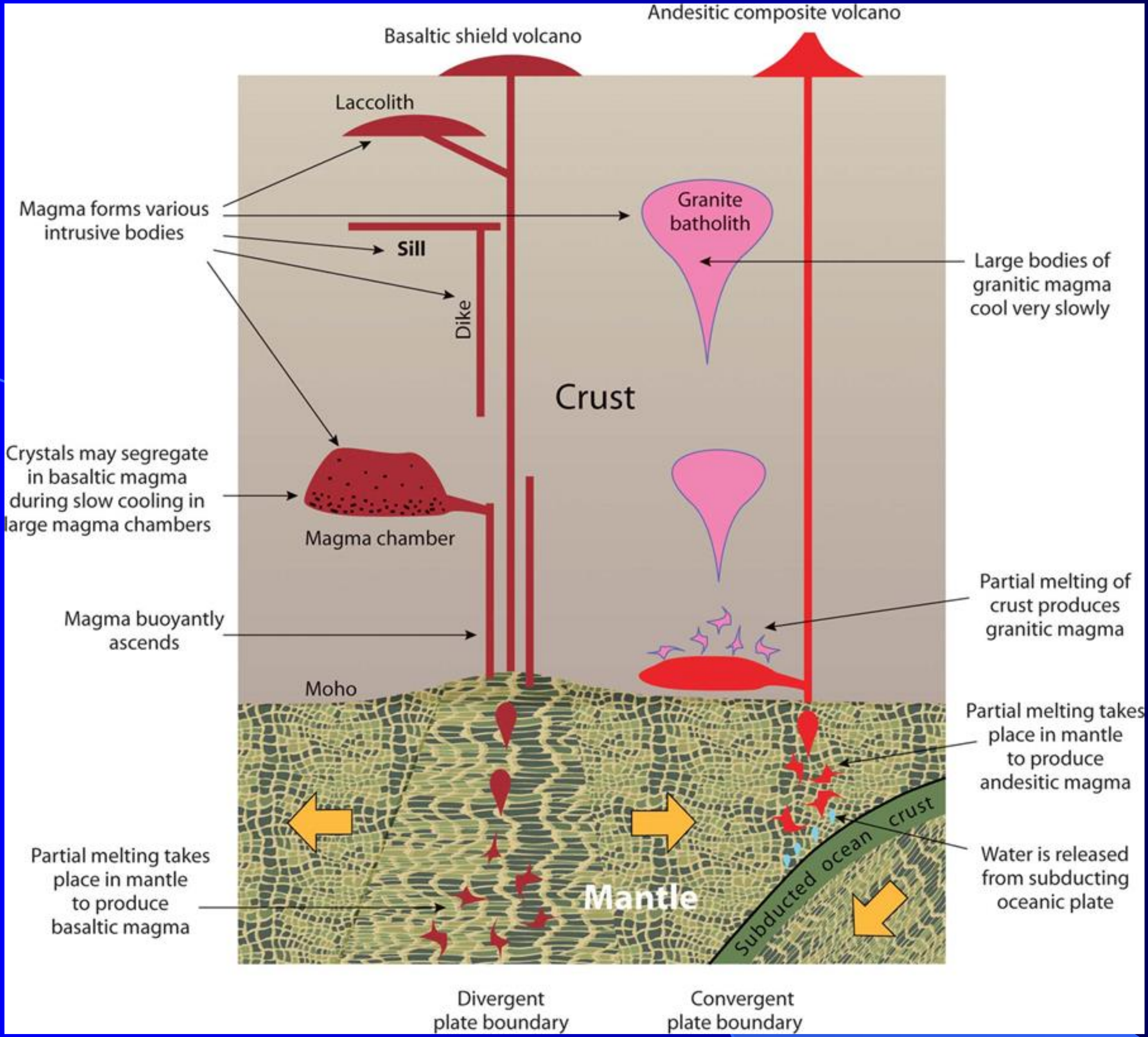
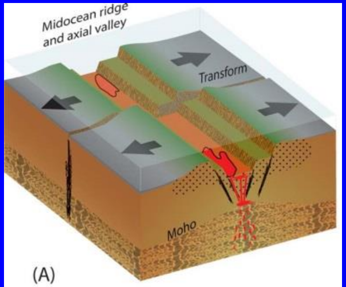
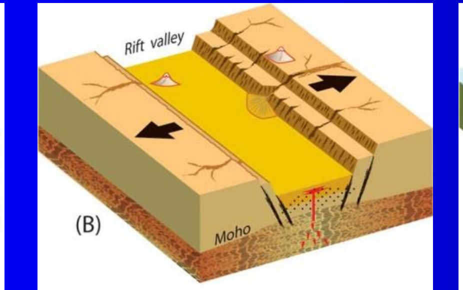
Formation of Igneous Rocks

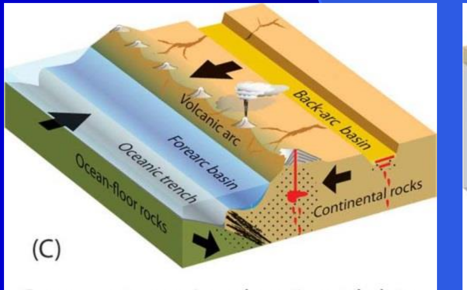




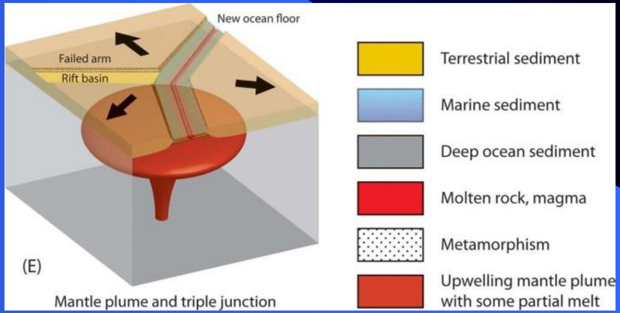
Divergent oceanic plates



Divergent continental plates



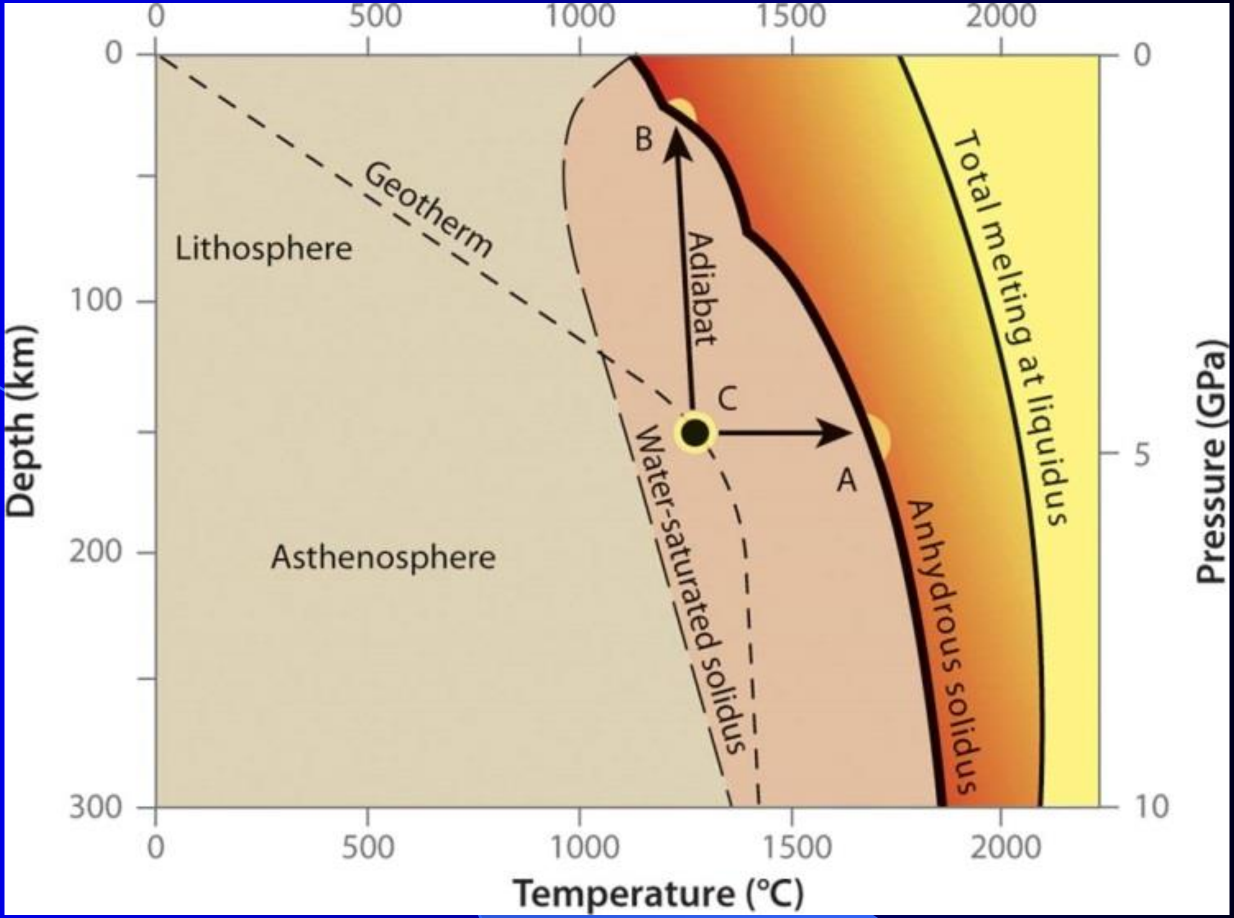
Convergent oceanic and continental plates



Mantle plume and triple junction

Why do rocks melt?

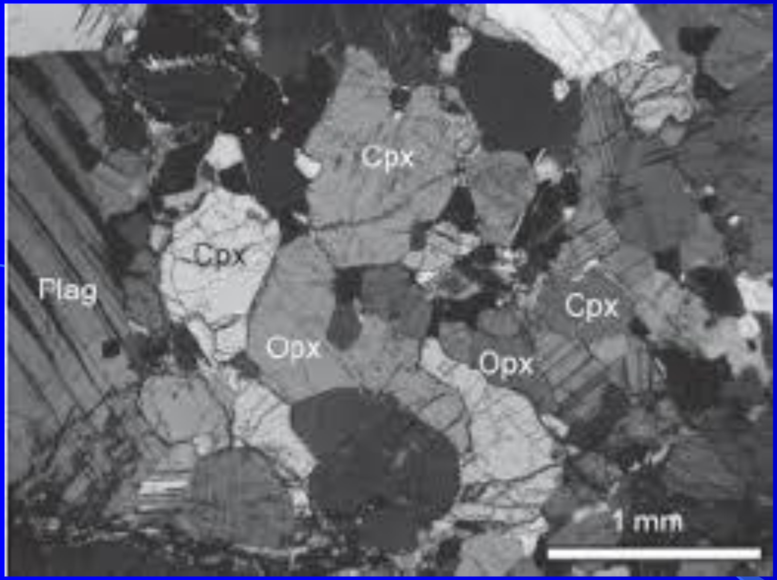
- Increasing temperature
- Decreasing pressure
- Adding water



