Volcanism and Extrusive Igneous Rocks

notes from the textbook, integrated with original contributions

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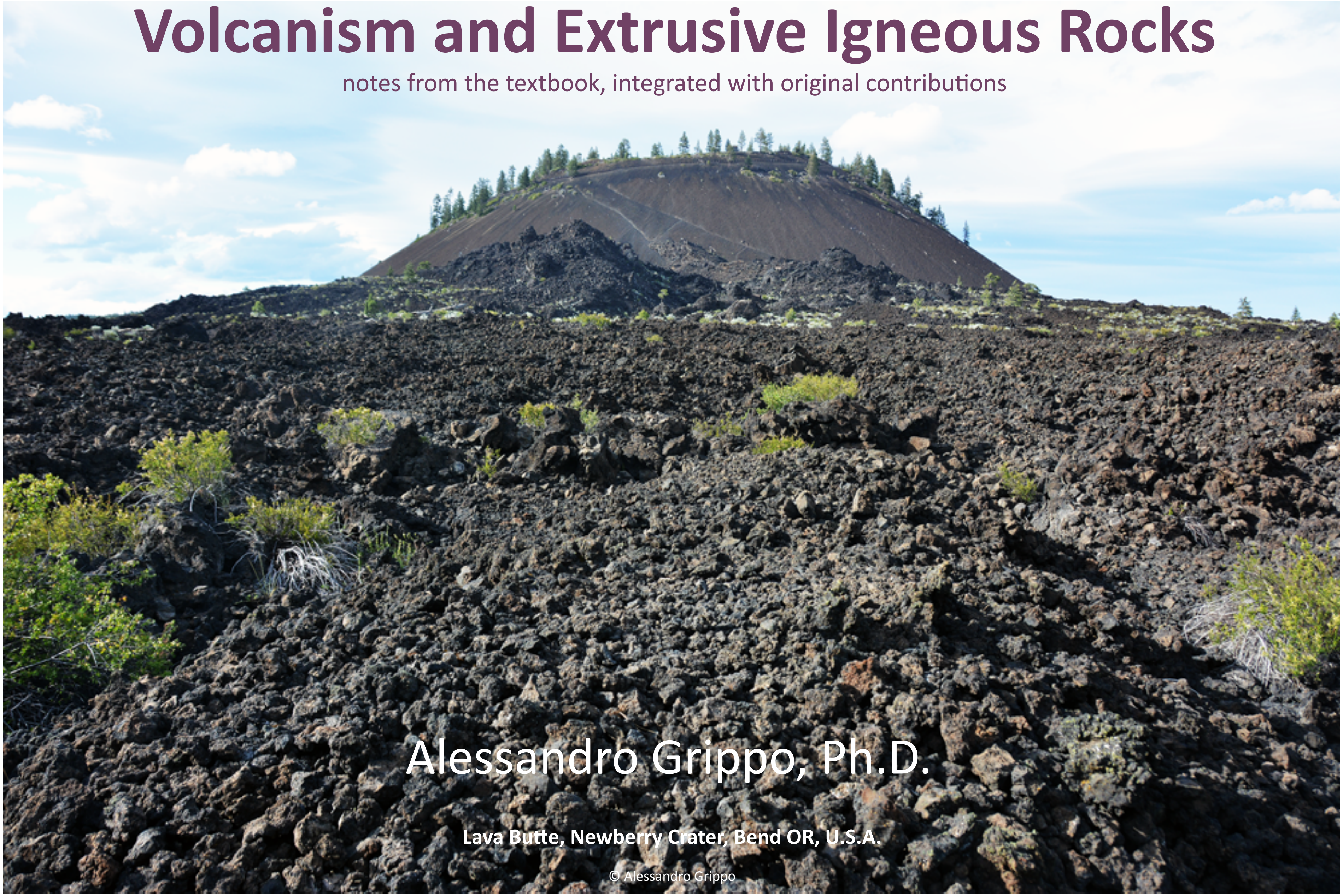


Lava Butte, Newberry Crater, Bend OR, U.S.A.

What Are Volcanoes

- Plutonism vs. Volcanism
- Magma vs. Lava

- Volcanoes are landforms originating by either:
  - extrusion of lava from a vent (lava flows)
  - ejection of rock fragments from a vent (explosions)

Top: **Volcan Momotombo, Nicaragua**
Bottom: **Amboy Crater, California, U.S.A.**

Why Should We Study Volcanoes

- Volcanoes come in many shapes and sizes
- Eruptions can vary widely in duration, violence, and the type of material erupted

- Volcanoes should be studied because:
  - we need to mitigate the consequences of their activity
  - we get information on processes occurring in the mantle
  - they can affect global climate
  - they can create new land
  - they can provide geothermal energy

effects on climate

- Volcanic gases originated Earth's early atmosphere (remember that oxygen is not a volcanic gas, and it was added later through photosynthetic activity)
- Volcanic gases such as CO_2 can have the opposite effect by increasing the amount of greenhouse gases, causing global warming

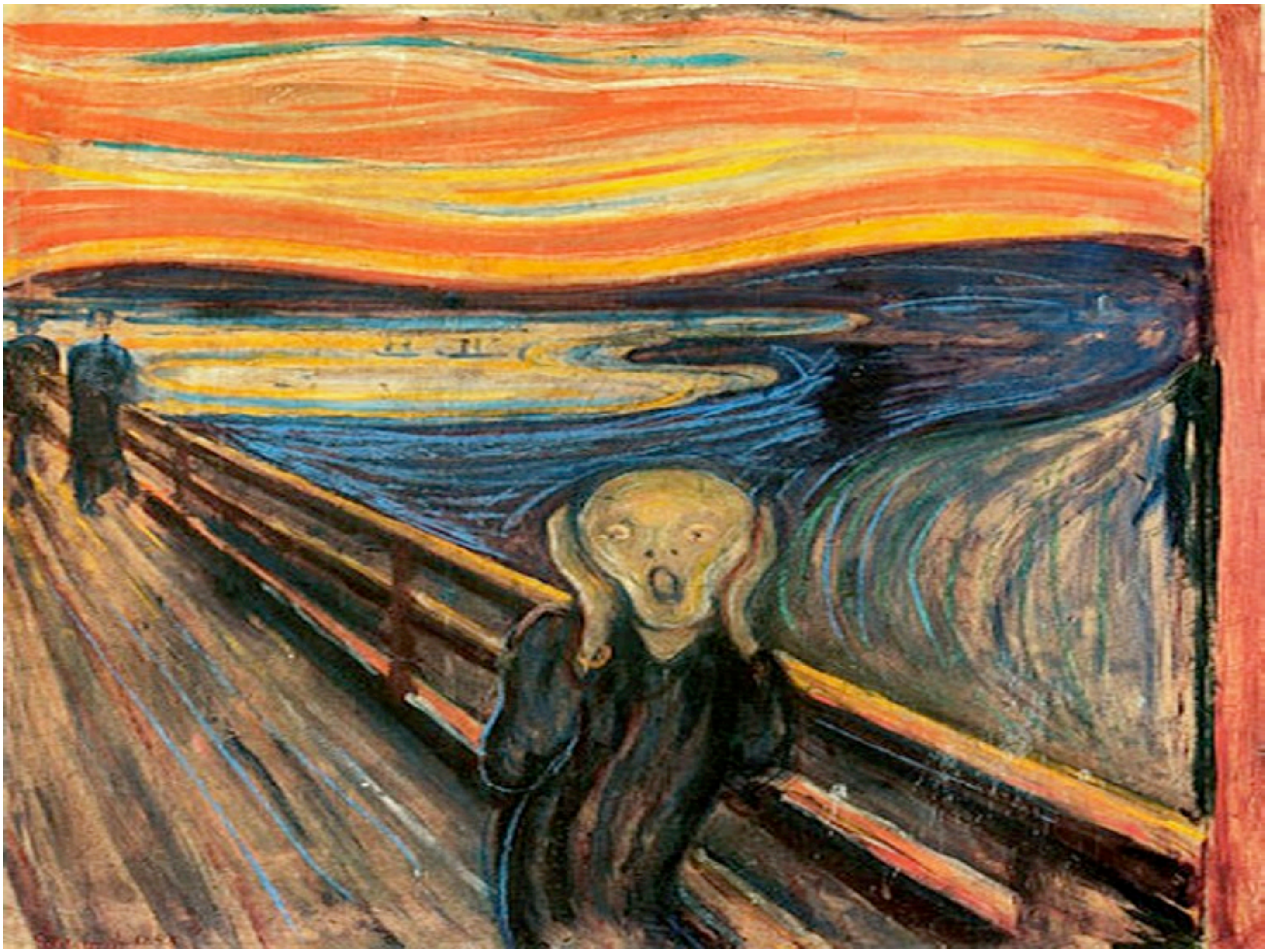
Volcanic gases released along the flanks of Mauna Loa
Hawaiian Volcanoes National Park, Hawai'i

- Volcanic dust can enter, even today, into the high atmosphere, reducing solar radiation penetrating through it (dark particles would absorb radiation), and causing global cooling

- 1816 was the "year without summer", a cool summer in Europe and North America that followed a giant eruption at Mount Tambora, in Indonesia

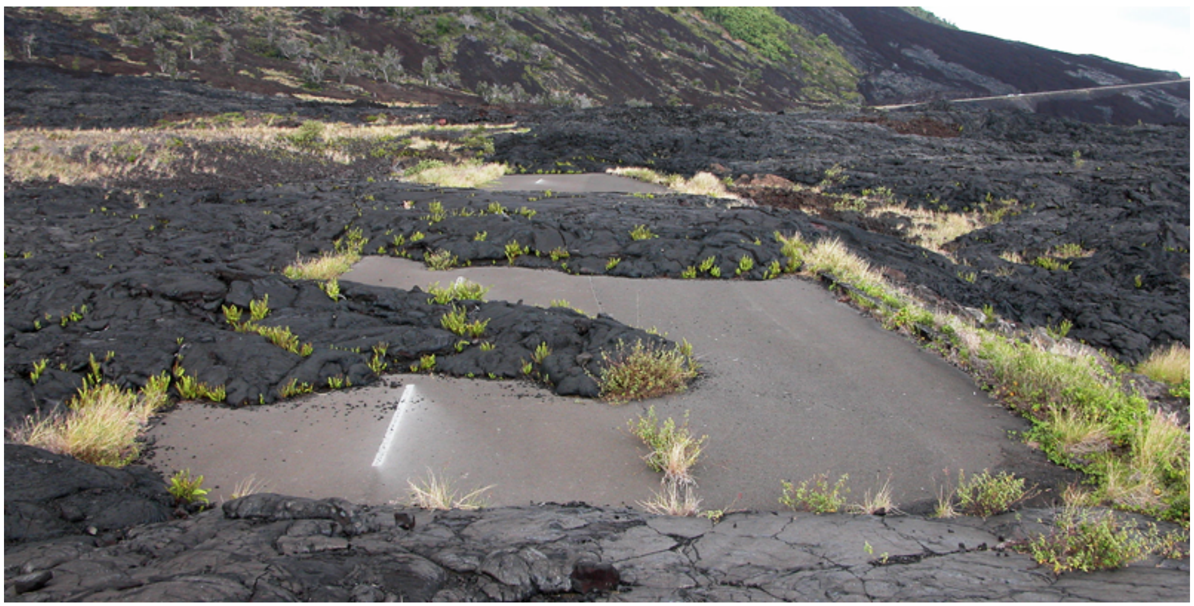
Edvard Munch's painting "The Scream"

depicts a red sky as it was seen in Oslo, Norway, and that developed as a consequence of debris ejected into the atmosphere by the eruption of Mount Krakatoa, Indonesia (1883)



formation of new land

- Volcanic eruptions in a place like Hawai'i can cause destruction but mostly add new land
- Hawai'i would not exist without volcanic activity
- Weathered volcanic ash and lava produce excellent, fertile soils
- Eruptions attract scientists and tourists, benefiting the Big Island economy



