The three primary groups of rocks

- Igneous

- Intrusive (plutonic)
- Extrusive (volcanic)

- Ultramafic
- Mafic
- Intermediate
- Felsic

peridotite ,gabbro, basalt, diabase, diorite, andesite, granodiorite, granite, rhyolite, tuff, pumice, glass, lahar, breccia

- Sedimentary

- Detrital
- Chemical

- Conglomerate
- Breccia
- Sandstone
- Siltstone
- Mudstone
- Limestone
- Dolomite

gravel, sand, silt, clay, till, diamictite, banded iron stone, chert, evaporite, gypsum, rock salt, coal, lignite, peat, shale, stalagmites, stalactites, sinter, travertine,

- Metamorphic

- Granulite
- Gneiss
- Schist
- Marble
- Greenstone

- Slate
- Phyllite
- Amphibolite
- Migmatitie

- Quartzite
- Hornfels
- Anthracite

GC Herman 2013

Igneous and Volcanic Rocks and processes

Magma and Lava
Igneous Rocks
Plutons
Volcanism and Volcanoes
Plate Tectonics, Volcanoes, and Plutons

Part 1. Igneous Rocks

An example of topographic inversion near Orland, California,
The basalt now capping a ridge once flowed into a valley

www.crack.seismo.unr.edu/ftp/pub/louie/class/plate/deformation.htmlwww.elements.geoscienceworld
geology.campus.ad.csulb.edu/people/bperry/IgneousRocksTour/VolcanoesAndLavaFlows.html
Lei, J. and Zhao, D., 2006, Physics of the Earth and Planetary Interiors, vol. 154, no. 1, p. 44–69
www.nature.com/nature/journal/v416/n6878/fig_tab/416310a_F1.html
ars.els-cdn.com/content/image/1-s2.0-S0031920105001780-gr24.jpg
www.2ndsemesterr.wikispaces.com/Plate+Tectonics+Vocabulary
www.aseptec-sg.com/images/sonocrystallisation.jpg
www.library.gl.ciw.edu/GLHistory/pg**bowen**.html
.org/content/8/4/257/F2/graphic-2.large.jpg

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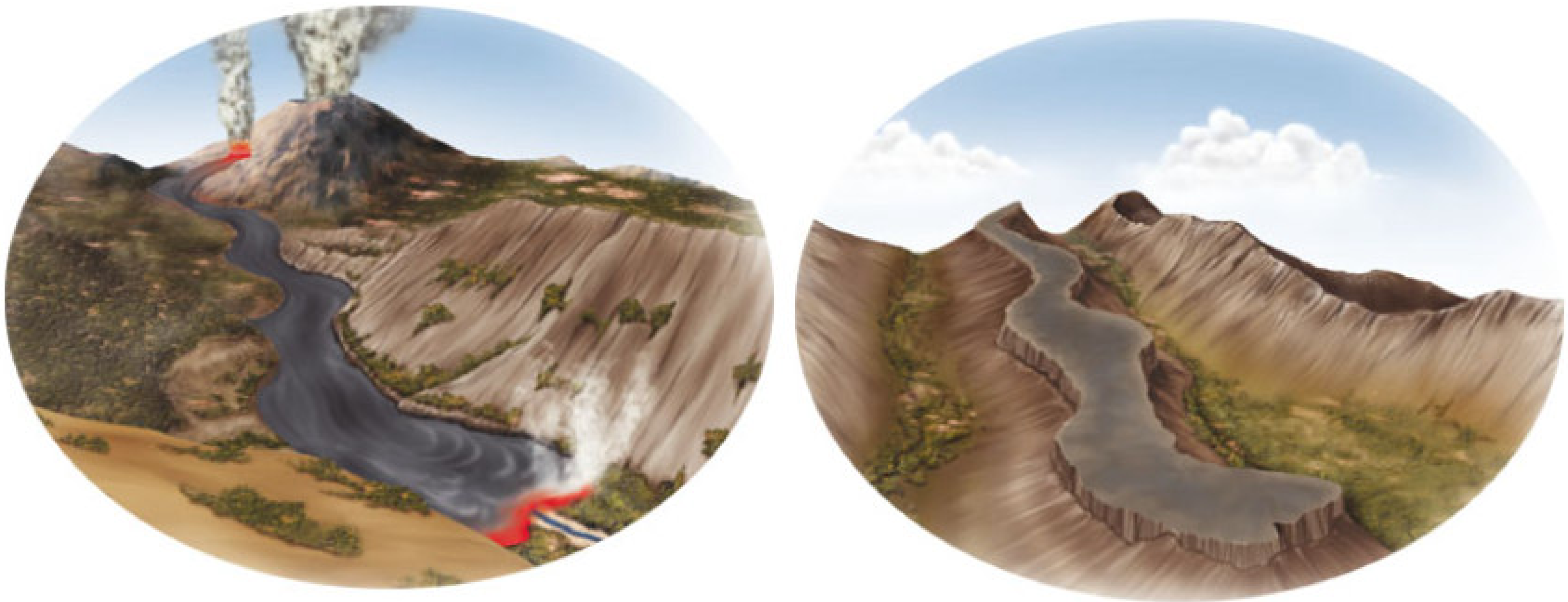
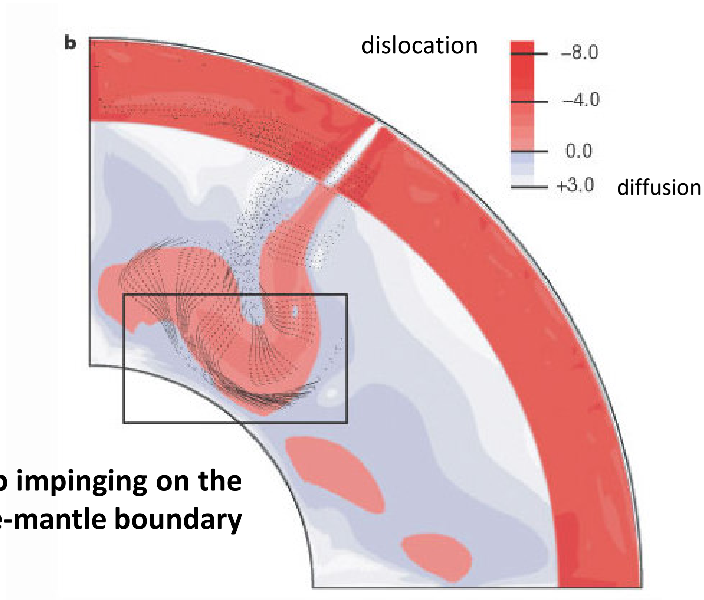
Igneous Rocks – Topographic Inversion



Igneous Rocks

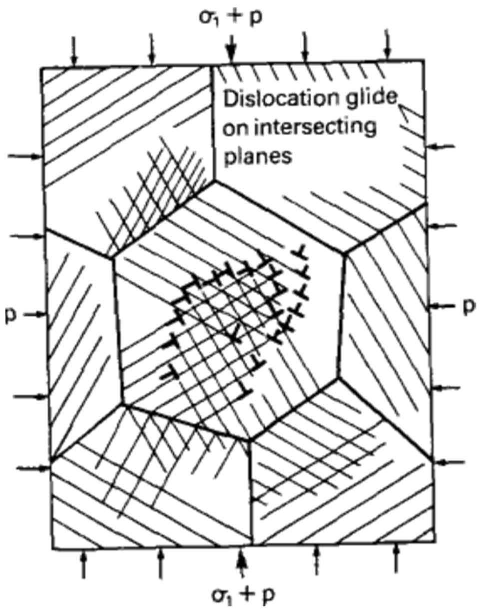
- The Earth is a heat engine that cools from the inside out.
- The outer core is liquid and carries heat upward and outward in fluid circulation cells and convection currents.
- The mantle is mostly solid, ductile (plastic) material that transfers heat via:
    1) ***Soild-state convection*** of slow-moving (creeping) mantle plumes
    2) ***Conduction***, and
    3) ***Magma generation and ascent*** within the asthenosphere and lithosphere

Ratio of viscosity due to dislocation creep over that due to diffusion creep.

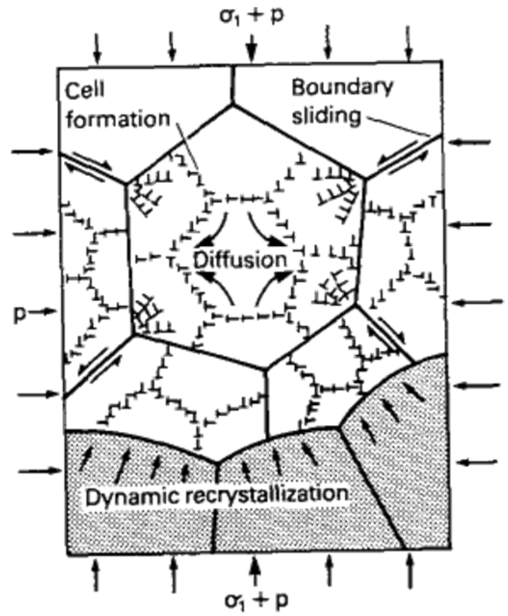


Igneous Rocks

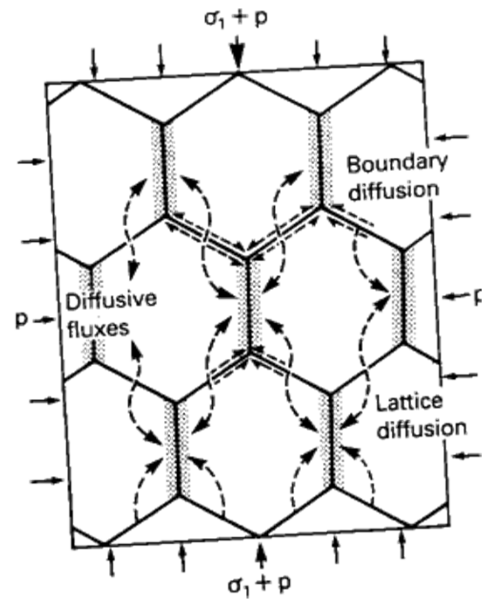
- Plasticity and Ductile Creep in the Mantle



Plastic Flow produces limited, permanent strains at high stresses when the yield strength of mineral grains is exceeded and they deform by gliding along internal dislocation planes or grain boundaries.



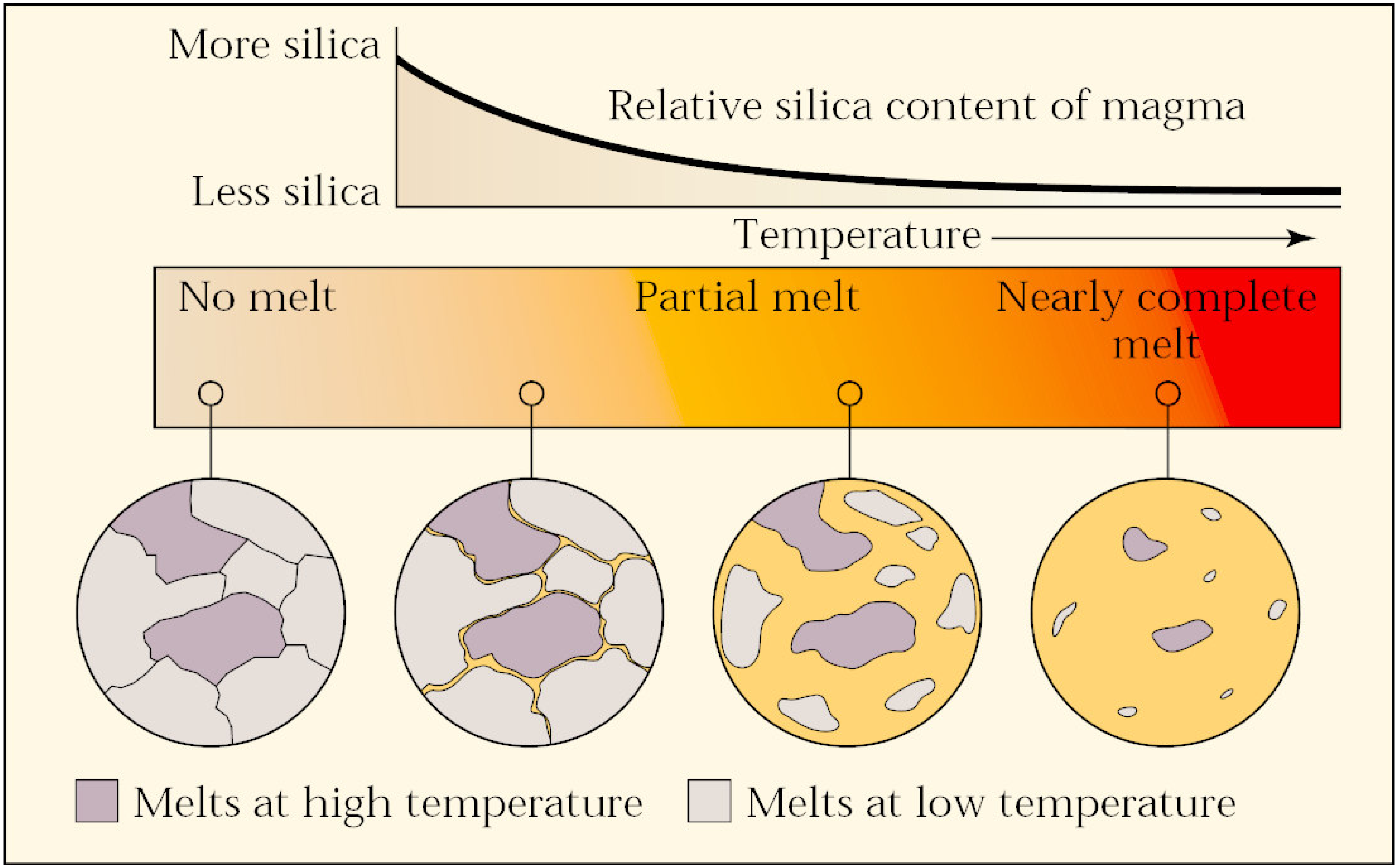
Power-Law Creep takes place only at high temperature, at least 55% of the melting temperature. Most minerals melt at temperatures between 400^{o} and 1800^{o} C, so power-law creep takes place in the lower crust or deeper.