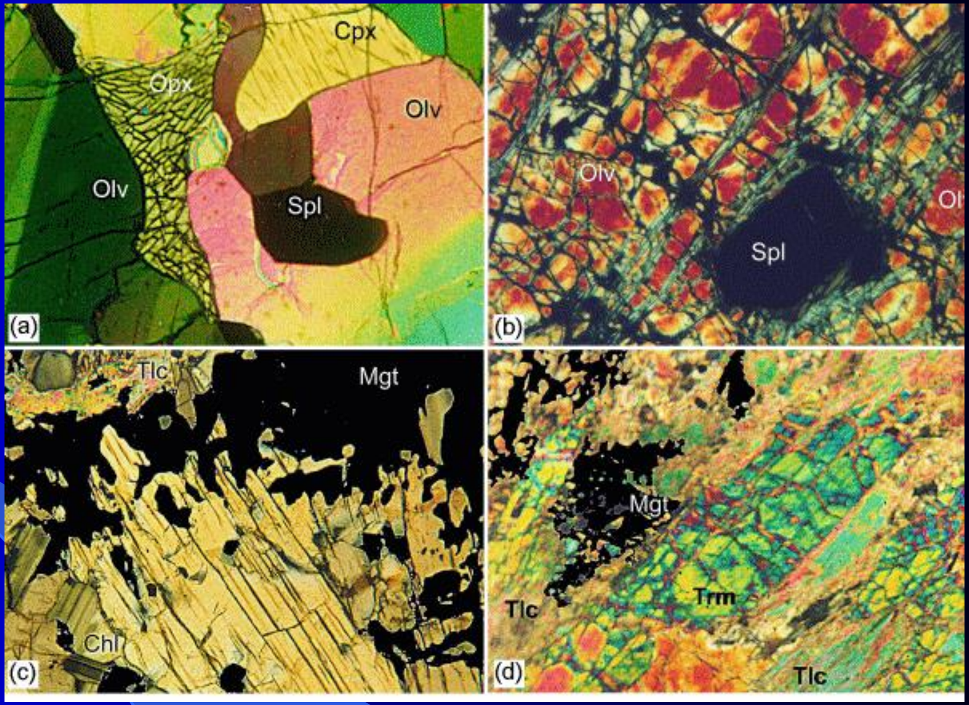
Types of Mantle rocks

- Plagioclase lherzolite
- Spinel lherzolite
- Garnet lherzolite

Lherzolite ⟶ olivine > orthopyroxene > Ca-pyroxene > aluminous phase



Plagioclase lherzolite



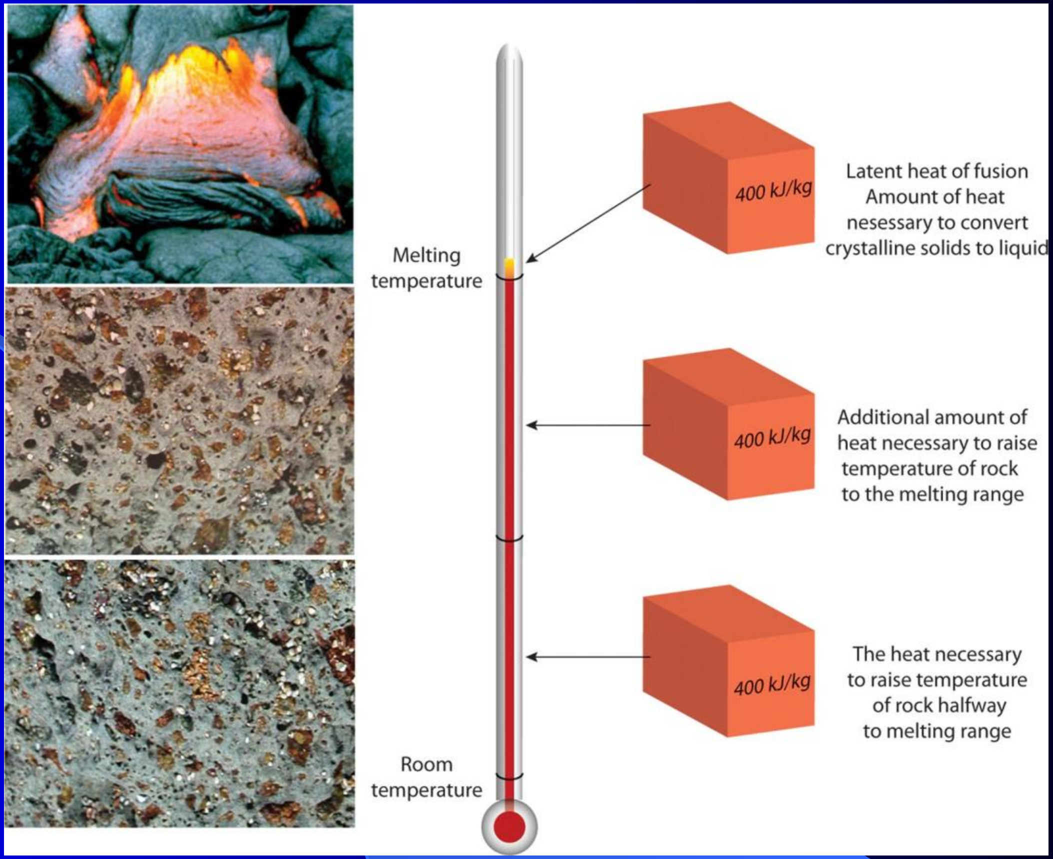
Spinel lherzolite

Garnet lherzolite

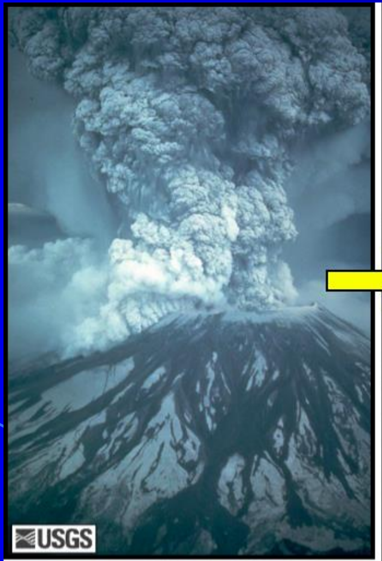
Heat required to melt a rock. Note the very high latent heat of fusion.

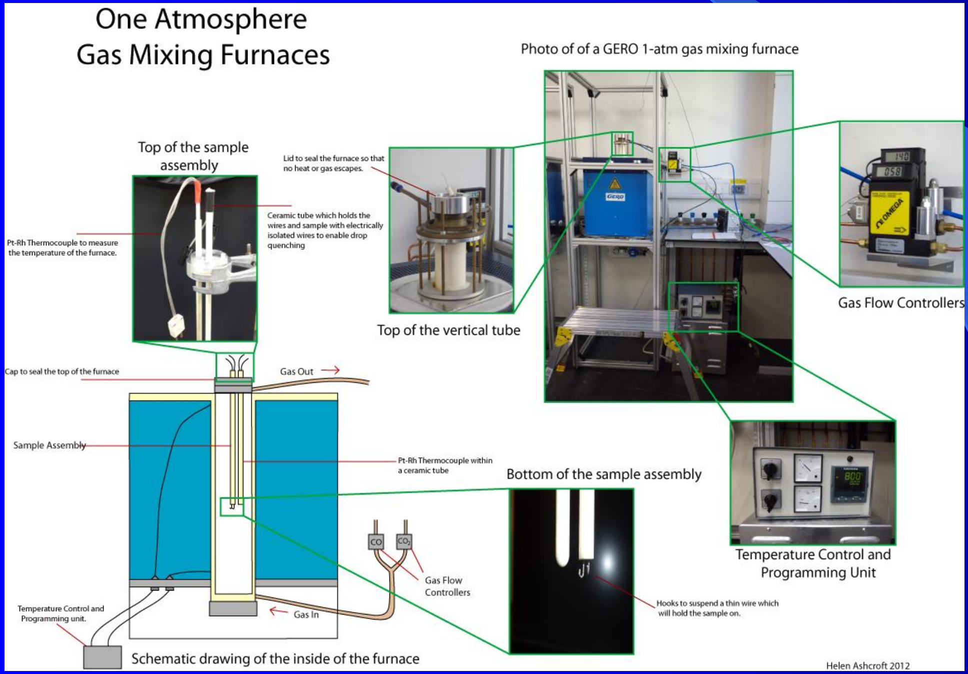
High latent heat of fusion leads to three outcomes

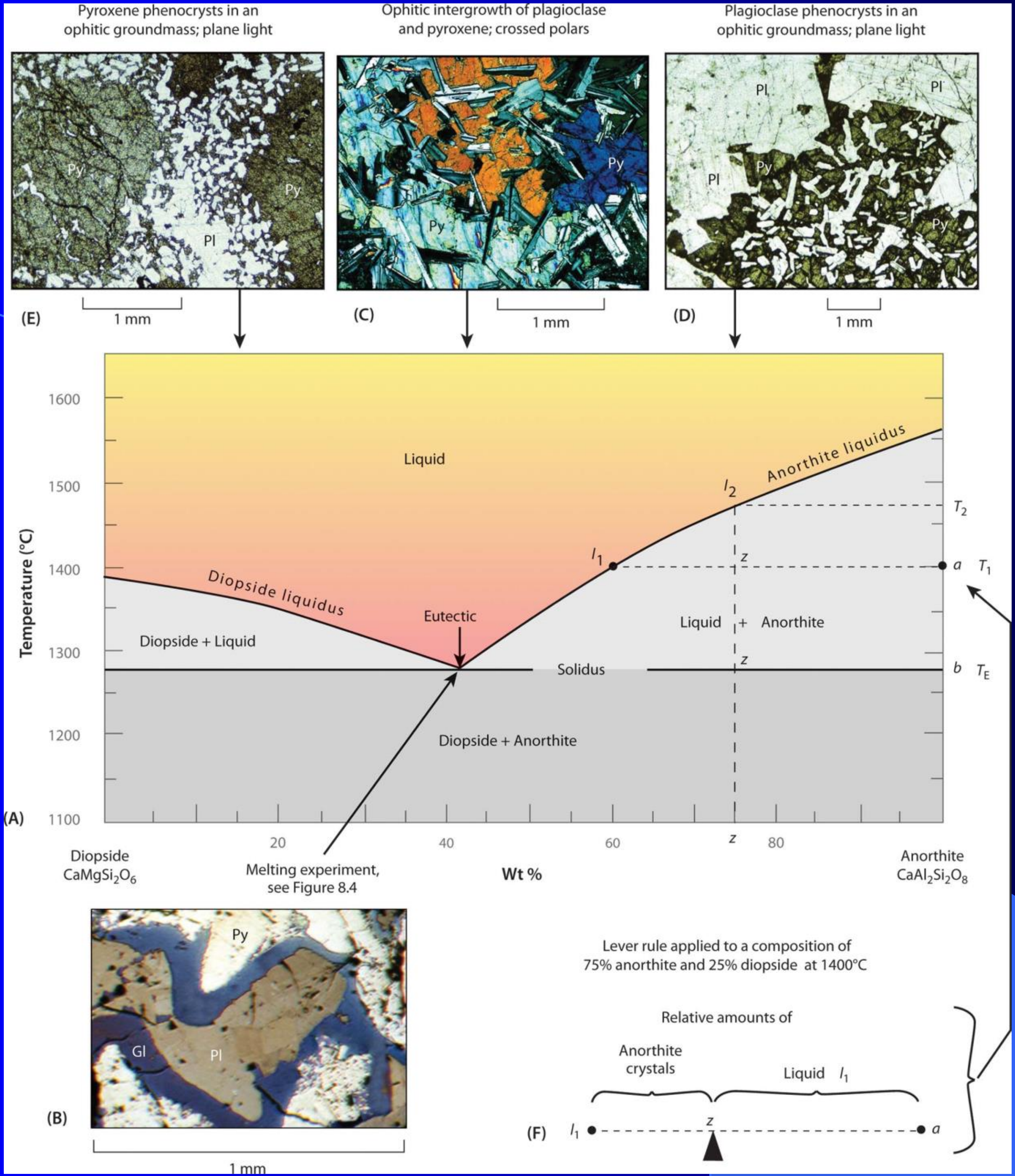
- Temperature of Earth does not rise far above the solidus
- Liquids that form are lowest possible melting fraction
- Earth's crust has formed from these low-melting fractions

