Alpine Orogeny- and Tyrrhenian Basin opening-related Volcanism

Rhyolites, rhyodacites, trachytes and latites: lavas and pyroclastic rocks (71)
Andesites, latiandesites and alkaline basalts: lavas and pyroclastic rocks (72)
Tephrites, phonolitic K-tephrites, K-phonolites, foidites, melilitites and carbonatites: lavas, hyaloclastic and pyroclastic rocks (73)
Pleistocene-Holocene

Alkaline basalts with tholeiitic affinity: lavas
Pleistocene

Rhyolites, rhyodacites, pantellerites with subordinate quartz latites and trachytes: pyroclastic rocks and lavas (75)
Alkaline basalts: trachybasalts and andesites: lavas (76)
Pliocene-Pleistocene

Trachyandesites and basalts: lavas, pyroclastic and hyaloclastic rocks; locally interbedded carbonate sediments
Upper Miocene

Rhyolites and calcalkaline rhyodacites: pyroclastic rocks (78)
Andesites and calcalkaline-to-shoshonitic basalt: lavas and pyroclastic rocks (79)
Upper Oligocene-Middle Miocene
Etna Summit 1987
Cinder cone and ski area, Mt Etna 1987
Cinder cones, southeast flank Mt Etna 1987
Lava tube, Mount Etna, 1987
Lewis Periodic Table Showing Outer Shell (Valence) Electrons

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>Li</td>
<td>Be</td>
<td>B</td>
<td>C</td>
<td>N</td>
<td>O</td>
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<tr>
<td>Na</td>
<td>Mg</td>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
<td>Cl</td>
<td>Ar</td>
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<tr>
<td>K</td>
<td>Ca</td>
<td>Ga</td>
<td>Ge</td>
<td>As</td>
<td>Se</td>
<td>Br</td>
<td>Kr</td>
</tr>
<tr>
<td>Rb</td>
<td>Sr</td>
<td>In</td>
<td>Sn</td>
<td>Sb</td>
<td>Te</td>
<td>I</td>
<td>Xe</td>
</tr>
<tr>
<td>Cs</td>
<td>Ba</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What do these have in common?

The Moon and Earth

The Willamette Meteorite

http://eoimages.gsfc.nasa.gov/images/imagerecords/3000/3020/apollo_lrg.jpg

http://blog.oregonlive.com/clackamascounty/2007/10/BigMeteor.JPG
What do these have in common?

The Earth

The Willamette Meteorite

Whole Earth

http://www.indiana.edu/~geol116/week2/earthcomp.jpg

http://blog.oregonlive.com/clackamascounty/2007/10/BigMeteor.JPG
What processes concentrate some elements in the crust?

Whole Earth:
- Oxygen: 30%
- Silicon: 15%
- Magnesium: 13%
- Aluminum: 1%
- Calcium: 1.1%
- Sulfur: 2%
- Nickel: 2.4%
- Other <1%

Crust:
- Oxygen: 46%
- Silicon: 28%
- Iron: 6%
- Aluminum: 8%
- Other 3.2%
- Potassium: 2.3%
- Calcium: 2.5%
- Magnesium: 4%

http://www.indiana.edu/~geol116/week2/earthcomp.jpg
Major elements: usually greater than 1%
SiO$_2$  Al$_2$O$_3$  FeO*  MgO  CaO  Na$_2$O  K$_2$O  H$_2$O

Minor elements: usually 0.1 - 1%
TiO$_2$  MnO  P$_2$O$_5$  CO$_2$

Trace elements: usually < 0.1% everything else

What processes concentrate the trace elements?

Abundance of the elements in the Earth’s crust

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt % Oxide</th>
<th>Atom %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td></td>
<td>60.8</td>
</tr>
<tr>
<td>Si</td>
<td>59.3</td>
<td>21.2</td>
</tr>
<tr>
<td>Al</td>
<td>15.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Fe</td>
<td>7.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Ca</td>
<td>6.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Mg</td>
<td>4.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Na</td>
<td>2.8</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Can we extract the trace elements economically? What geologic processes further increase their concentration?
What processes alter crustal composition?