Diffusion Creep occurs when temperatures exceed 85% of the melting temperature. Such temperatures lead to rapid diffusion and atom migration along stress gradients, promoting continual recrystallization.

Igneous Rocks

• *Partial melting of slica-rich minerals first*

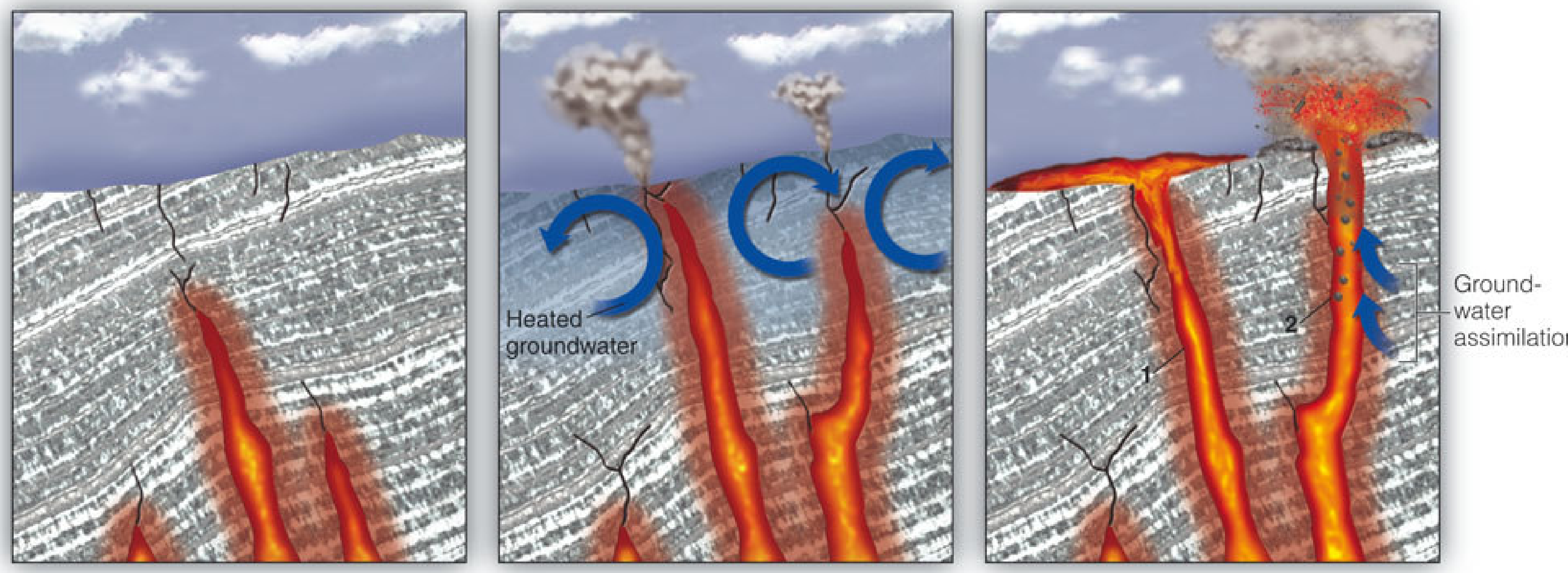


Igneous Rocks

Molten rock material below the Earth's surface is called ***magma***.

If the magma reaches the surface it is called ***lava***.

Magma is erupted as either lava flows or ***pyroclastic*** materials



Heated and assimilated groundwater can aid in fracturing and eruption at shallow depths

(a) Magma rises, but too deep to create visible surface effects.

(b) Magma close enough to create steam vents and hot springs.

(c) Volatile-poor magma erupts as lava (1), while volatile-rich magma erupts explosively (2), creating breccia and other pyroclastic deposits.

Igneous Rocks

•Temperature and composition are the main determinants of *viscosity* in lava flows, with relatively cool and/or more felsic (silica-rich) flows being more viscous than hotter and/or more mafic (silica-poor) ones.

Big Obsidian Flow, Oregon; a rare example of fluid behavior by felsic lava; photograph credit to W. Scott, USGS

Cooling of flowing mafic lava causes surface to darken and solidify; by J.D. Griggs, USGS

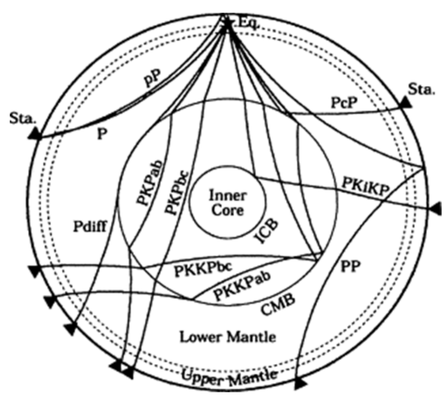
Igneous Rocks

•At normal temperatures and pressures in the mantle, the hottest rocks rise buoyantly in ductile convection currents

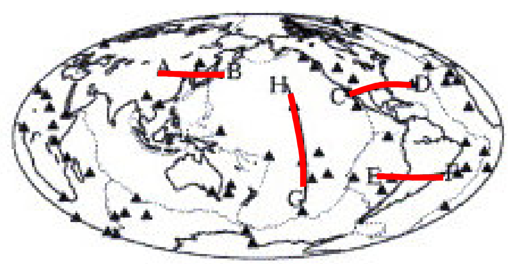
• During ascent, pressure decreases fast with little temperature loss

•Upon reaching the *asthenosphere*, rising mantle currents encounter lower *lithostatic pressures* and can initiate melting and generate magma

These images were inferred from different seismic wave data sets

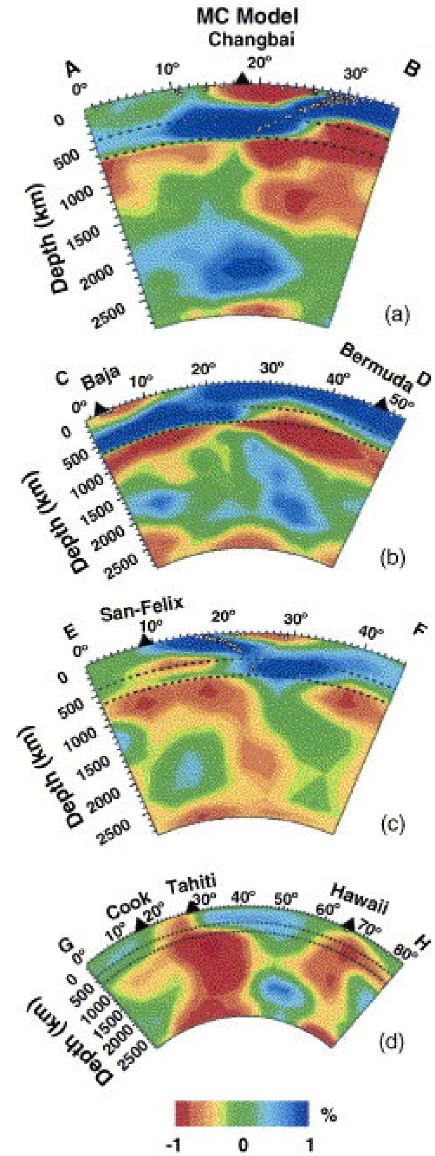


Many global tomographic inversions and resolution tests are carried out to investigate the …. 3D velocity structure of the Earth's interior



The triangles denote the hotspots in the world except for 3 in East Asia.

P-wave seismic velocity anomalies



velocity-perturbation scale

Igneous Rocks

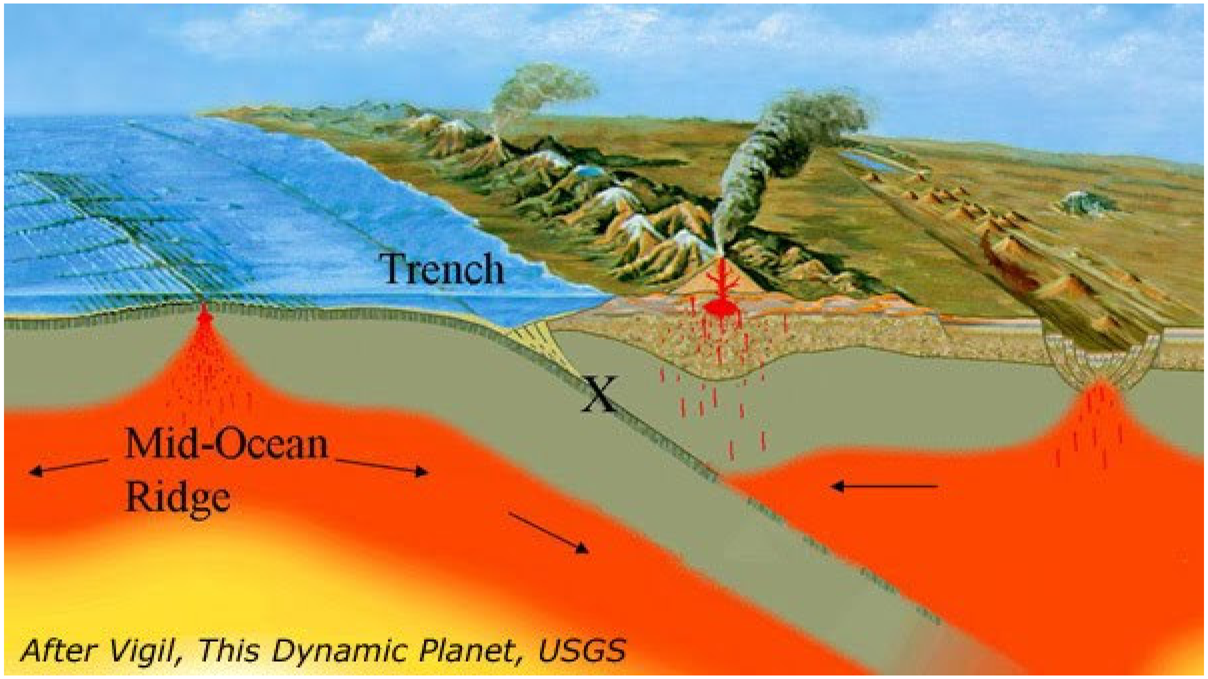
•The production of magma and igneous activity is associated with plate tectonic boundaries, hot spots, and continental rifts

•Magmas accumulate in magma chambers at depths of a few kilometers below divergent boundaries and at tens of kilometers below convergent boundaries.

depth (km)

0

20



Magmas forms beneath spreading ridges as a result of mantle plumes and are mafic.

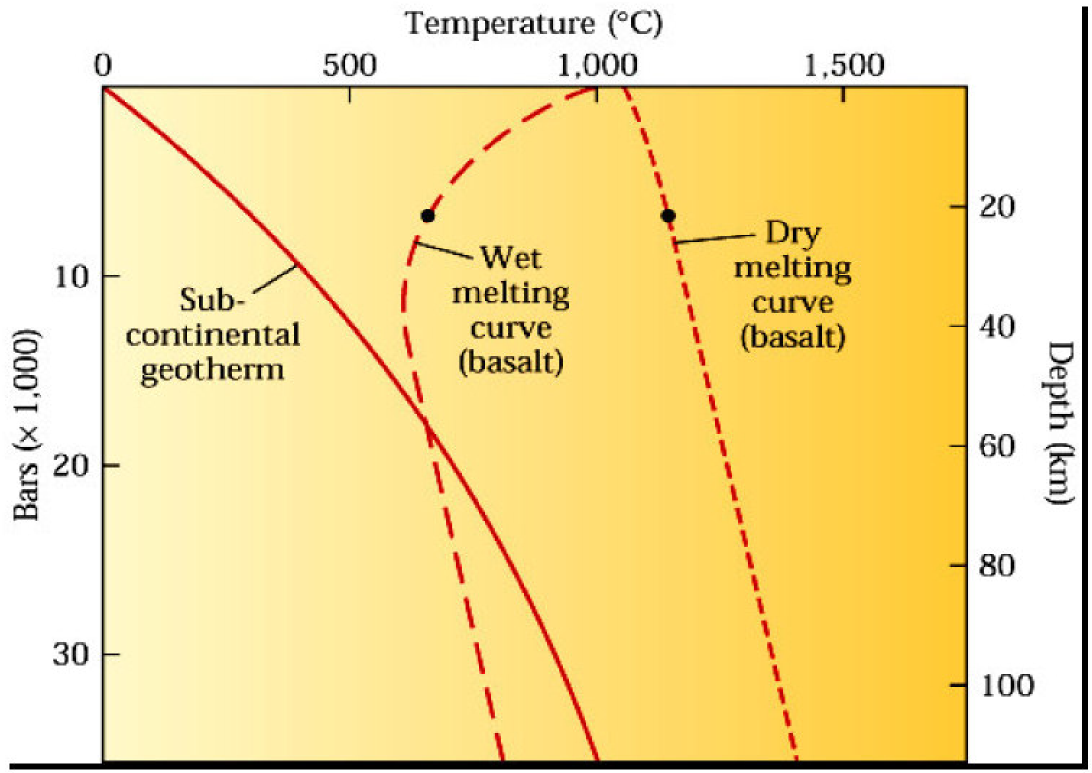
Along subduction zones at convergent boundaries, partial melting of the subducting plate produces intermediate to felsic magmas.