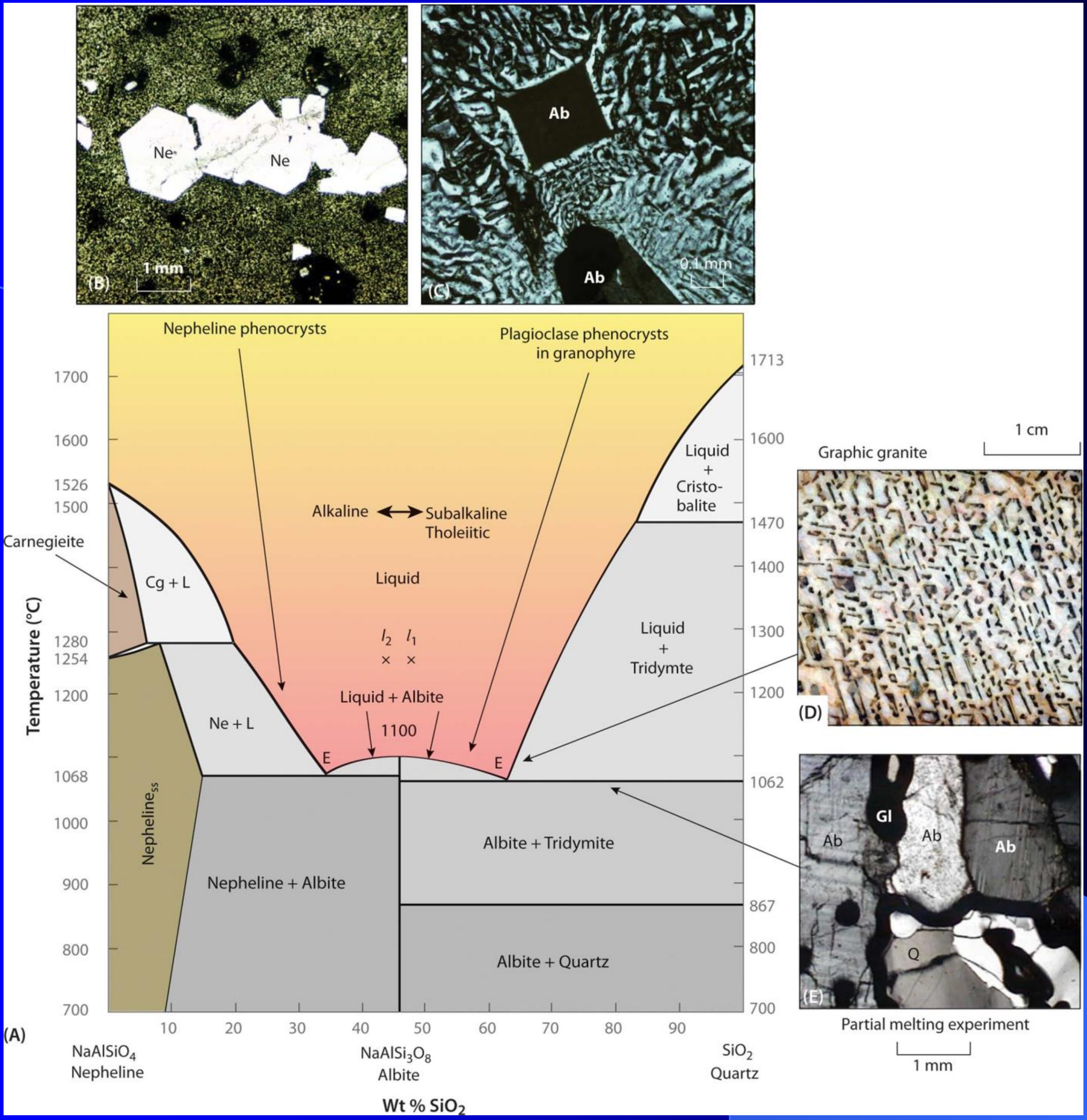


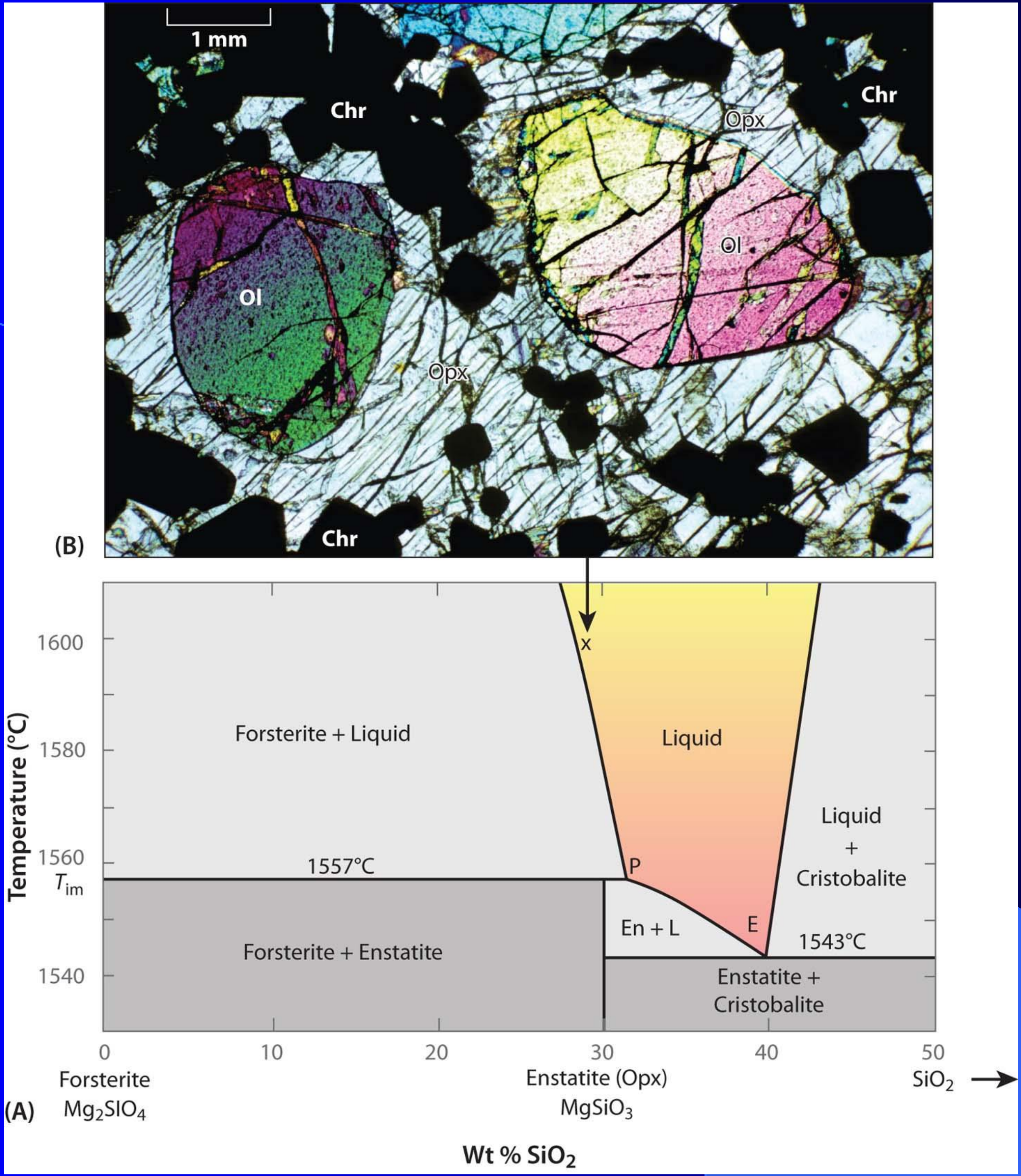
Experimental Petrology

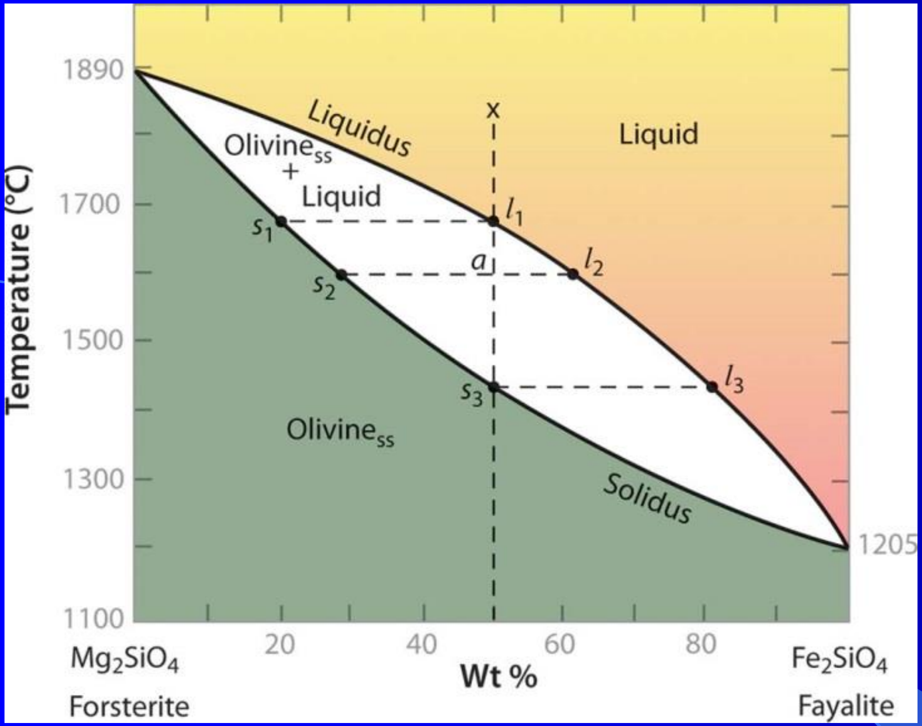


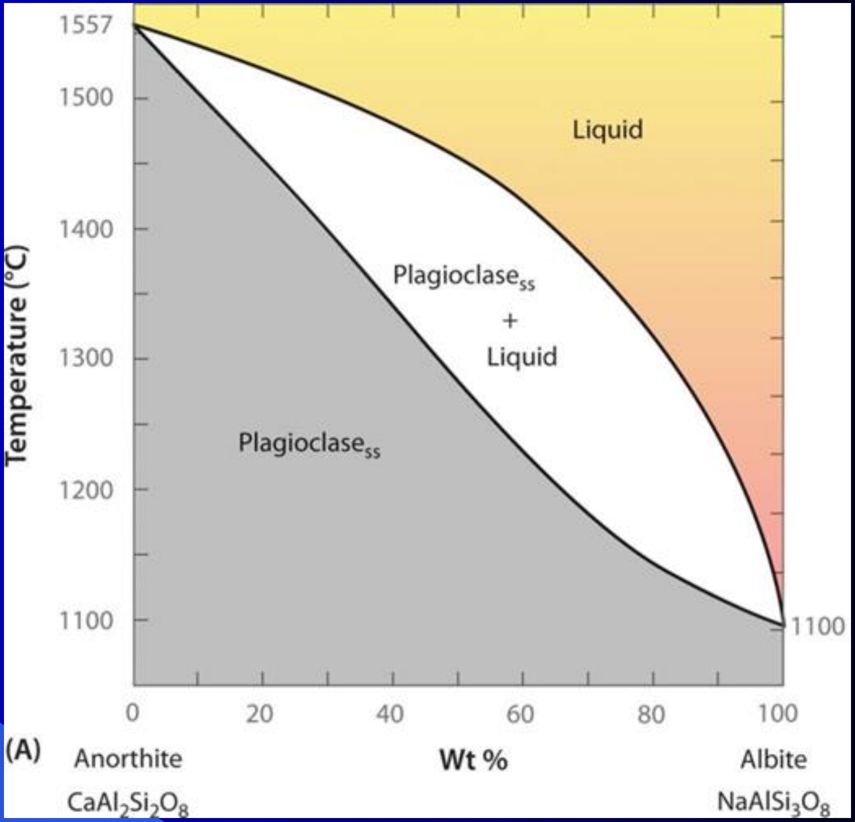


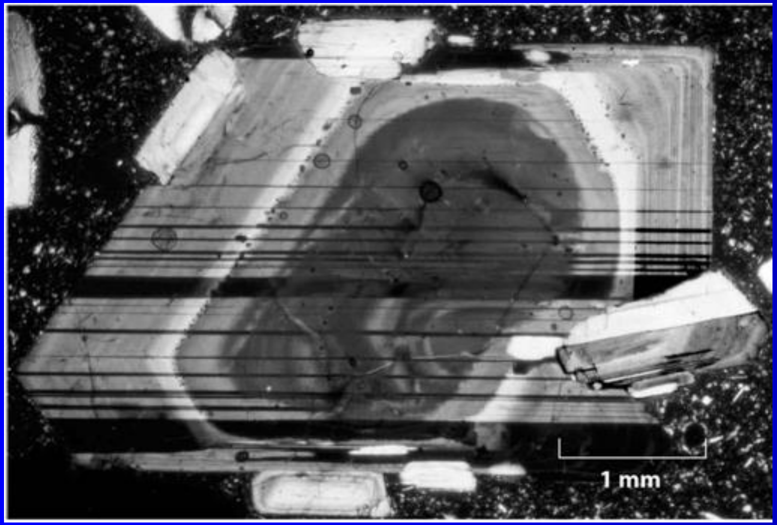

Pyroxene phenocrysts in an ophitic groundmass; plane light
Ophitic intergrowth of plagioclase and pyroxene; crossed polars
Plagioclase phenocrysts in an ophitic groundmass; plane light
Py
Py
Pl
Py
Py
Pl
Pl
Pl
Py
Py
(E)
1 mm
(C)
1 mm
(D)
1 mm
1600
1500
1400
1300
1200
1100
Temperature (°C)
Liquid
Anorthite liquidus
l_2
T_2
l_1
z
a
T_1
Diopside liquidus
Eutectic
Liquid + Anorthite
Diopside + Liquid
z
Solidus
b
T_E
Diopside + Anorthite
(A)
20
40
60
z
80
Diopside
$CaMgSi_2O_6$
Melting experiment, see Figure 8.4
Wt %
Anorthite
$CaAl_2Si_2O_8$
Py
Gl
Pl
(B)
1 mm
Lever rule applied to a composition of 75% anorthite and 25% diopside at 1400°C
Relative amounts of
Anorthite crystals
Liquid l_1
(F)
l_1
z
a


Ne
Ne
1 mm
(B)
Ab
Ab
0.1 mm
(C)
Nepheline phenocrysts
Plagioclase phenocrysts in granophyre
1713
1700
1600
1526
1500
1280
1254
1200
1068
1000
900
800
700
Temperature (°C)
Liquid + Cristo-balite
1600
1470
1400
1300
1200
1062
867
800
700
Alkaline ↔ Subalkaline Tholeiitic
Liquid
Carnegieite
Cg + L
l_2 l_1
× ×
Liquid + Albite
1100
Ne + L
E
E
Liquid + Tridymte
Nepheline$_{ss}$
Nepheline + Albite