- Magmatism
- Sedimentation
- Metamorphism
Magmatism produces these major element averages:

<table>
<thead>
<tr>
<th>Chemical analyses of some representative Igneous Rocks</th>
<th>Ultra-Basic</th>
<th>Basic</th>
<th>Intermed</th>
<th>Felsic</th>
<th>Intermed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peridotite</td>
<td>Basalt</td>
<td>Andesite</td>
<td>Rhyolite</td>
<td>Phonolite</td>
</tr>
<tr>
<td>SiO2</td>
<td>42.26</td>
<td>49.20</td>
<td>57.94</td>
<td>72.82</td>
<td>56.19</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.63</td>
<td>1.84</td>
<td>0.87</td>
<td>0.28</td>
<td>0.62</td>
</tr>
<tr>
<td>Al2O3</td>
<td>4.23</td>
<td>15.74</td>
<td>17.02</td>
<td>13.27</td>
<td>19.04</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>3.61</td>
<td>3.79</td>
<td>3.27</td>
<td>1.48</td>
<td>2.79</td>
</tr>
<tr>
<td>FeO</td>
<td>6.58</td>
<td>7.13</td>
<td>4.04</td>
<td>1.11</td>
<td>2.03</td>
</tr>
<tr>
<td>MnO</td>
<td>0.41</td>
<td>0.20</td>
<td>0.14</td>
<td>0.06</td>
<td>0.17</td>
</tr>
<tr>
<td>MgO</td>
<td>31.24</td>
<td>6.73</td>
<td>3.33</td>
<td>0.39</td>
<td>1.07</td>
</tr>
<tr>
<td>CaO</td>
<td>5.05</td>
<td>9.47</td>
<td>6.79</td>
<td>1.14</td>
<td>2.72</td>
</tr>
<tr>
<td>Na2O</td>
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<td>2.91</td>
<td>3.48</td>
<td>3.55</td>
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</tr>
<tr>
<td>K2O</td>
<td>0.34</td>
<td>1.10</td>
<td>1.62</td>
<td>4.30</td>
<td>5.24</td>
</tr>
<tr>
<td>H2O+</td>
<td>3.91</td>
<td>0.95</td>
<td>0.83</td>
<td>1.10</td>
<td>1.57</td>
</tr>
<tr>
<td>Total</td>
<td>98.75</td>
<td>99.06</td>
<td>99.3</td>
<td>99.50</td>
<td>99.23</td>
</tr>
</tbody>
</table>

This slide from: www.whitman.edu/geology/winter/ Petrology/Ch%2008%20Major%20Elements.ppt
Major Digression!

Atoms?

Elements?

Compounds?

Minerals?

Rocks?

What is going on here?
One Illustrated Helium Atom

http://schools-wikipedia.org/wp/a/Atomic_nucleus.htm
One Oxygen Atom

There are three factors that determine the electron configuration in an atom.

a) Attractive force from the nucleus to negative charged electrons.

b) Buoyant force exerted on the electrons by space matter in the atom.

c) Repulsive forces between electrons (electrons within a shell and electrons from inner and outer shells).

Since the incredibly constant density and elasticity of space matter at every fixed distance from the center of the nucleus of an atom, each of that region of space matter act as resonant columns with unique natural frequencies. Since the density of space matter decreases with the increasing of the distance from nucleus, each of the different space matter density regions act as shells.

Cross sectional diagram of an oxygen atom

Please note: Electrons in an electron shell will be configured in spherically.
One Silicon Atom

Electrons
Nucleus
Electron Shell
Need for electron

12 Silicon Atoms

Silicon Atoms sharing electrons to make each other happy.

http://electronics-for-beginners.com/pages/page/3/
Silicon Tetrahedron: the building block of most minerals
Nesosilicate:
- Garnet
- Fosterite
- Fayalite
- Kyanite
- Olivine
- Sillimanite
- Sphene
- Topaz
- Zircon

Sorosilicate
- Epidote
- Zoisite
- Bertrandite
- Idocrase

http://www.uwsp.edu/geo/projects/geoweb/participants/dutch/PETROLGY/NesoSoro.HTM
Single Chain: Pyroxenes (Augite, Diopside, Enstatite, Jadite)

http://www.earth.ox.ac.uk/~davewa/pt/pt02_px.html
Double Chains: Amphiboles (Hornblende, Riebeckite, Tremolite)
Cyclosilicate
Tourmalines
Beryl