Lava flowed over pavement, destroying the road, but building up new land

Hawaiian Volcanoes National Park, Hawai'i, U.S.A.

geothermal energy

- In many parts of the world (U.S.A. Italy, Philippines, Indonesia, etc.), underground heat is harnessed for human needs
- Steam or superheated water is tapped to power turbines that generate electricity
- In Iceland, geothermal fluids are used for domestic heating

Geothermal plants (above) and geothermal well (left)

Salton Sea
Imperial County, California

Eruptive Violence and Physical Characteristics of Lava

TABLE 5.2 Volcanic Explosivity Index (VEI)

VEI	Eruption Type	Typical Volcano Type	Eruption Behavior	Plume Height	Ejecta Volume	Frequency	Eruption Examples
0	Hawaiian	Shield	Effusive, not explosive	< 100 m	< 10,000 m^3	Constant	Kilauea (1983–present)
1	Hawaiian/ Strombolian	Shield, Cinder cone	Effusive, mildly explosive	100–1000 m	< 10,000 m^3	Daily	Stromboli, Eldfell (1973)
2	Strombolian/ Vulcanian	Cinder cone, Stratovolcano	Mild	1–5 km	> 1,000,000 m^3	Weekly	Galeras (1993), Mount Sinabung (2010)
3	Vulcanian/ Peléan	Stratovolcano, Lava dome	Severe	3–15 km	> 10,000,000 m^3	Few months	Mount Unzen (1995), Nevado del Ruiz (1985), Soufriere Hills (1995)
4	Peléan/ Plinian	Stratovolcano	Cataclysmic	10–25 km	> 0.1 km^3	≥ 1 yr	Mount Pelée (1902), Eyjafjallajökull (2010)
5	Plinian	Stratovolcano	Cataclysmic	20–35 km	> 1 km^3	≥ 10 yrs	Mount Vesuvius (A.D. 79), Mount St. Helens (1980), Chaitén (2008; Figure 5. 6)
6	Plinian/ Ultra-Plinian	Stratovolcano, Continental caldera	Colossal	> 30 km	> 10 km^3	≥ 100 yrs	Krakatoa (1883), Mount Pinatubo (1991)
7	Ultra-Plinian	Continental caldera	Super-colossal	> 40 km	> 100 km^3	≥ 1,000 yrs	Mazama (5600 B.C.), Tambora (1815)
8	Supervolcanic	Continental caldera	Mega-colossal	> 50 km	> 1,000 km^3	≥ 10,000 yrs	Yellowstone (640,000 B.C.), Toba (74,000 B.C.)

Source: Based on "Volcanic Explosivity Index," Wikipedia, available at http://en.wikipedia.org/wiki/Volcanic_Explosivity_Index.

Flow or Explosion?

- Factors:
  - Amount of gas present in the magma
  - Viscosity (resistance to flow) of magma

  - The greater the amount of gases in lava and the higher its viscosity, the more violent the eruption

  - These factors also influence the shape and height of a volcano

- Lava is a mixture of molten silicate rocks (melt) but also solid crystals and various gases

A

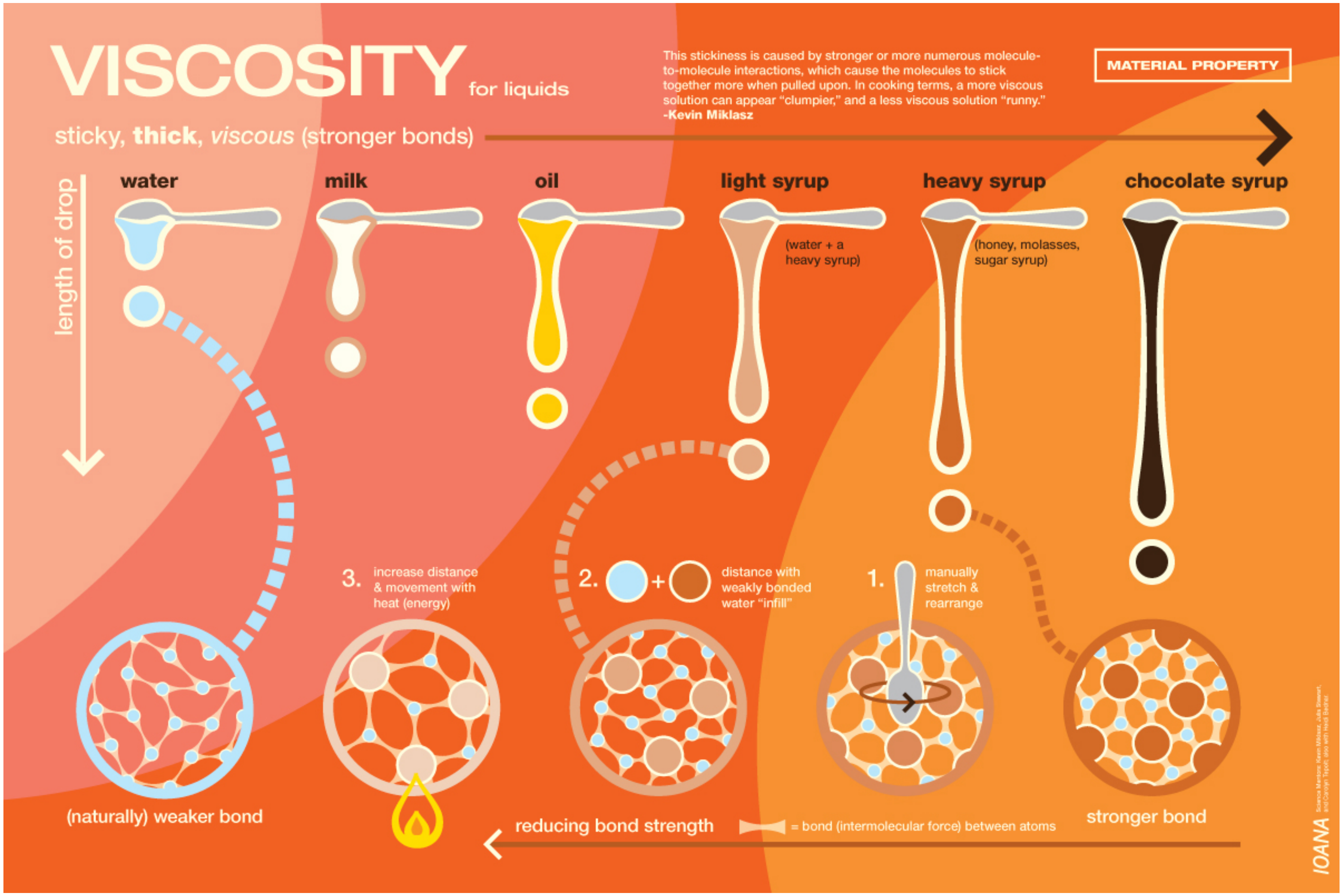
Porphyritic Andesite
This rock formed from cooling of lava that already contained solid crystals at the moment of solidification

Vesicular Basalt
This rock formed from cooling of lava at the moment gases dissolved in it expanded and escaped, leaving a trace in the rock (vesicles)

What controls lava viscosity?

– Temperature
  - high temperature lavas are more fluid
– Composition (silica content)
  - high silica content increases viscosity
– Amount of dissolved gases
  - high amounts of gases (including water vapor) make lava more fluid

apparent contradiction: explosive eruptions are driven by expansion of dissolved gases, but gases make lava more fluid



Mafic lava is about 10,000 times more viscous than water, whereas felsic lava is about 100,000,000 times the viscosity of water. This difference is function of the kinds of silicon tetrahedra bonds that would form when mafic and felsic lava start to cool: isolated tetrahedra, single and double chains would allow lava to be more fluid in mafic composition. When your lava instead is more felsic, relatively big clumps of framework silicates create obstacles to lava flow, thus increasing the viscosity

dissolved gases

- Most of gas released in eruptions consist of H_2O, condensing as steam
- Other gases, released in smaller amounts, include CO_2, SO_2, H_2S, HCl
- Gas content affects mobility
  - *more gases in lava make it more fluid* (like water in honey)
- Gases expand within magma as it nears Earth's surface (decreasing pressure)
  - So, intrusive igneous rocks would not let gases escapes, while extrusive igneous rocks will
- The violence of an eruption is related to how easily gases can escape from magma
  - more gases trying to escape would make the magma more viscous (note the apparent contradiction with the increase in mobility listed above)
  - a more felsic magma would also slow down the movements of gases, further increasing viscosity (and setting condition for volcanic explosions)

- Felsic lavas (rhyolitic) are the most viscous
  - expect explosive eruptions
- Mafic lavas (basaltic) are the least viscous
  - expect mostly lava flows
- Intermediate lavas (andesitic)
  - expect both explosions and flows, depending mostly on the amount of dissolved gases in the magma

- Surface water lowers the melting point of lavas, thus increasing explosivity (by increasing viscosity)

The Eruptive Products of Volcanoes

- A **vent** is the opening through which an eruption (lava flow or explosion) takes place
- A **crater** is a basin-like depression over a vent at the summit of a volcano
- A **caldera** is a volcanic depression whose size diameter is at least 1 km (0.6 mi)
- Materials can sometime be ejected from the side of a volcano. In that case we speak of a **flank eruption**

vent, crater, and caldera
Karymsky volcano, Kamchatka peninsula, **Russia**

Effusive Eruptions (Flows)

- Effusive eruptions are commonly basaltic, due to the low viscosity of mafic lavas
- Intermediate and felsic lavas can erupt effusively (producing andesite, rhyolites and obsidian) if the gas content is quite low

an obsidian effusive structure: Obsidian Butte

Calipatria, California, U.S.A.

