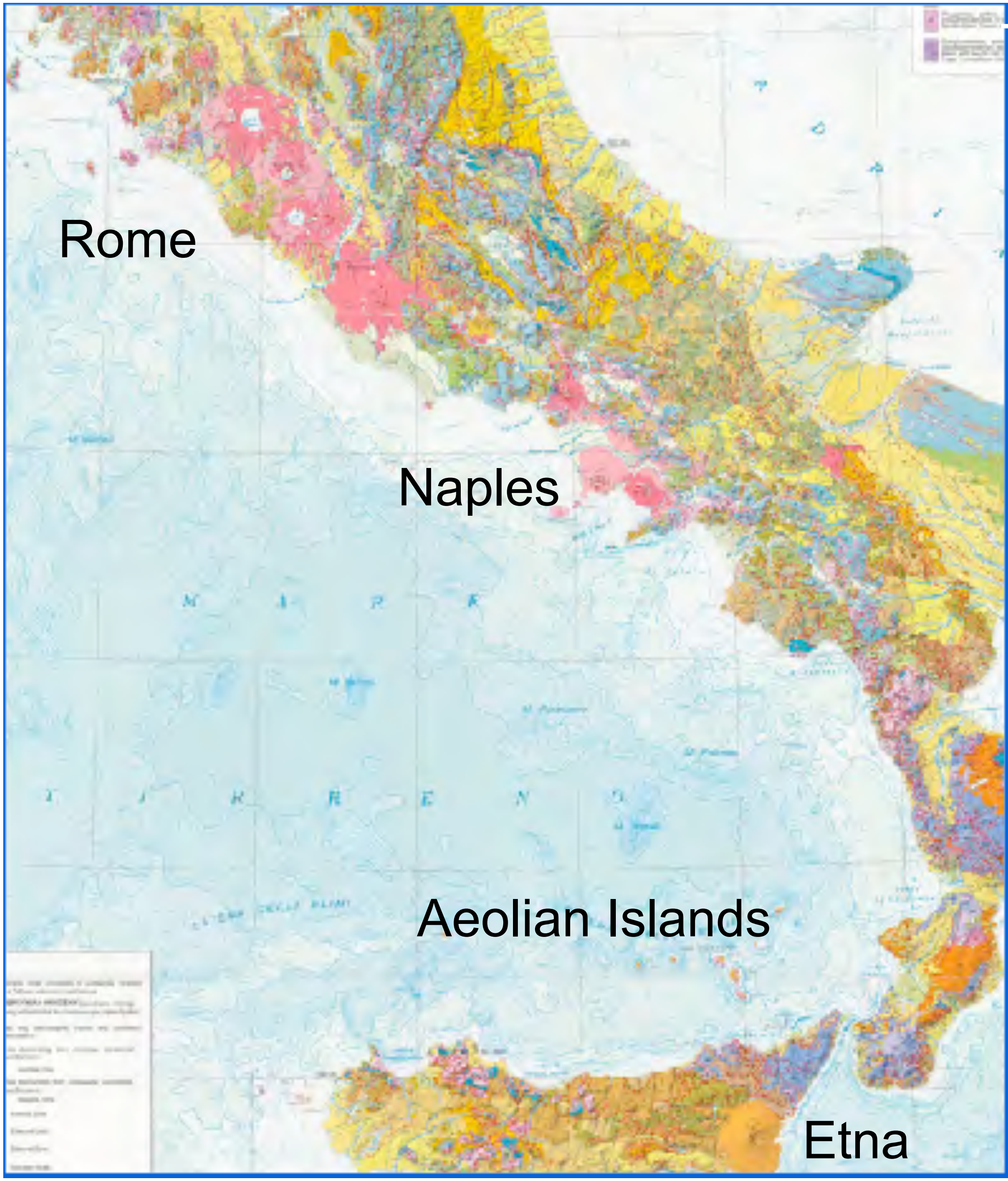
Mount Etna and Volcanic Rocks

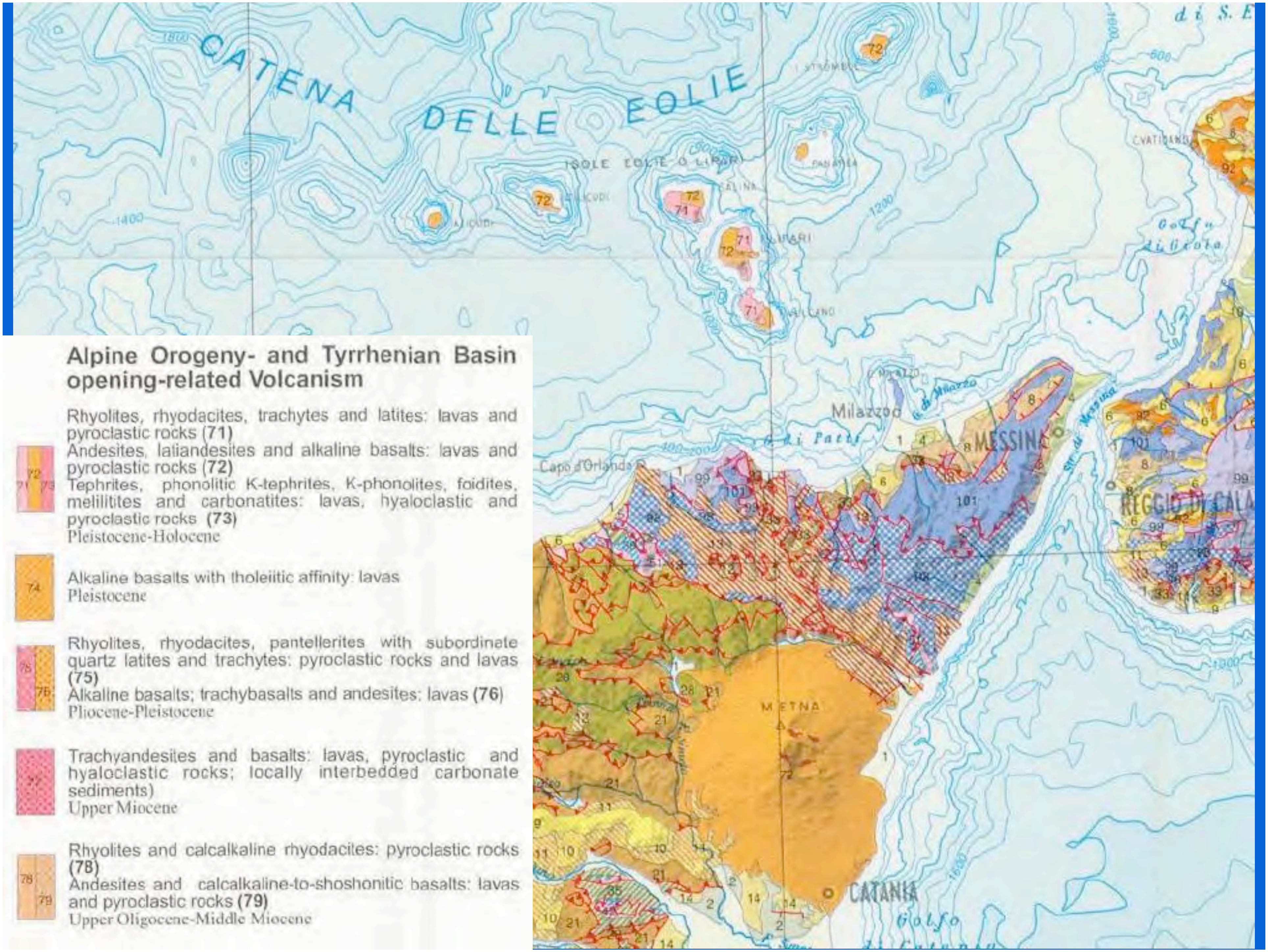
Mount Etna, Sicily August 2, 2006

http://eol.jsc.nasa.gov/


APAT
Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici
Dipartimento Difesa del Suolo
Servizio Geologico d'Italia
GEOLOGICAL MAP OF ITALY
1:1 250 000 Scale
MAIN TECTONO-STRATIGRAPHIC UNITS
ESPECIALLY PRINTED FOR THE 32nd INTERNATIONAL GEOLOGICAL CONGRESS
ITALIA 2004

Three Volcanic Regions





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 basalts: lavas and pyroclastic rocks (**79**)
Upper Oligocene-Middle Miocene

