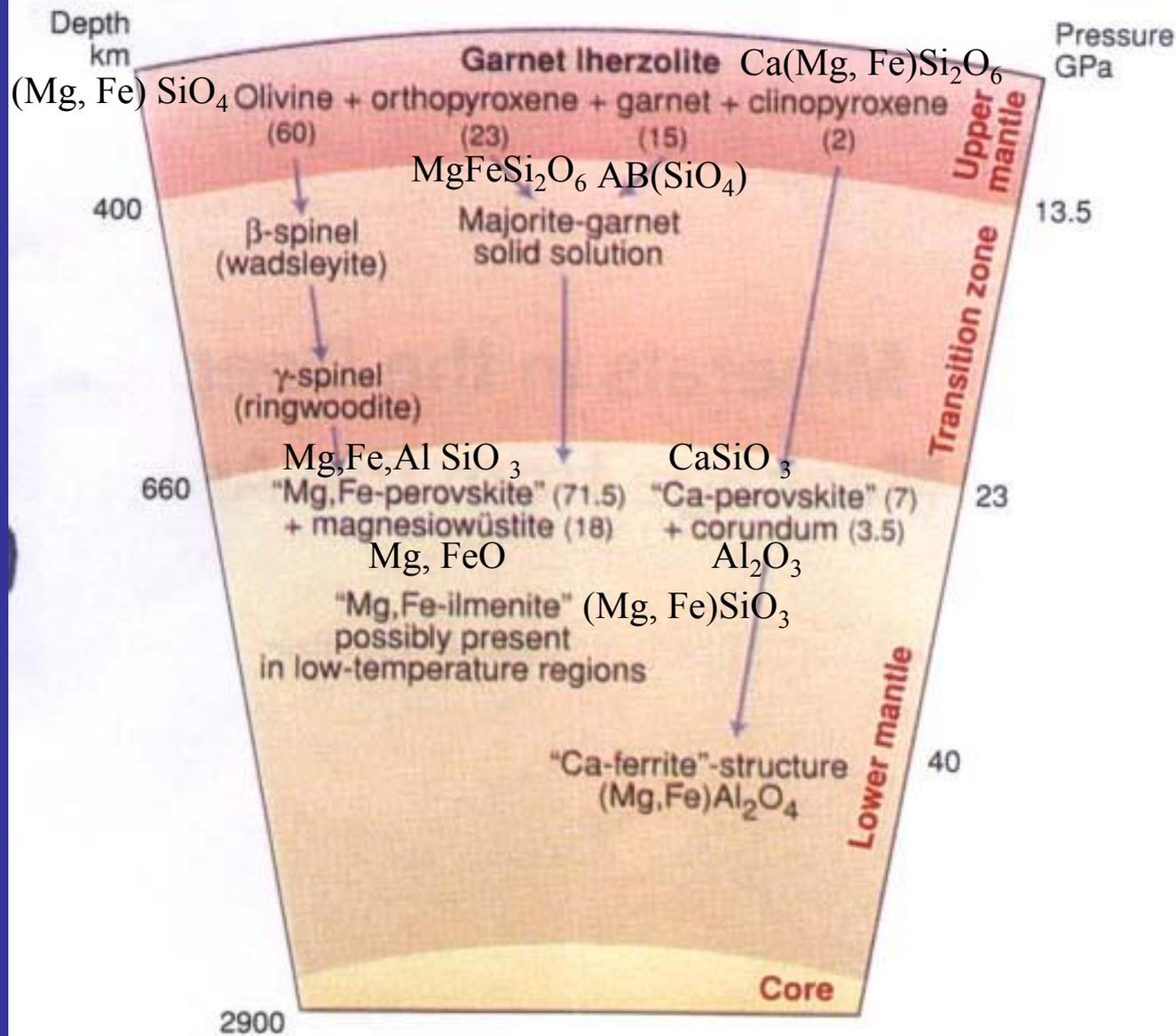


Thomas J. Ahrens
Caltech

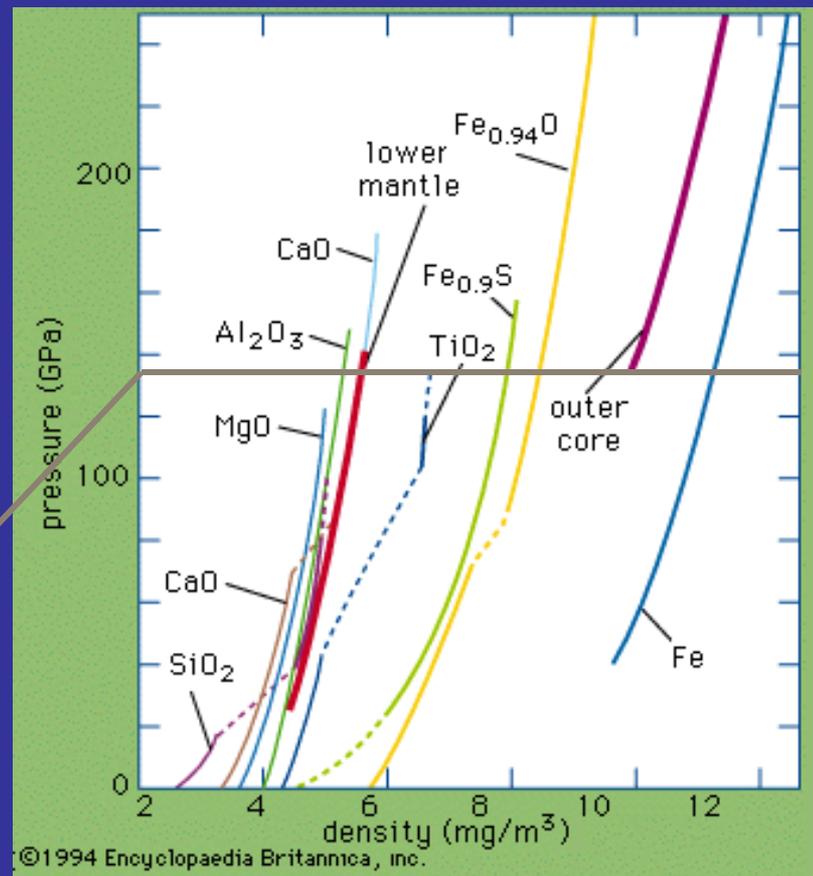
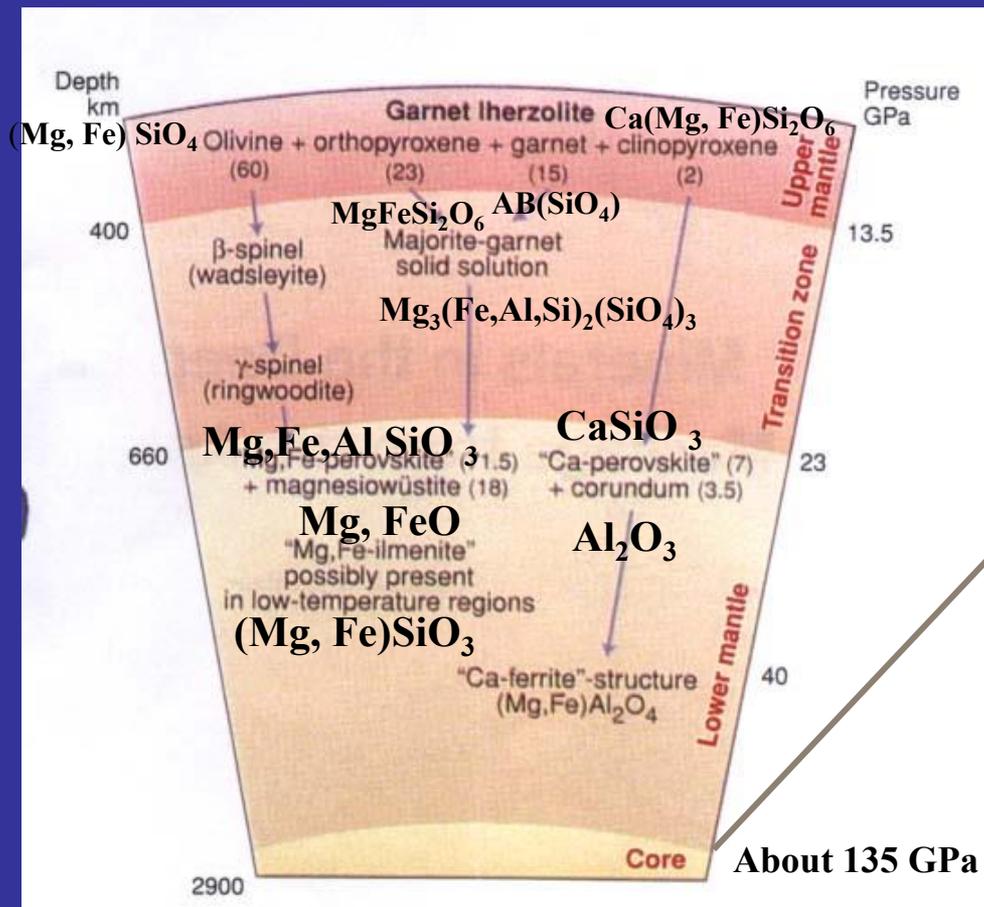


The 27 mm light gas gun is being used in this picture in the Lindhurst Laboratory, Caltech, on samples and experiments in August 1999.