Igneous Rocks

•The introduction of *volatiles* including water (H_2O) and gases (like CO_2 and H_2S) can lower the melting point of rocks

•In hot rock, volatiles help break bonds at crystal surfaces.

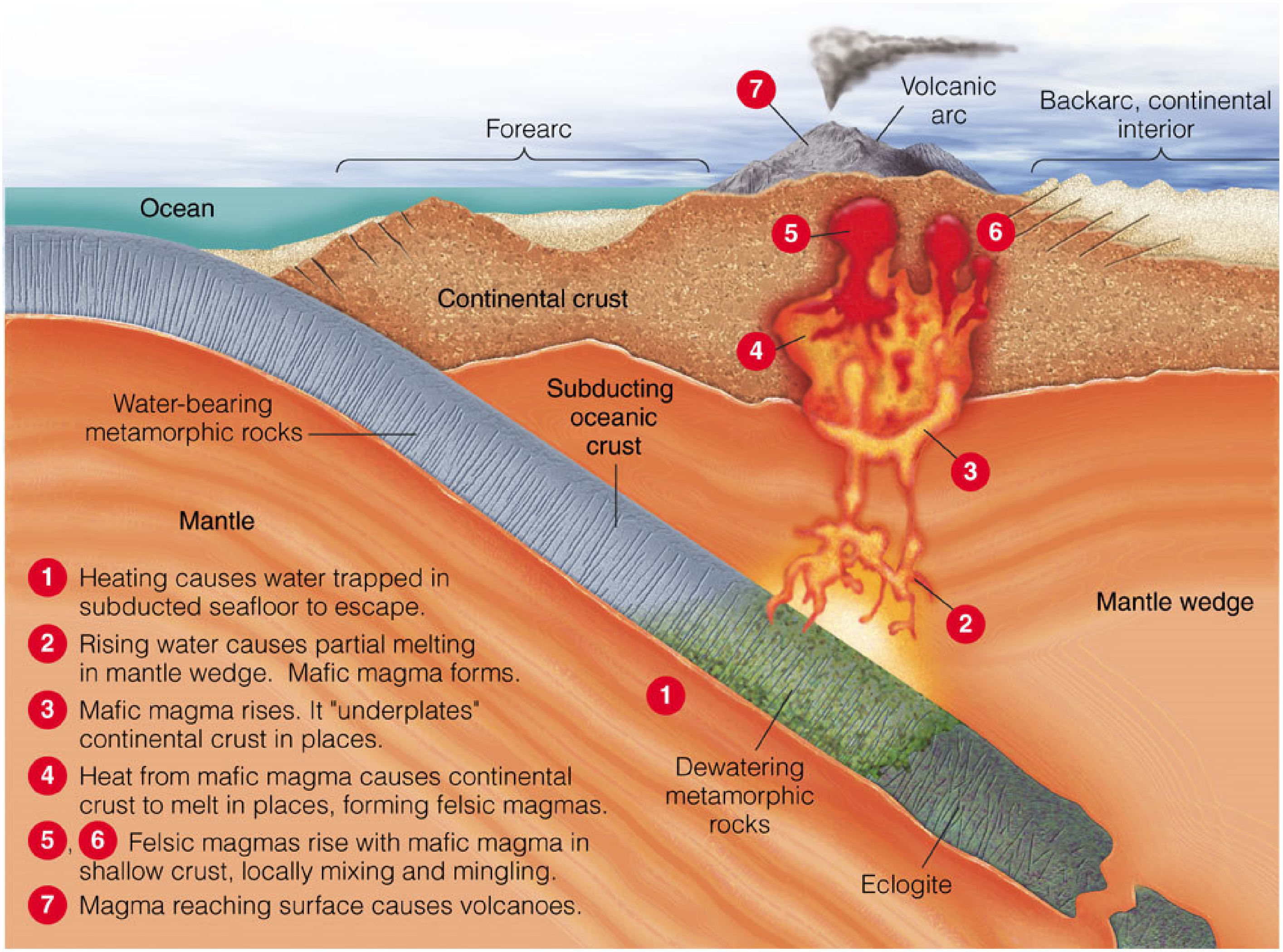
•Volatiles build up in the magma reservoir and expand into bubbles whenever pressure drops



•***The force of expanding gases is the primary agent of volcanic eruptions***

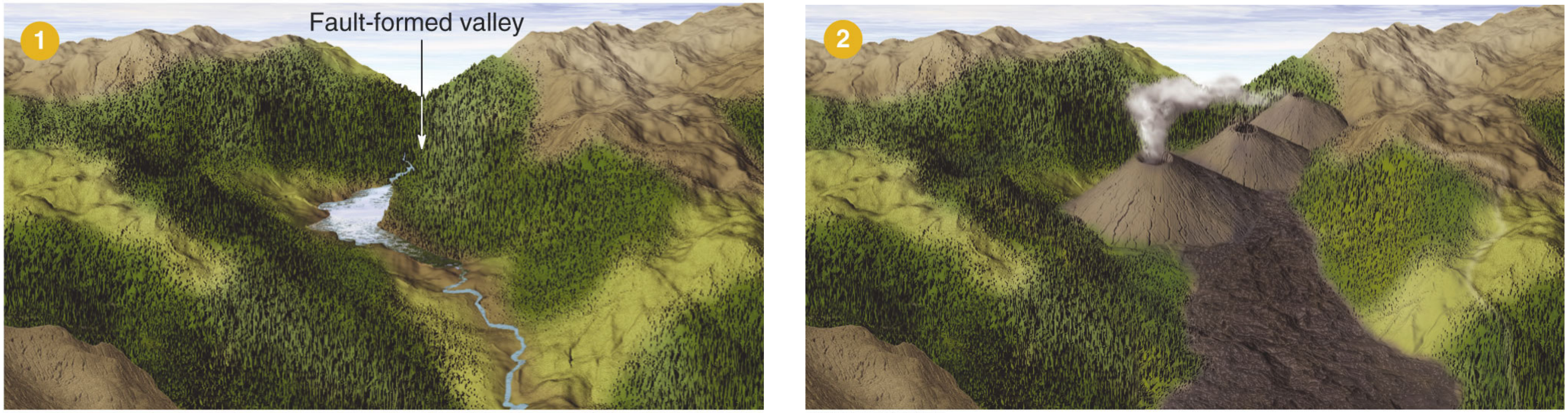
Igneous Rocks

•The introduction of volatiles by slab subduction commonly lowers the melting point of rocks and creates magma within *mantle wedges* at *ocean-ocean,* and *ocean-continent convergent plate margins.*



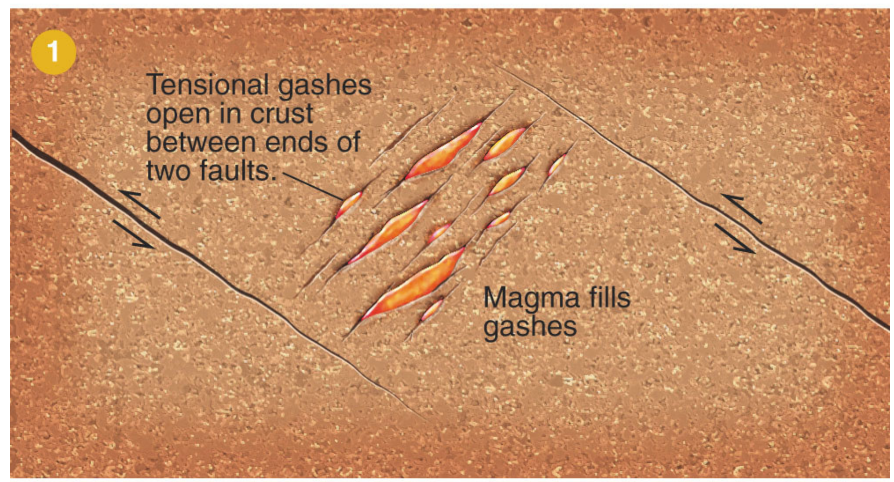
Igneous Rocks

What's seen at the surface

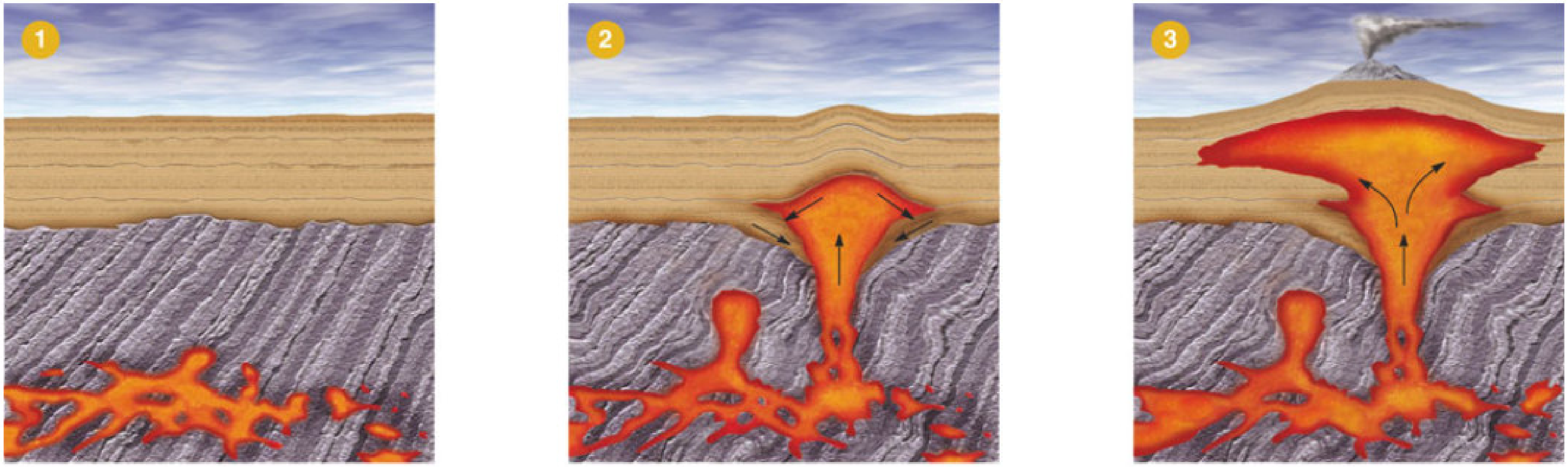


- Within the lithosphere, brittle cracking locally creates fissures and openings in solid rock where confining pressures drop, rock melts, and magma forms, accumulates, and sometimes escapes to the surface.

What's happening underground



Igneous Rocks



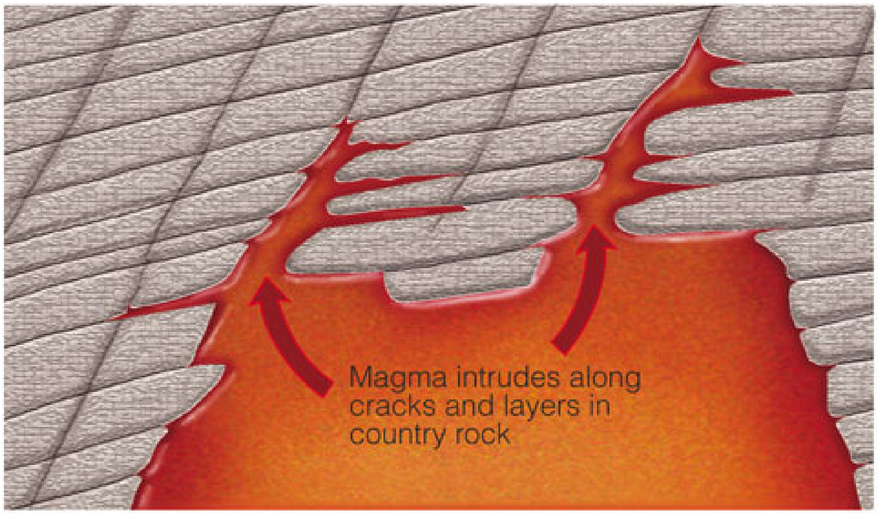
Rock melts partly deep in crust. Melt is widely dispersed

Molten batches grow large enough to start rising, shouldering aside overlying rock.