Flows:

- **Pahoehoe** flows vs. **A'a** lava flows

Pahoehoe flow

Pāhoehoe flows have smooth or ropy surfaces and normally begin as very thin flows (less than 1 ft/ 0.3 m). Common on flatter ground, they flow relatively slowly

island of **Hawai'i, Hawai'i, U.S.A.**

A'a flow

'A'ā lava flows have a very rough, rubbly surface called "clinker" and a glowing, molten core that solidifies to very dense rock

island of **Hawai'i, Hawai'i, U.S.A.**

Pāhoehoe toes bud from the front of a flow. This close-up shot shows the stretched, glassy outer skin. When air first touches lava, it immediately begins to cool and harden to rock on the outside, but it stays hot and molten on the inside

- **Spatter cones** are small, steep-sided cones built from lava sputtering out of a vent

- **Lava tubes** are tunnel-like conduits for lava that develop after most of a pahoehoe-like flow has solidified. Tubes provide insulation so that lava inside remains fluid

A


Above: Thurston Lava Tube (Nahuku), Hawaiian Volcanoes National Park, **Hawai'i, U.S.A.**
Below: Mushpot Cave, Lava Bed National Monument, **California, U.S.A.**


- Lava that is very fluid and flows almost like water does not build a cone around a vent, but rather spreads in layers
- **Flood basalts** are vast outpourings of mafic lavas from fissures that can cover wide areas with multiple lava flows, building thick lava plateaus

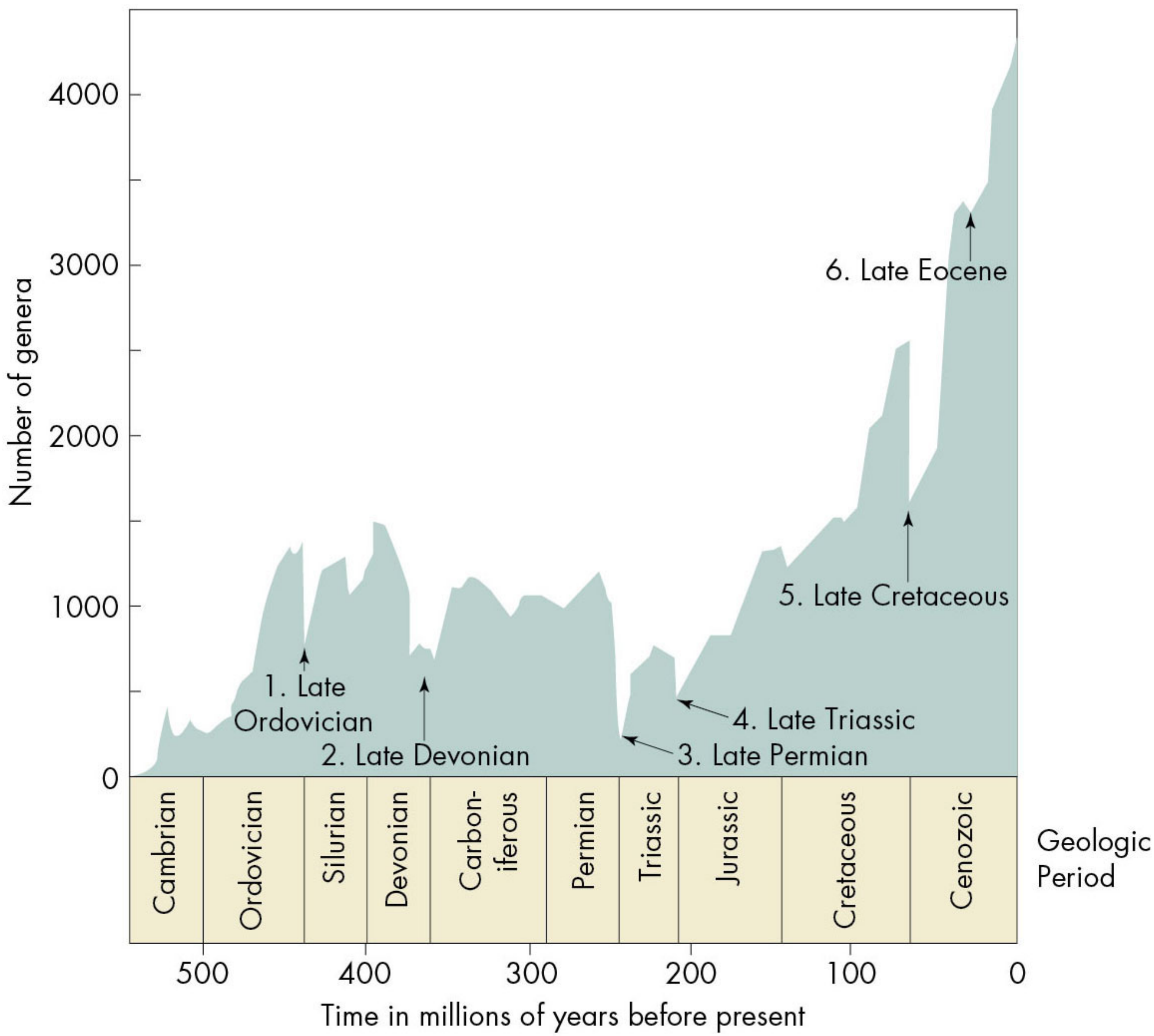
Horizontal beds of lava in the Columbia Plateau
Columbia River, separating Washington State (bottom) from Oregon (top)
Goldendale, Washington

Flood basalts produce large eruptions of CO_2, which would warm Earth (but remember that silica-rich explosions produce volcanic ash, which would reflect solar radiation, thus cooling Earth)

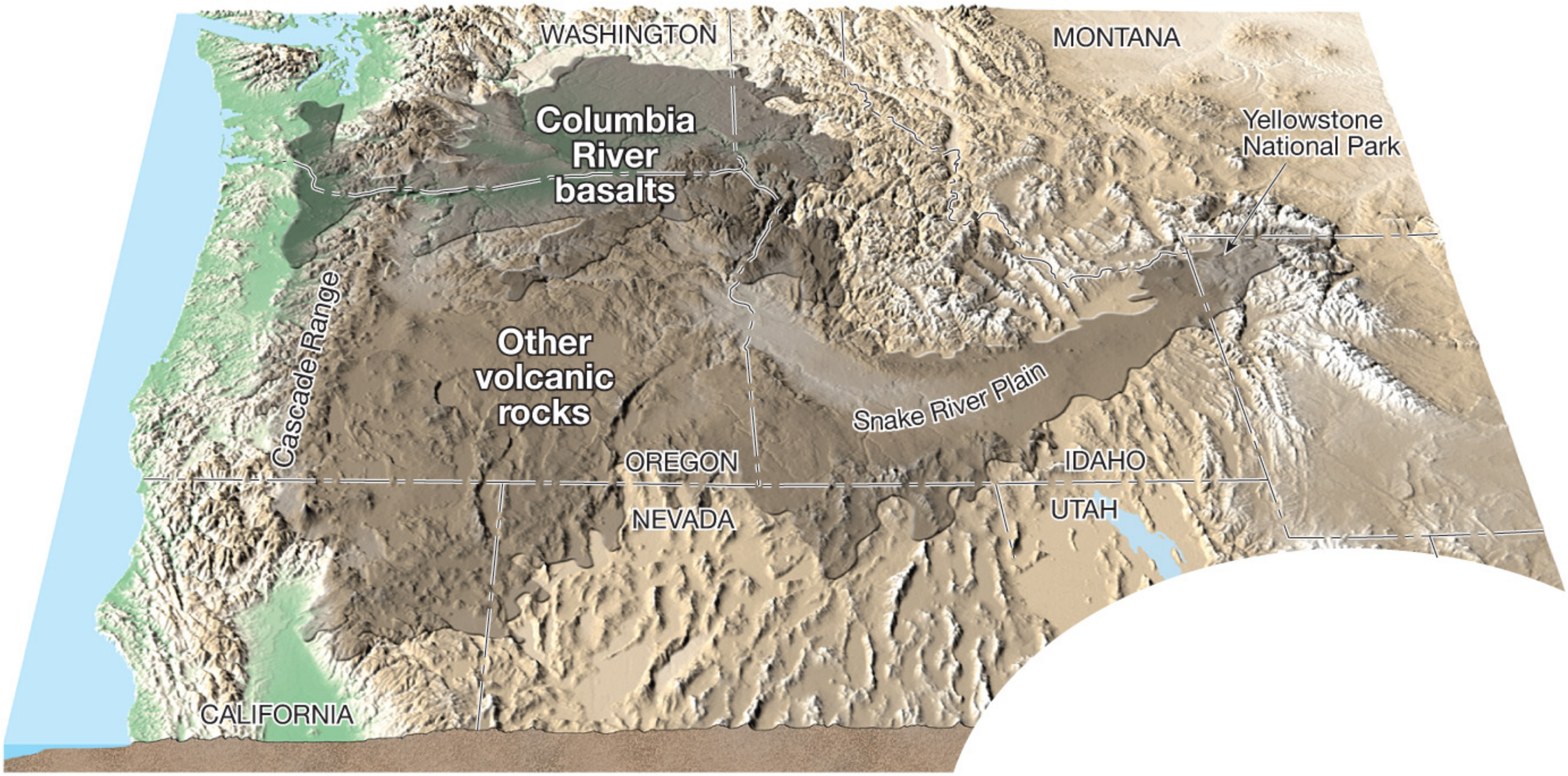
The Columbia Plateaus area of Washington, Idaho, and Oregon was built in the Miocene layer upon layer of basalt, in places as thick as 3000 m. Larger lava plateaus exist in Siberia, Russia (Siberian Traps) at the Permian/Triassic boundary, and in India (Deccan Traps), at the Cretaceous/Paleogene boundary. Could they have had a role in the mass extinction episodes that occurred at that time?