Previously shock wave experiments on minerals involved measurements of pressure and density along the locus of shock states called the **Hugoniot**. Ahrens' group has pioneered the use of optical radiation versus time at a series of wavelengths to determine shock temperatures directly. Former graduate student Thomas Duffy has demonstrated how thermal expansion of the materials of the earth's lower mantle and core can be obtained from these shock temperature data. For example, iron, which has a density of 7.8 g/cm^3 and a thermal expansivity of $41 \times 10^{-6} \text{ K}^{-1}$ at normal pressure and temperature, is found to have a density of 13.5 g/cm^3 and a thermal expansivity of $6 \times 10^{-6} \text{ K}^{-1}$ at the center of the earth. This work implies that the earth's inner solid core, assumed to have an average temperature of $6750 \pm 1000 \text{ K}$, is less dense than pure iron (13.5 g/cm^3) by $4 \pm 2\%$. Visiting Associate Jay Bass and Ahrens' group have recently employed methods developed for measuring shock temperatures of metals to an iron-chromium-nickel alloy and determined its melting point to be 5500 to 6000 K in the pressure regime of the lowermost outer core of the earth. This compares to about 7000 K for pure iron. It is believed these data and parallel experiments, using our method, conducted by the shock wave group at Lawrence Livermore National Laboratory support our previous, highly controversial shock temperature measurements for pure iron, and our determination of the earth's central temperature of $6900 \pm 1000 \text{ K}$. (*Thomas J. Ahrens*)



Proposed mantle mineralogy using the meteorite data (Stöffler, 1997)



Notice the excellent agreement between the experimental data and the meteorite evidence! Thus it is almost certain that 98.9% of the entire mantle consists of silicates!

Why are the silicates so abundant? And why are their compounds with Mg and Al? And why is there so much iron in the core?

To all these questions there is a simple answer: Their primitive abundances during the formation of the solar system and the specific gravity of the substances they form were responsible. The table in the next slide shows their primitive abundances and their fates.

How do we know those abundances?

There are two sources: One is the composition of the sun, which we know through spectroscopy, and the other is the composition of the chondritic meteorites, which closely resembles the composition of the sun. They thus afford us an opportunity to infer what the initial materials of the earth-making processes might have been and what the original abundances of various elements in the solar system were.

Table 1: Relative abundance of the first 28 elements and their fates during the formation of the terrestrial planets (after Boecker, 1985).

Element Number	Element Name	Compound Solid	Compound Gas	Rel. Abundance In Sun*	Fate†	Rel. Abundance in Chondrites**
1	Hydrogen		H ₂	40,000,000,000	(1)	–
2	Helium		He	3,000,000,000	(1)	trace
3	Lithium	Li ₂ O		60	(3)	50
4	Beryllium	BeO		1	(3)	1
5	Boron	B ₂ O ₃		43	(2)	6
6	Carbon		CH ₄	15,000,000	(1)	2,000
7	Nitrogen		NH ₃	4,900,000	(1)	50,000
8	Oxygen		H ₂ O**	18,000,000	(2)	3,700,000
9	Fluorine		HF	2,800	(1)	700
10	Neon		Ne	7,600,000	(1)	trace
11	Sodium	Na ₂ O		67,000	(2)	46,000
12	Magnesium	MgO		1,200,000	(3)	940,000
13	Aluminum	Al ₂ O ₃		100,000	(3)	60,000
14	Silicon	SiO ₂		1,000,000	(3)	1,000,000
15	Phosphorous	P ₂ O ₅		15,000	(3)	13,000
16	Sulfur	FeS	H ₂ S	580,000	(2)	110,000
17	Chlorine		HCl	8,900	(1)	700
18	Argon		Ar	150,000	(1)	trace
19	Potassium	K ₂ O		4,400	(2)	3,500
20	Calcium	CaO		73,000	(3)	49,000
21	Scandium	Sc ₂ O ₃		41	(3)	30
22	Titanium	TiO ₂		3,200	(3)	2,600
23	Vanadium	VO ₂		310	(3)	200
24	Chromium	CrO ₂		15,000	(3)	13,000
25	Manganese	MnO		11,000	(3)	9,300
26	Iron	Feo,FeS,Fe		1,000,000	(3)	690,000
27	Cobalt	CoO		2,700	(3)	2,200
28	Nickel	NiO		58,000	(3)	49

*Relative to 1,000,000 silicon atoms.

†(1) Highly volatile; mainly lost;

(2) Moderately volatile; partly captured;

(3) Very low volatility; largely captured.

**Plus metal oxides.

Noble gas



Noble gas



Noble gas



Earth-
making
elements



Life-
making
elements



The most abundant elements in the earth-making nebular dust:

Hydrogen

Oxygen

Carbon

Nitrogen

Magnesium

Iron

Silicon

Sulfur

Aluminum

LIFE

EARTH

Why did earth-making precede life-making?

Organic (i.e. C-bearing compounds) formed as early as the rest. But life requires a more complex chemical basis; this seems to have awaited a hydrous environment

We have just seen that 92% of the crust and 98.9% of the mantle consist of silicates. Since it is these two layers of the earth that form some 71% of the total earth mass and that they almost alone are the theatre of the geological processes, geologists first need to familiarise themselves with the mineralogy of the silicate minerals. Then come the oxides and then the carbonates in order of importance.

Si^{+4} is the only kind of silicon occurring in the silicates.

Radius of Si^{+4} is 0.41 \AA

Radius of O^{-2} is 1.4 \AA

What do we learn from this?

In the continental crust, the most abundant elements are Si, O and Al.

We know that Si takes on a 4-fold coordination and Al can take on 4 or 6 depending on the presence of other cations. Thus, in the continental crust, the most abundant coordination is four-fold, i.e. tetrahedral. In the oceanic crust, it is again Si, O but for cation Mg dominates with 6-fold octahedral coordination. Because of the preponderance of the Si and O, in the oceanic crust, it is again the tetrahedral form that actually dominates.

As we descend in the mantle, increasing pressure forces the O atoms together. So first the octahedral (6-fold) and, finally, the cubic (8-fold) forms take over the dominance.

Now let us look at the silicate structure to see how this is borne out.

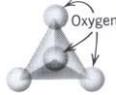
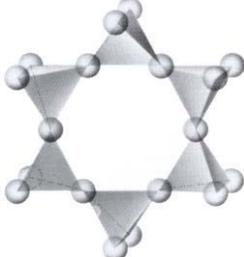
According to their internal structure, the silicates are divided into *six* main groups:

1

2

3

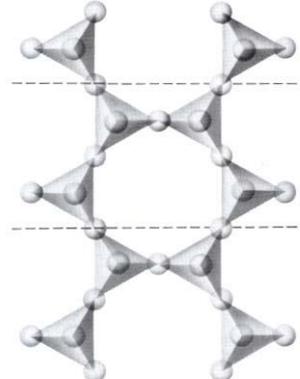
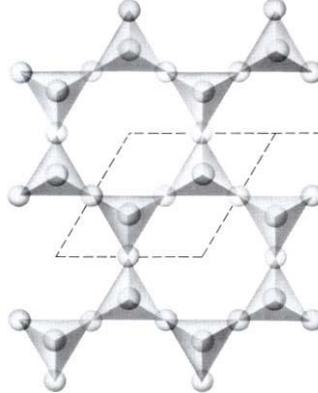
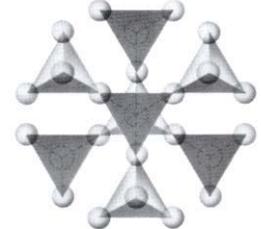
4a

Class	Arrangement of SiO ₄ tetrahedra (central Si ⁴⁺ not shown)	Unit composition	Mineral example
Nesosilicates		(SiO ₄) ⁴⁻	Olivine, (Mg, Fe) ₂ SiO ₄
Sorosilicates		(Si ₂ O ₇) ⁶⁻	Hemimorphite, Zn ₄ Si ₂ O ₇ (OH)·H ₂ O
Cyclosilicates		(Si ₆ O ₁₈) ¹²⁻	Beryl, Be ₃ Al ₂ Si ₆ O ₁₈
Inosilicates (single chain)		(Si ₂ O ₆) ⁴⁻	Pyroxene e.g. Enstatite, MgSiO ₃

4b

5

6

Inosilicates (double chain)		(Si ₄ O ₁₁) ⁶⁻	Amphibole e.g. Anthophyllite, Mg ₇ Si ₈ O ₂₂ (OH) ₂
Phyllosilicates		(Si ₂ O ₂) ²⁻	Mica e.g. Phlogopite, KMg ₃ (AlSi ₃ O ₁₀)(OH) ₂
Tectosilicates		(SiO ₂) ⁰	High cristobalite, SiO ₂

The nesosilicates

(from the classical Greek $\nu\eta\sigma\omicron\varsigma$ {nesos}= island or an islet), i.e. the “island” silicates.

The “island” silicates are so called, because their structure consists of isolated SiO_4 tetrahedra connected by cations.

Let us look at the electrical charges on an isolated SiO_4 tetrahedron:

The charge of the Si ion is +4, and the O ion is -2, so:



This combination has an excess of -4 charges, which means that this unit cannot stay isolated. A +4 charge has to be added to neutralise it. By the addition of cations to do so, we generate the nesosilicates.

The most important nesosilicates are the **olivines**, the **garnets**, and **kyanite**, **andalusite** and **sillimanite**.

The olivines

Forsterite $\text{Mg}_2(\text{SiO})_4$

Named after Johann Forster

Crystal system: Orthorhombic

Cleavage: two cleavages, one good the other one not well-developed

Colour: Generally green, greenish yellow, yellow, rarely white

Average density: 3.27

Hardness: 6-7

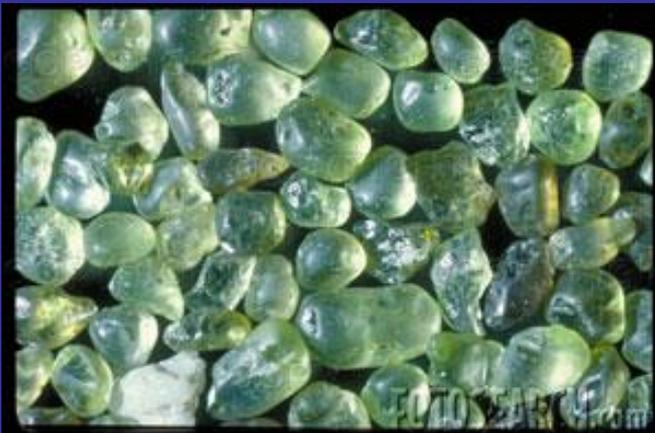
Streak: White

Luster: Vitreous

Fracture: Conchoidal

Olivine sands in Hawaii

Occurs in ultramafic rocks, dolomite, some basalts and gabbros.