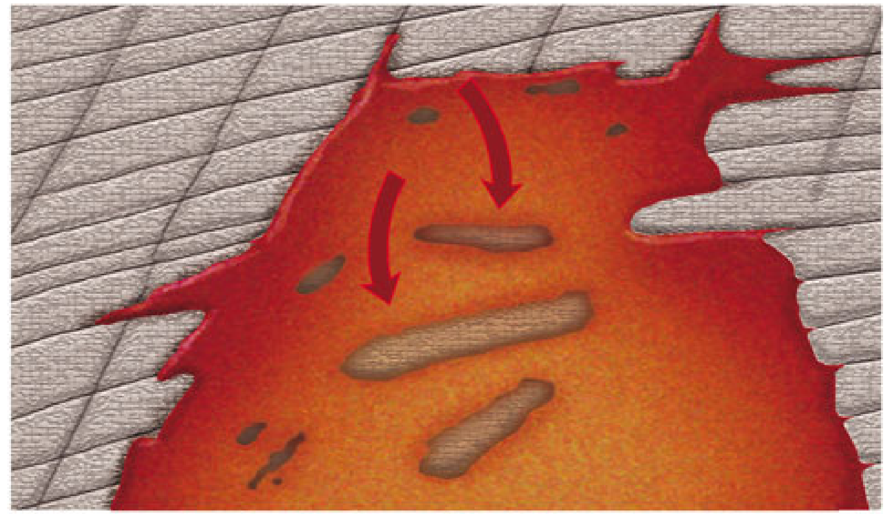
Magma spreads out and swells incrementally in shallow crust, forming giant, lens-shaped pluton.

b Magma bouyantly displaces overlying rock and inflates in heated shallow crust

Igneous Rocks

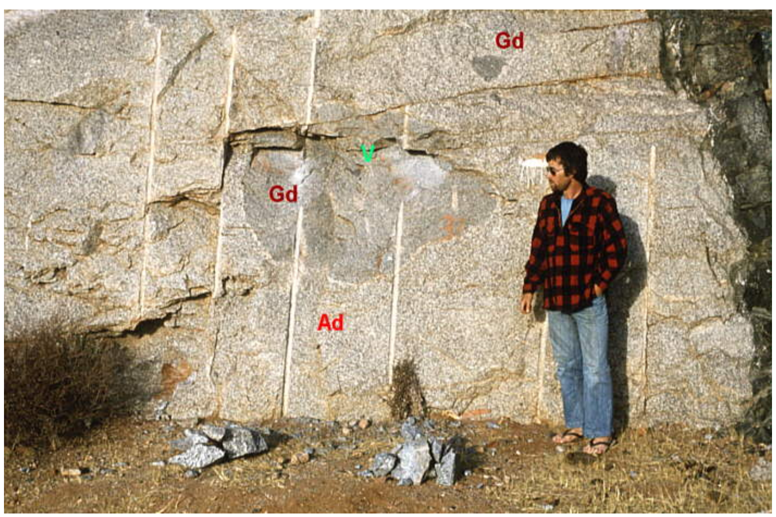


Note: Stoping can assist a magma body to become shallower, but is not a major process in making magma bodies grow larger overall.



Loosened blocks of country rock settle into melt. They may be assimilated deeper inside the magma chamber.

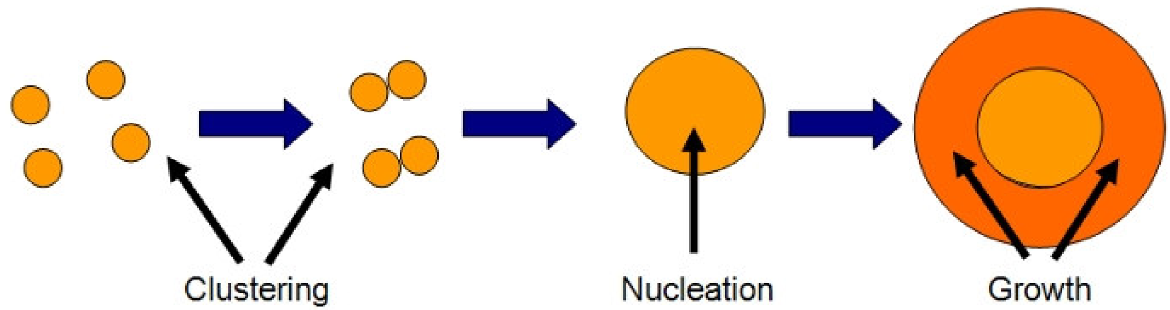
c Magma detaches ceiling blocks ("stopes" them), which it may digest ("assimilate").



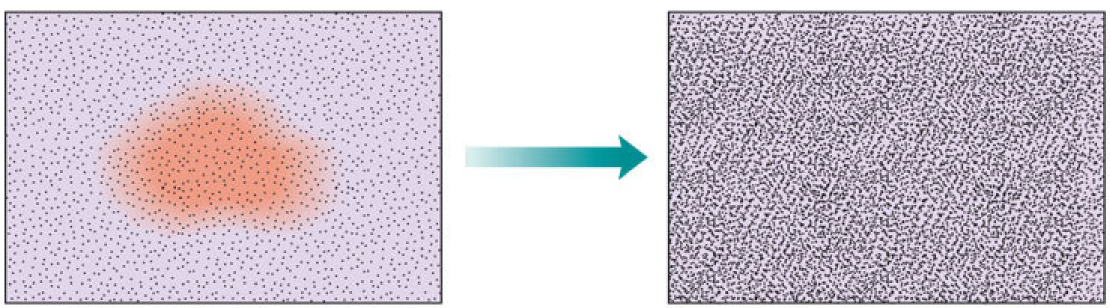
web.uct.ac.za/depts/geolsci/dlr/images/pl48a.jpg

Igneous Rocks

•Upon cooling, minerals begin to crystallize from magma and lava after small crystal nuclei cluster, form, and grow.



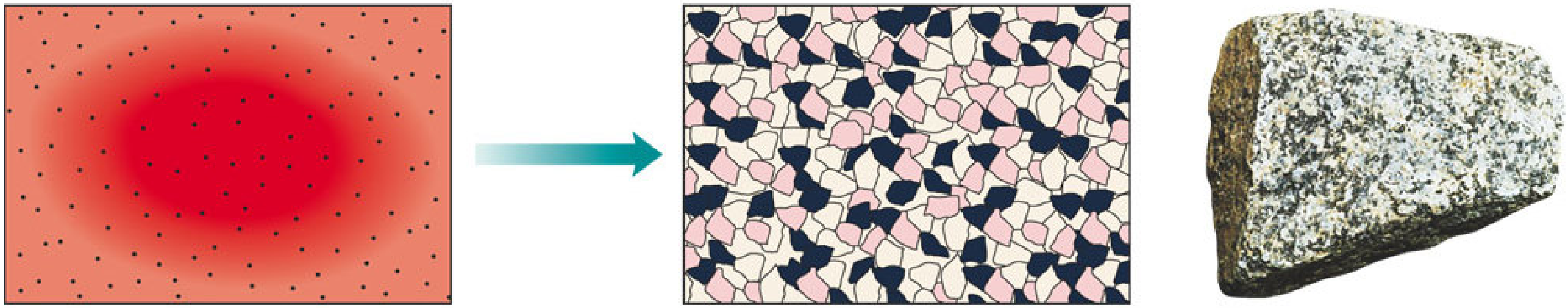
•Rapid cooling typifies volcanic rock and produces ***aphanitic*** textures.



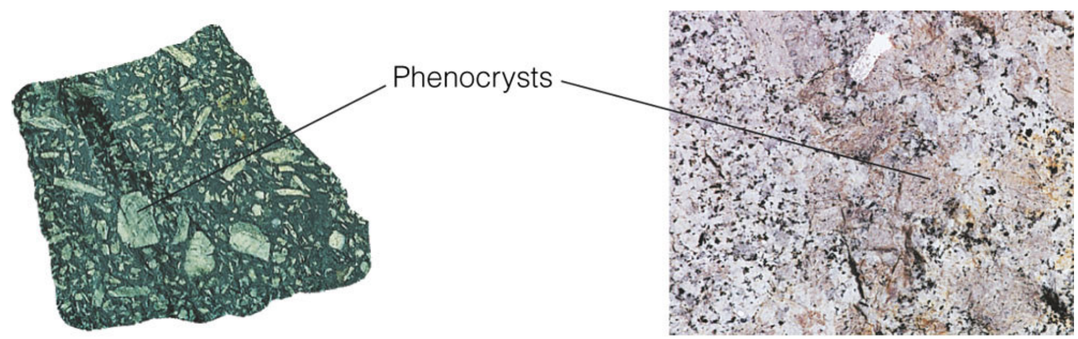
www.aseptec-sg.com/images/sonocrystallisation.jpg

Igneous Rocks

•Slow cooling of plutonic magmas produces ***phaneritic*** textures with mineral grains that are easily visible without magnification.



•Rocks with ***porphyritic*** textures are characteristic of complex cooling histories and contain mineral grains of distinctly different sizes.



Igneous Rocks

•Other igneous rock textures

www.mbari.org/expeditions/vance/images/Aphyric_640.jpg

glassy

vesicular

pyroclastic

meteorites.wustl.edu/id/vesicles_0003.jpg

Igneous Rocks

•Silica is the primary constituent of magmas, but magmas are *differentiated* into mafic, intermediate, and felsic types based on the relative proportions of silica, iron, and magnesium.

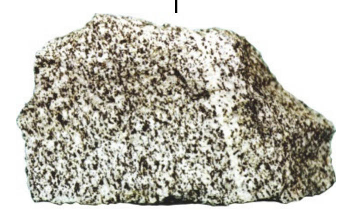
TABLE 4.1

The Major Igneous Rocks

Decreasing Iron and Magnesium, Increasing Silica	Plutonic Rock Names	Volcanic Rock Names	General Compositional Group
	Peridotite	n/a	Ultramafic
	Gabbro	Basalt	Mafic
	Diorite	Andesite	Intermediate
	Granodiorite	Dacite	Intermediate
	Granite	Rhyolite	Felsic

ultramafic

Gabbro



Diorite

Granite

felsic

Igneous Rocks

•Parent magma composition largely determines the composition of igneous rocks.

TABLE 4.2

The Most Common Types of Magma and Their Characteristics

Type of Magma	Silica Content (%)	Sodium, Potassium, and Aluminum	Calcium, Iron, and Magnesium
Ultramafic	<45	↓	Increase
Mafic	45–52	↓	↑
Intermediate	53–65	↓	↑
Felsic	>65	Increase	↑

•A single magma can, however, yield different rock types.

Igneous Rocks

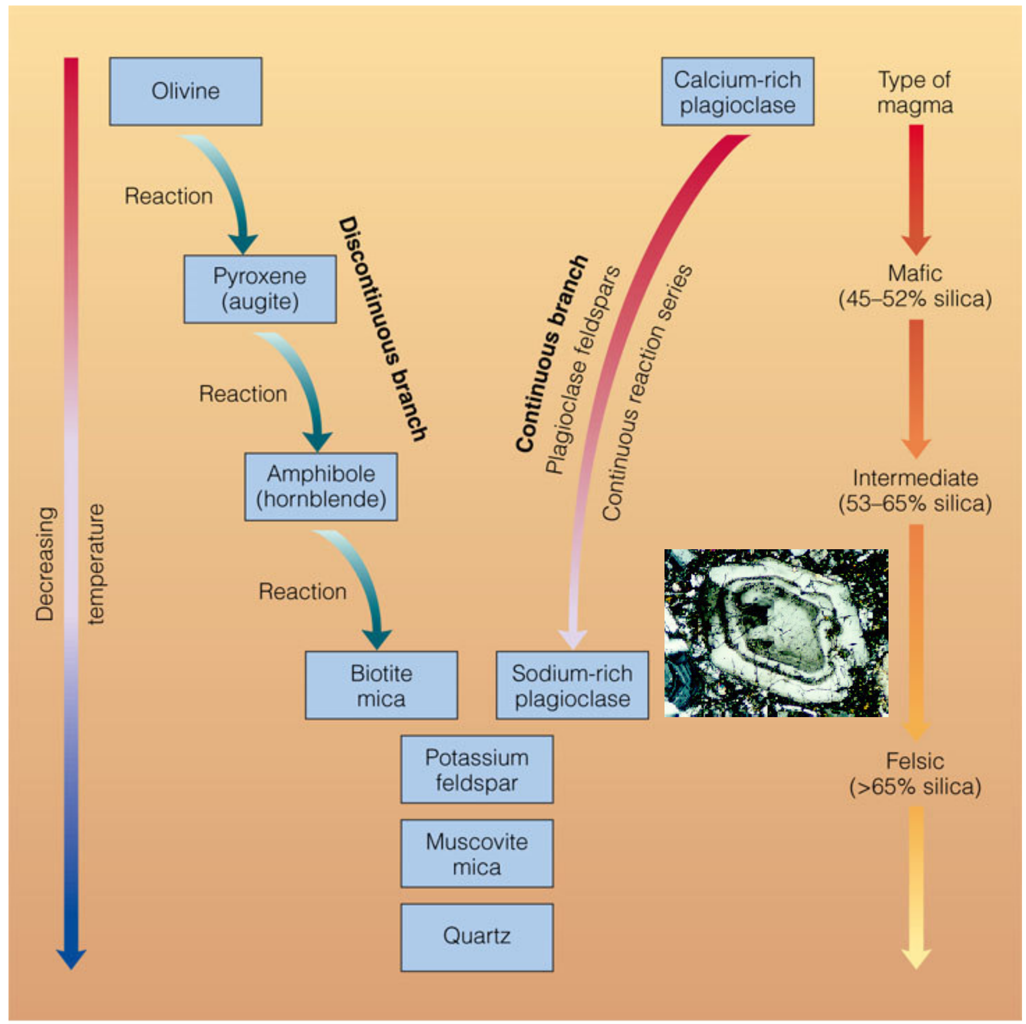
•Given ideal cooling conditions, a mafic magma will yield a sequence of different minerals, each of which is stable within specific temperature ranges.

•The ***Bowen's Reaction Series*** contains one *discontinuous series* and one *continuous series*.