Albite + Tridymite
Albite + Quartz
(A)
10
20
30
40
50
60
70
80
90
$NaAlSiO_4$ Nepheline
$NaAlSi_3O_8$ Albite
SiO_2 Quartz
Wt % SiO_2
Graphic granite
1 cm
(D)
Gl
Ab
Ab
Ab
Q
(E)
Partial melting experiment
1 mm

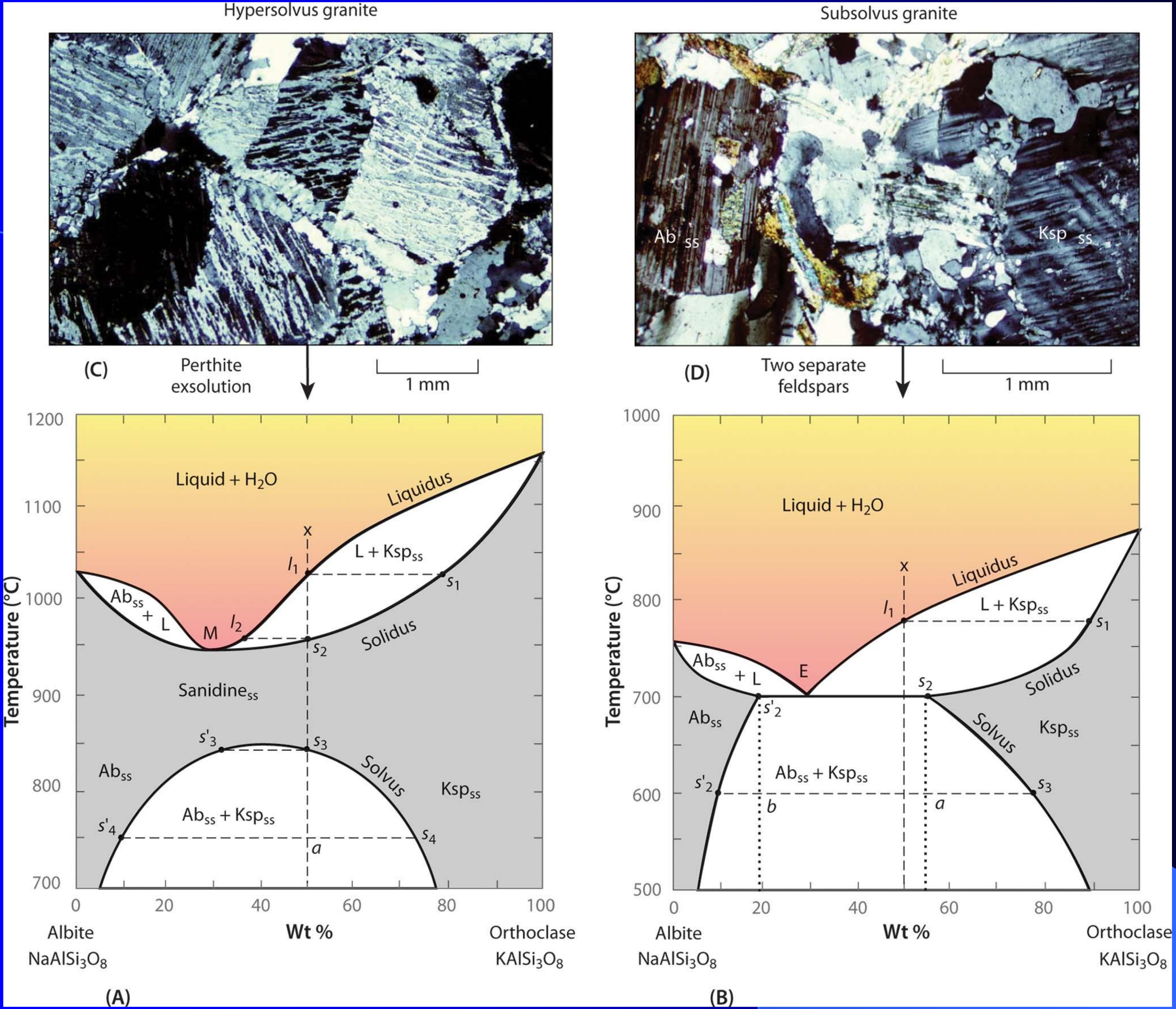

1 mm
Chr
Chr
Opx
Ol
Ol
Opx
Chr
(B)
x
1600
1580
1560
T_{im}
1540
Temperature (°C)
Forsterite + Liquid
Liquid
Liquid + Cristobalite
1557°C
P
E
En + L
1543°C
Forsterite + Enstatite
Enstatite + Cristobalite
0
10
20
30
40
50
Forsterite Mg_2SiO_4
Enstatite (Opx) $MgSiO_3$
SiO_2
(A)
Wt % SiO_2

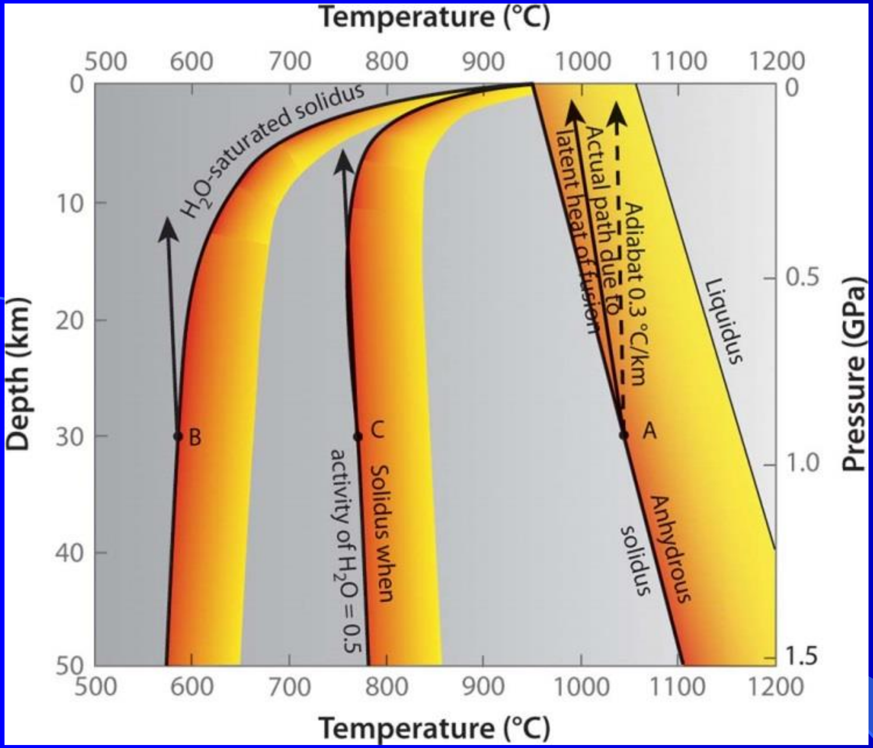




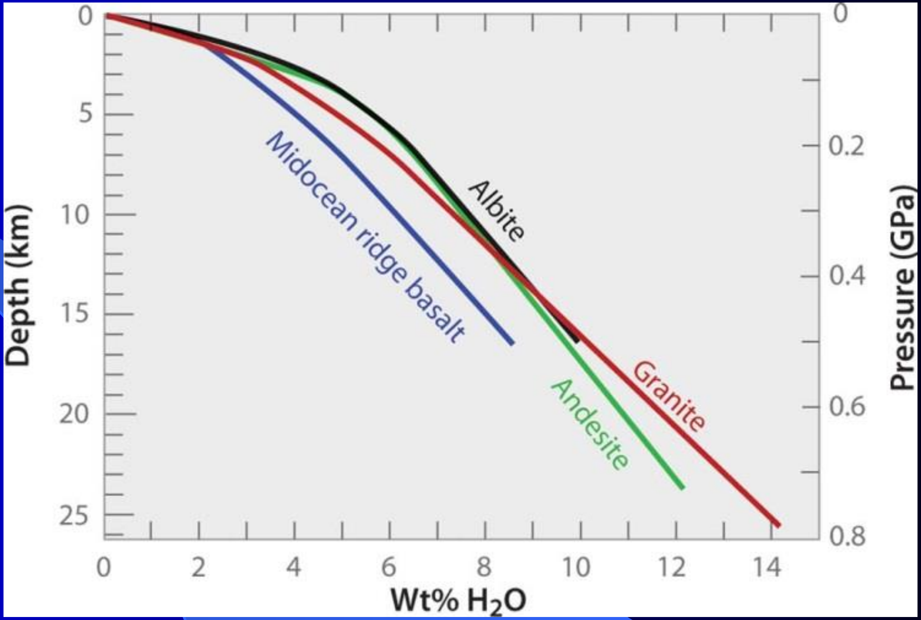


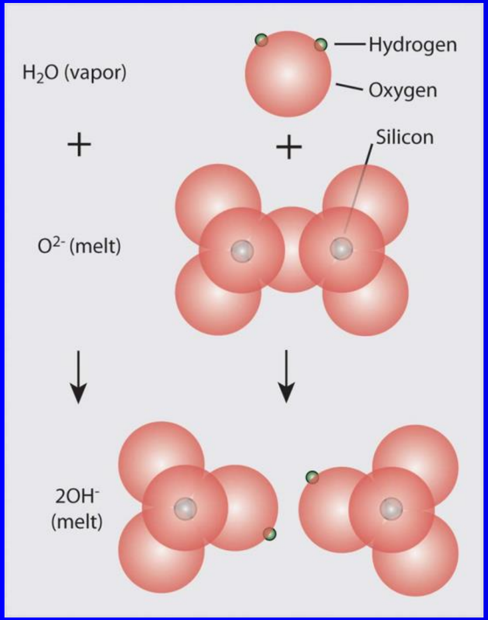
Zoning in plagioclase crystal


Hypersolvus granite
Subsolvus granite
Ab ss
Ksp ss
(C)
Perthite exsolution
1 mm
(D)
Two separate feldspars
1 mm
1200
1100
1000
900
800
700
Temperature (°C)
Liquid + H_2O
Liquidus
x
l_1
L + Ksp_{ss}
s_1
Ab_{ss} + L
M
l_2
s_2
Solidus
$Sanidine_{ss}$
s'_3
s_3
Solvus
Ab_{ss}
Ksp_{ss}
s'_4
s_4
Ab_{ss} + Ksp_{ss}
a
0
20
40
60
80
100
Albite
$NaAlSi_3O_8$
Wt %
Orthoclase
$KAlSi_3O_8$
(A)
1000
900
800
700
600
500
Temperature (°C)
Liquid + H_2O
x
Liquidus
l_1
L + Ksp_{ss}
s_1
Ab_{ss} + L
E
s_2
Solidus
s'_2
Ab_{ss}
Solvus
Ksp_{ss}
Ab_{ss} + Ksp_{ss}
s'_2
s_3
b
a
0
20
40
60
80
100
Albite
$NaAlSi_3O_8$
Wt %
Orthoclase
$KAlSi_3O_8$
(B)