Occurs in ultramafic rocks,
some Lunar mafic rocks and
Pallasite meteorites

Fayalite $\text{Fe}^{++}_2(\text{SiO})_4$

Named after Fayal Island, Azores

Crystal system: Orthorhombic

Cleavage: indistinct

Colour: brownish black to black

Average density: 4.39

Hardness: 6-7

Streak: White

Luster: Vitreous

Fracture: Conchoidal



Occurs in carbonatites
(CaCO₃ lavas!)

Monticellite CaMg(SiO)₄

Named after Teodoro Monticelli (1759-1846), Italian mineralogist

Crystal system: Orthorhombic

Cleavage: indistinct

Colour: colourless, greenish grey, grey

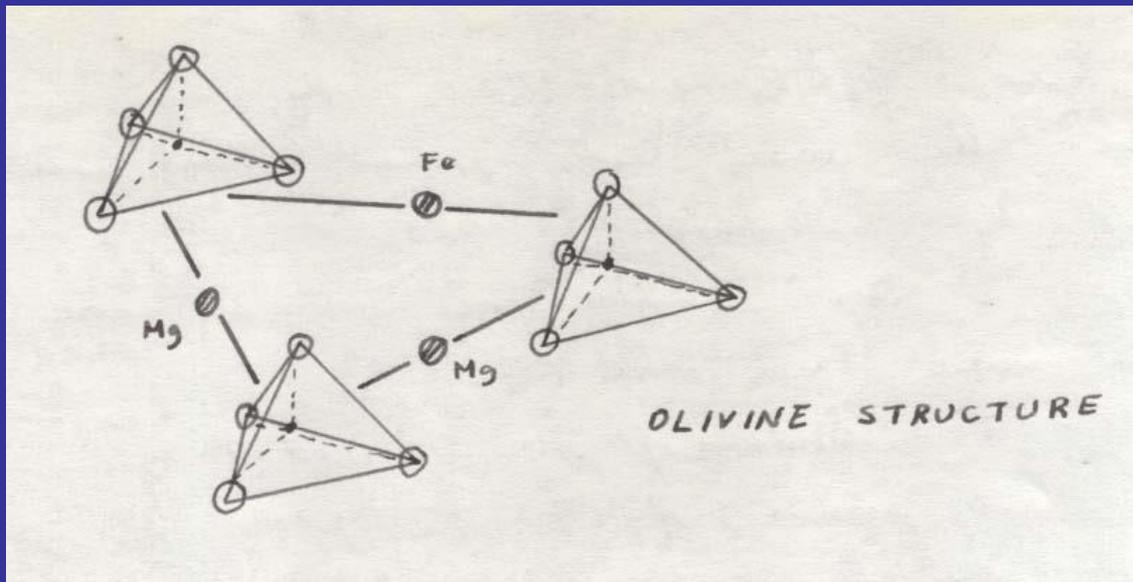
Average density: 3.2

Hardness: 5

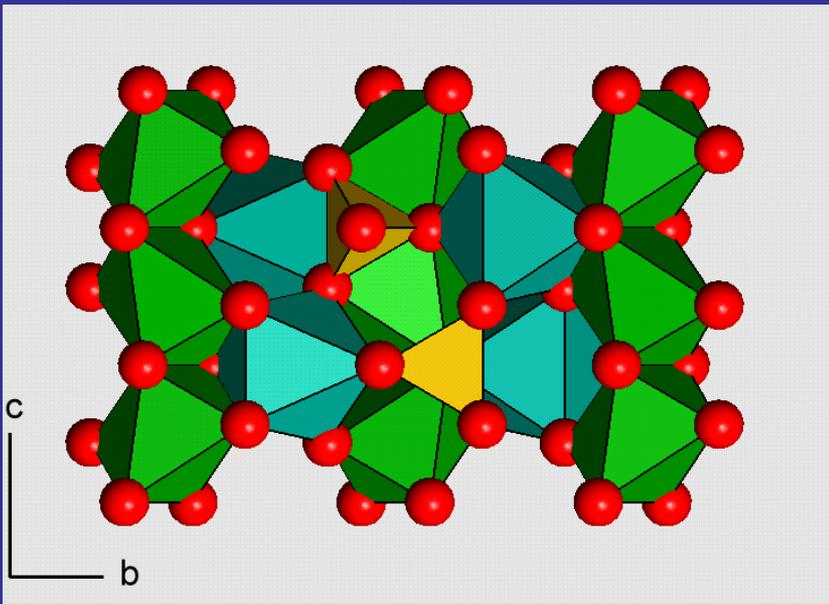
Streak: White

Luster: Vitreous

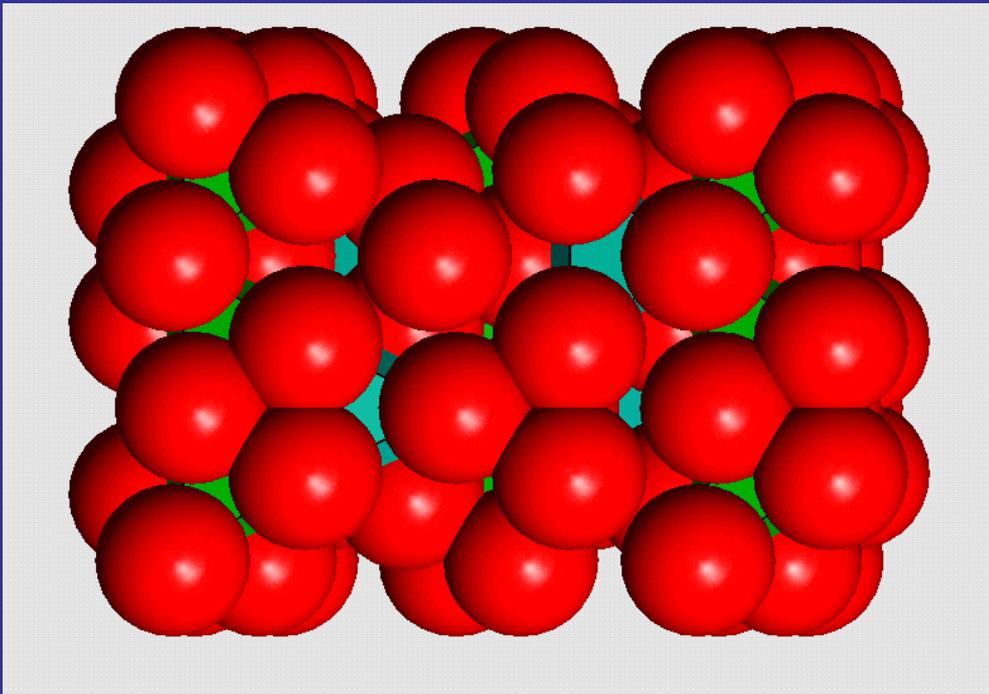
Fracture: Brittle



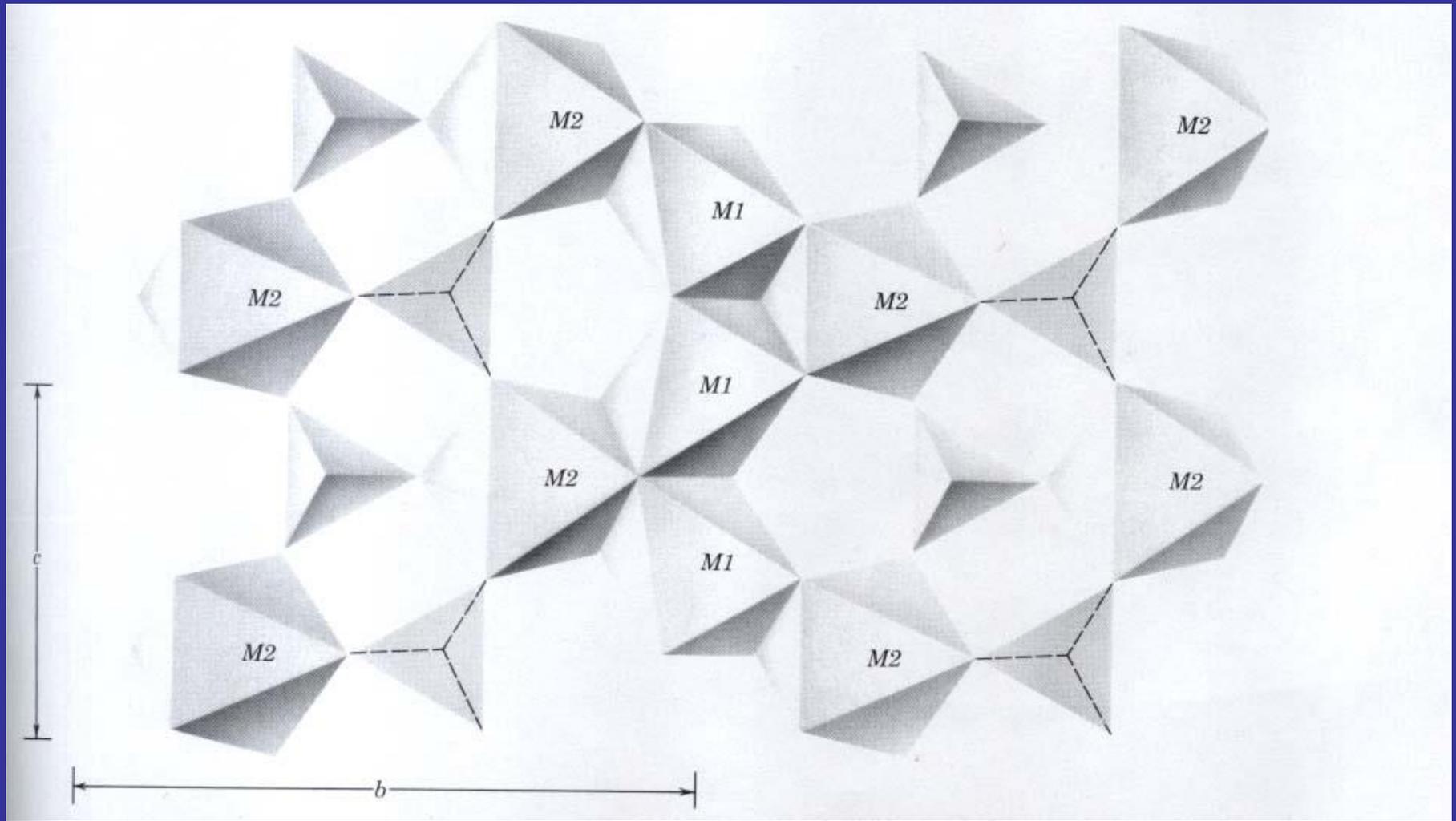
This is what olivine structure in principle is like: individual SiO_4 tetrahedra held together by Mg, Fe or Ca cations. Here the Si-O bonds are shorter and stronger (because they are covalent) than the cation-O bonds that are ionic. When olivine is scratched (hardness!), or when it is melted (melting temperature) the cation-O ionic bonds are broken.