•As each mineral is formed it reacts with the remaining melt to form the next mineral in the sequence.

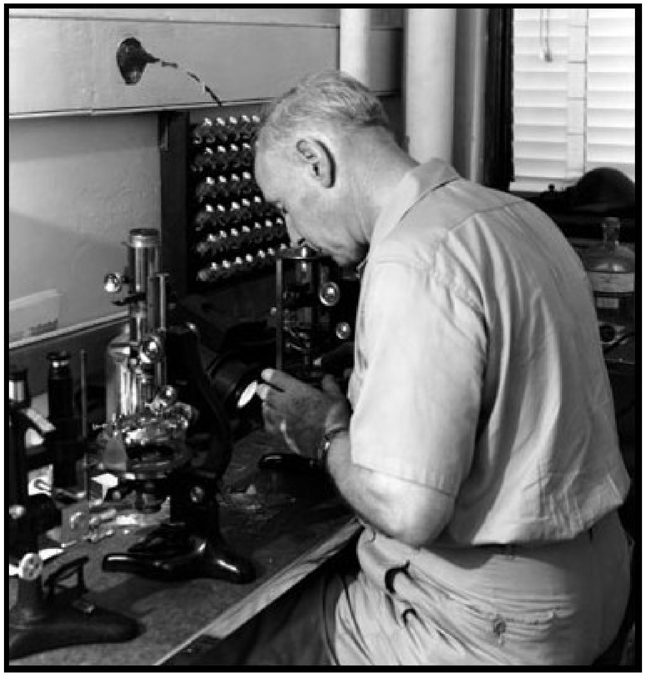
The *discontinuous series* produces ferromagnesian minerals early on.

The *continuous series* involves a transformation of the plagioclase feldspar crystal structure by the replacement of calcium with sodium.



Igneous Rocks

The ***Bowen's Reaction Series***



N. L. Bowen peering into a microscope at the Geophysical Laboratory.

- Tells the stable temperature and pressure conditions of the different minerals that formed the igneous rock.

- Helps us deduce the possible original melt chemistry that crystallized the rock.

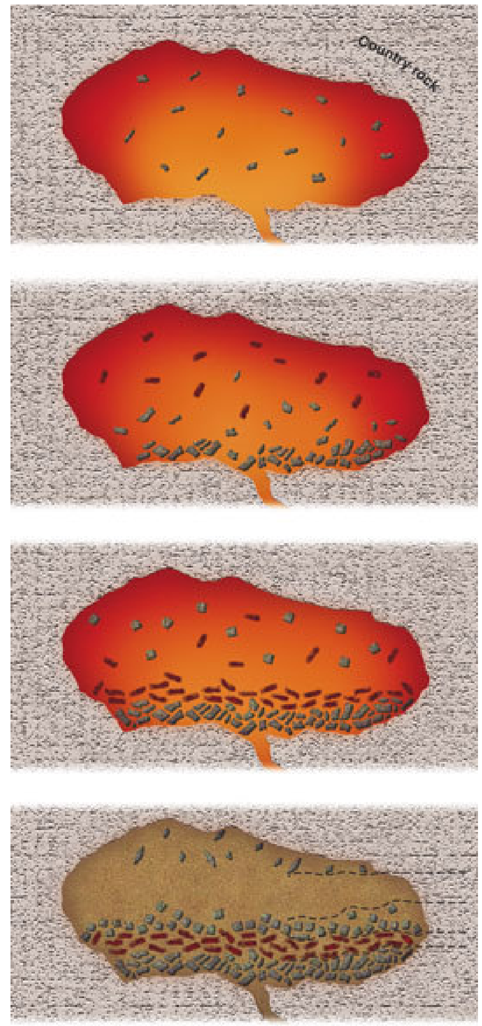
- Allows us to model initial possible conditions and predict outcomes

•M.A., Queens University, 1907
•B.S. in Mineralogy and Geology, Queens University, 1909
•Ph.D. in Geology, Massachusetts Institute of Technology, 1912
1915 paper and reaction series study, published in 1922
• 1928 The Evolution of the Igneous Rocks is his most famous book, based on a series of lectures he gave at Princeton University in 1927.
•D.Sc., Harvard University, 1936
•D.Sc., Yale University, 1951

Igneous Rocks

•*Gravitational differentiation* can result in the different mineral phases crystallizing at different temperatures to form sequentially and accumulate in layers at the bottom of a magma chamber.

• **With differentiation, a layered, heterogenous pluton forms**

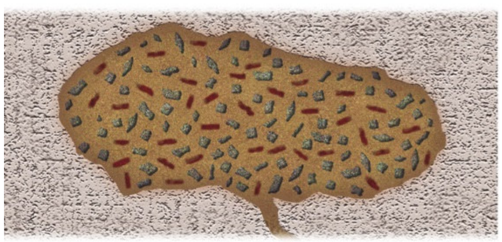


Olivine crystals form and settle

Pyroxene crystals form and settle over olivine layer

Amphibole crystals form and settle above pyroxene and olivine layers

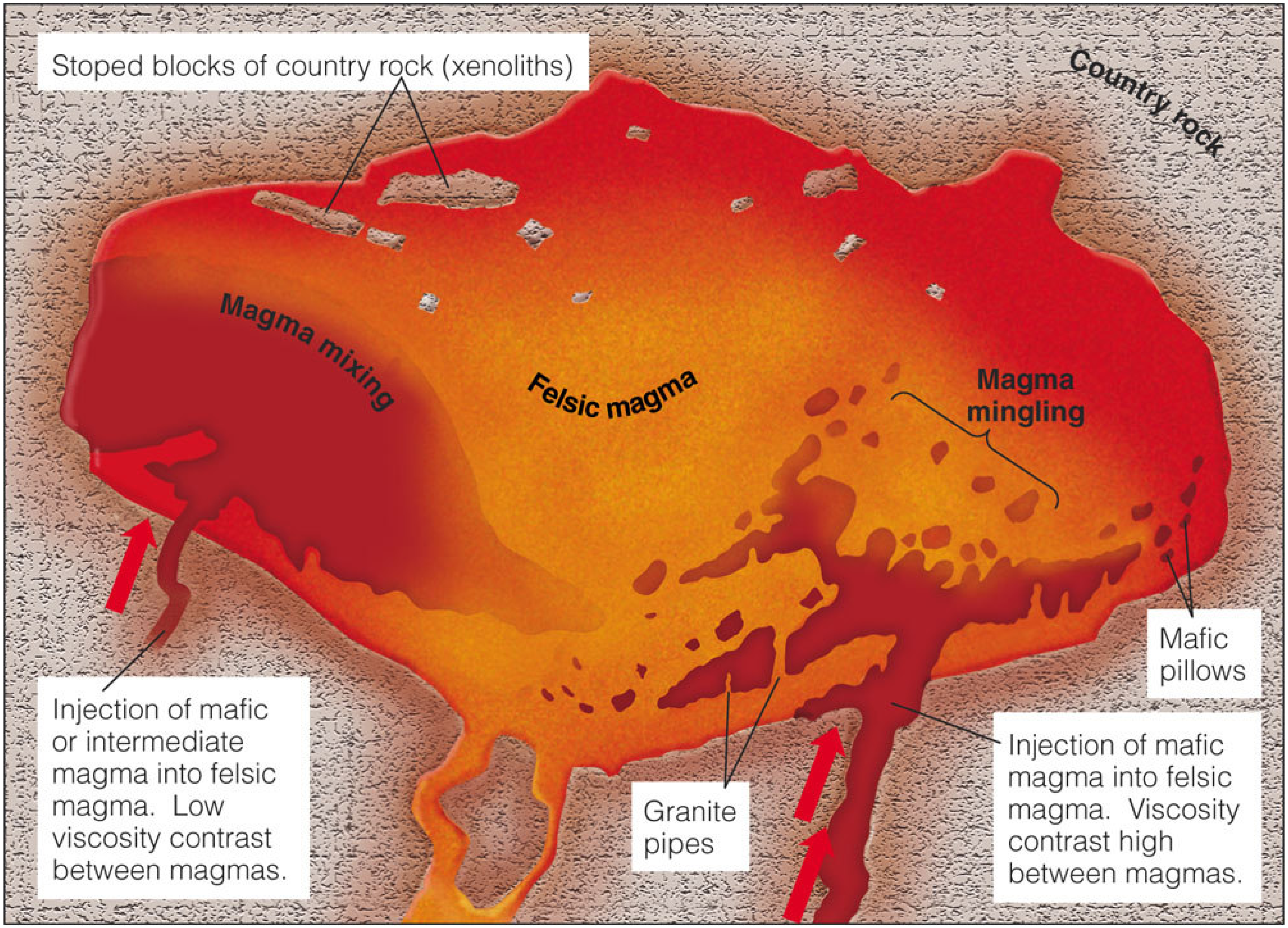
A cooled and layered pluton



•Without differentiation, a homogenous *pluton* would result

Igneous Rocks

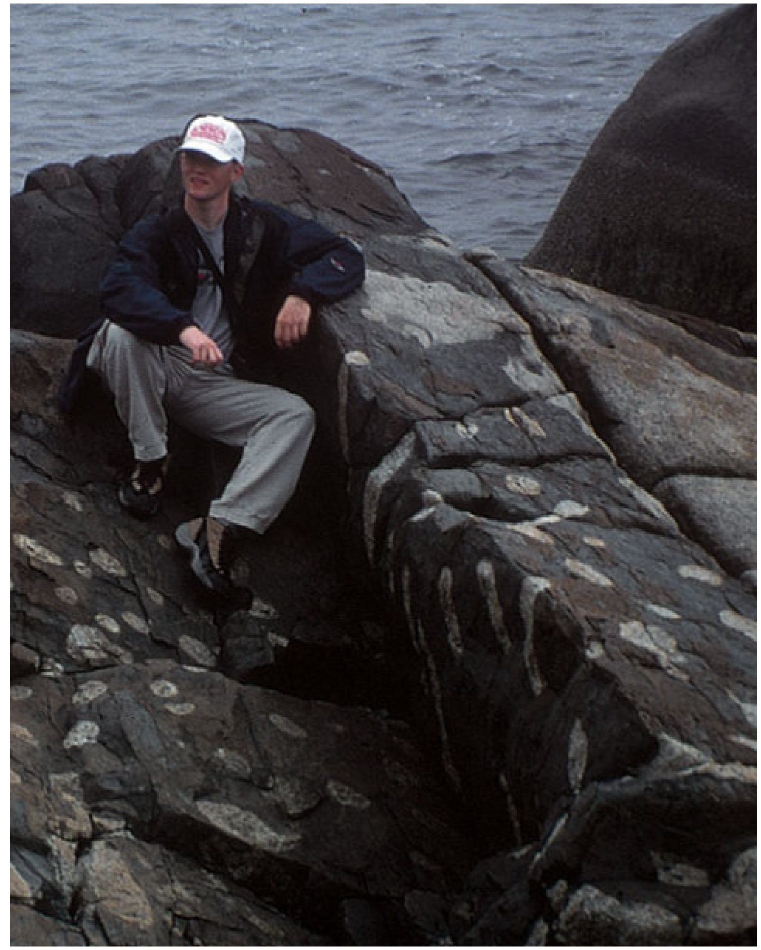
- Different compositions of magma will mix in different ways within a magma chamber.



Igneous Rocks

•Granite pipes in mafic basalt results when a mafic magma mixes into a felsic magma chamber

Mafic pillows in granite



Granite pipes in basalt

Igneous Rocks

TABLE 4.1

The Major Igneous Rocks

Decreasing Iron and Magnesium, Increasing Silica	Plutonic Rock Names	Volcanic Rock Names	General Compositional Group
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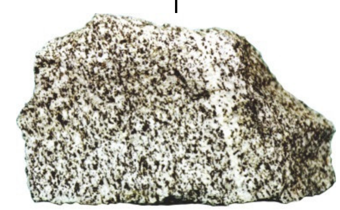
	Gabbro	Basalt	Mafic
	Diorite	Andesite	Intermediate
	Granodiorite	Dacite	Intermediate
	Granite	Rhyolite	Felsic

- Silica is the primary constituent of magmas, but magmas *differentiate* into mafic, intermediate, and felsic types based on the relative proportions of silica, iron, and magnesium.