Phyllosilicates
Micas
  Biotite
  Muscovite
  Lepidolite
  Phlogopite
Clays
  Chlorite Clay
  Kaolinite
  Pyrophyllite
  Talc
Prehnite
Serpentine

http://wwwuraniummineralscom/Tutorials/Silicates/Phyllosilicate
Aluminum Octahedron: A major component of clay minerals

http://pubpages.unh.edu/~harter/crystal.htm
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<tr>
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<td>99.3</td>
<td>99.50</td>
<td>99.23</td>
</tr>
</tbody>
</table>
Figure 18-2. Alumina saturation classes based on the molar proportions of $\text{Al}_2\text{O}_3/(\text{CaO+Na}_2\text{O+K}_2\text{O})$ (“A/CNK”) after Shand (1927). Common non-quartz-feldspathic minerals for each type are included. After Clarke (1992). Granitoid Rocks. Chapman Hall.
The rocks to the left do not fit easily into the chart above.
<table>
<thead>
<tr>
<th>Composition</th>
<th>FELSIC</th>
<th>INTERMEDIATE</th>
<th>MAFIC</th>
<th>ULTRAMAFIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock types</td>
<td>Granite Rhyolite</td>
<td>Diorite Andesite</td>
<td>Gabbro Basalt</td>
<td>Peridotite</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentage of mineral by volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthoclase feldspar</td>
</tr>
<tr>
<td>Quartz (Sodium-rich)</td>
</tr>
<tr>
<td>Plagioclase feldspar</td>
</tr>
<tr>
<td>(Calcium-rich)</td>
</tr>
<tr>
<td>Pyroxene</td>
</tr>
<tr>
<td>Muscovite</td>
</tr>
<tr>
<td>Biotite mica</td>
</tr>
<tr>
<td>Amphibole</td>
</tr>
</tbody>
</table>

Silica content: 40%
Sodium and potassium content
Iron, magnesium, and calcium content

Temperature at which melting starts: 1200°C

http://www-personal.umich.edu/~jmpares/igneous1.jpg
Summary of Digression:

Atoms - made of p, e, n

Elements - differ in number of p, e, n

Compounds - made of elements

Minerals - mostly silicates

Rocks - made of minerals
How do we get different magmas from a single melt?

Bowen’s Reaction Series

- Peridotite
- Basaltic
- Andesitic
- Granite

1200°C

Olivine → Pyroxene → Amphibole → Biotite → Potassium Feldspar → Muscovite → Quartz

100% Ca Plagioclase

900°C

100% Na Plagioclase

600°C
AFM showing change of magma Composition from primitive to More evolved types.
What is “partial melting of the mantle?"

**Incompatible Elements**: elements that do not fit well in a mineral structure.

During partial melting the **incompatible elements** move from the solid mineral phase to the newly forming liquid phase.
Which elements are “compatible” with each other?

The Goldschmidt Classification of Elements

http://www4.nau.edu/meteorite/Meteorite/Images/GoldschmidtClassification.jpg
How to describe a volcanic hand specimen

Color?
Phenocrysts?
(visible grains)
Vesicles?
(pores/holes)

Grande Ronde Flow, Columbia River Basalt Group
Upper Clackamus River, Oregon
How to describe a volcanic hand specimen

Dark grey, Slightly vesicular basalt

Grande Ronde Flow, Columbia River Basalt Group
Upper Clackamus River, Oregon
Color?
Phenocrysts?
(visible grains)
Vesicles?
(pores/holes)

Lava flow hand specimen, Monte Somma, Naples, Italy
Medium to dark grey leucite basalt porphyry

Lava flow hand specimen, Monte Somma, Naples, Italy
Hand specimen lava flow, Craters of the Moon, Arco, Idaho
Dark reddish grey
Vesicular basalt

Hand specimen lava flow, Craters of the Moon, Arco, Idaho
Hand specimen, lava flow, Timberline Lodge, Mt Hood, Oregon

Color?
Phenocrysts?
Vesicles?

Grain size?
Hand specimen, lava flow, Timberline Lodge, Mt Hood, Oregon

Andesite

Grain size?
Do your labels distinguish these four samples?
Air Fall Tuff

Coldwater Canyon, Mount St Helens, Washington
Color?
Penocrysts?
Vesicles?

Grain size?
Light to medium grey Pumice

East flank, South Sister, Oregon Cascades
Color?
Phenocrysts?
Vesicles?

Grain size?
Medium Grey vesicular, glassy, rhyodacite

Rock Mesa, west flank South Sister, Oregon Cascades
Geological map of Mount Etna from INGV Catania web site (courtesy of Stefano Branca).