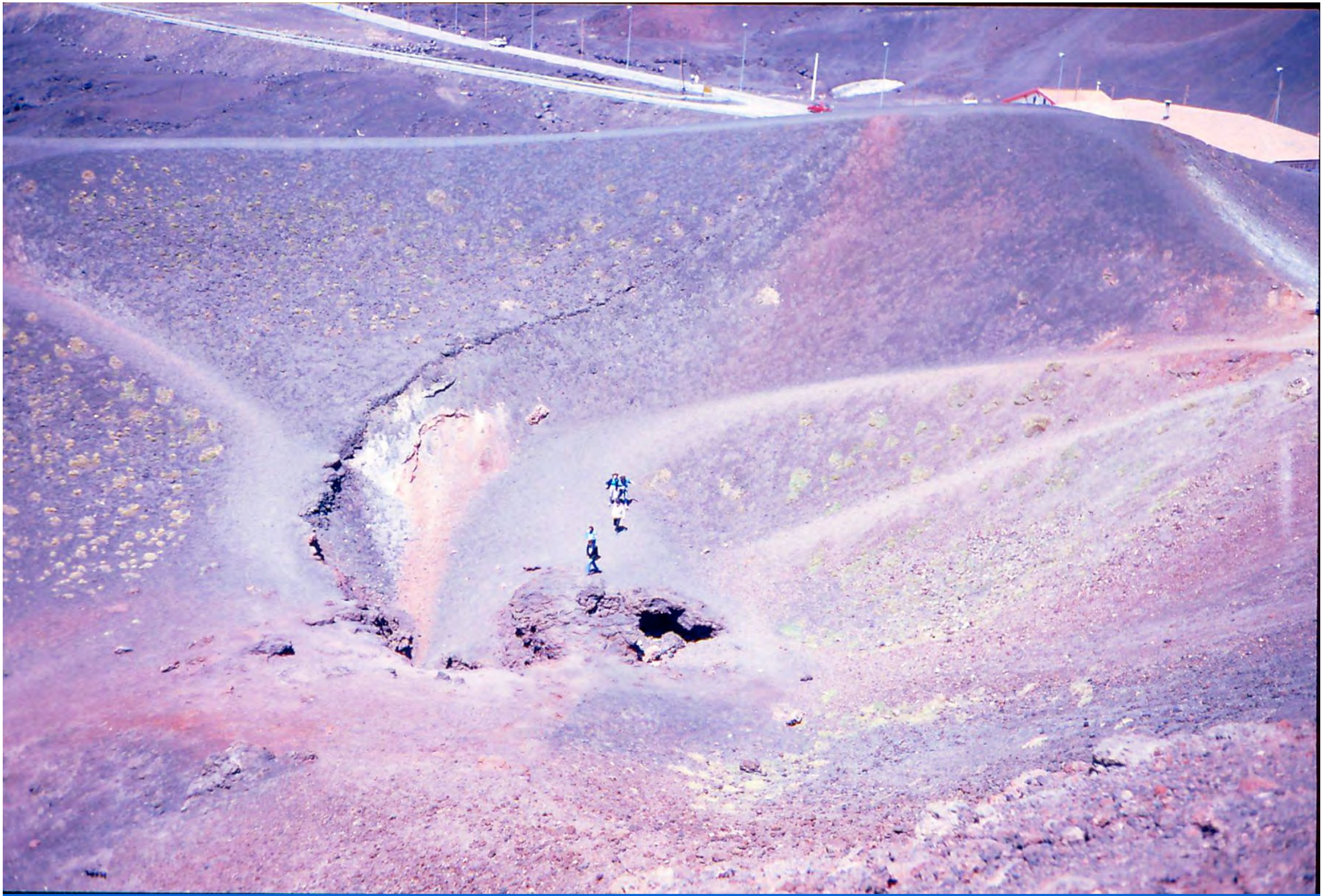
Mount Etna, Sicily August 2, 2006

http://eol.jsc.nasa.gov/

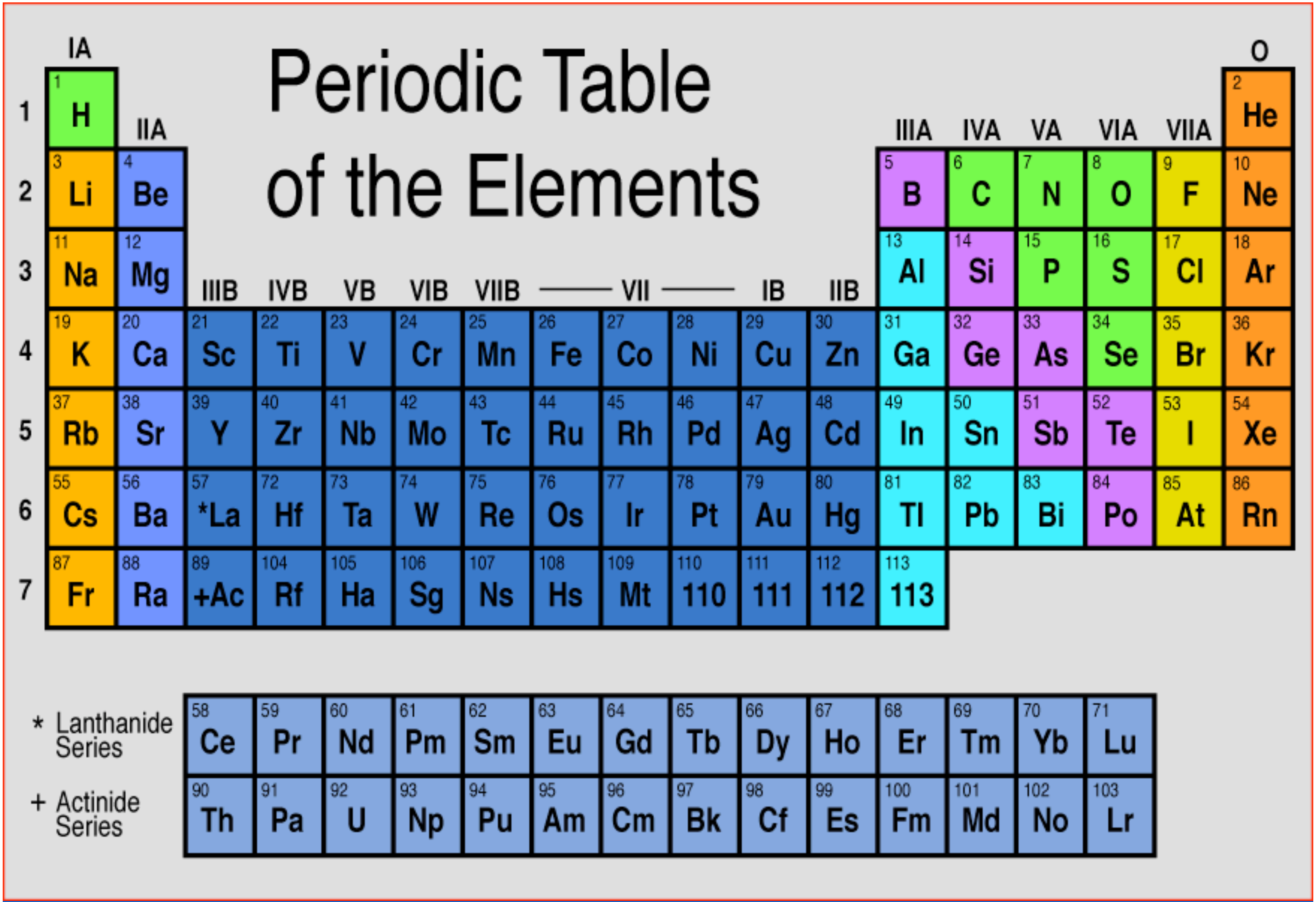
Etna Summit 1987

Cinder cone and ski area, Mt Etna 1987