ultramafic

Gabbro



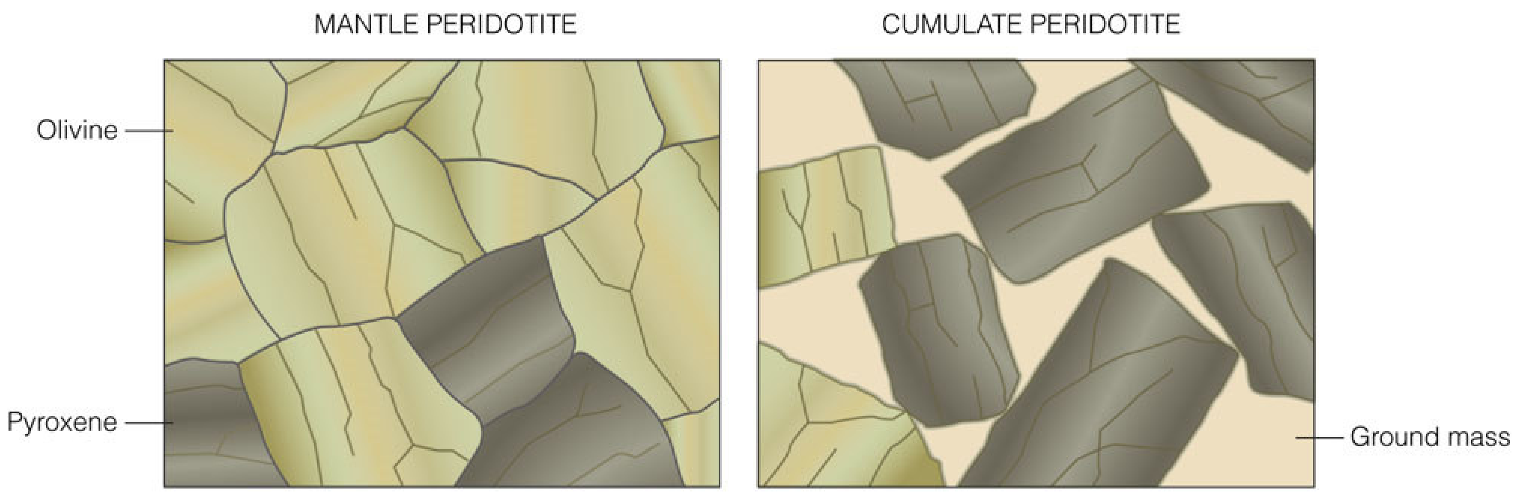
Diorite

Granite

felsic

Igneous Rocks

•Two type of ultramafic peridotites



Igneous Rocks

ultramafic

•Intrusive or *plutonic*

•Extrusive or *volcanic*

gabbro

basalt

diorite

andesite

granite

rhyolite

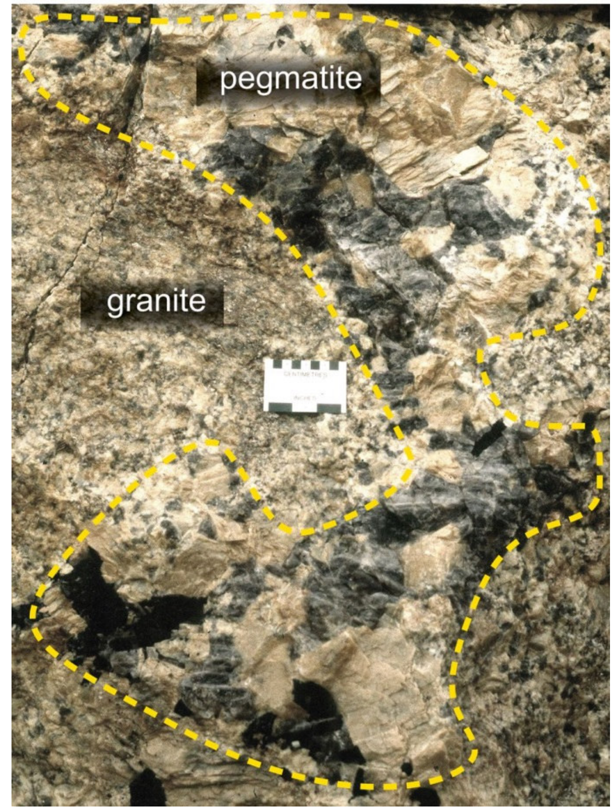
felsic

Igneous Rocks

•Pegmatite is a special type of felsic, very coarse-grained plutonic rock, that is commonly developed at the end stages of magma crystallization.

•The very large crystals result from crystallization of a vapor-rich phase

•Similar in composition to granite, pegmatites can contain complex, economically important, *accessory minerals*, like tourmaline and beryl.



Watermelon and green tourmaline

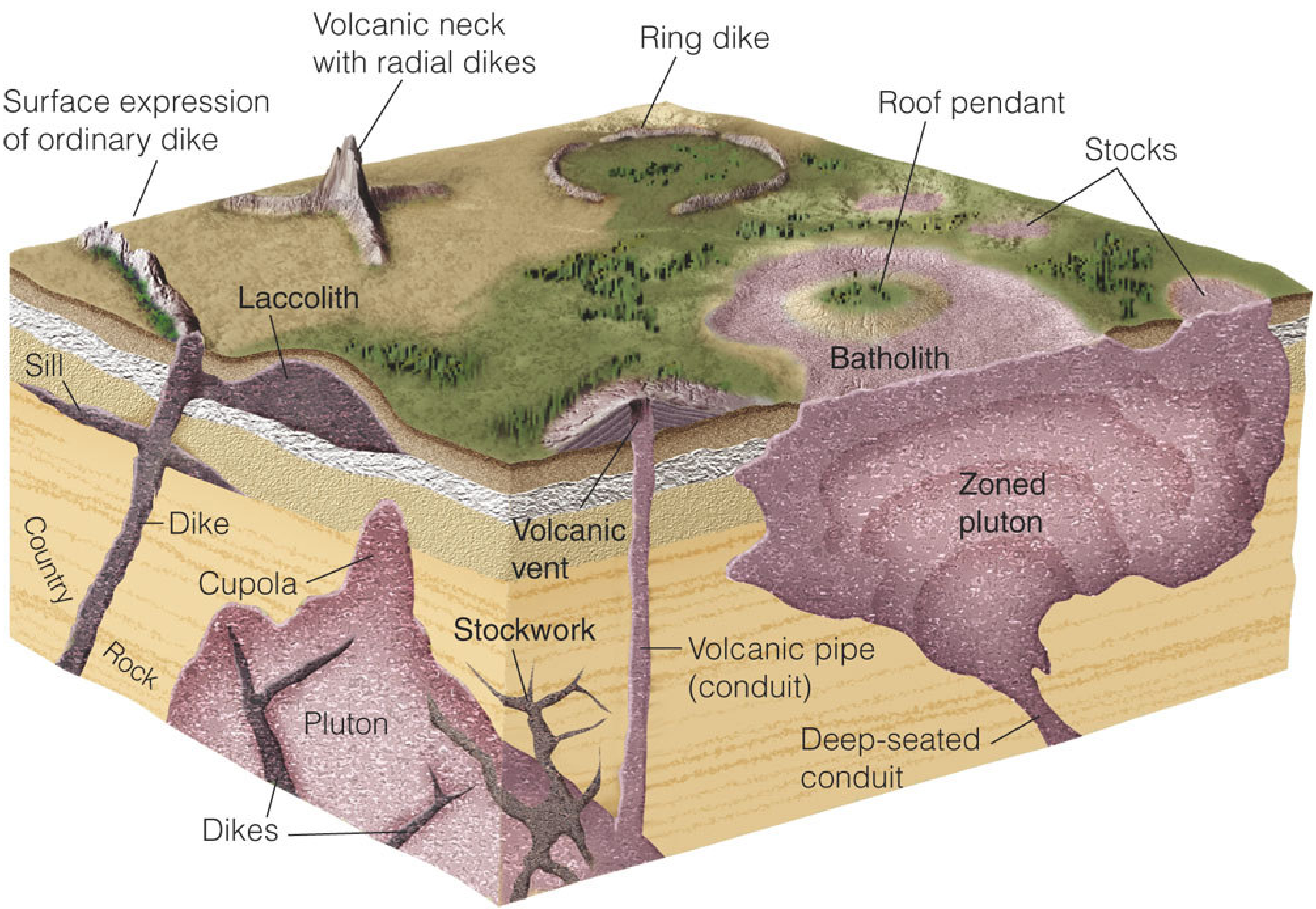
Golden and blue beryl

Golden and blue beryl

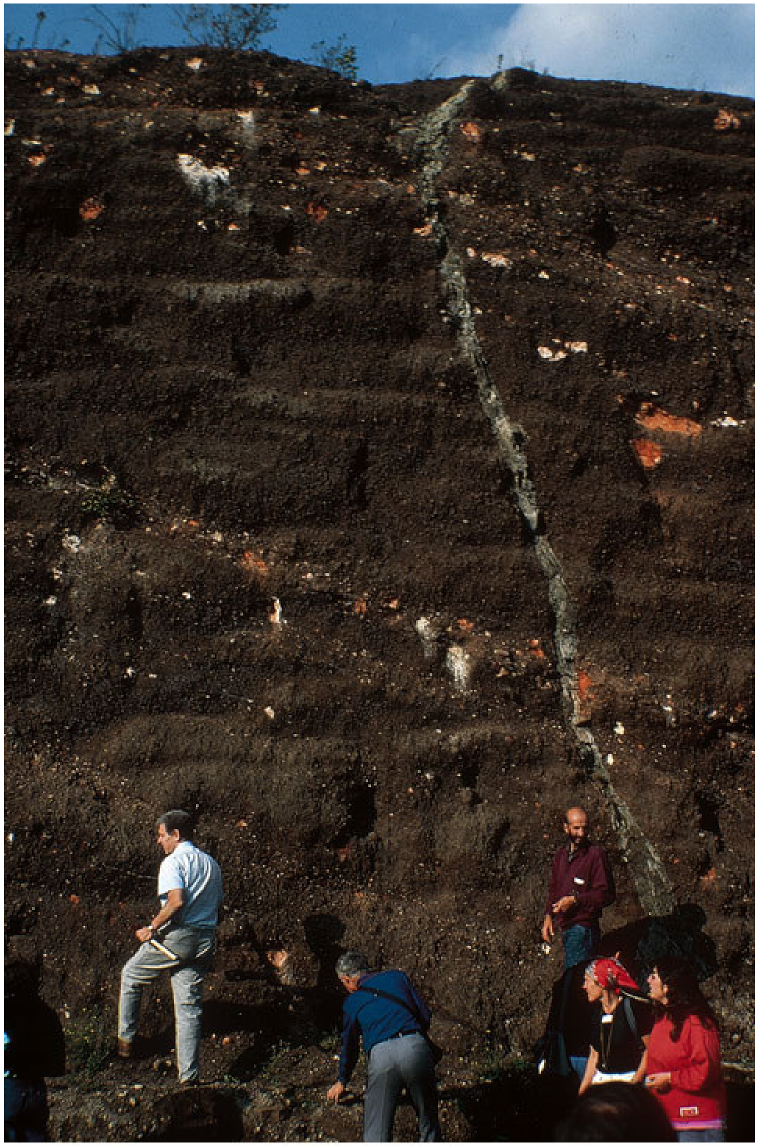
Garnet

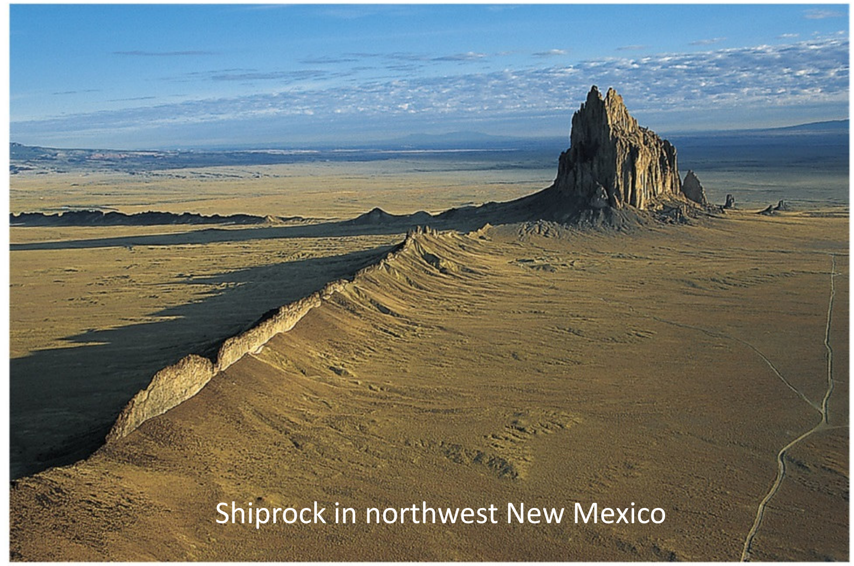
crystal-cure.com/pics/watermelon-tourmaline-slice.jpg   upload.wikimedia.org/wikipedia/commons/b/bc/Beryl-Schorl-er32d.jpg