This is what in reality the olivine structure is



And this is what it really looks like, because the O ions are so fat.



In an olivine this is how the tetrahedra are arranged (as projected onto the 100 face). The M1 and M2 are the octahedral sites. Here the M1 site is distorted. It is that distortion that does not allow the olivine to become hexagonal and forces it to become orthorhombic!

Most olivines do not have the pure end-member compositions of the minerals we just mentioned. *They are mostly mixtures of forsterite and fayalite.* When an olivine is mentioned it is usually indicated what percentage of forsterite or fayalite it contains.

This happens as Fe^{++} and Mg^{++} ions easily substitute for each other, because:

- 1) They have the same electrical charge
- 2) They have similar ionic radii ($r_{\text{Mg}^{++}}=0.65 \text{ \AA}$; $r_{\text{Fe}^{++}}=0.73 \text{ \AA}$)
- 3) They have the same octahedral (six-fold) sites.

When ions substitute for each other in a mineral structure in this manner, the resulting mixture is called a **solid solution**. *Most minerals are solid solution series.*

Definition of solid solution: The substitution of one atom for another in a random fashion throughout a crystal structure is called solid solution.

The garnets

The garnets are another solid solution series occurring mostly in metamorphic rocks. Their general formula is expressed as $A_2B_2(SiO_4)_3$. Here A is the 8- and the B is the 6-fold coordination site for cations holding the silicon-oxygen tetrahedra together. This makes garnet classification easy:

- A sites may be filled with either: Ca^{++} (ionic radius = 0.99\AA)
- Or one of the trivalent ions of Al^{+++} (ir = 0.50\AA), Fe^{+++} (ir = 0.64\AA) and Cr^{+++} (ir = 0.69\AA)

Accordingly, we can distinguish two garnet groups on the basis of the ions in the A sites:

Pyrospites

Pyrope $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

Almandine $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

Spessartine $\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

And

Ugrandites

Uvarovite $\text{Ca}_3\text{Cr}_2\text{Si}_3\text{O}_{12}$

Grossular $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

Andradite $\text{Ca}_3\text{Fe}^{+++}_2\text{Si}_3\text{O}_{12}$

We can also group the garnets on the basis of the ions in the B sites:

Aluminum garnets

Ferri-garnet

Chrome-garnet

Pyrope

Andradite

Uvarovite

Almandine

Spessartine

Grossular

Pyrope (also called Rhodolite; $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12}$)

Named from the Greek designation $\piυρορ+οπ-$ (pyrop =fiery-eye) owing to its bright red colour and round shape.

Crystal system: cubic (=isometric)

Cleavage: none

Colour: blood red, orange red, purple red, pink,

Average density: 3.65-3.84; average 3.74

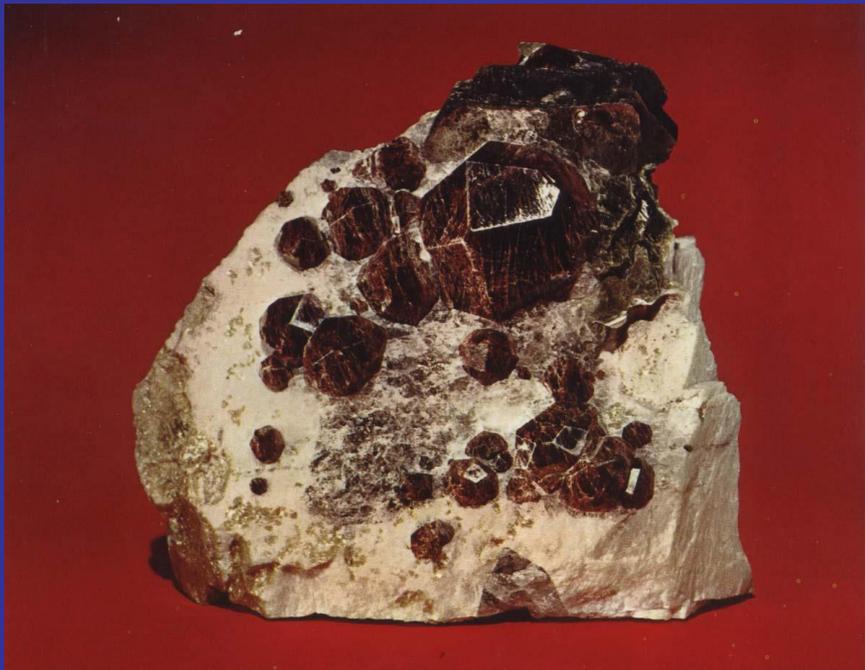
Hardness: 7.5

Streak: White

Luster: vitreous

Fracture: conchoidal





Almandine (also called Almandite) $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

Named after the ancient town of Alabanda, Now in Turkey, in the Aydın province, near Çine, in the village of Alaphisar (or Araphisar). The village is now called Doğanıyurt.

Crystal system: cubic (=isometric)

Cleavage: none

Colour: brown, brownish red, red, black, black red.

Average density: 4.09-4.31; average 4.19

Hardness: 7-8

Streak: White

Luster: vitreous-resinous

Fracture: brittle-conchoidal





Spessartine (also called
Spessartite; $\text{Mn}^{++}_3\text{Al}_2\text{Si}_3\text{O}_{12}$)

Named after the Spessart Mountains in
South Germany, locality Aschaffenburg

Crystal system: cubic (=isometric)

Cleavage: distinct

Colour: red, reddish orange, yellowish
brown, reddish brown, brown.

Average density: 4.18

Hardness: 6.5-7.5

Streak: White

Luster: vitreous-resinous

Fracture: brittle-conchoidal

*Cautionary note: Amphibole lamprophyres,
an ultrapotassic ultramafic rock, are also
called spessartites*

Uvarovite (also called
chromium garnet;
 $\text{Ca}_3\text{Cr}_2\text{Si}_3\text{O}_{12}$)

Named after Count S. S. Uvarov (1765-1855), Russian statesman and ardent amateur mineral collector. The type locality is in the Uralian chromite deposits

Crystal system: cubic (=isometric)

Cleavage: distinct

Colour: green

Average density: 3.4-3.8, average: 3.59

Hardness: 6.5-7

Streak: White

Luster: vitreous

Fracture: brittle



Uvarovite from the Urals,
Russia



Reddish-brown grossular



White grossular

Grossular (also called Grossularite or Hessonite, if brownish orange, Tsavorite if emerald green) $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$

Named after the Latin word *grossularia* meaning gooseberry (= *Ribes grossularia*).

Crystal system: cubic (=isometric)

Cleavage: none

Colour: brown, colourless, green, grey, yellow.

Average density: 3.42-3.72; average 3.57

Hardness: 6.5-7.5

Streak: brownish white

Luster: vitreous-resinous

Fracture: subconchoidal

Grossular



Grossular



Gooseberry (*Ribes grossularia*)
bektaşî üzümü in Turkish



Green andradite garnets in
asbestos

Andradite $\text{Ca}_3\text{Fe}^{+++}_2\text{Si}_3\text{O}_{12}$

Named after the Brazilian mineralogist J. B. de Andrada e Silva {1763-1838}. Melanite, if black; topazolite, if yellow.

Crystal system: cubic (=isometric)

Cleavage: none

Colour:black, yellowish brown, red, greenish yellow, gray.

Average density: 3.7-4.1; average 3.9

Hardness: 6.5-7

Streak: white

Luster: vitreous

Fracture: conchoidal

The aluminosilicates of the nesosilicate group

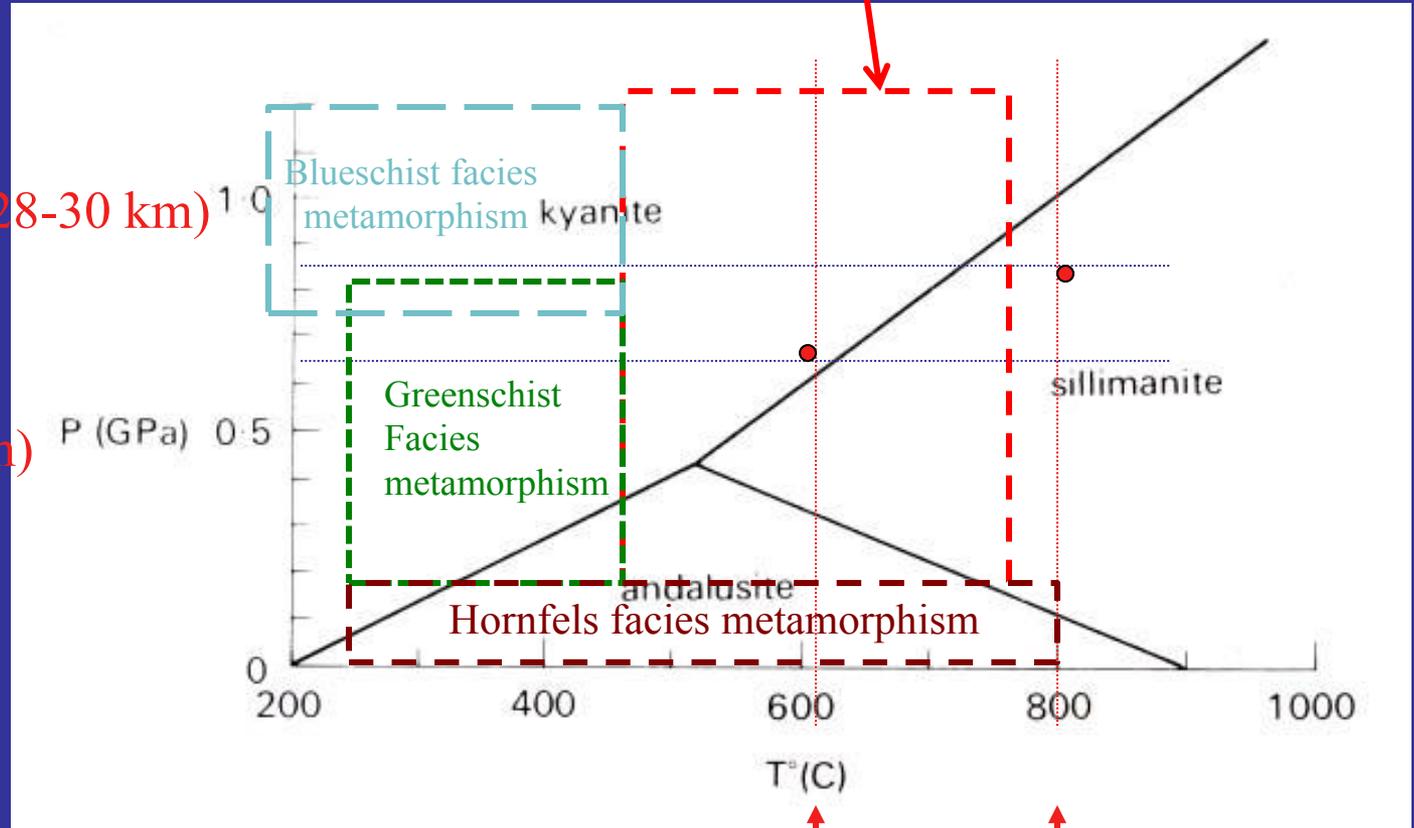
Another important group of nesosilicates consists of the three polymorphs of Al_2SiO_5 , **kyanite** (in Turkish we use the French form **disten**), **sillimanite** and **andalusite**. These are *aluminosilicates* and are found in highly metamorphosed, aluminum-rich (i.e. “continental”) *regional metamorphic rocks*