- Hydrostatic and Lithostatic Equation
- Pressure and anhydrous melting
- Dissolution of water in melts – (OH) at low pressures, (H_20) at high pressures
- Water undersaturated and water saturated melting
- Other gases in magmas





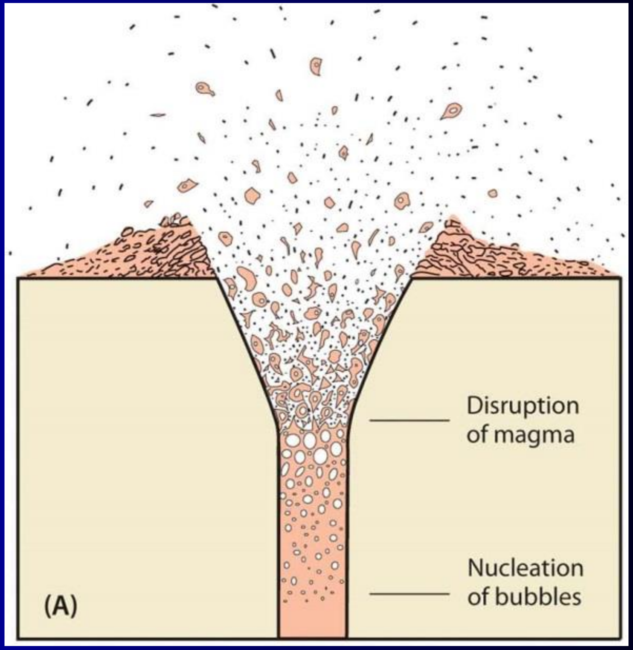
Hydrostatic equation:

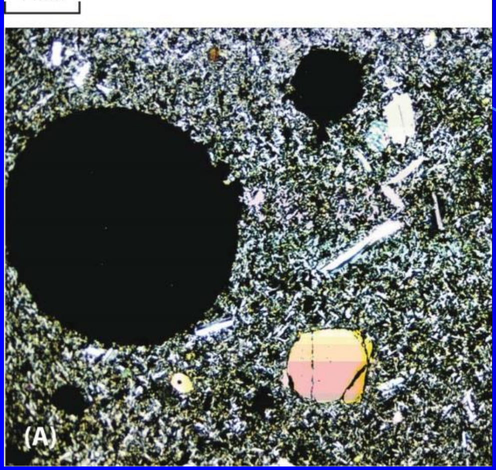
$$P = \rho g h$$

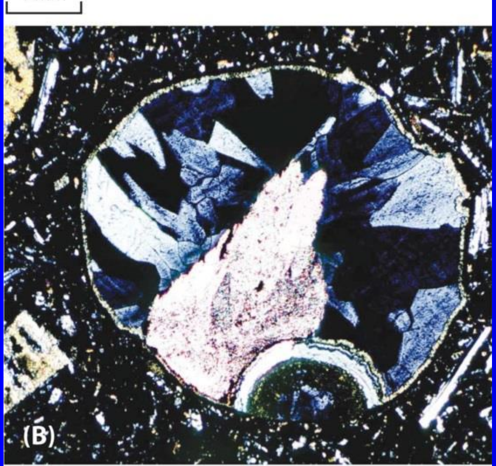
Stoke's Law:

$$V = \frac{2}{9}\frac{g(\rho_s - \rho_f)r^2}{\mu}$$

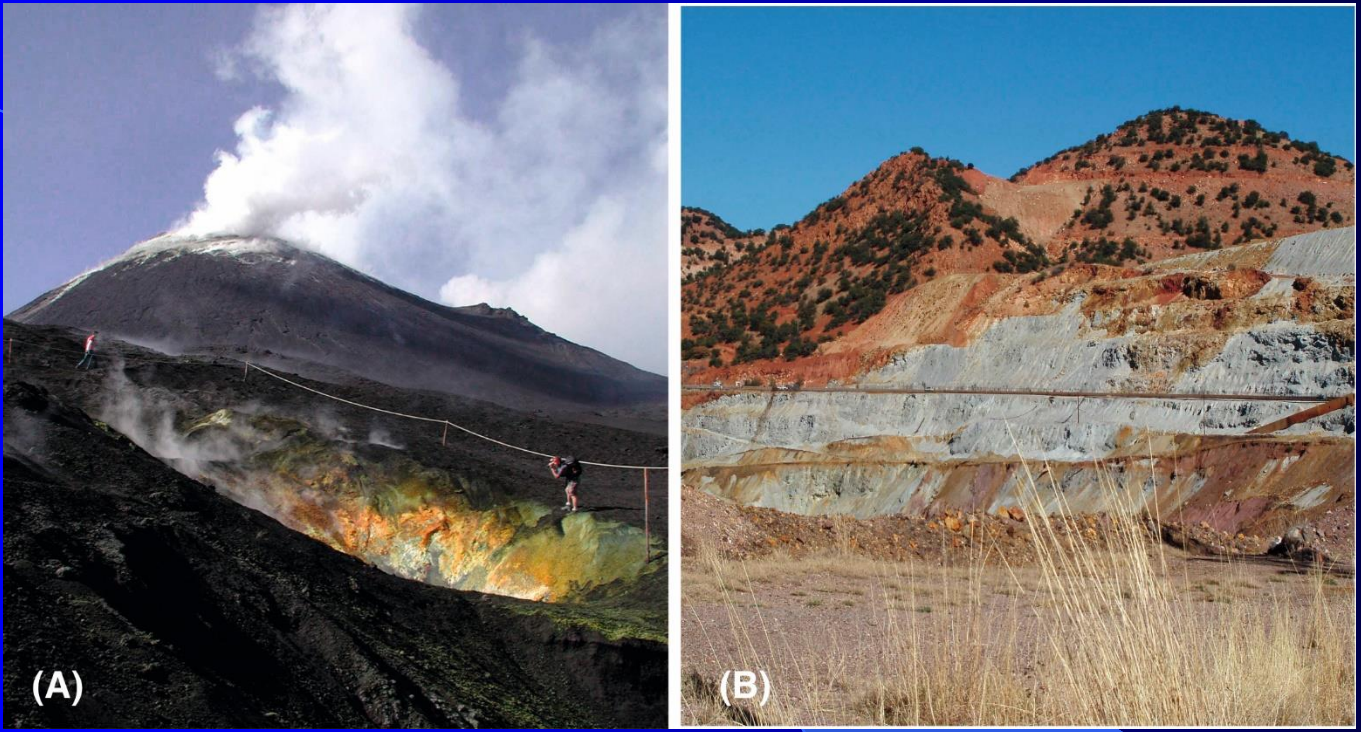
Exsolution of magmatic gases and explosive volcanism