Basalt plateaus also form in oceans, such as the Ontang Java Plateau, in the SW Pacific

mass extinctions of the Phanerozoic



the Columbia Plateau



A.

columnar jointing

- distinctive pattern of fractures that originates most commonly 6-sided (sometimes 4, 5, or 7) hexagonal vertical columns
- forms because of shrinking of basalt, causing tension cracks to form between centers of contraction
- sometimes, other mafic to intermediate composition can develop similar patterns

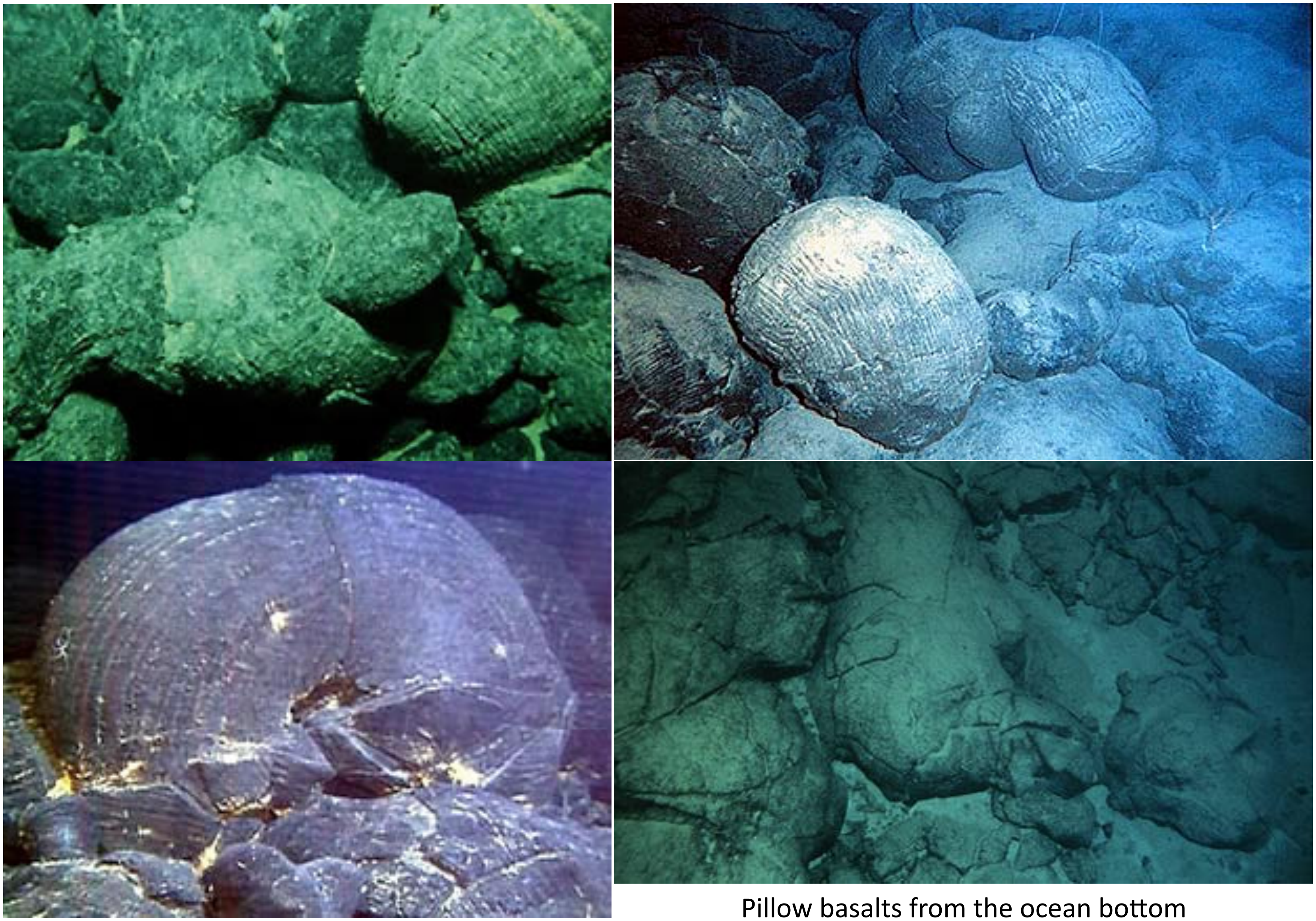
Columnar basalt
Giant's Causeway (Clochán an Aifir)**,**
Ulster (Northern Ireland), United Kingdom

Columnar basalt

Devil's Tower, Wyoming, U.S.A.

submarine lava flows

- when lava erupts into water, it cools rapidly forming a pillow structure (pillow basalt)
- magma that cannot come to the surface solidifies in fractures as dikes
- when lava flows enter the ocean, as in Hawai'i, lava shatters



Pillow basalts from the ocean bottom

Archean pillowed Greenstones (metamorphosed pillow basalts)

Gilbert, Minnesota, U.S.A.

Lava cooling and shattering upon entering the Pacific Ocean

Hawai'i, U.S.A.

intermediate and felsic lava flows

- these are less common because of higher viscosity
- when they flow, they tend to form smaller lava bodies
- if the lava is too viscous to flow, it will build up a lava dome

Obsidian Dome
Owens Valley, California, U.S.A.

Explosive Eruptions

- Explosive eruptions are driven by the expansion of gases in viscous magma

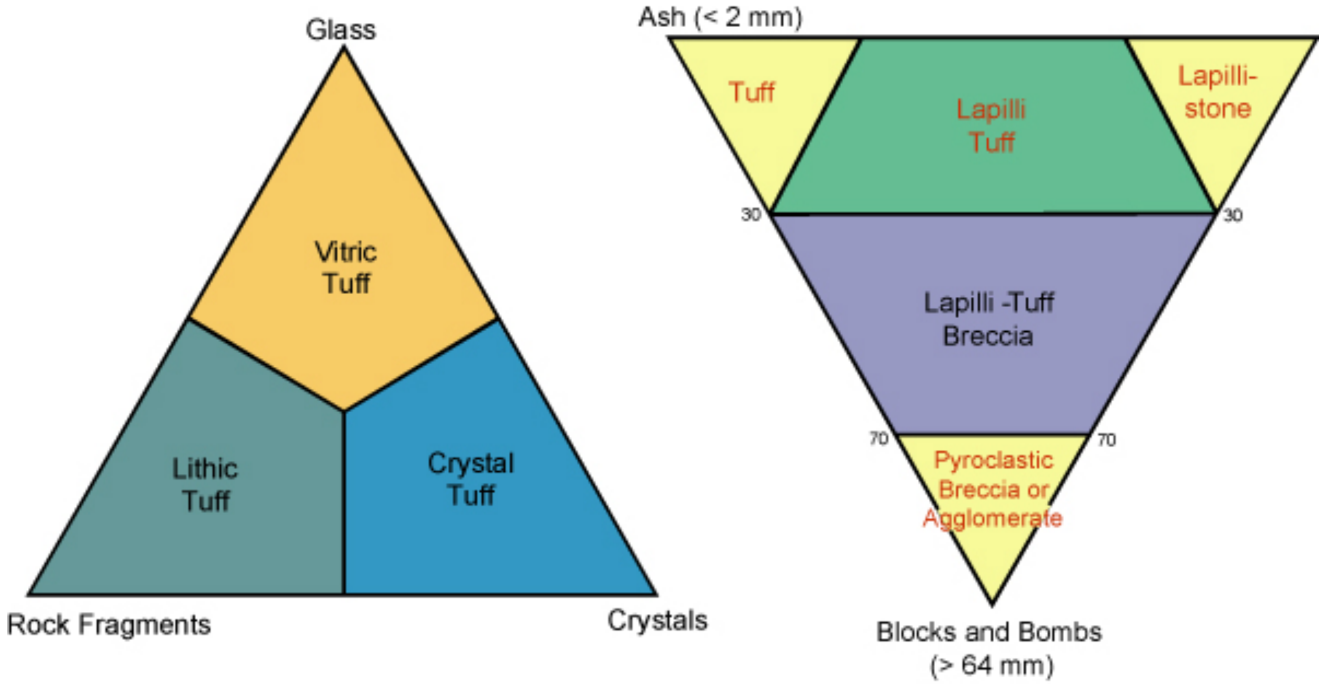
- At depth, gas is kept dissolved by pressure
- Towards the surface, the decrease in pressure causes the gas to come out of solution and expand

- During an explosive eruption, hot gases fragment the rapidly cooling magma into pieces and blast them into air
- These fragments are called pyroclasts
- Hot gas and pyroclasts are blasted upward as a plume, which draws air as it rises

pyroclastic materials

- known collectively as tephra, pyroclasts are classified according to their size
  - Bombs (> 64 mm): generated when molten blobs of lava are ejected into the air, becoming lens-shaped and streamlined during solidification
  - Blocks (> 64 mm): generated as angular fragments when explosion blast apart already existing rocks
  - Lapilli (2 – 64 mm)
  - Cinders: general term for small size pyroclasts
  - Ash (1/8 - 2 mm)
  - Dust (< 1/8 mm): fine, glassy fragments

Pyroclastic rock classification



(a) type of material **(b) size of material**

- during an eruption, expanding hot gases can propel pyroclasts high into the atmosphere as a column rising from a volcano
- at high atmospheric altitudes, pyroclasts often spread out into a dark mushroom cloud
- fine particles can be transported by high atmospheric winds
- eventually, debris settles back to Earth as pyroclastic fall (ashfall or pumice fall) deposits

Mount Etna eruption, December 2015
Catania, Sicily, Italy

pyroclastic flows

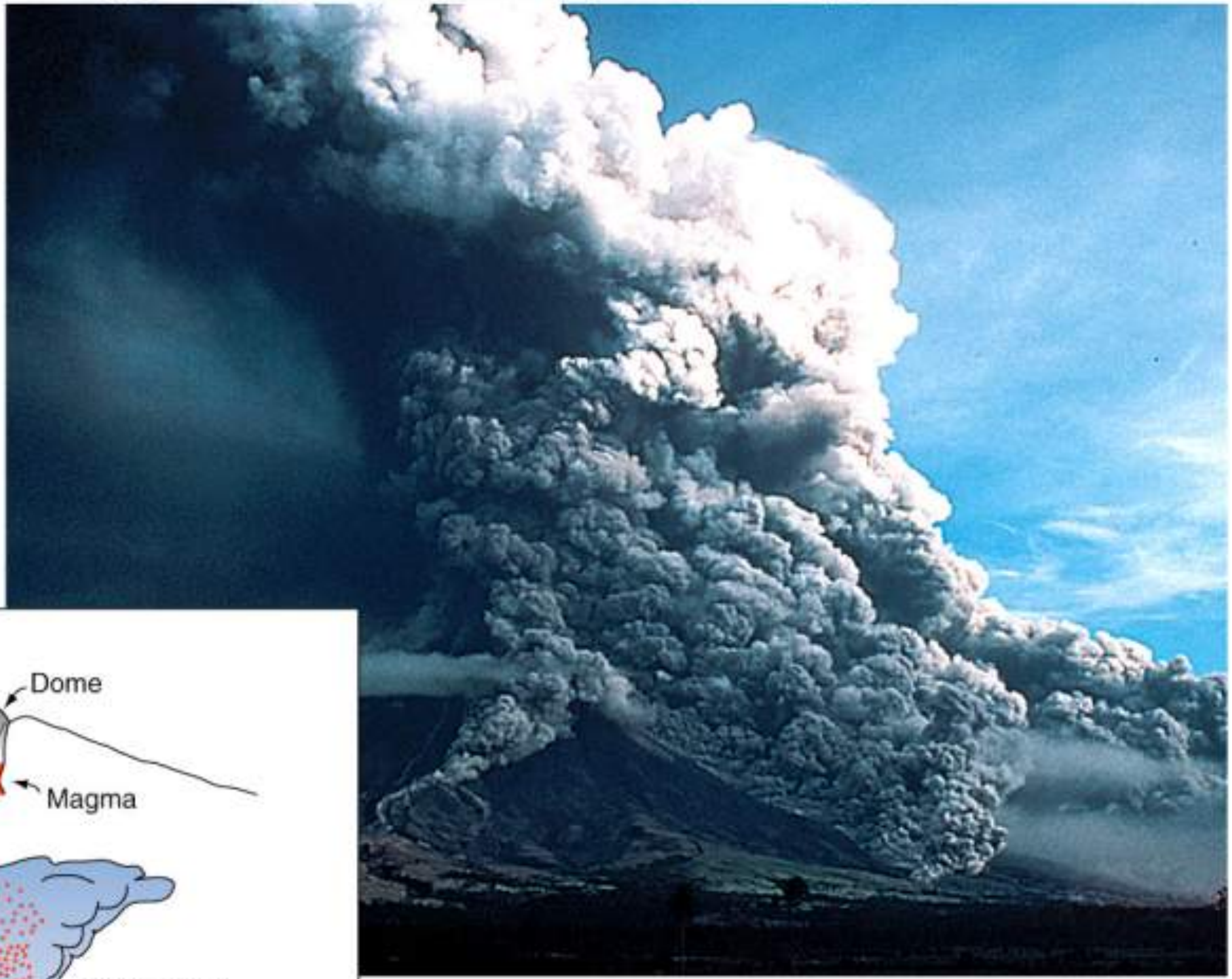
- mixtures of gas and pyroclastic debris that are so dense that they move on the ground while flowing rapidly into low areas
- some flows are associated with volcanic domes
- some flows result from collapse of a column of gas and pyroclastic debris that was initially blasted vertically into the air