Amphibolite facies metamorphism

Lower crust (c. 28-30 km)

Mid-crust (c. 12-15 km)

1 bar = 10^5 Pa



Melting point
of wet granite

Melting point
of dry granite

The stability fields of andalusite, kyanite and sillimanite.

(Note: metamorphic facies fields are approximate. Boundary between blueschist and greenschist slopes upwards to the right and there is in reality no overlap)



Kyanite Al_2SiO_5

Named after the Greek word $\kappa\upsilon\alpha\nu\omicron\varsigma$ (kyanos =dark blue).

Crystal system: triclinic

Cleavage: good in one direction parallel with pinacoid face

Colour: Almost always sky-blue, but can be black, grey, greenish grey, even white

Average density: 3.58+

Hardness: 4.5 when scratched parallel with the long axis of the crystal, 6.5 when scratched across that direction

Streak: white

Luster: vitreous to almost pearly

Fracture: splintery

Andalusite Al_2SiO_5

Named after the southern Spanish province of Andalusia where it was first discovered.

Also called *chiastolite*

Crystal system: orthorhombic

Cleavage: good in one direction [110]

Colour: dark green, grey, brown, even red

Average density: 3.15

Hardness: 6.5-7

Streak: white

Luster: vitreous

Fracture: splintery owing to cleavage intersections



Sillimanite Al_2SiO_5

Named after the American natural scientist Benjamin Silliman (1779-1824) of Yale University

Crystal system: orthorhombic

Cleavage: perfect [010]

Colour: colourless, grey, grey, green, blue

Average density: 3.24

Hardness: 7

Streak: white

Luster: vitreous

Fracture: splintery



The sorosilicates

(from the Latin *soror* {=sister}, i.e. the “sister” silicates.

The “sister” silicates are so called, because their structure consists of two connected SiO_4 tetrahedra plus connecting cation.

Let us look at the electrical charges on a double SiO_4 tetrahedra:

The charge of the Si ion is +4, and the O ion is -2, so:



This combination has an excess of -6 charges, which means that this unit cannot stay isolated. A +6 charge has to be added to neutralise it. By the addition of cations to do so, we generate the sorosilicates. The most important sorosilicates are the minerals of the **epidote** group, **lawsonite** and **hemimorphite**.

Among the prominent minerals of the sorosilicates is the *epidote group*. This group is a prominent member of low grade metamorphic rocks, contact metamorphic aureoles and some hydrothermal vein environments. The important minerals of this group are:

Epidote, clinozoisite, piemontite and orthite.



Epidote from Green Monster Mountain, Prince of Wales Island, Prince of Wales-Outer Ketchikan Borough, Alaska (USA)

Epidote



Named after the Greek word *επιδοσις* (epidosiς=to grow, to advance, to progress)

Crystal system: monoclinic

Cleavage: perfect [001]

Colour: yellowish green, brownish green, yellow, grey, black

Average density: 3.45

Hardness: 7

Streak: greyish white

Luster: vitreous

Fracture: regular with flat surfaces

Occurs in low to medium grade metamorphic rocks and in contact metamorphic zones



Clinozoisite



Named after its resemblance to zoisite and its monoclinic crystal form. Zoisite was named after the Austrian naturalist *Siegmund Zois* (1747-1819)

Crystal system: monoclinic

Cleavage: perfect [001]

Colour: greenish to pale yellow, pink, reddish and grey.

Average density: 3.21-3.38

Hardness: 6.5

Streak: white

Luster: vitreous

Fracture: uneven



Occurs mostly in low to medium grade metamorphic areas and in contact metamorphic zones.

Occurs in metamorphic and contact metasomatic rocks

Piromontite (rarely also called
“manganiferous epidote”)



Named after its locality, Piemonte, Italian Alps

Crystal system: monoclinic

Cleavage: good [001], distinct [100].

Colour: blood red, reddish black, reddish brown,
yellow

Average density: 3.4

Hardness: 6 to 7

Streak: red

Luster: vitreous

Fracture: splintery, falls apart along thin,
elongated fractures produced by cleavage
intersection



Found in manganese
deposits, low temperature
hydrothermal veins and
low grade metamorphic
rocks





Orthite (=Allanite)
 $(\text{Ca, Ce, La, Y})_2(\text{Al, Fe})_3(\text{SiO}_4)_3(\text{OH})$



Allanite was named after the Scottish mineralogist Thomas Allan (1777-1833)

Crystal system: monoclinic

Cleavage: perfect [001], imperfect [100].

Colour: black, brown, reddish brown

Average density: 3.75

Hardness: 5.5

Streak: greyish brown

Luster: vitreous-greasy or vitreous glassy

Fracture: conchoidal

Ce-Orthite



La-Orthite



Hemimorphite from China

Hemimorphite is a secondary mineral associated with the oxidised parts of zinc deposits.

Hemimorphite $Zn_4(Si_2O_7)(OH)_2 \cdot H_2O$:

Formerly called *calamine*. Named after the hemimorphic (literally, “half-shaped”) nature of its crystals. It produces a different termination at each end! One end flat (pinacoid) the other pyramidal

Crystal system: orthorhombic

Cleavage: [110] perfect

Colour: white; in some cases faint bluish or greenish hues, it can be also yellow or even brown

Average density: 3.4-3.5

Hardness: 4.5-5

Streak: white

Luster: vitreous-resinous

Fracture: brittle, conchoidal



Lawsonite crystals in a glaucophane schist from the Franciscan Complex, near San Francisco, California



Lawsonite



Named after the great American geologist Andrew Cowper Lawson (1861-1952)

Crystal system: orthorhombic

Cleavage: [010] Perfect, [001] Perfect, [110] Poor

Colour: colourless, grey, blue, white, pinkish

Average density: 3.09

Hardness: 7.5

Streak: white

Luster: vitreous-greasy

Fracture: brittle and irregular

Ransome, Frederick Leslie (1895), On lawsonite, a new rock-forming mineral from the Tiburon Peninsula, Marin County: *Univ. Calif., Dept. Geol. Sci. Bull.*: 1: 301-312.

Almost entirely confined to glaucophane schists

The cyclosilicates

(from the Greek κυκλος {*kueklos* = ring, circle, round}, i.e. the “ring” silicates.

The “ring” silicates are so called, because their structure consists of SiO_4 so connected as to form a closed ring.

Let us look at the electrical charges on a ring of SiO_4 tetrahedra:

The charge of the Si ion is +4, and the O ion is -2, so:



This combination has an excess of -12 charges, which means that this unit cannot stay isolated. A +12 charge has to be added to neutralise it. By the addition of cations to do so, we generate the cyclosilicates. The most important cyclosilicates are the **beryl**, the **tourmaline group** and **cordierite**.

Beryl $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$

From the ancient Greek, *beryllos*, signifying a "precious blue-green color of sea water" stone, but through later usage, applied only to beryl (from <http://webmineral.com/data/Beryl.shtml>. I could *not* verify this). Synonyms: *Aquamarine* if blue; *emerald*, if green; *heliodor* if yellow, and *goshenite* if colourless)

Crystal system: hexagonal

Cleavage: [0001] imperfect

Colour: blue, green, yellow, pink, colourless

Average density: 2.76

Hardness: 7.5-8

Streak: white

Luster: vitreous-resinous

Fracture: brittle, conchoidal



Found most commonly in granite pegmatites and in mica schists

Tourmaline group general formula:



From the Sinhalese *tòramalli*. It is obscure where the final **n** came from.

Important tourmaline group minerals are:

Schorl (the most common), buergerite, chromdravite, dravite, elbaite (superb gem tourmalines), feruvite, foitite, liddicoatite, magnesiofoitite, olenite, povondraite, rossmanite, uvite



The most common tourmaline is **schorl**. It is an old name of obscure origin, but probably a miners' term of German pedigree.



Crystal system: hexagonal

Cleavage: [1011] indistinct

Colour: black, brownish black, or dark grey

Average density: 3.15

Hardness: 7.5

Streak: brown

Luster: vitreous

Fracture: brittle, conchoidal



Mainly in high grade continental metamorphic rocks



The most common gem variety tourmaline is **elbaite**. Named after the island of Elba in Italy.