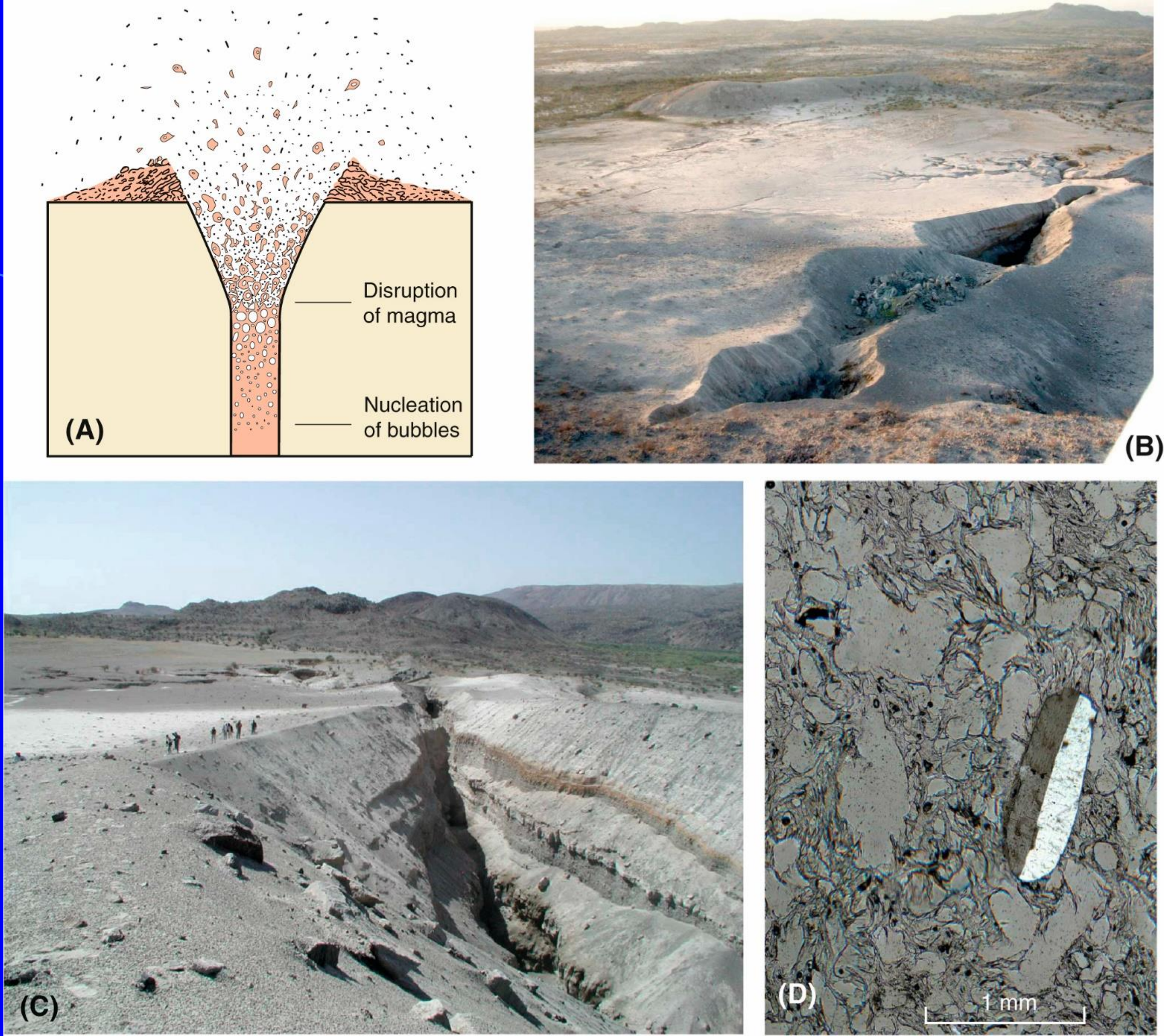


Affect of hot gases

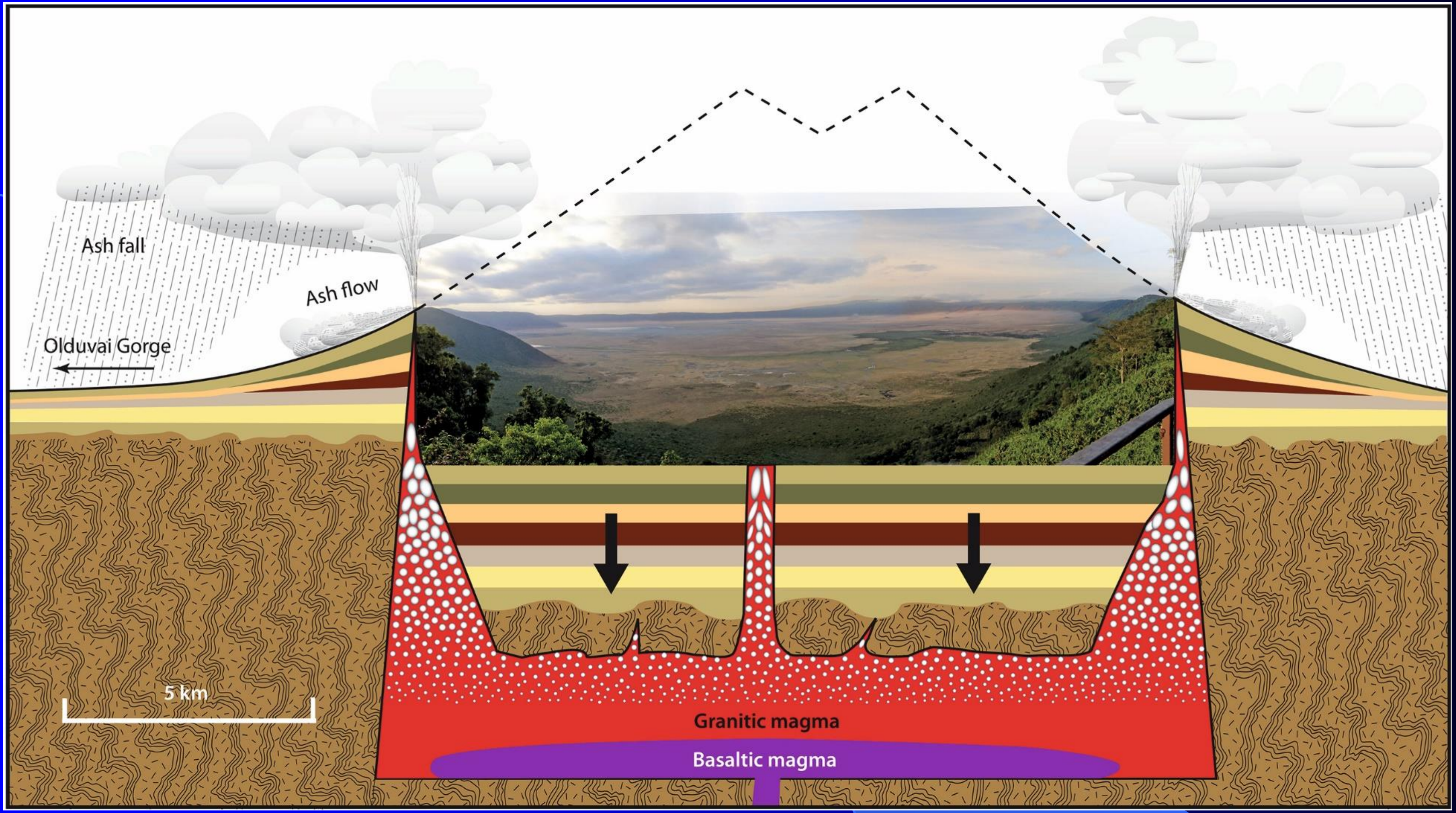


Etna

Bisbee



Rhyolitic eruption Afar



Ngorongoro crater - volcanic eruption and caldera collapse




Magma Density and Viscosity

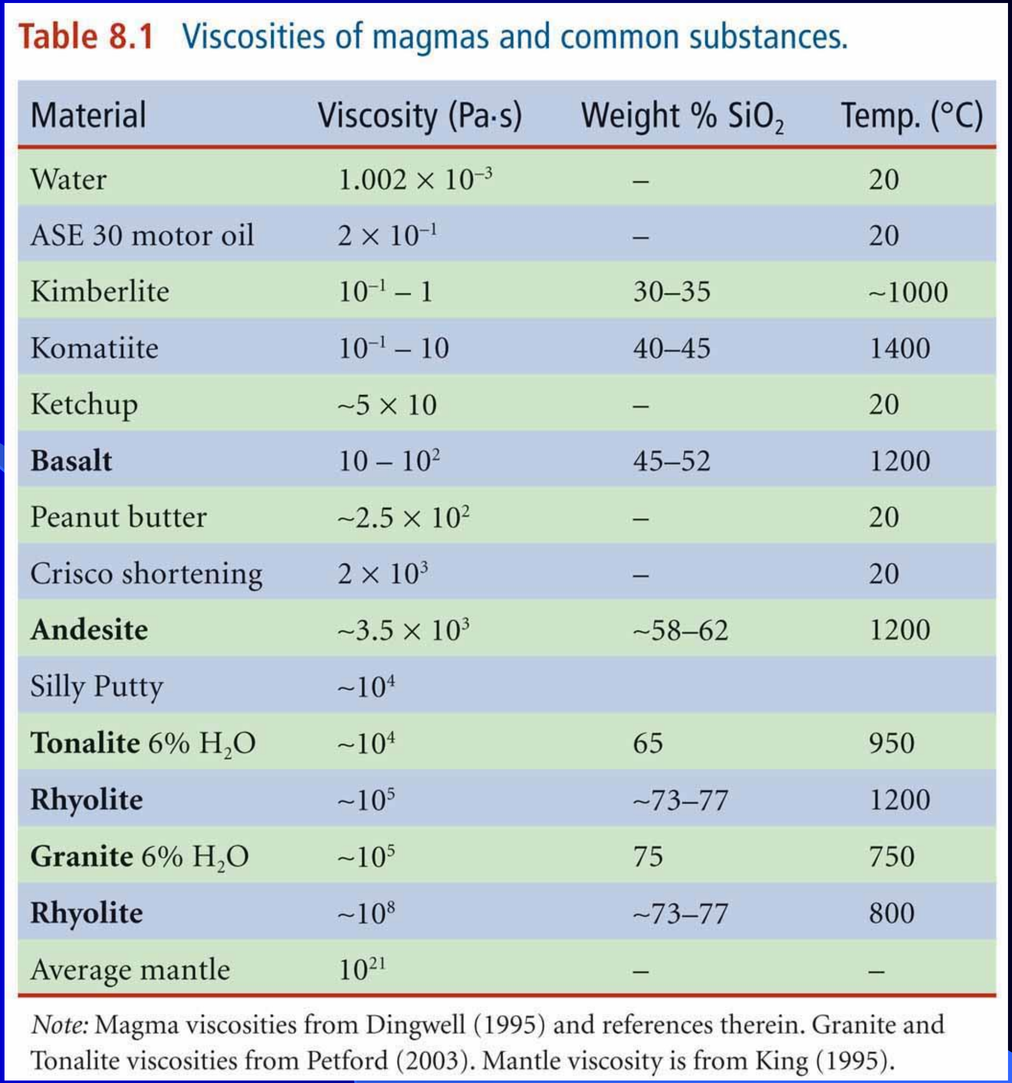


Table 8.1 Viscosities of magmas and common substances.

Material	Viscosity (Pa·s)	Weight % SiO_2	Temp. (°C)
Water	1.002×10^{-3}	–	20
ASE 30 motor oil	2×10^{-1}	–	20
Kimberlite	$10^{-1} – 1$	30–35	~1000
Komatiite	$10^{-1} – 10$	40–45	1400
Ketchup	~5 × 10	–	20
Basalt	$10 – 10^{2}$	45–52	1200
Peanut butter	$\sim 2.5 \times 10^{2}$	–	20
Crisco shortening	2×10^{3}	–	20
Andesite	$\sim 3.5 \times 10^{3}$	~58–62	1200
Silly Putty	$\sim 10^{4}$		
Tonalite 6% H_2O	$\sim 10^{4}$	65	950
Rhyolite	$\sim 10^{5}$	~73–77	1200
Granite 6% H_2O	$\sim 10^{5}$	75	750
Rhyolite	$\sim 10^{8}$	~73–77	800
Average mantle	10^{21}	–	–

Note: Magma viscosities from Dingwell (1995) and references therein. Granite and Tonalite viscosities from Petford (2003). Mantle viscosity is from King (1995).

Pahoehoe flow on side of large blister

Pahoehoe flow on top of aa flow

Large blocks of obsidian on rhyolitic lava flows.

Diffusion in magma – crystal growth and grain size

Average Magma Compositions

	Lunar Basalt	**Basalt**	**Andesite**	**Rhyolite**	**Phonolite**
SiO_2	43.56	49.2	57.94	72.82	56.19
TiO_2	2.60	1.84	0.87	0.28	0.62
Al_2O_3	7.87	15.74	17.02	13.27	14.04
Fe_2O_3		3.79	3.27	1.48	2.79
FeO	21.66	7.13	4.04	1.11	2.03
MnO	0.28	0.20	0.14	0.06	0.17
MgO	14.88	6.73	3.33	0.39	1.07
CaO	8.26	9.47	6.79	1.14	2.72
Na_2O	0.23	2.91	3.48	3.55	7.79
K_2O	0.05	1.10	1.62	4.30	5.24
P_2O_5	0.11	0.67	0.39	0.08	0.05
H_2O		0.95	0.83	1.10	1.57

Magma density is a function of

- Composition of the magma → higher atomic mass elements result in higher density
- Temperature – higher temperatures → lower density
- A rough rule of thumb is that a magma density is about 0.9 of its equivalent rock density

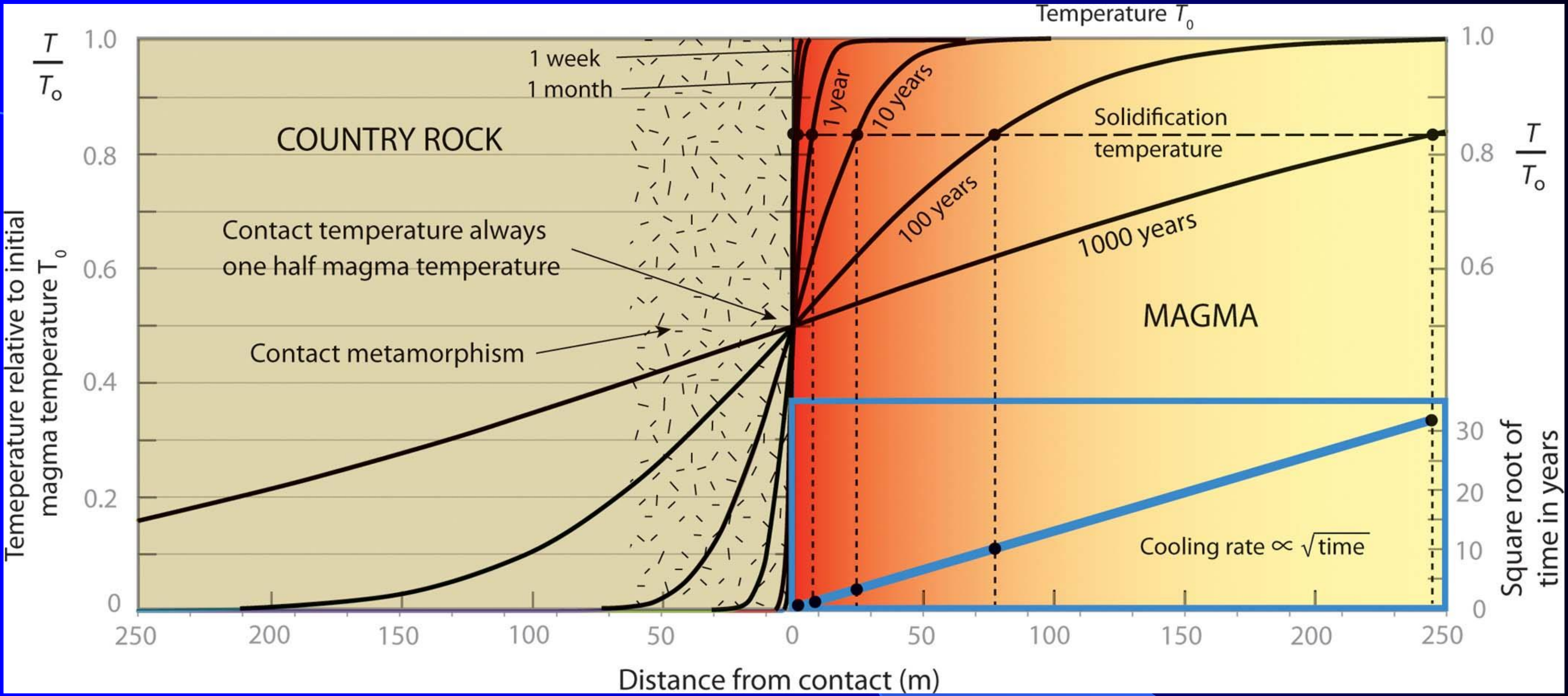
Example – density of basalt = 3000 kg/m^3. If you melt basalt the resulting magma will have a density of 2700 kg/m^3. A more precise value can be obtained by calculation.