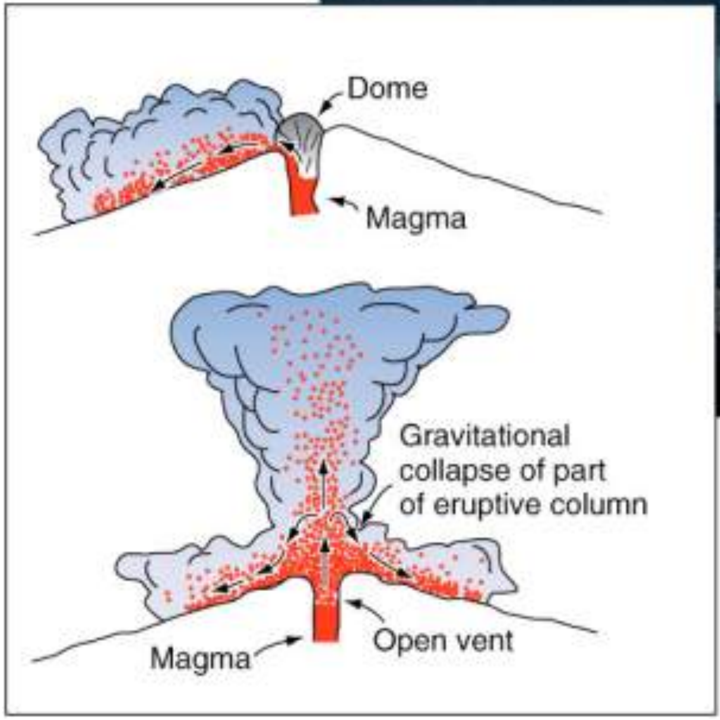
- pyroclastic flows can travel up to 200 km/h and are extremely dangerous

- Mt. Unzen (Japan, 1991)
- St, Pierre (Martinique, 1902)

B.

Pyroclastic flow (1991)
Mount Unzen, Japan

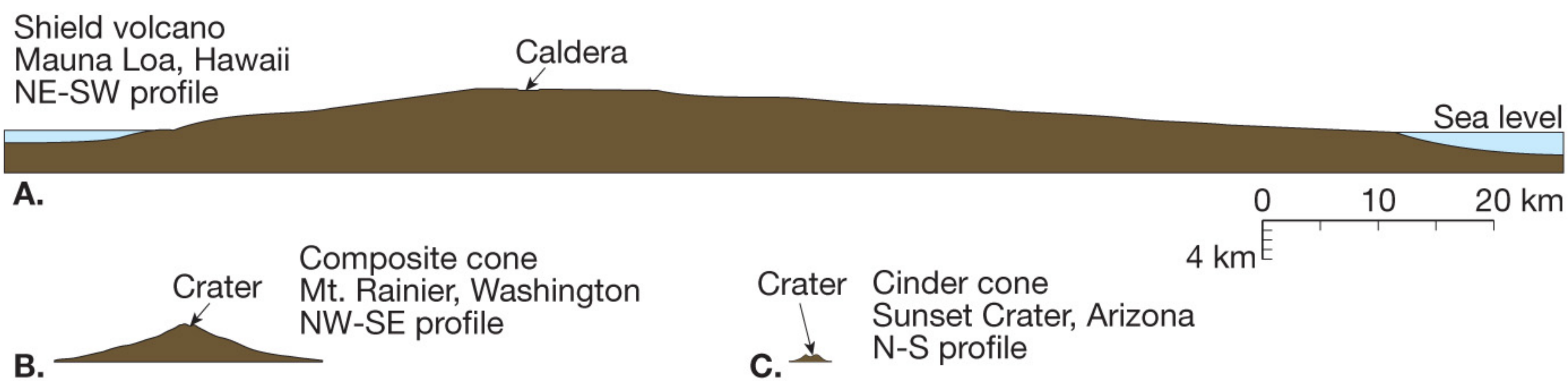



Dome
Magma
Gravitational
collapse of part
of eruptive column
Magma
Open vent

Destruction following the 1902 pyroclastic flow
St. Pierre, Martinique (part of the Caribbean volcanic arc)

Types of Volcanoes

- The major types of volcanoes are markedly distinct one from the other
  - Shield volcanoes, Composite Cones (or Stratovolcanoes, Cinder Cones, Lava Domes, Calderas



Shield Volcanoes

- Broad, gently sloping volcanoes constructed of solidified lava flows
- effusive eruptions at low viscosity (mostly basalt)
- lava spreads widely and thinly during eruptions due to its low viscosity
- gentle slopes create a flattened dome, or “shield”
- examples: Hawaiian Islands
- generally non-violent eruptions
- common features include pahoehoe and a’a lavas, spatter cones, lava tubes, etc.

a shield volcano: **Mauna Loa, Hawai'i**

Cinder Cones

- built of pyroclastic fragments ejected from a central vent and accumulating around a vent
- cinder cones are formed exclusively of pyroclasts and, because of that, they are steep and small
- they form because of gases buildup and are independent from composition
- most cinder cones are associated with mafic or intermediate lavas, but pumice cones (felsic) are also known
- they have short lives: gas is depleted rapidly during eruptions, and once they form, being formed by loose pyroclast, they tend to erode relatively easily

Sunset Crater, the tallest cinder cone in the continental U.S.

Flagstaff, Arizona, U.S.A.

Amboy Crater, a Mojave desert cinder cone

Amboy, California, U.S.A.

Amboy Crater

Clockwise from upper left: trail entrance; climbing the crater; the interior; rim and volcanic lava field around the crater

Amboy, California, U.S.A.

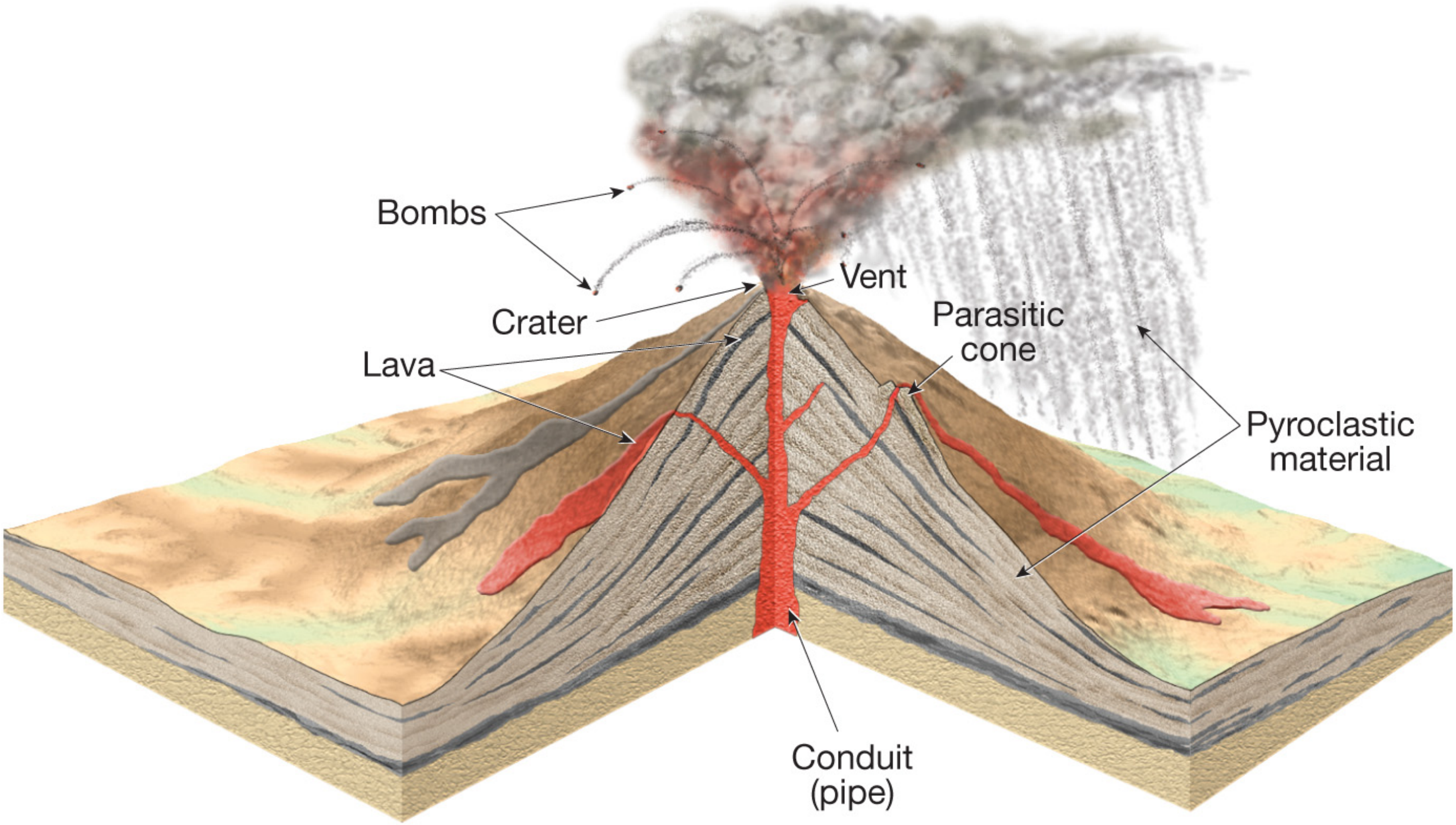
Panum Crater

Part of the Mono Craters of Mono Lake volcanic field, characterized by rhyolites and obsidians (felsic composition)

Lee Vining, California, U.S.A.