Crystal system: hexagonal

Cleavage: [1011] indistinct

Colour: variable: commonly green, yellow and pinkish, bluish or even white bands alternate or singly dominate a specimen.

Average density: 3.05

Hardness: 7.5

Streak: white

Luster: vitreous

Fracture: brittle, subconchoidal

Elbaite as “watermelon tourmalines” (internally zoned).



Elbaite zoned perpendicular to the c-axis



Watermelon tourmalines — detail

The inosilicates

(from the Greek ινως {inos = thread, sinew, muscle}, i.e. the “thread” or “chain” silicates.

The “chain” silicates are so called, because their structure consists of SiO₄ tetrahedra so connected as to form a continuous chain or two parallel chains.

Let us look at the electrical charges on a chain of SiO₄ tetrahedra:

The charge of the Si ion is +4, and the O ion is -2, so, in a single chain of silicate tetrahedra:



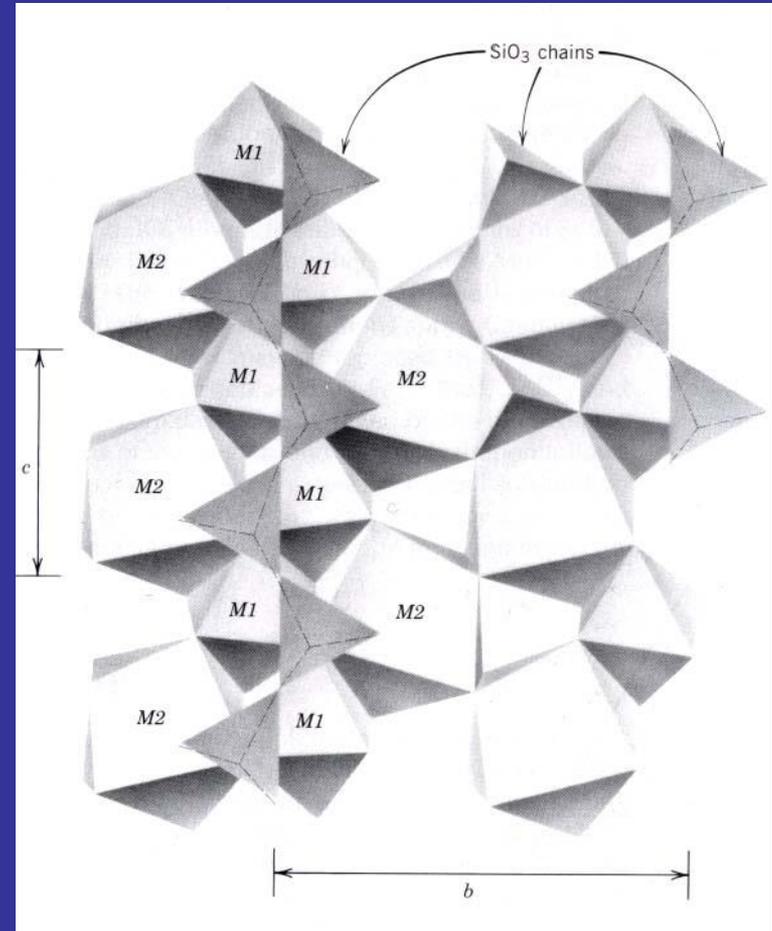
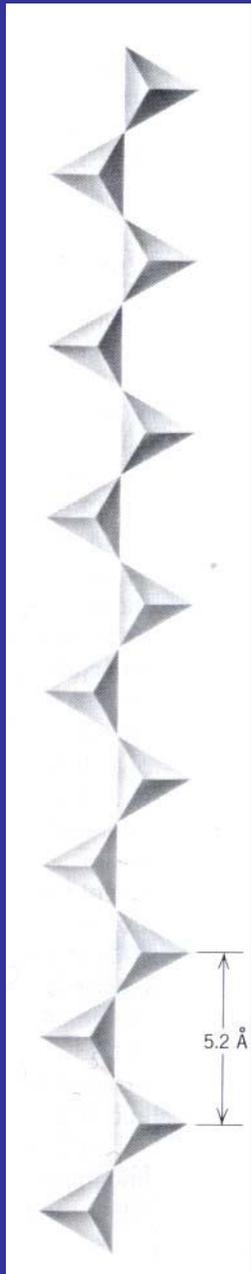
This combination has an excess of -4 charges, which means that this unit cannot stay isolated. A +4 charge has to be added to neutralise it. By the addition of cations to do so, we generate the *single-chain inosilicates*. The most important single-chain inosilicates are the pyroxene group of minerals.

Single SiO_3 chains forming the fundamental pyroxene structure

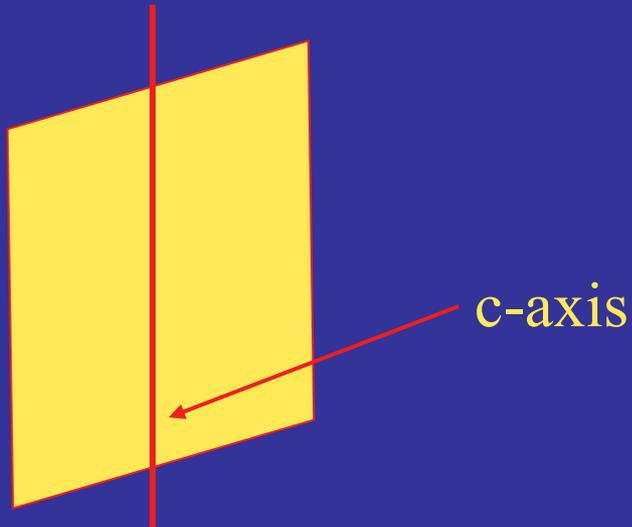
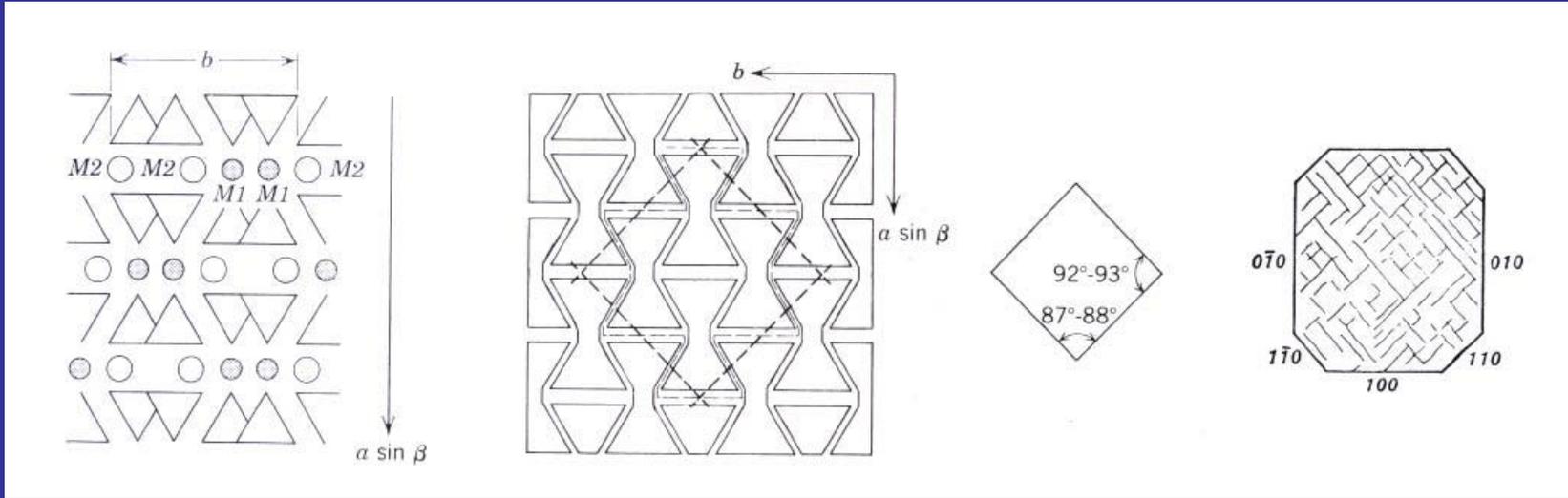
Jadeite structure ($\text{NaAlSi}_2\text{O}_6$) as projected onto the (100) surface.

Notice the position of the SiO_3 chains.

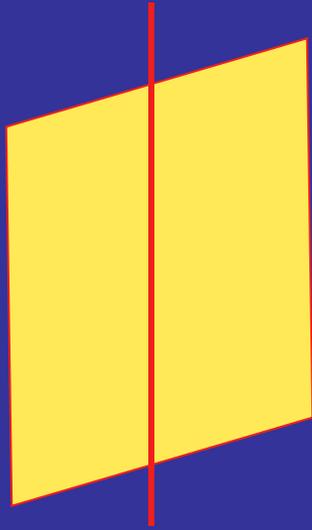
The M1 and M2 sites are the cation sites filled according to the general pyroxene formula



Now let us look down the **c-axis** of a pyroxene structure:

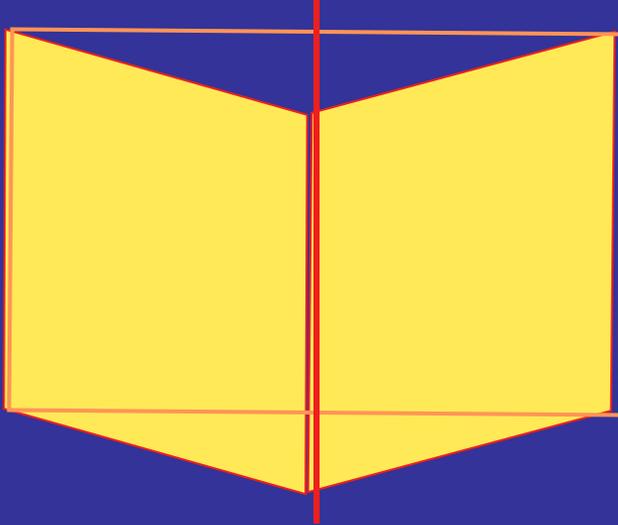


Monoclinic pyroxene structure



Monoclinic pyroxene structure

(Clinopyroxenes: main basalt makers!)