Key: (1) Recent alluvial deposits;

(2) Mongibello (past 15,000 years) eruptive products
(2a) "Chiancone" volcanioclastic debris deposit;

(3) Ellittico eruptive products;

(4) Valle del Bove centers eruptive products;

(5) Timpe phase eruptive products;

(6) Basal Tholeiites;

(7) Sedimentary basement;
"Faglia" = fault, 
"Orlo della Valle del Bove" = Valle del Bove rim; "Crateri Sommitali" = Summit craters
Figure 2 - Cross-section sketch, NNW-SSE (Randazzo – Summit area - Acireale) of Mount Etna, showing the relationship between the main units within the volcanic sequence and the underlying basement. Note the different scale of elevations above and below sea level (lm). Mb: Mongibello Unit; TR: Trifoglieto Unit; BU: Basal volcanic Units (older than 80 ka); SB: Sedimentary Basement Successions; MR: Main magma reservoirs; C: Continental crust; M: Mantle.
<table>
<thead>
<tr>
<th>Synthème</th>
<th>Lithosomatic Unit</th>
<th>Unit</th>
<th>Centre (Edifice)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Il Piano</td>
<td>Ellittico</td>
<td>MONGIBELLO</td>
<td>Recent Mongibello</td>
</tr>
<tr>
<td>Le Concaze</td>
<td>Pomiciaro</td>
<td>Ellittico</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tripodo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuvigliani</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Giannicola</td>
<td>Salifizio</td>
<td>TRIFOGLIETTO</td>
<td>Trifoglietto 2</td>
</tr>
<tr>
<td></td>
<td>Giannicola Grande</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trifoglietto</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rocca Capra</td>
<td>ANC. ALK. CENTRES</td>
<td>Trifoglietto 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Culanaa</td>
</tr>
</tbody>
</table>

Table 1 - Tentative correlation between UBS Units and earlier ones for the Etna succession more recent than above.

Figure 1 - Schematic representation of the Etna succession (modified after Cristofolini and Romano, 1982). RM: Recent Mongibello; AM: Ancient Mongibello; TR: Trifoglietto Unit; AAC: Ancient Alkaline Centres; BT: Basal Tholeiitic to transitional lavas (mostly subaerial); ET: Earliest Tholeiites (submarine and subvolcanic); SL: Sedimentary pleistocene Levels
Photo taken by Giuseppe Scarpinati on 22 July 2001
July 2001 Eruption

July 22, 2001

July 28 Piano del lago

July 28

F4 lava flow

1982 lava

1983 lava

Fig. 1 Eruptive and non-eruptive fissures and lava flows of the July–August 2001 eruption of Mt. Etna. Features and locations mentioned in the text are indicated. F1 Eruptive fissure at 3,050 m elevation (NNE side of Southeast Crater), active 17–25 July 2001. F2 Eruptive fissure at 2,950 m elevation (Torre del Filosofo vents), active 17 July–1 August 2001. F3 Eruptive fissure at ~2,700 m elevation, active 17 July–8 August 2001. F4 Eruptive fissure at 2,100 m elevation, active 18 July–9 August 2001. F5 Eruptive vents at 2,570 m elevation (Piano del Lago vents), active 19 July–6 August 2001. F6 Eruptive fissure at ~2,600 m elevation (Valle del Leone vents), active 20–29 July 2001. F7 Eruptive fissure at 3,050 m elevation (SE side of the Southeast Crater), active 23–25 July 2001. NEC Northeast Crater; VOR Voragine; BN Bocca Nuova; SEC Southeast Crater. Inset at upper left shows the 2001 lava flow fields and major population centers in the SE sector of Mt. Etna. Location of volcano is indicated in inset at lower left. Contours in meters.
Fig. 2  a Lava flows produced by 1995–2001 eruptions of summit craters of Mt. Etna. Contours in metres. b Sequence and character of eruptive events at the summit craters, 1995–2001. First four rows contain qualitative information regarding time, duration, and style of eruptive activity, and minor events are omitted. 1 More or less continuous mild Strombolian activity; 2 sporadic Strombolian activity and ash emissions; 3 more or less continuous emissions of (mostly lithic) ash; 4 episodes of violent fire-fountaining, tephra emission, often with fast-moving lava flows; 5 intermittent intracrater lava effusion; 6 lava overflows onto the external flanks of Etna. Gaps in the activity diagrams represent periods of quiet degassing. Periods of heightened activity at all four summit craters in 1997, 1998, and 1999 are clearly visible, whereas in 2000 and early 2001 most activity occurred at the Southeast Crater. Fifth row shows the approximate cumulative volume increase of lavas erupted between July 1995 and 17 July 2001. Note that the period covered in this diagram ends with onset of flank eruption on 17 July 2001.
Fig. 5 Comparative maps showing evolution of lava flow-fields produced by F1–F3 and F5–F7. 17–25 July All lava fields grow mainly downslope, but new lateral branches develop on 25 July below F2 and F3. 26–31 July Several distinct lava flows extend from F5 toward S and E, a new branch of lava extends S from F2, and flows from F3 are diverted by lavas from F5 toward SW. Little growth occurs at the F6 lava flow-field, and activity at F1 and F7 has ended. 1–9 August Only F3 and F4 remain active, with growth being restricted to the lava field emitted from F3.
Fig. 6 Comparative maps showing evolution of lava flow-field produced by F4. 17–25 July First major lava surge between 18 and 25 July generates the longest single flow unit of the entire eruption. 26–30 July Advance of the second lava surge (28–30 July). Note that during this period negligible net growth of the surface area of the lava flow-field occurred (mostly at its E-central margin). 31 July–9 August Advance of a small eastern lava branch (2–7 August) and progressive retreat of actively flowing lava (31 July–9 August), as effusion rate diminishes. Net growth of lava field during this period is about 0.4 km², compared to a total area of 2.4 km². Lava flows from F3 and F5 in the map area are not shown for clarity.
Fig. 9 A Hypothetical N–S section across the Piano del Lago–Montagnola area, showing possible stratigraphic relationships and inferred position of a shallow aquifer on top of an impermeable horizon, fed by meltwater currents from the summit area. Box indicates area enlarged in B and C. B Cartoon depicting magma–water interaction at F5 when the Fragmentation level (indicated by horizontal yellow arrow) was at about the same elevation (or immediately below) the assumed aquifer and Phreatomagmatic (Surtseyan) activity was generated (19–24 July). C The same scene, but during 25–31 July, when the Fragmentation level had risen above the aquifer, essentially preventing phreatomagmatic interaction and permitting magmatic activity with rapid growth of a pyroclastic cone. Proportions of the conduit, fill of early-stage vent, and position and thickness of aquifer are hypothetical.
Volcanic Magnitude