Igneous Rocks

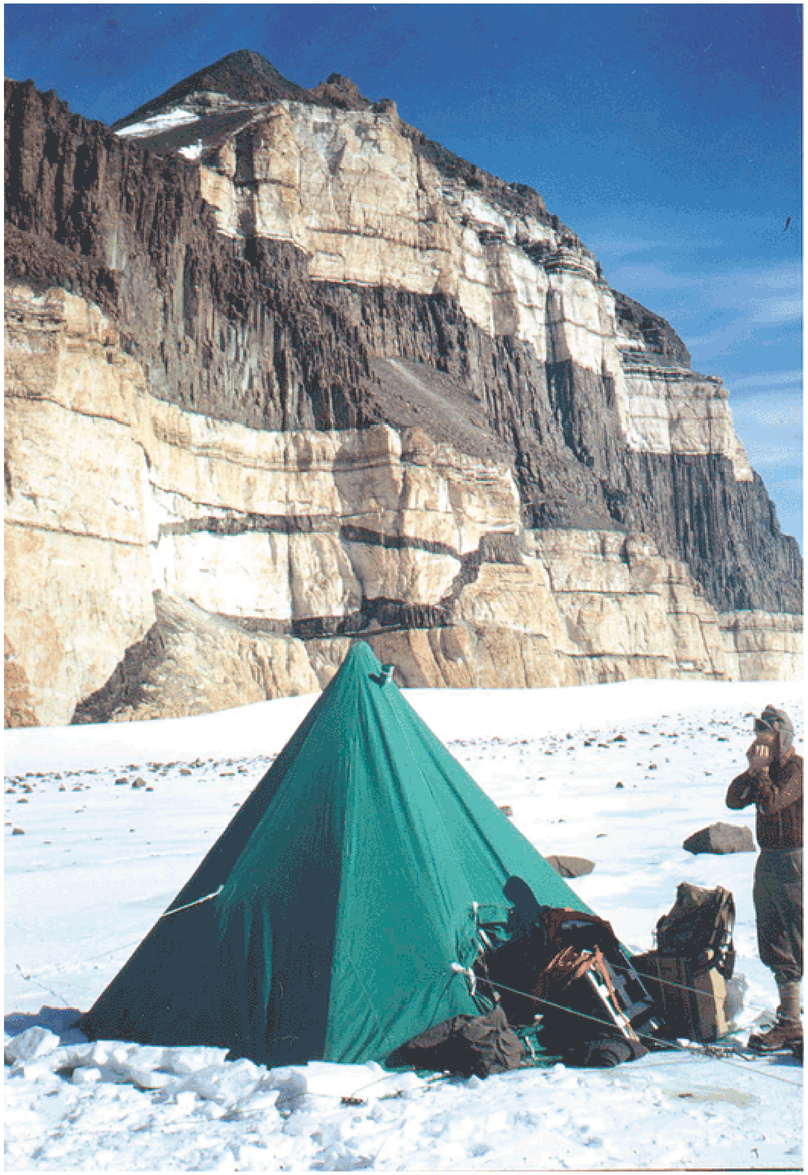


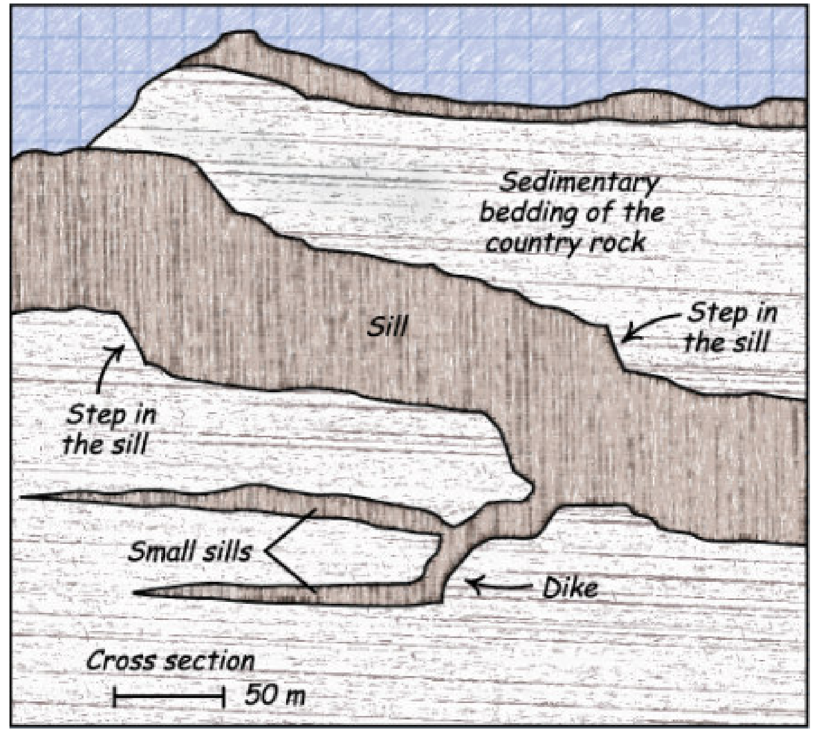
Igneous Rocks – dikes cut across preexisting layering



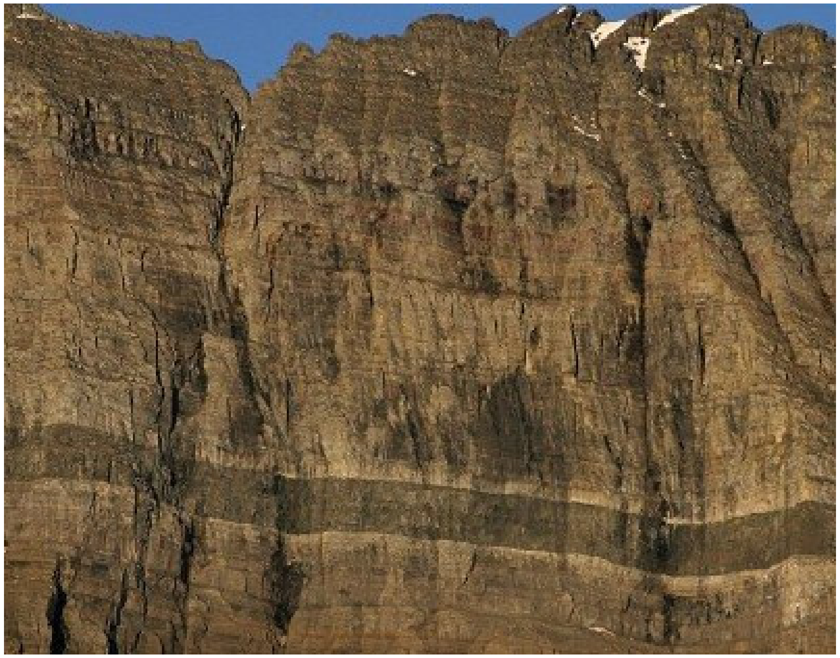


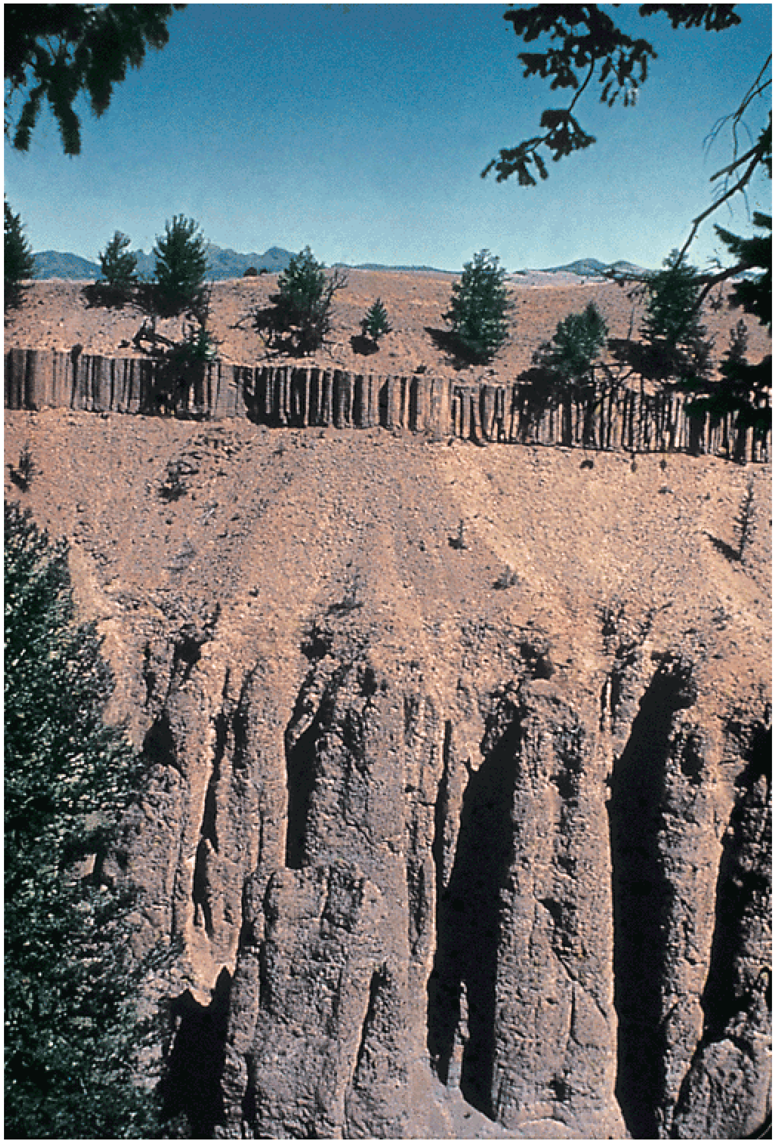
Igneous Rocks – sills inject along preexisting layering

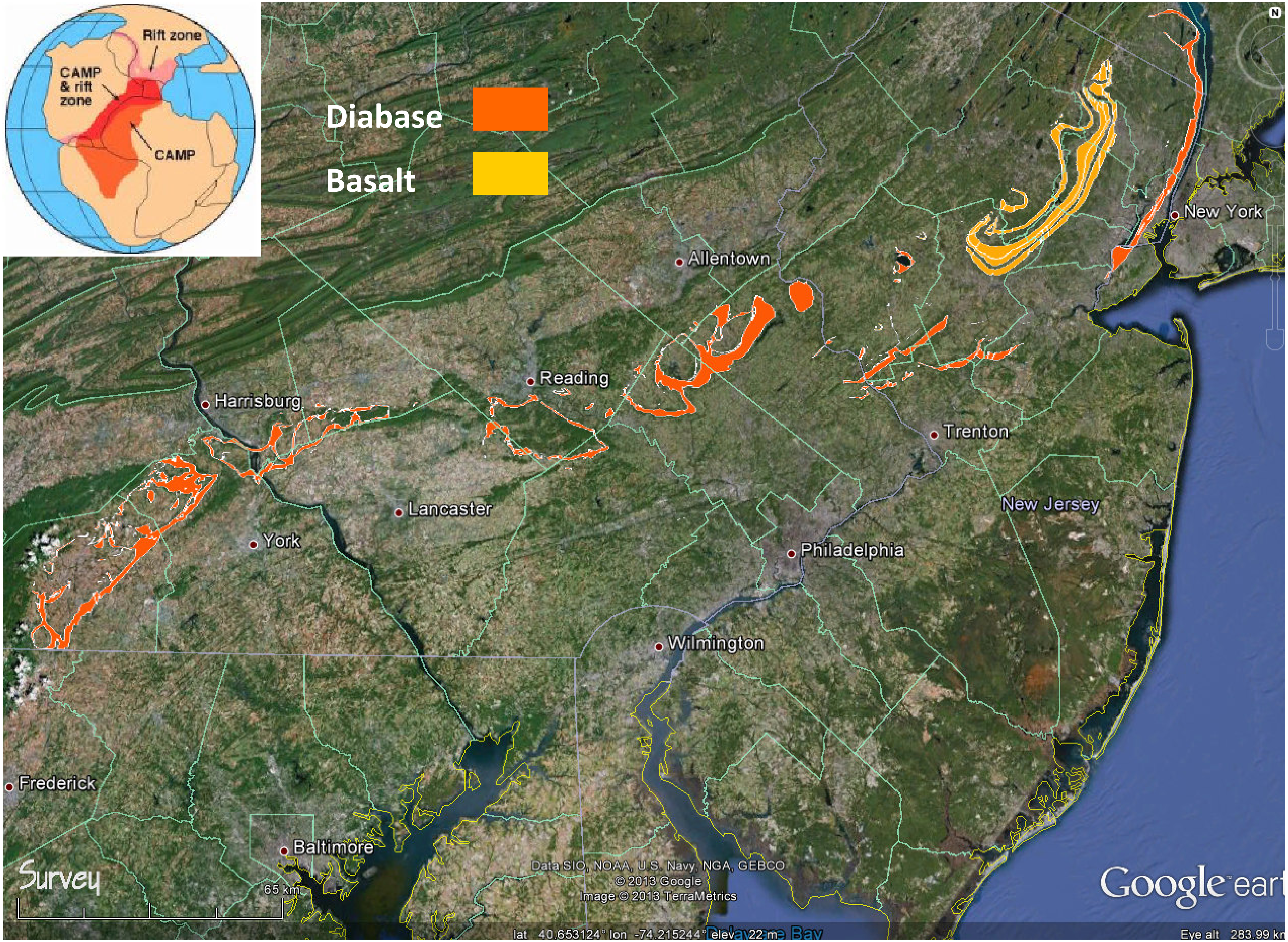




Igneous Rocks – sills injects along preexisting layering






Rift zone
CAMP & rift zone
CAMP
Diabase
Basalt
Allentown
New York
Reading
Harrisburg
Trenton
Lancaster
York
New Jersey
Philadelphia
Wilmington
Frederick
Baltimore
Survey
65 km
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2013 Google
Image © 2013 TerraMetrics
Google
lat 40.653124° lon -74.215244° elev 22 m
Eye alt 283.99 km