Cinder cones, southeast flank Mt Etna 1987



Lava tube, Mount Etna, 1987



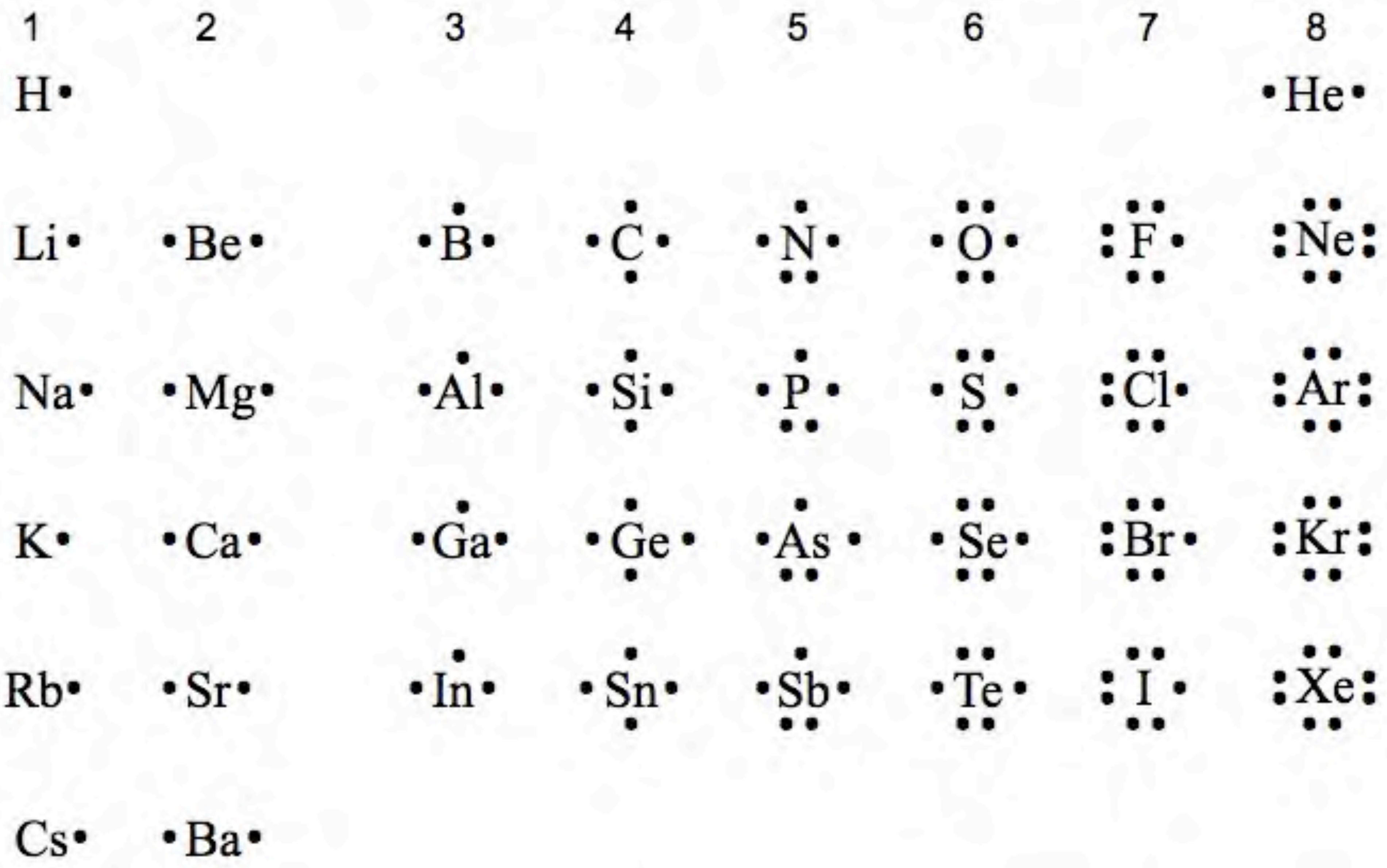
Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	—— VII ——			IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Source:SERC @ Carleton College

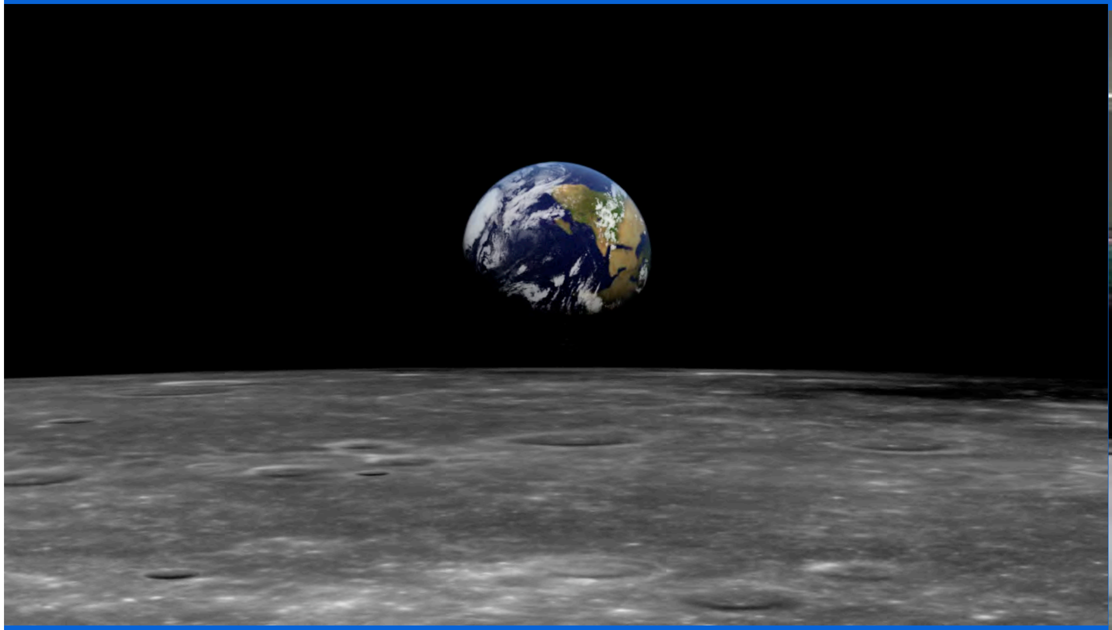
Lewis Periodic Table Showing Outer Shell (Valence) Electrons