Orthorhombic pyroxene structure

(Orthopyroxenes)

Pyroxenes constitute a solid-solution family that has four end-members:

Clinopyroxenes:

Diopside: $\text{CaMgSi}_2\text{O}_6$

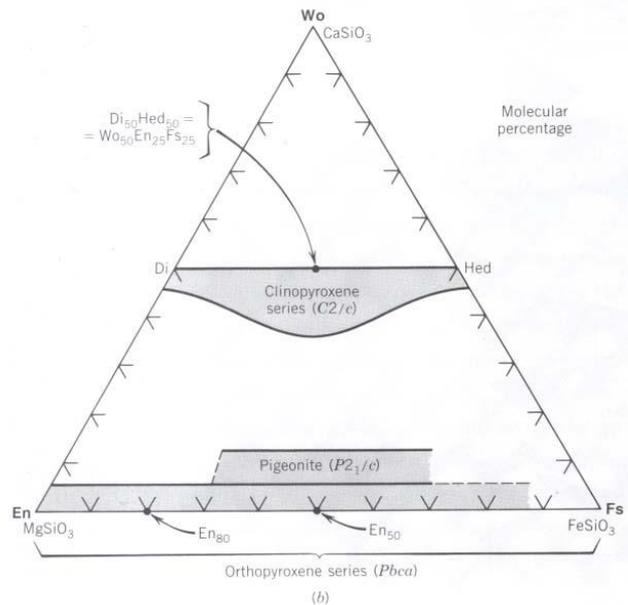
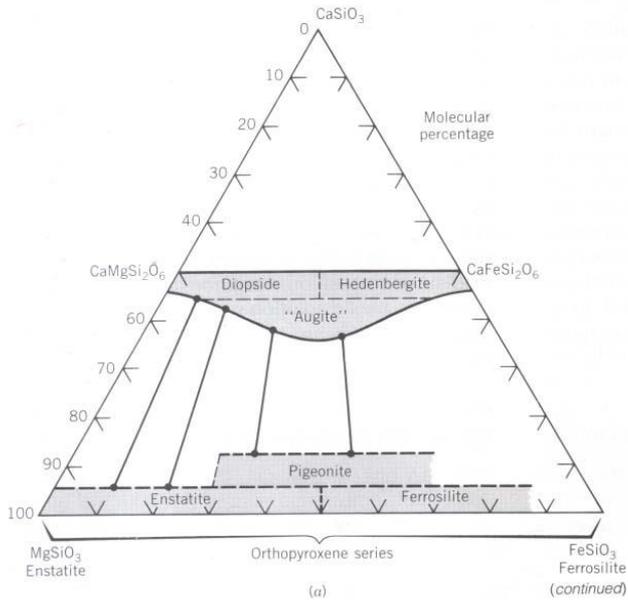
Hedenbergite: $\text{CaFeSi}_2\text{O}_6$

Orthopyroxenes:

Enstatite: MgSiO_3

Ferrosilite: FeSiO_3

In the modern mineralogical nomenclature all pyroxenes are referred to as percentages of the end members (which means you have to know only four names!)



HOWEVER! Life is not so simple, because many other cations also enter into the structure of the pyroxenes creating very important rock-making or gem minerals.

Let us recall the general pyroxene formula:



Now:

The X site may be filled with: Na^+ , Ca^{2+} , Mn^{2+} , Fe^{2+} , Mg^{2+} , Li^{2+}

The Y site may be filled with: Mn^{2+} , Fe^{2+} , Mg^{2+} , Fe^{3+} , Al^{3+} , Cr^{3+} , Ti^{4+}

The Z site is filled either with Si^{4+} or Al^{3+}

We can have, for example,
jadeite:



which is both an important
high pressure mineral
characteristic of blueschists
and a very important gem
and ornamental stone
(called jade in English). In
Turkish it is called *yeşim* (in
central Asia, *kaş*)

JADE

STONE OF HEAVEN

An authoritative account of the fabulous history and
romance of the prized stone of the exotic East, jade



Illustrated with color and black-and-white photographs

RICHARD GUMP



Jadeite crystals, California

Jadeite ($\text{Na}(\text{Al},\text{Fe})\text{Si}_2\text{O}_6$)

The name derives from the Spanish “piedra de ijada”, meaning “side stone” because it was believed to cure kidney ailments! Introduced by Damour in 1863

Crystal system: monoclinic (hence a clinopyroxene)

Cleavage: [110] good

Colour: white, whitish green, pale grey, pale pink, greyish green

Average density: 3.3

Hardness: 6.5

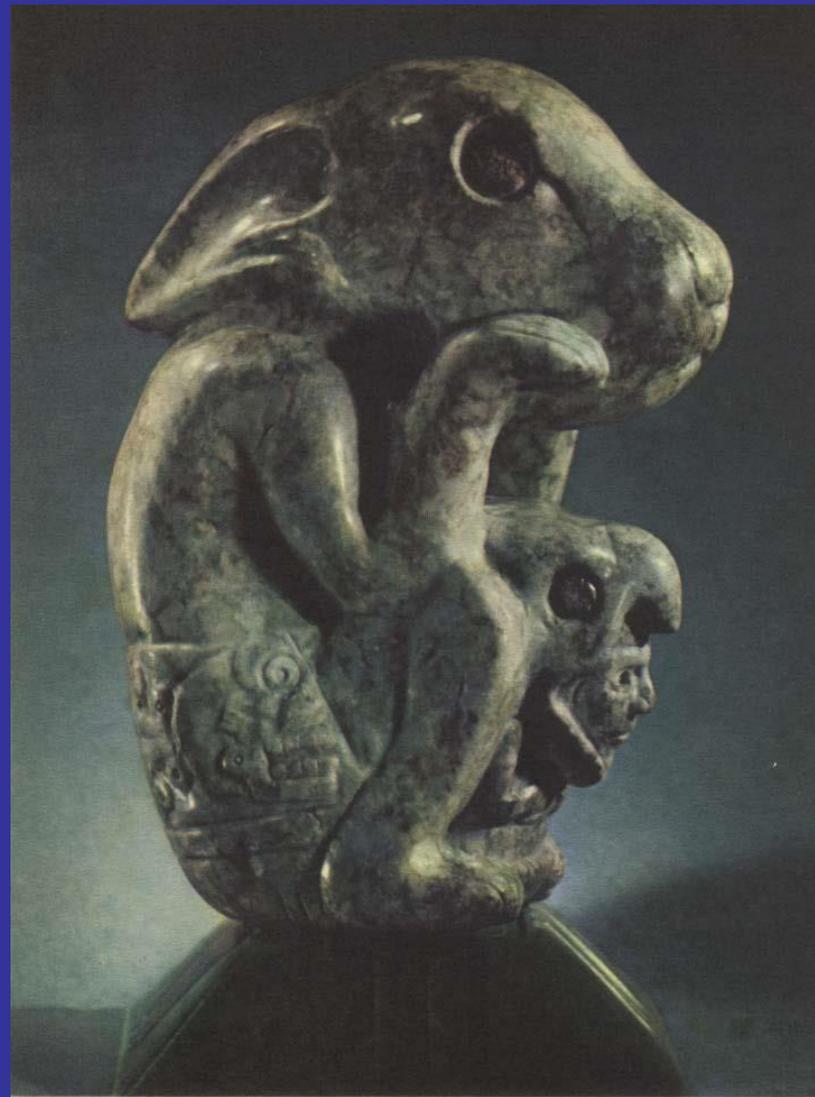
Streak: white

Luster: vitreous

Fracture: tough, but fibrous. Extremely difficult to break



Jadeite from Mandalay,
Burma



Jadeite rabbit statue made by
the Aztecs, Mexico

But not all jade is jadeite!

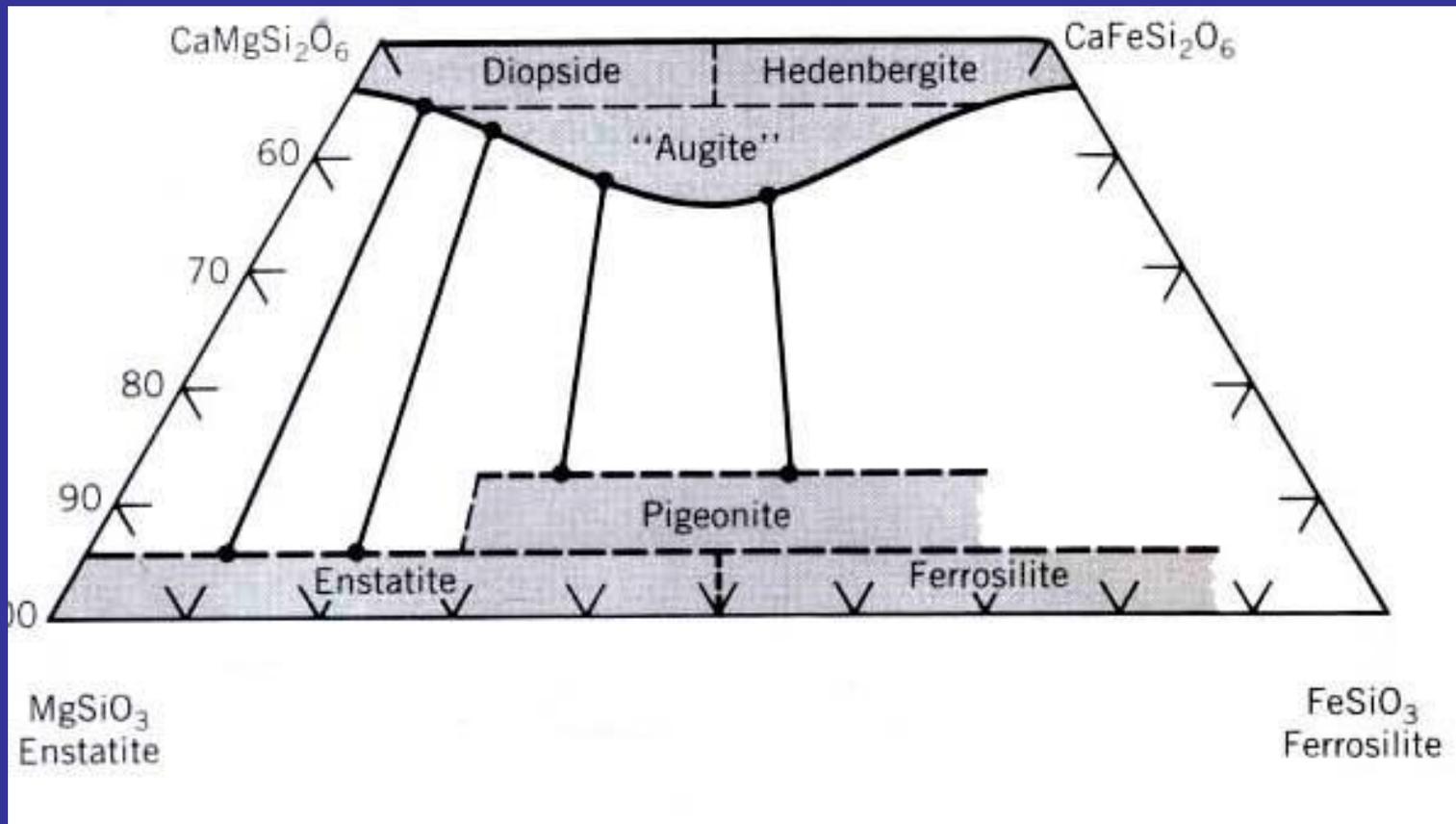
First of all the English word “jade”, meaning an “inferior breed of horse” or a “disreputable woman” has nothing to do with jadeite. The mineralogical word jade in English derives from the misspelled French word “*pierre de jade*” (it should have been *pierre de l’ejade*), which in turn derives from the Spanish “*piedra da ijada*”.