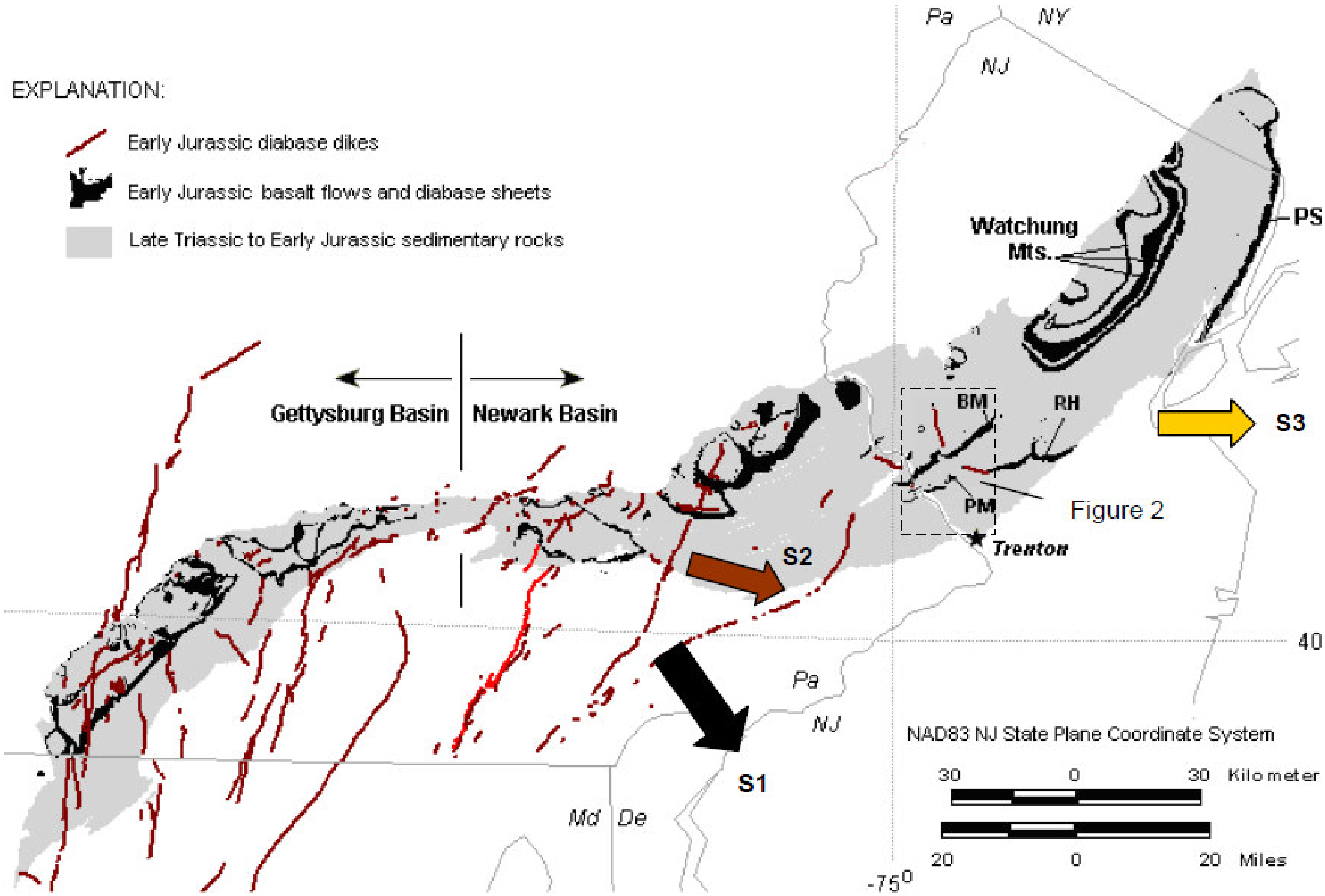
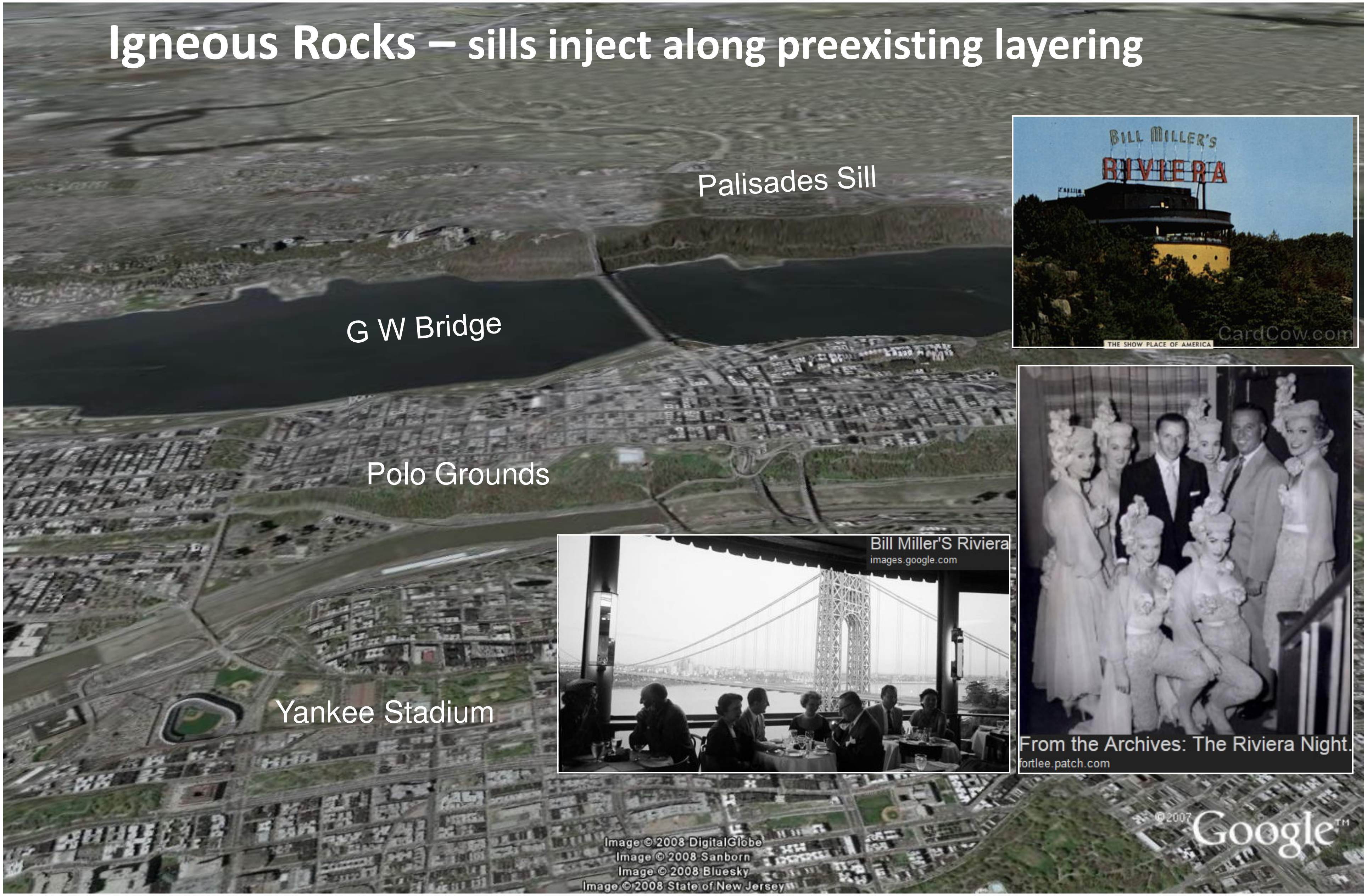
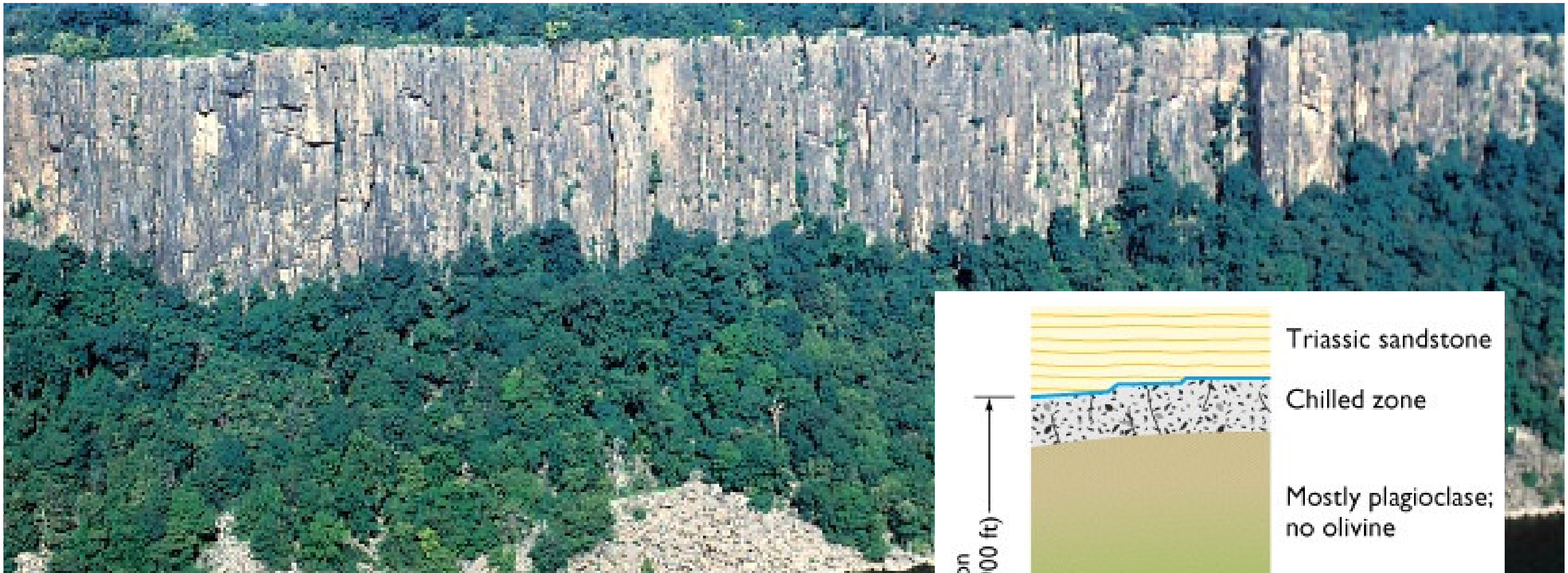


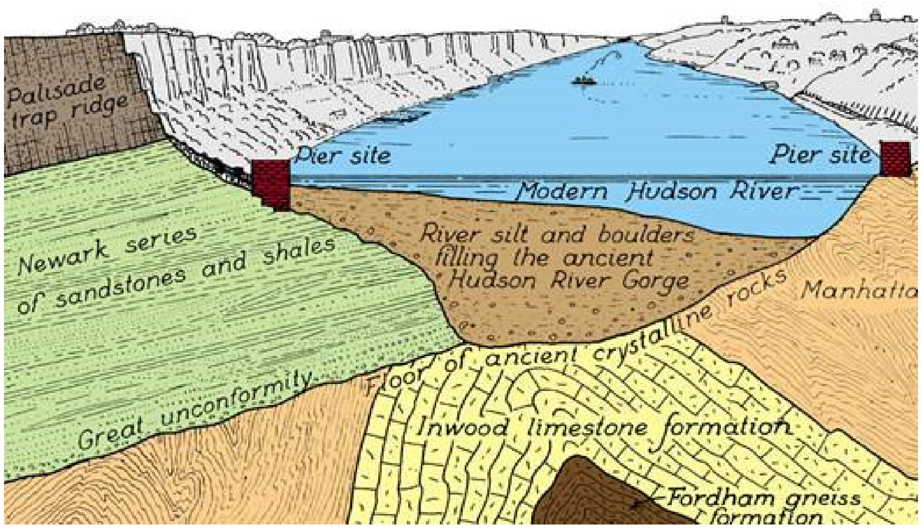
Figure 1. Generalized geologic map of the Newark and Gettysburg basins showing the distribution of Early Jurassic diabase and basalt (trap rock) in Maryland (Md), Pennsylvania (Pa), New Jersey (NJ) and New York (NY).

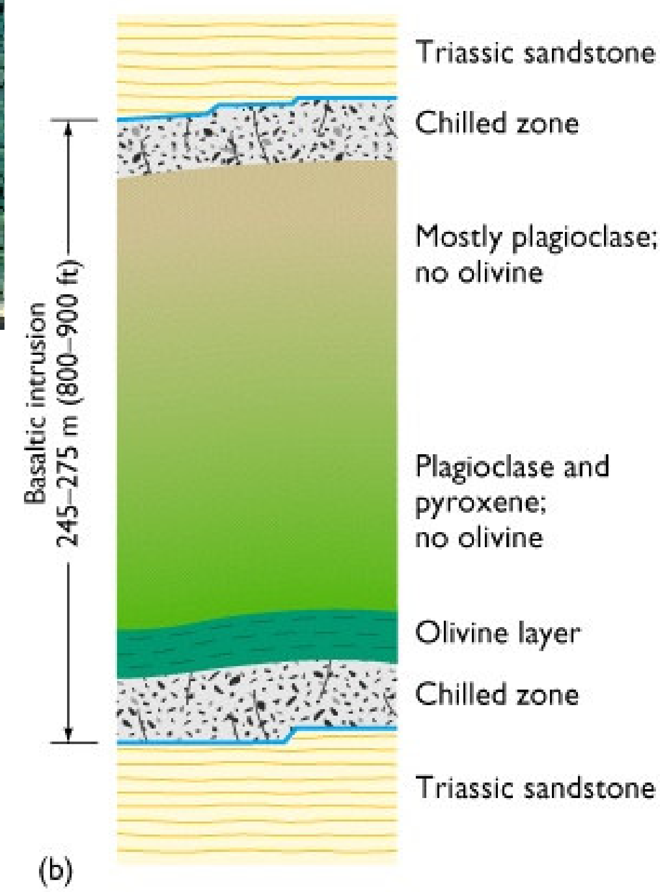
Igneous Rocks – sills inject along preexisting layering



Igneous Rocks – Palisades sill, New Jersey – New York







_____ SS - red sandstone _______ B - basalt dike leading to basalt flow ______ D - diorite stock and sills

______Gr – granite ________ Pg – pegmatite ______ Gb – Gabbro