http://www.meta-synthesis.com/webbook/35_pt/pt_database.php?PT_id=335

What do these have in common?

The Moon and Earth



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

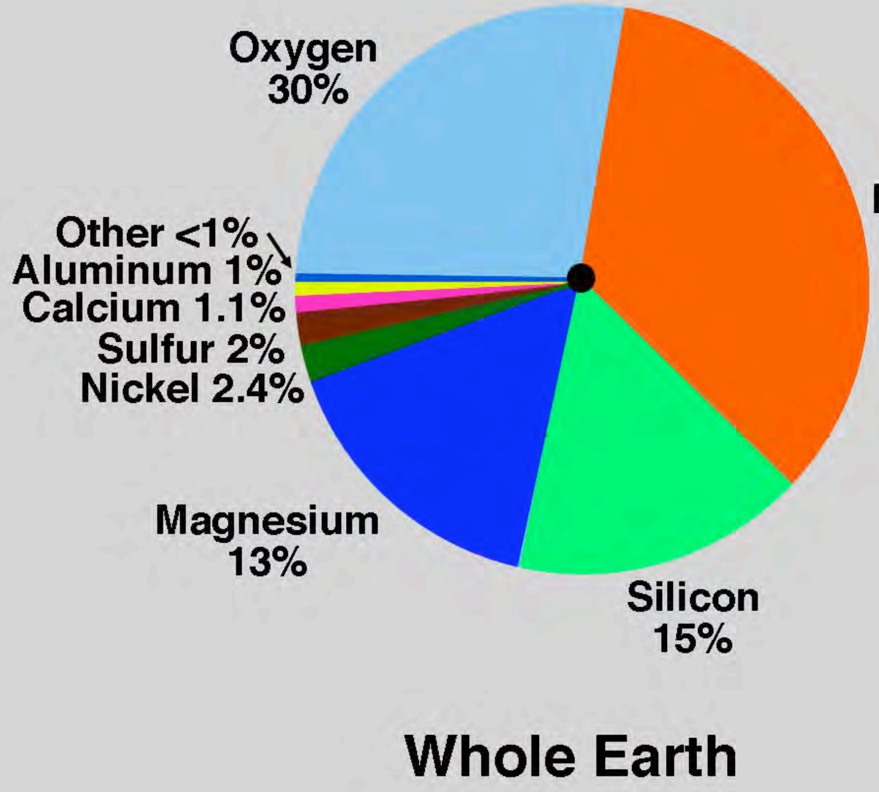
The Willamette Meteorite

http://blog.oregonlive.com/clackamascounty/2007/10/BigMeteor.JPG

What do these have in common?