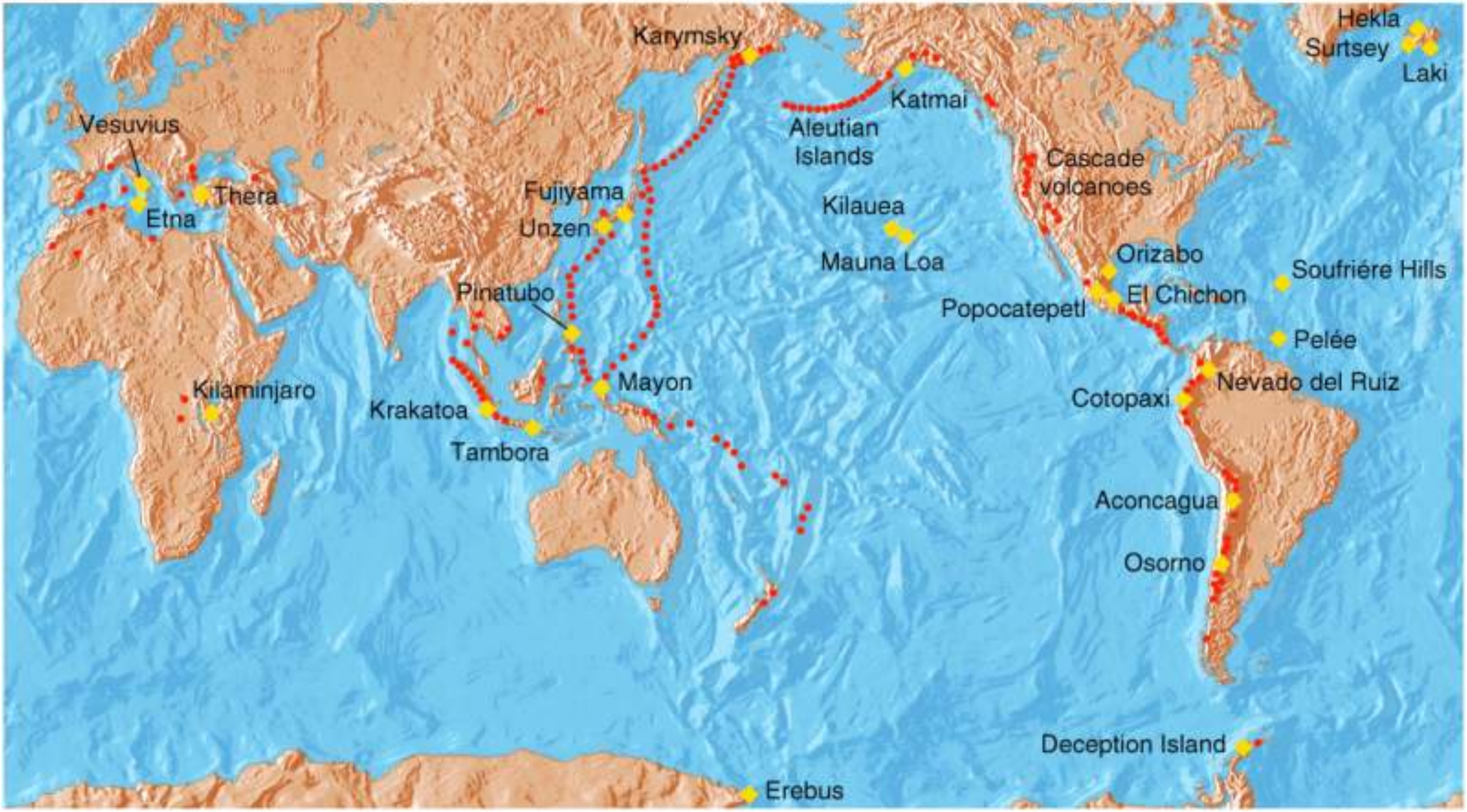
Composite Volcanoes

- also called stratovolcanoes, these volcanoes are built by alternating layers of pyroclastic fragments and solidified lava flows
- lava flows protect loose pyroclasts, allowing the volcano to grow in size over time
- eruptions are intermittent and volcanoes remain active (dormant) for thousands of years, during which the volcano is subject to natural phenomena like any other mountain
- mostly, lavas are intermediate in composition, but both felsic and mafic compositions occur
- dominant rock is andesite
- even in the same volcanic arc, composition and activity can be very different (Mount Rainier, mostly flows vs. Mount St. Helens, mostly eruptions)


Bombs
Vent
Crater
Parasitic
cone
Lava
Pyroclastic
material
Conduit
(pipe)

Distribution of Composite Volcanoes

- Nearly all the larger and better-known volcanoes of the world are stratovolcanoes
- There are two major belts
  - the circum-Pacific belt, also known as “Ring of Fire”, which is the largest of the two
  - the Mediterranean belt


Karymsky
Hekla
Surtsey
Laki
Katmai
Vesuvius
Aleutian Islands
Cascade volcanoes
Thera
Etna
Fujiyama
Unzen
Kilauea
Mauna Loa
Orizabo
Soufriére Hills
Pinatubo
El Chichon
Popocatepetl
Pelée
Mayon
Kilaminjaro
Nevado del Ruiz
Cotopaxi
Krakatoa
Tambora
Aconcagua
Osorno
Deception Island
Erebus

Cascades Volcanic Arc: Mount Rainier as seen from I-5

Seattle, Washington, U.S.A.

Cascades Volcanic Arc: Mount Shasta as seen from I-5

Weed, California, U.S.A.

the Cascades

- from Mount Garibaldi (British Columbia, Canada) to Lassen Peak (California) the continental arc of the Cascade is originated by subduction of the Juan de Fuca plate underneath the westward moving North American plate
- big cities such as Vancouver BC, Seattle WA, and Portland OR are in close proximity to these volcanoes
- famous volcanoes include Mount Baker, Mount Rainier, Mount St. Helens, Mount Hood, Crater Lake, and Mount Shasta

part of the Mexico volcanic arc, including (not all visible here):
Volcan Popocatepetl, Volcan Itzaccihuatl, and Nevado de Toluca
seen from **Xochimilco, Mexico D.F., Mexico**

the Andes
Volcan Villarica
seen from **Loncoche, Araucania, Chile**

Mount Fuji**, Japan**

Momotombo and Momotombito volcanoes
Leon Viejo, Lago de Managua, Nicaragua

A

the Mediterranean arc: Mount Vesuvius, Napoli (Naples), Italy

as seen from the ruins of the ancient Roman city of **Pompeii, Italy** (destroyed by an eruption in the year 76)

- The name “volcano” comes from the island of Vulcano (Italy), a cone that was already active in ancient times and that was identified as the location of the ancient namesake Greek/Roman god
- Vulcano, together with Stromboli and other islands, is part of the Isole Eolie, in the Mediterranean arc north of Mount Etna, the largest volcano in Europe
- In 1991, during an eruption of Mount Etna that lasted more than one year, experimental efforts to save a town from being buried by lava flows included building a dam to retain the lava, plugging some natural channels, and diverting lava into other, newly constructed channels

Lava Domes

- Lava domes are steep-sided, dome- or spine-shaped masses of volcanic rock formed from viscous lava that solidifies in or immediately above a volcanic vent

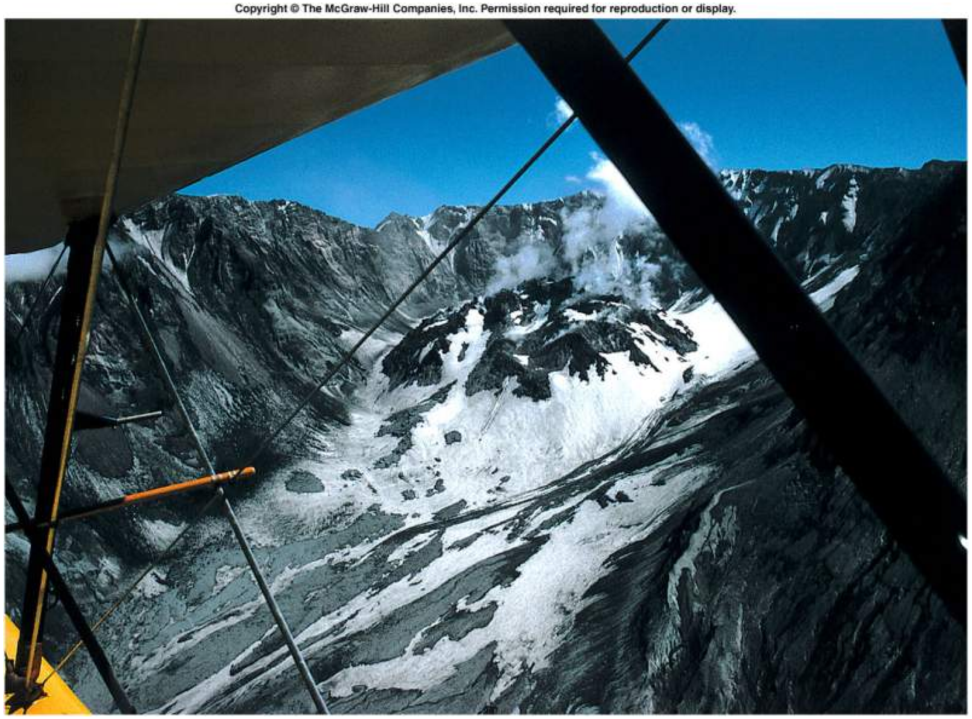
- Most of these lavas are very felsic, crystallizing as obsidian or, less commonly, rhyolite; andesite can also be found

- They often form within the crater of composite volcanoes, such as at Mount St. Helens

- Because this lava is so thick and viscous to flow, it builds up a steep-sided dome

- Some of the most destructive volcanic explosions known have been associated with lava domes

Lava Domes



Lava (volcanic) dome within the crater at
Mount St. Helens, Washington, U.S.A.