\[ M = \log_{10} m - 7 \]

M = magnitude

M = mass of tephra or lava
Fig. 5.5 Magnitude–frequency plot for subaerial volcanic eruptions based on records for last 300 yr for $2 \leq M < 6$; last 2 kyr for $6 \leq M < 8$; and for all known ‘super-eruptions’ of the past 45 Myr for $M \geq 8$. Note that extrapolation of the more or less reliable record for the past 300 years or even the last 2 kyr, to estimate the frequency of very large eruptions ($M \geq 8$), would result in a significant over-estimation of the their recurrence. The only $M = 9$ eruption in this compilation is the Fish Canyon Tuff eruption associated with La Garita caldera in the United States (Section 11.7), the implied frequency of magnitude 9 events should therefore be regarded cautiously. Data from D. Pyle and R. Mason.
Fig. 5.5 Magnitude–frequency plot for subaerial volcanic eruptions based on records for last 300 yr for $2 \leq M < 6$; last 2 kyr for $6 \leq M < 8$; and for all known 'super-eruptions' of the past 45 Myr for $M \geq 8$. Note that extrapolation of the more or less reliable record for the past 300 years or even the last 2 kyr, to estimate the frequency of very large eruptions ($M \geq 8$), would result in a significant over-estimation of the their recurrence. The only $M = 9$ eruption in this compilation is the Fish Canyon Tuff eruption associated with La Garita caldera in the United States (Section 11.7), the implied frequency of magnitude 9 events should therefore be regarded cautiously. Data from D. Pyle and B. Mason.
A Simplified Volcanic Activity Classification

- Diffuse degassing and fumeroles
- Hawaiian eruptions
- Lava lakes
- Strombolian eruptions
- Vulcanian eruptions
- Visuvian or sub-plinian eruptions (M<4)
- Plinian eruptions (M=4+)
- Pelean eruptions
- Hydrovolcanic eruptions
Viscosity of Diverse Materials

http://www.earth.northwestern.edu/people/seth/107/Rocks/Image24.gif
Fig. 5.2 Some terms commonly used in describing the sites of eruptions relative to a simple conical volcano. Flank eruptions commonly commence with summit activity, but activity shifts to lower levels where most lava emerges. ‘Lateral’ eruptions are similar, but may involve only minimal summit activity.
Impact of water on small basaltic eruptions
Formation of Crater Lake
Howell Williams (1941)

(reproduced in Francis and Oppenheimer 2004)

Fig. 11.5 Howel Williams’s classic diagrams illustrating the formation of Crater Lake caldera Oregon [13]. His original
Fig. 9.7 Three common mechanisms for generating PDCs. (a) Simple gravitational collapse of a growing lava dome or flow on a volcano (merapi type). (b) Explosive disruption of growing lava dome (peléan type). (c) Collapse from eruption column (soufrière type).