The Earth

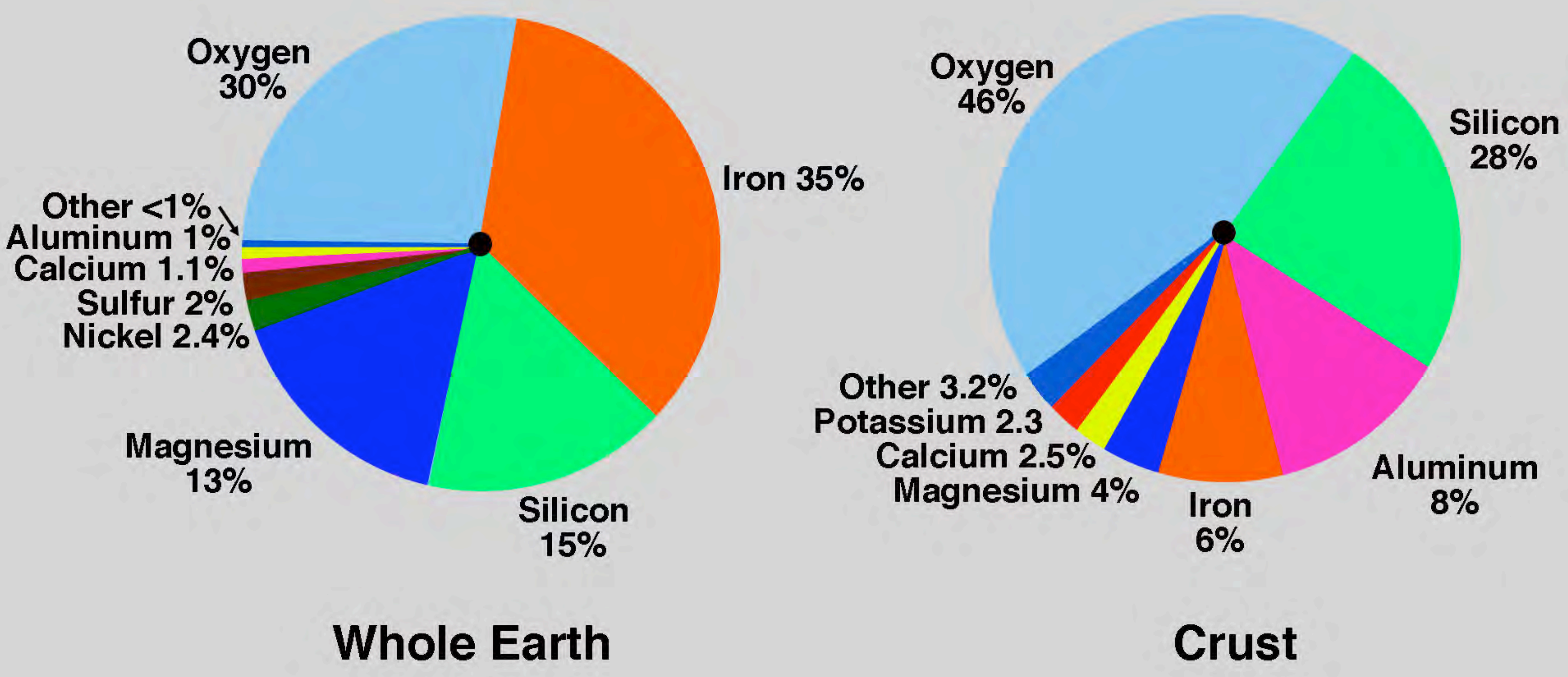
The Willamette Meteorite



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?



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

Abundance of the elements in the Earth's crust

Element	Wt % Oxide	Atom %
O		60.8
Si	59.3	21.2
Al	15.3	6.4
Fe	7.5	2.2
Ca	6.9	2.6
Mg	4.5	2.4
Na	2.8	1.9