Ascent of magmas

- By buoyancy when the magma has a lower density than the surrounding rock. When the density of the surrounding rock = that of the magma the magma will stop rising. For example, the density of a lower granitic crust is 2650 kg/m^3. Magma will stop rising.
- Differential pressure – magmastatic pressure less than lithostatic pressure

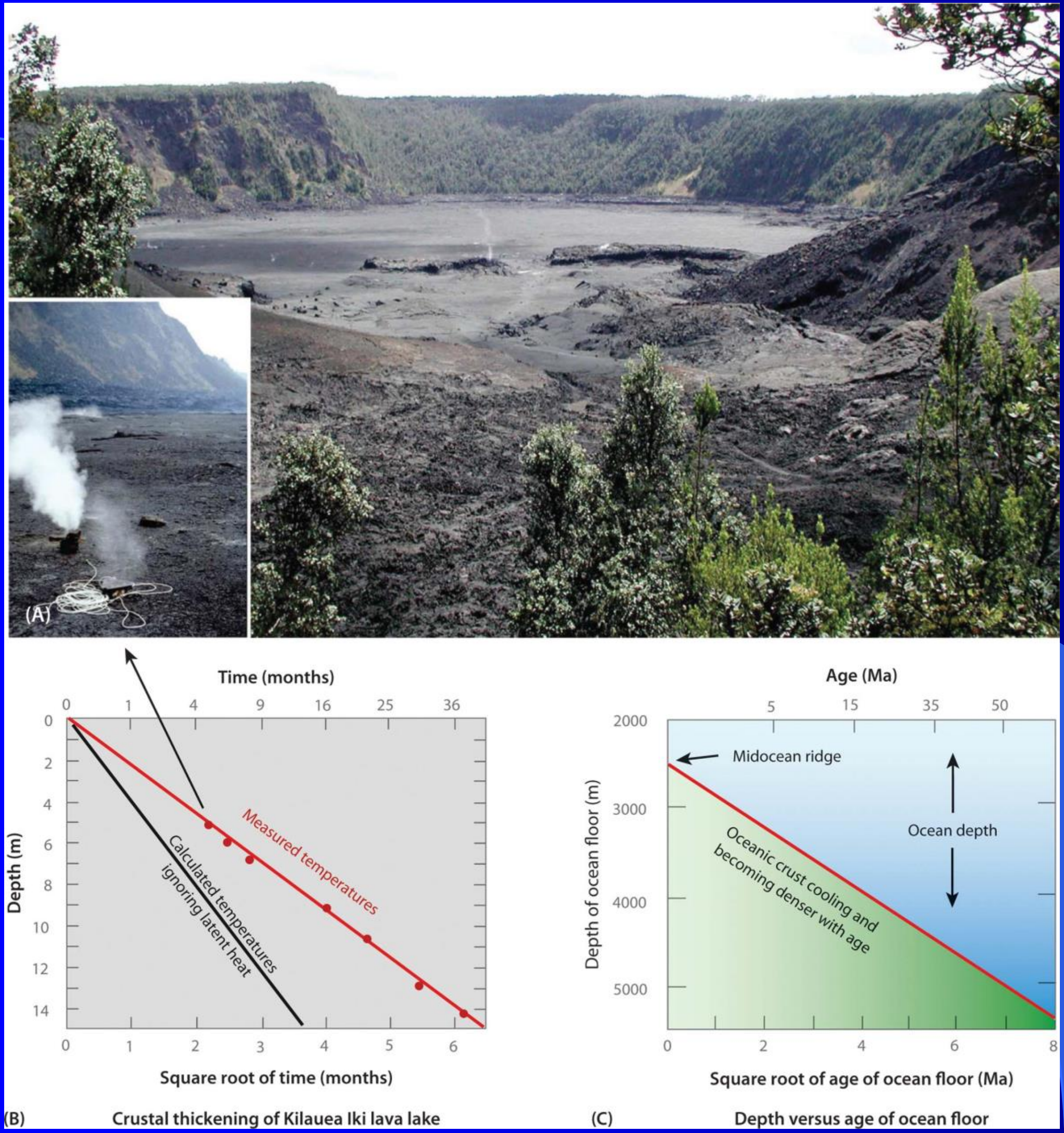
  Pressure = density x acceleration due to gravity x thickness

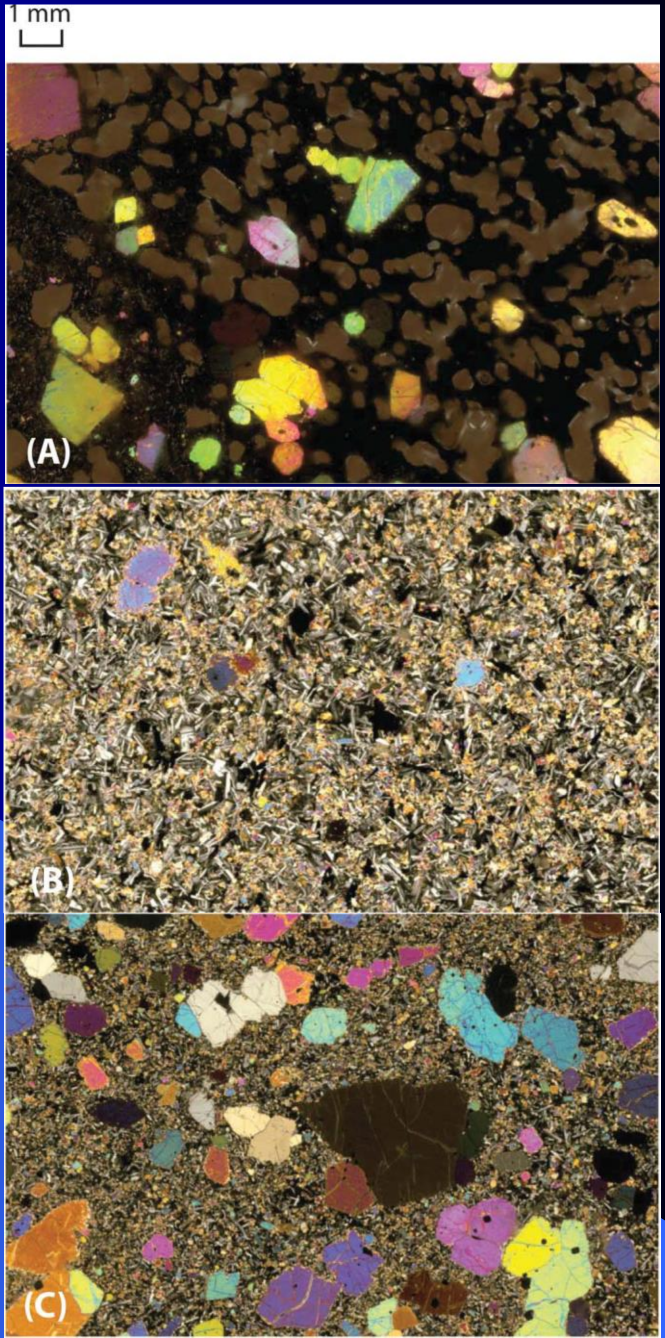
Cooling of magma bodies by conduction and convection

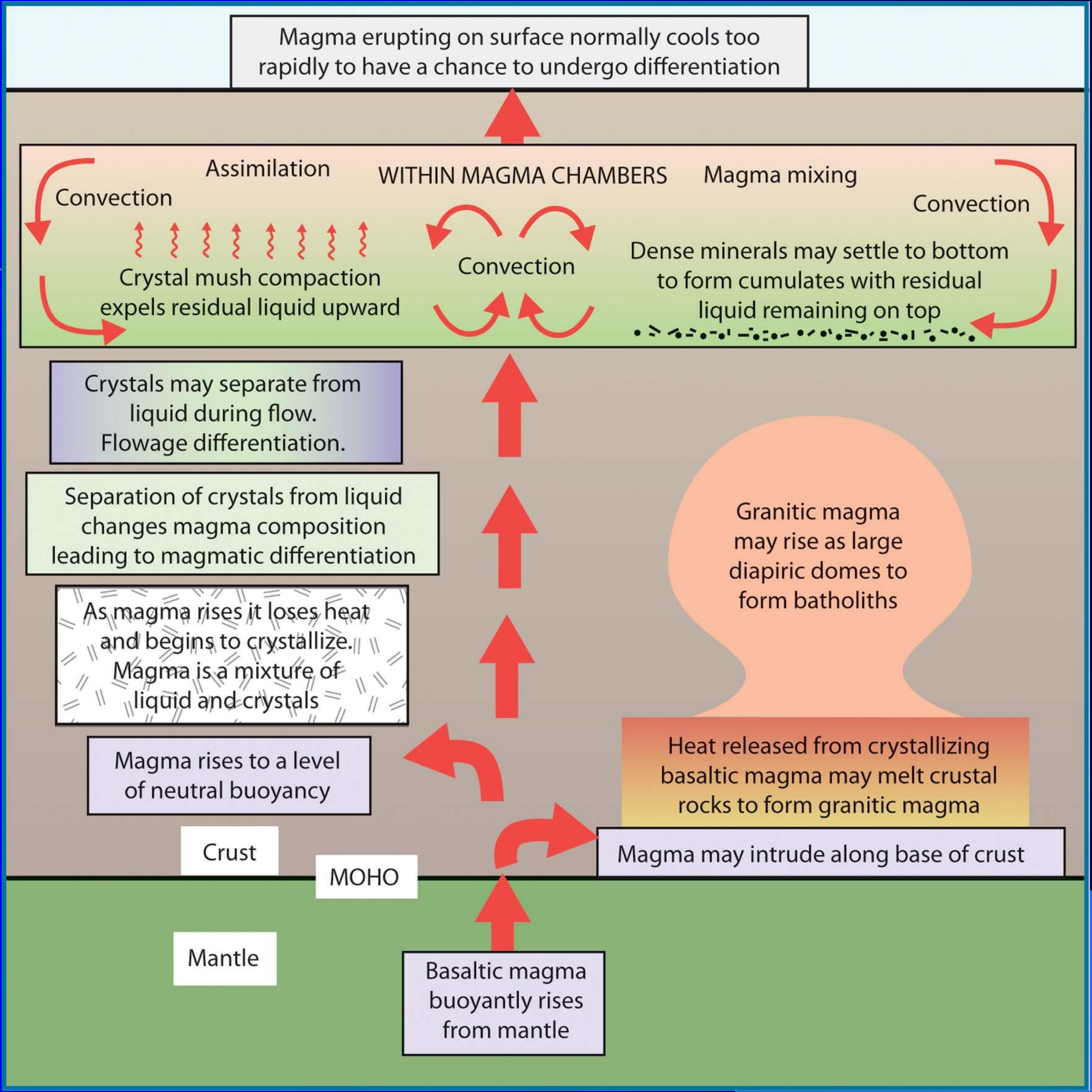


Cooling across an igneous contact.