However, another mineral called **nephrite**, a compact variety of actinolite ($\text{Ca}_2(\text{MgFe})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$) (which is also an inosilicate, but an amphibole), is also called jade in the world of gemstones and ornamental stones.

Nephrite is softer than jadeite (5 to 6 vs. 6.5) Its cleavage angle is 120° vs. the 90° of jadeite

Now let us see the four end-member minerals of the pyroxene quadrilateral

Clinopyroxene series



(Mostly) Orthopyroxene series



Diopside $\text{Ca Mg}(\text{Si}_2\text{O}_6)$

The name derives from the Greek dis (=two) and ophis (= opinion)

Crystal system: monoclinic (hence a clinopyroxene)

Cleavage: $[110]$ good

Colour: Blue, colourless, brown, grey

Average density: 3.4

Hardness: 6

Streak: white green

Luster: vitreous

Fracture: Brittle, conchoidal





Hedenbergite $\text{Ca Fe}(\text{Si}_2\text{O}_6)$

The name given by Jöns Jakob Berzelius in 1819 after the Swedish chemist and mineralogist M. A. L. Hedenberg

Crystal system: monoclinic (hence a clinopyroxene)

Cleavage: [??] perfect, [??] indistinct

Colour: black, greyish black, grey green, brownish green, dark green

Average density: 3.55

Hardness: 5-6

Streak: white green

Luster: vitreous

Fracture: brittle, conchoidal





Enstatite MgSiO_3

The name derives from the Greek enstate (=opponent)

Crystal system: orthorhombic (hence an orthopyroxene)

Cleavage: [110] distinct, [010] distinct

Colour: grey, greenish white, white, yellowish green, brown

Average density: 3.2

Hardness: 5.5

Streak: grey

Luster: vitreous, pearly

Fracture: brittle





Ferrosilite FeSiO_3

The name derives from its composition: ferrous silicate named by Norman Bowen in 1935

Crystal system: orthorhombic (hence an orthopyroxene)

Cleavage: [210] good, [100] parting

Colour: bluish, dark brown, green, colourless

Average density: 3.95

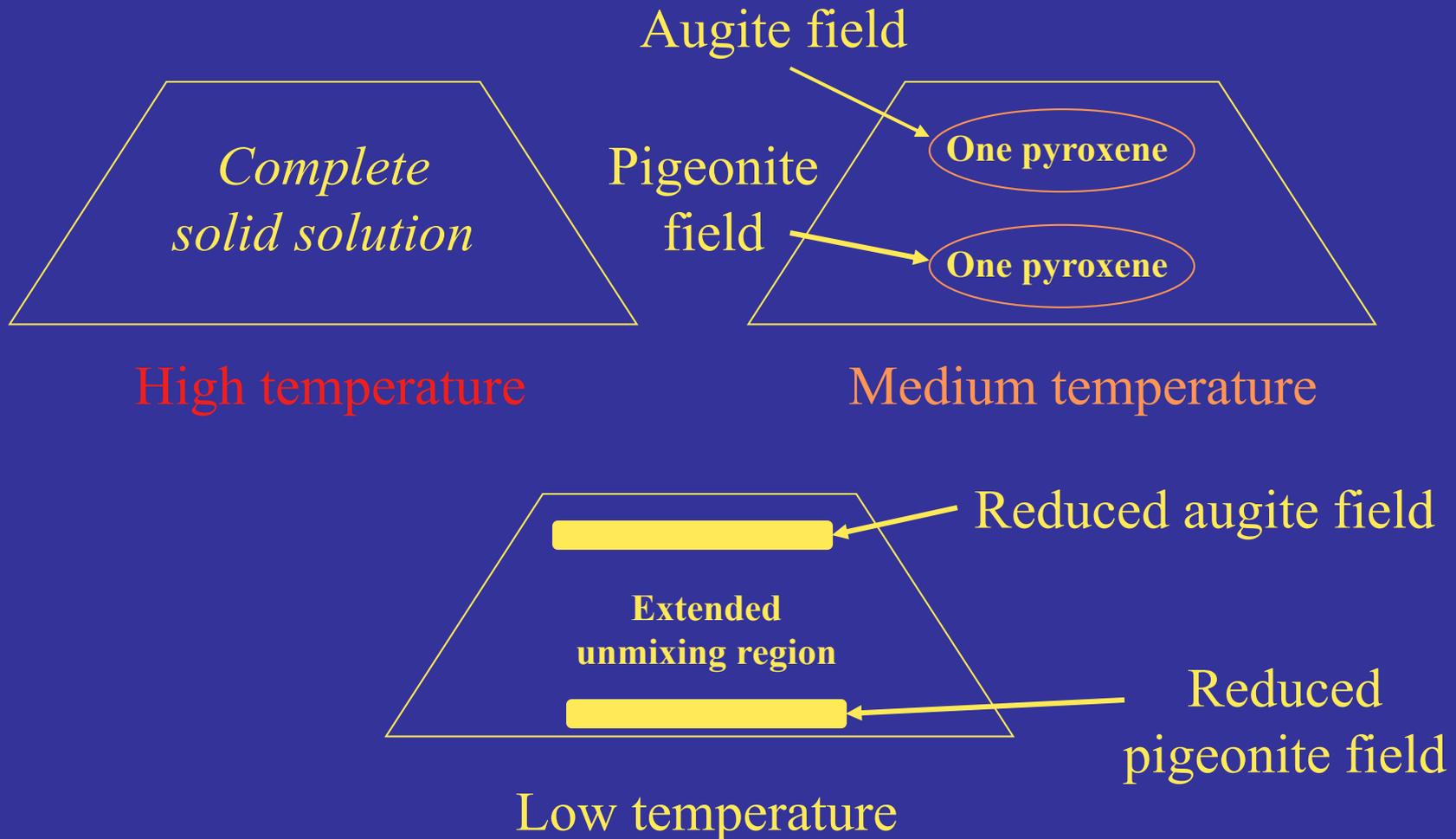
Hardness: 5-6

Streak: pale brownish grey

Luster: vitreous

Fracture:

However, none of the four corners of the pyroxene quadrilateral represent particularly common minerals. Let us see why that is so:



At high temperatures there is complete solid solution and thus a **single pyroxene** forms. As temperature drops, however, two fields, namely the **augite field** and the **pigeonite field** form and any composition falling outside these two fields must split into two and thus create two pyroxenes. At low temperatures, the two fields shrink considerably in favour of the immiscibility gap.

That is why augites and pigeonites are important minerals we have to know about. They are the most common pyroxenes!



Augite $(\text{Ca, Na})(\text{Mg, Fe, Al, Ti})(\text{Si, Al})_2\text{O}_6$

The name derives from the Greek *augeg* (=luster). Also called fassaite

Crystal system: monoclinic (hence a clinopyroxene)

Cleavage: [110] perfect, [010] indistinct

Colour: mostly black, dark brown, brownish green, dark green

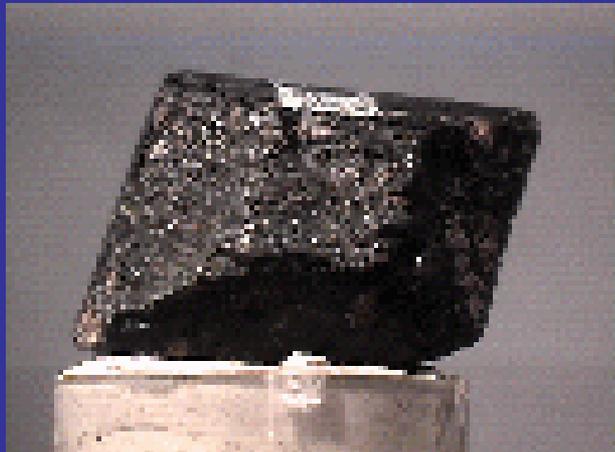
Average density: 3.4

Hardness: 5-6.5

Streak: greenish grey

Luster: vitreous-resinous

Fracture: brittle, conchoidal





Pigeonite $(\text{Mg}, \text{Fe}^{2+}, \text{Ca})\text{Si}_2\text{O}_6$

The name comes from its type locality, the Pigeon Point, Cook County, Minnesota, USA. It was discovered in 1900

Crystal system: monoclinic (hence a clinopyroxene)

Cleavage: $[110]$ good

Colour: black, brown, greenish brown, purple brown.

Average density: 3.38

Hardness: 6

Streak: pale brownish grey

Luster: vitreous-dull

Fracture: brittle conchoidal