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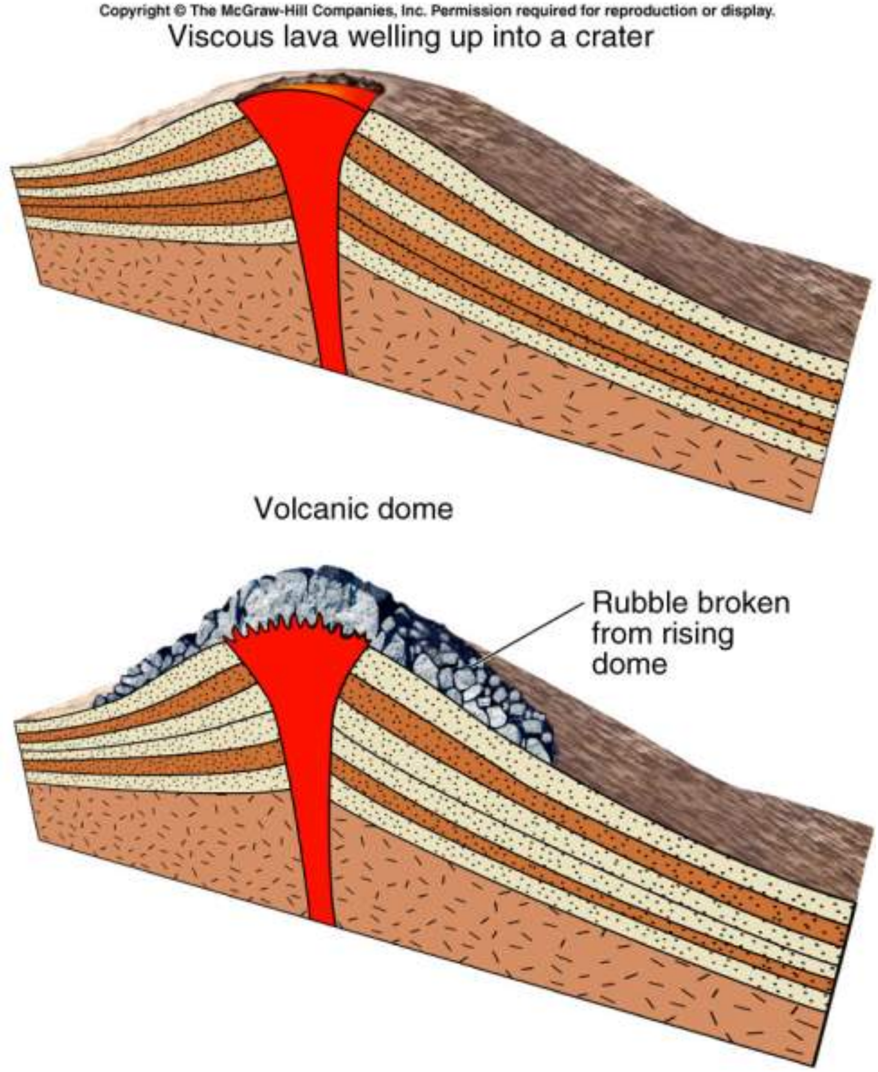


Calderas

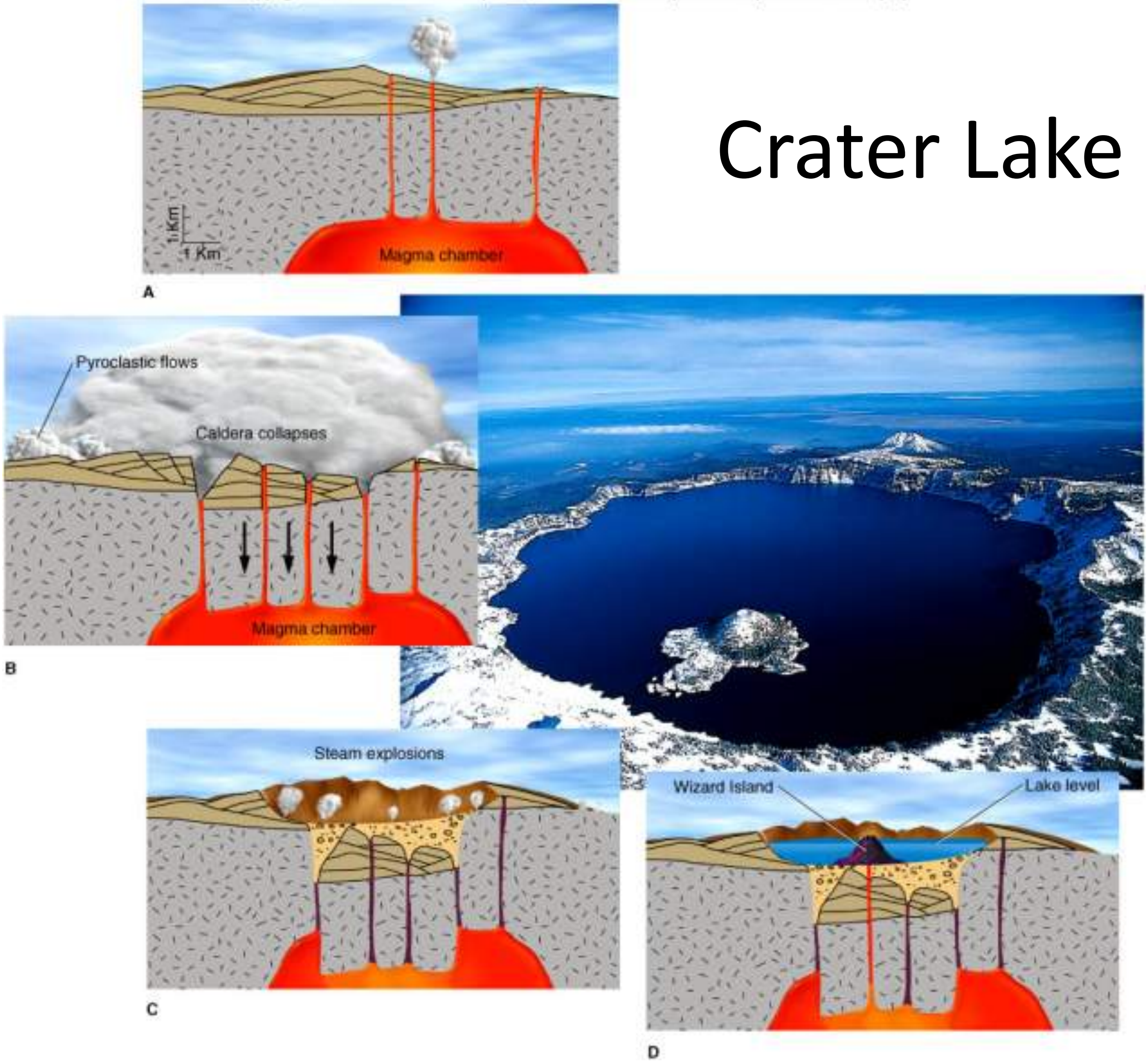
- Calderas are volcanic depressions having a diameter of at least 1 km
- Calderas can be created:
  - when a volcano’s summit is blown off by exploding gases
  - when a volcano (or several volcanoes) collapse into a partially emptied magmatic chamber

Calderas

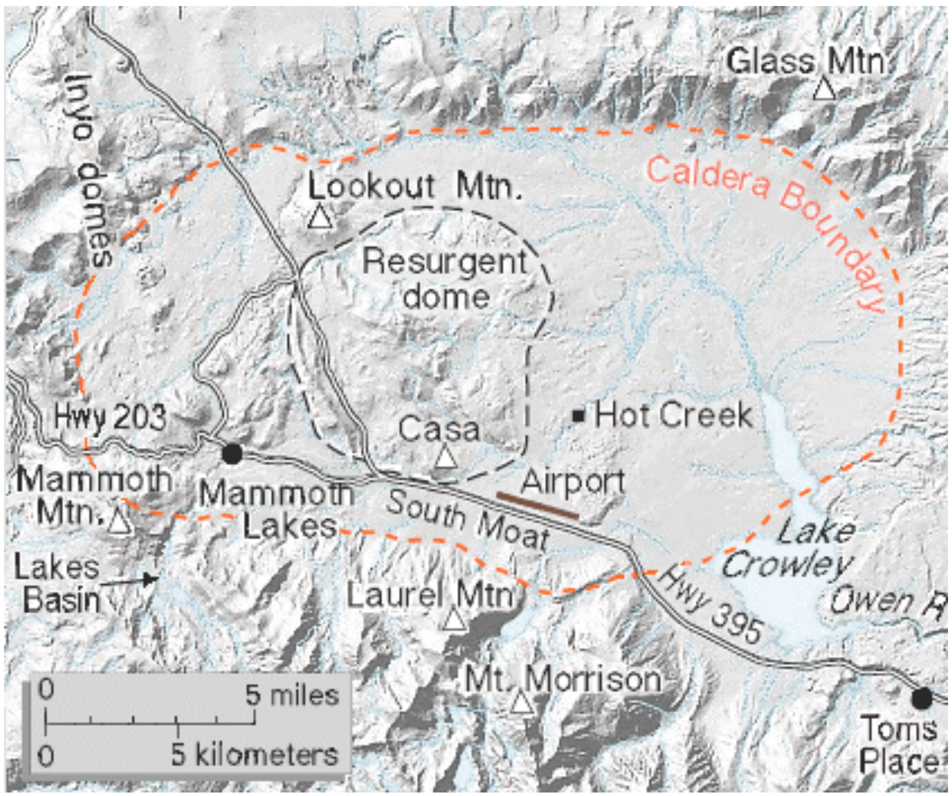
- Caldera-forming eruptions are extremely violent, blasting enormous amounts of pyroclast into the atmosphere and generating huge pyroclastic flows

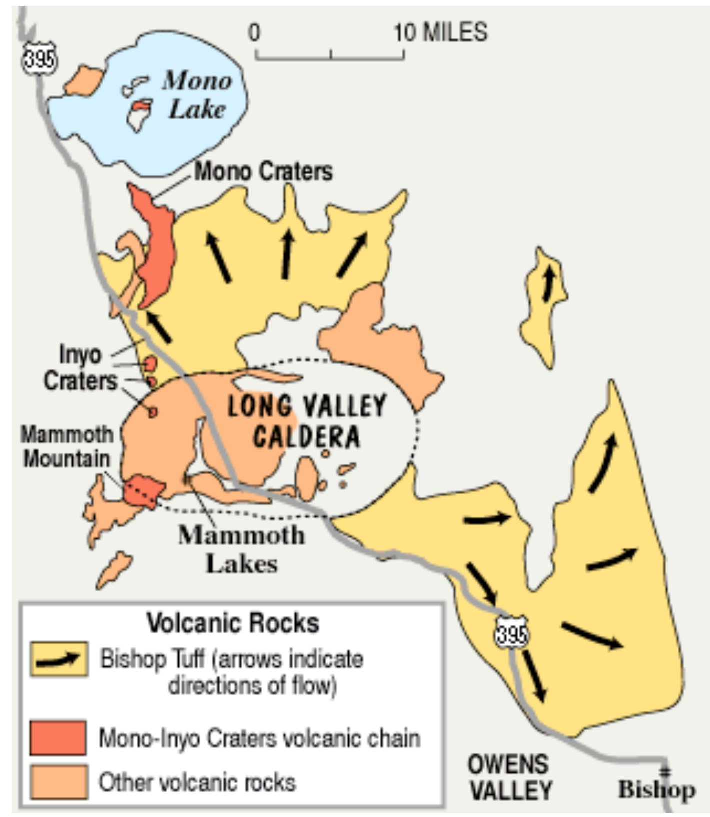
- Calderas in the United States include:
  - Crater Lake caldera, Oregon (collapse, dormant)
  - Yellowstone caldera, Wyoming (explosion, active)
  - Long Valley caldera, California (explosion, active)