Release of latent heat increases cooling time



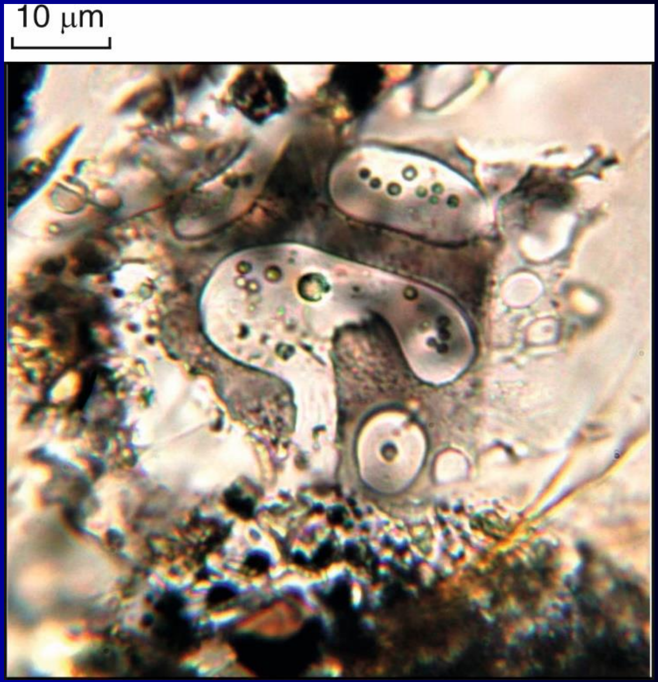


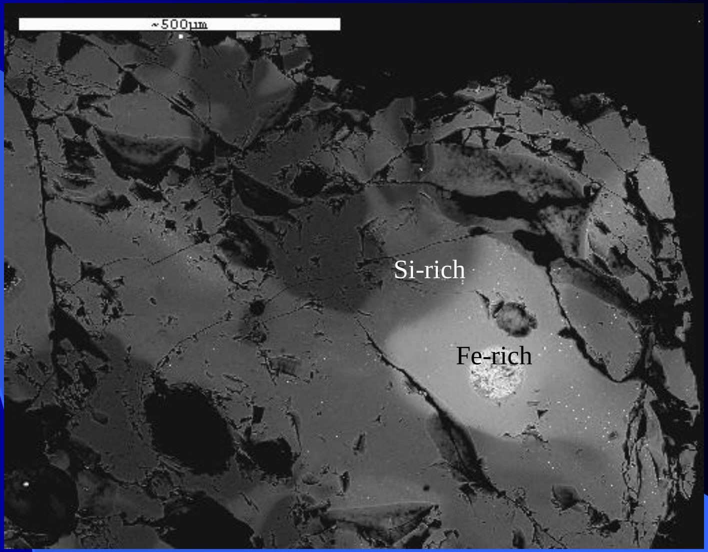

Magma erupting on surface normally cools too rapidly to have a chance to undergo differentiation
Assimilation
WITHIN MAGMA CHAMBERS
Magma mixing
Convection
Convection
Crystal mush compaction expels residual liquid upward
Convection
Dense minerals may settle to bottom to form cumulates with residual liquid remaining on top
Crystals may separate from liquid during flow. Flowage differentiation.
Separation of crystals from liquid changes magma composition leading to magmatic differentiation
As magma rises it loses heat and begins to crystallize. Magma is a mixture of liquid and crystals
Granitic magma may rise as large diapiric domes to form batholiths
Magma rises to a level of neutral buoyancy
Heat released from crystallizing basaltic magma may melt crustal rocks to form granitic magma
Crust
MOHO
Magma may intrude along base of crust
Mantle
Basaltic magma buoyantly rises from mantle

Magmatic Differentiation

- Crystal settling
- Crystal mush compaction
- Assimilation and fractional crystallization
- Liquid immiscibility

Assimilation





Liquid immiscibility

Stoke's Law

$$V = \frac{2gr^2(\rho_s - \rho_l)}{9\eta}$$

V = the settling velocity (m/sec)

g = the acceleration due to gravity (9.8 m/sec^2)

r = the *radius* of a spherical particle (m)

ρ_s = the density of the solid spherical particle (kg/m^3)

ρ_l = the density of the liquid (kg/m^3)

η = the viscosity of the liquid ($kg \cdot m^{-1} \cdot s^{-1} = 1\ Pa \cdot s$)

Olivine in basalt magma

Olivine (ρ_s = 3300 kg/m^3, r = 0.005 m)

Basaltic liquid (ρ_l = 2650 kg/m^3, η = 100 Pa·s)

$V = 2 \cdot 9.8 \cdot 0.005^2 (3300-2650)/9 \cdot 100 = 3.5 \times 10^{-4}$ m/sec

Rhyolitic magma

$\eta = 10^5$ Pa·s and ρ_l = 2300 kg/m^3

hornblende crystal (ρ_s = 3200 kg/m^3, r = 0.001 m)

$V = 2 \times 10^{-8}$ m/sec, or 0.6 m/year

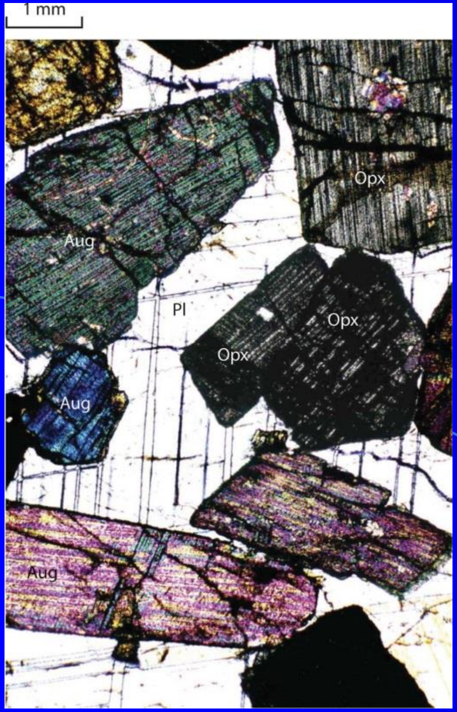
feldspar crystal (ρ_l = 2700 kg/m^3)

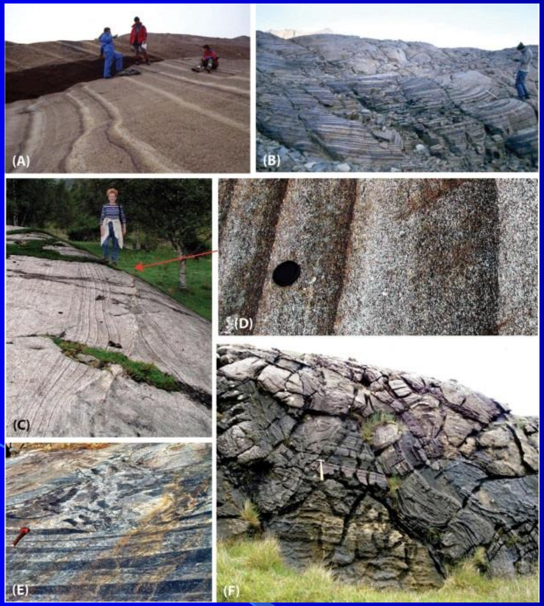
V = 0.27 m/year

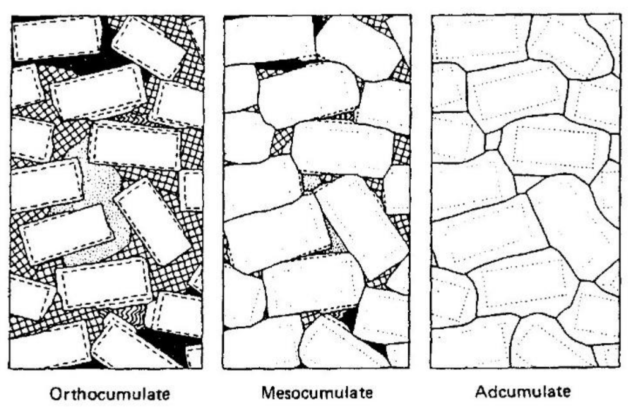
= 2747 m in the 10^4 years that a stock might cool

If 0.005 m in radius (0.01 m diameter) settles at 0.65 meters/year, or 6.5 km in 10^4 year cooling of stock

Cumulus textures and cumulate rocks







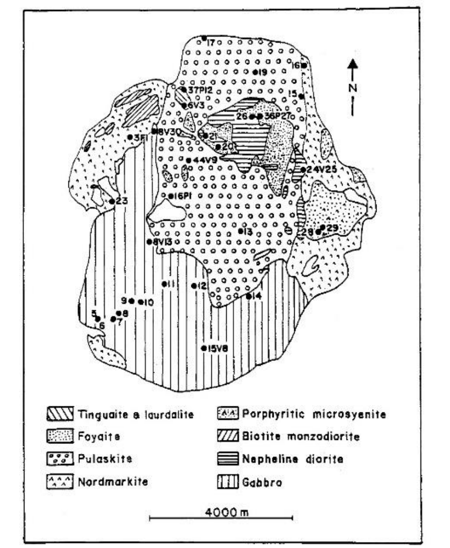
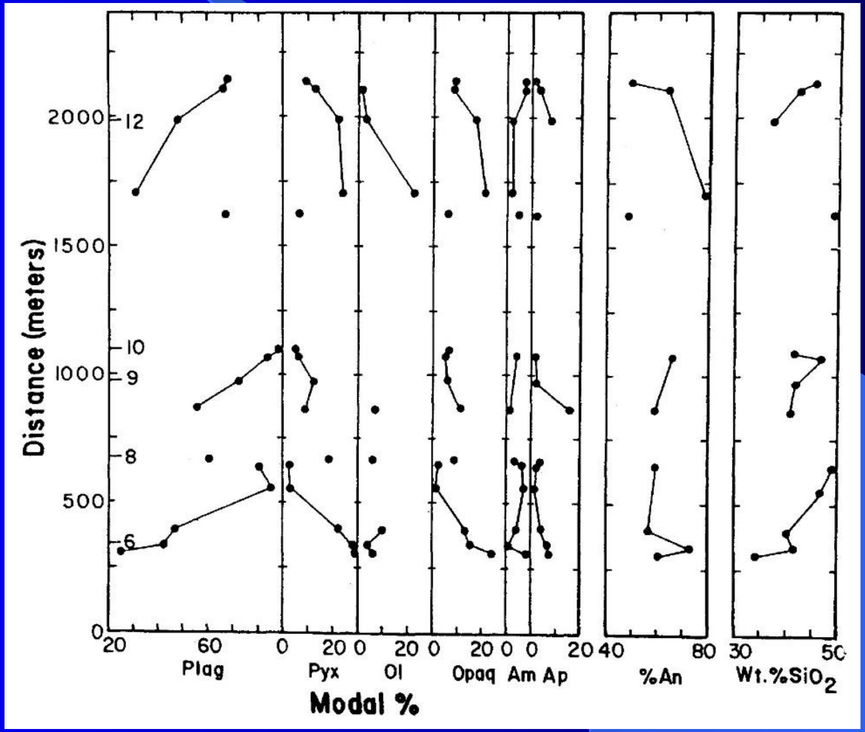


FIG. 2. Geologic map of Mt. Brome showing sample locations. From Valiquette & Pouliot (1977).



Evolution of the Isotopic Reservoirs in the Earth's Mantle