Crater Lake Caldera

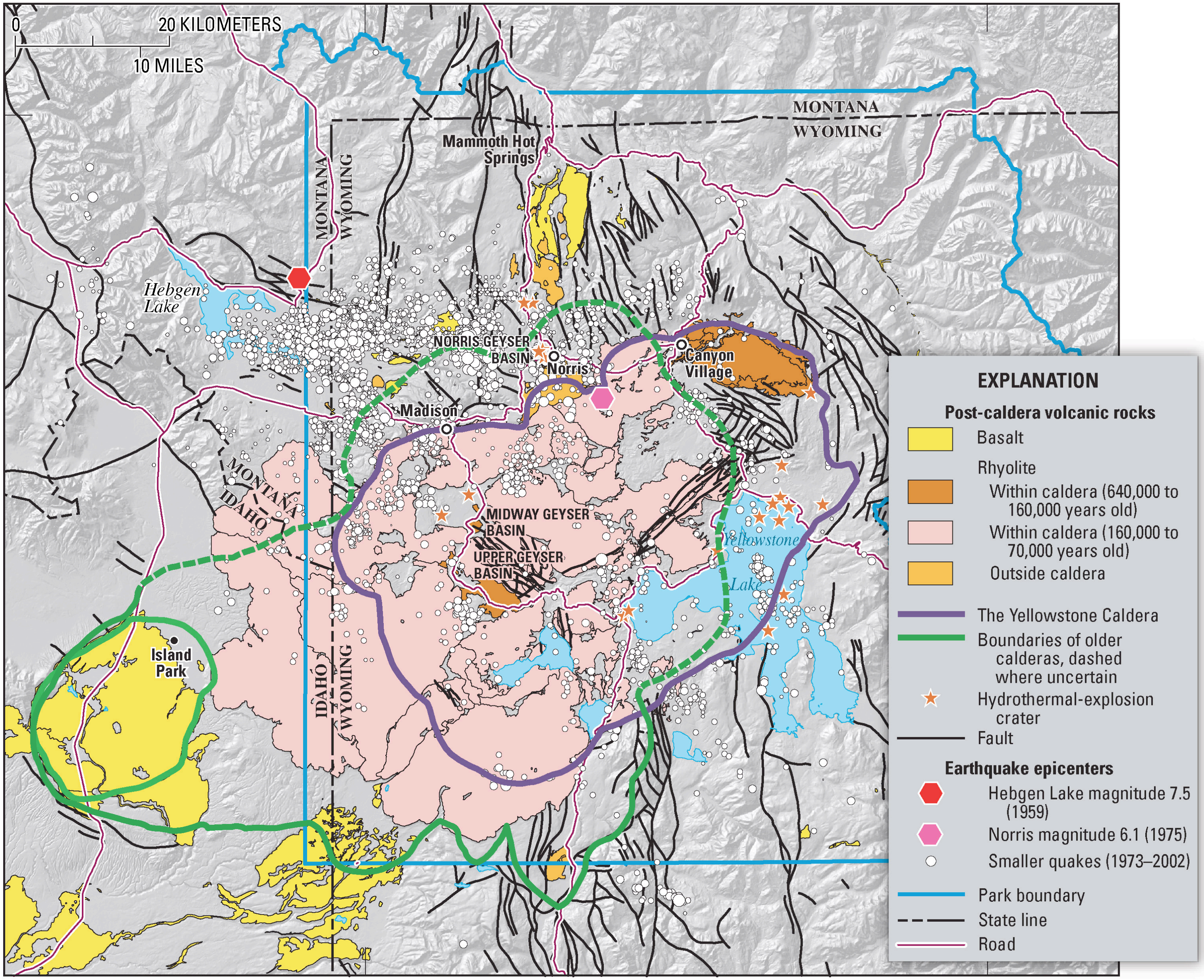


Long Valley Caldera





Yellowstone Caldera



Living With Volcanoes

- Hazards include:
  - ash clouds
  - pyroclastic flows
  - mudflows
- Reducing the impact of volcanic eruptions (mitigation) involves:
  - monitoring
  - hazard mapping
  - alerting populations about a potential eruption

- Volcanoes fatalities have increased recently not because of greater danger but because of increase in earth's population and encroaching around volcanic areas
- Volcanoes can kill with:
  - pyroclastic flows – Mount Unzen, Japan
  - pyroclastic (ash) falls – Pompeii, Italy
  - release of deadly gases – Lake Nyos, Cameroon
  - lahars – Nevado del Ruiz, Armero, Colombia
  - famine and crop destruction – Tambora, Indonesia
  - volcanic lightning – Paricutin, Mexico, and Chaiten, Chile

B

Molds or Roman citizens buried in the ash from Mount Vesuvius eruption in the year 76. People died of suffocation, under the collapse of building because of ash weight, or direct exposure to scorching temperatures in the hot pyroclastic surges of the eruption

Pompeii, Napoli, Italy

Monitoring Volcanoes

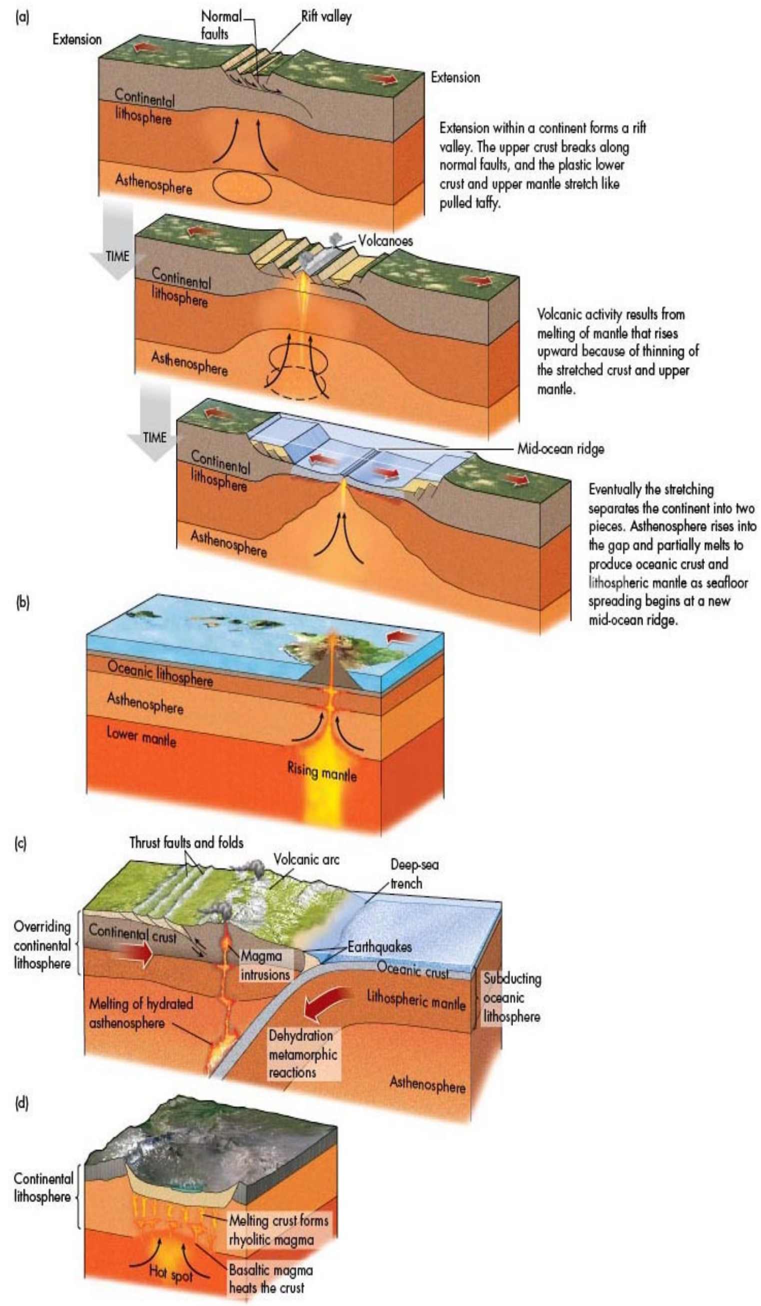
- Volcanoes can be:
  - active
    - currently erupting or has erupted recently
  - dormant
    - have not erupted in many thousands of years but are expected to at some point in the future
  - extinct
    - have not erupted for a very long time and show no signs of ever erupting again

Monitoring Volcanoes

- Volcanic hazard mitigation has three important components:
  - hazard mapping
    - study and mapping of ancient eruptions
    - maps allow creation of evacuation plans
  - monitoring
    - seismometers, tiltmeters, satellite and GPS observations
    - gas, heat, hot and cold springs monitoring
  - alerts
    - previous information is used to alert populations but also to assist the aviation industry (case of the 2010 Eyjafjallajökull eruption, in Iceland)

Plate Tectonics and Volcanism

- **Divergent Boundaries**
  - decompression partial melting creates basaltic magmas from mantle compositions
  - mid-ocean ridges, pillow basalts
  - exceptions, as in Iceland
  - almost always effusive eruptions
- **Convergent Boundaries**
  - flux melting (water injection), partial melting create andesitic to rhyolitic magmas
  - trenches, subduction, volcanic arcs (island and continental)
  - often explosive eruptions
- **Intraplate Volcanic Activity**
  - Hot Spots (Hawai'i, Columbia Plateau, Yellowstone)
  - type of eruptions function of location


(a)
Normal faults
Rift valley
Extension
Extension
Continental lithosphere
Asthenosphere
Extension within a continent forms a rift valley. The upper crust breaks along normal faults, and the plastic lower crust and upper mantle stretch like pulled taffy.
TIME
Volcanoes
Continental lithosphere
Asthenosphere
Volcanic activity results from melting of mantle that rises upward because of thinning of the stretched crust and upper mantle.
TIME
Mid-ocean ridge
Continental lithosphere
Asthenosphere
Eventually the stretching separates the continent into two pieces. Asthenosphere rises into the gap and partially melts to produce oceanic crust and lithospheric mantle as seafloor spreading begins at a new mid-ocean ridge.
(b)
Oceanic lithosphere
Asthenosphere
Lower mantle
Rising mantle
(c)
Thrust faults and folds
Volcanic arc
Deep-sea trench
Overriding continental lithosphere
Continental crust
Magma intrusions
Earthquakes
Oceanic crust
Subducting oceanic lithosphere
Melting of hydrated asthenosphere
Lithospheric mantle
Dehydration metamorphic reactions
Asthenosphere
(d)
Continental lithosphere
Melting crust forms rhyolitic magma
Hot spot
Basaltic magma heats the crust

the Mid-Atlantic Ridge in Iceland

on the left, North American Plate; on the right, European Plate

Volcanism and Extrusive Rocks

the end