Major elements: usually greater than 1%

SiO_2 Al_2O_3 FeO* MgO CaO Na_2O K_2O H_2O

Minor elements: usually 0.1 - 1%

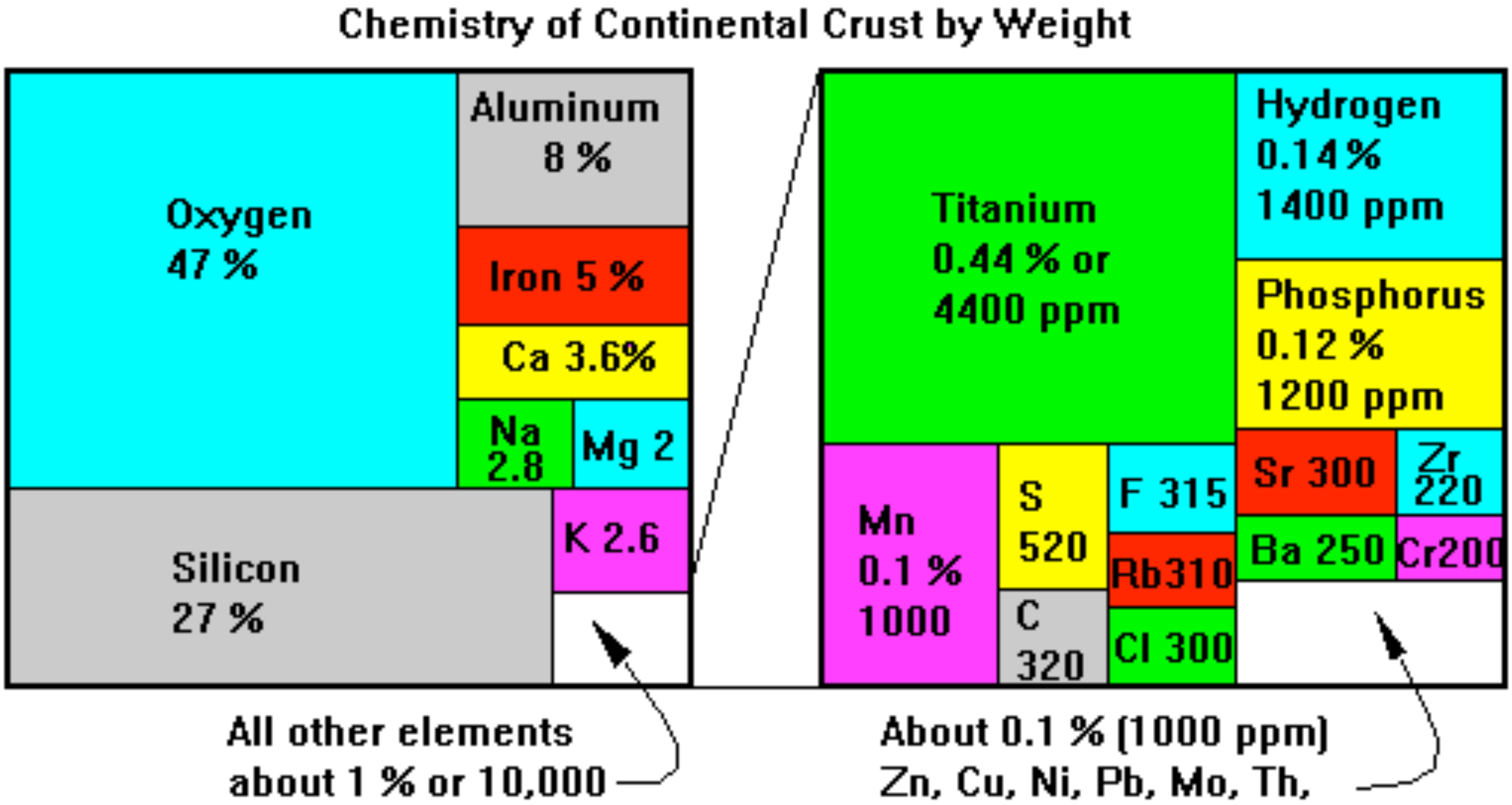
TiO_2 MnO P_2O_5 CO_2

Trace elements: usually < 0.1%everything else

What processes concentrate the trace elements?

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

Can we extract the trace elements economically?
What geologic processes further increase their concentration?



http://www.uwgb.edu/dutchs/Graphics-Geol/rockmin/ccrustwt.gif

What processes alter crustal composition?

- Magmatism
- Sedimentation
- Metamorphism

Magmatism produces these major element averages:

Chemical analyses of some representative Igneous Rocks

	Ultra-Basic	**Basic**	**Intermed**	**Felsic**	**Intermed**
	Peridotite	Basalt	Andesite	Rhyolite	Phonolite
SiO2	42.26	49.20	57.94	72.82	56.19
TiO2	0.63	1.84	0.87	0.28	0.62
Al2O3	4.23	15.74	17.02	13.27	19.04
Fe2O3	3.61	3.79	3.27	1.48	2.79
FeO	6.58	7.13	4.04	1.11	2.03
MnO	0.41	0.20	0.14	0.06	0.17
MgO	31.24	6.73	3.33	0.39	1.07
CaO	5.05	9.47	6.79	1.14	2.72
Na2O	0.49	2.91	3.48	3.55	7.79
K2O	0.34	1.10	1.62	4.30	5.24
H2O+	3.91	0.95	0.83	1.10	1.57
Total	98.75	99.06	99.3	99.50	99.23

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

Major Digression!

Atoms?

Elements?

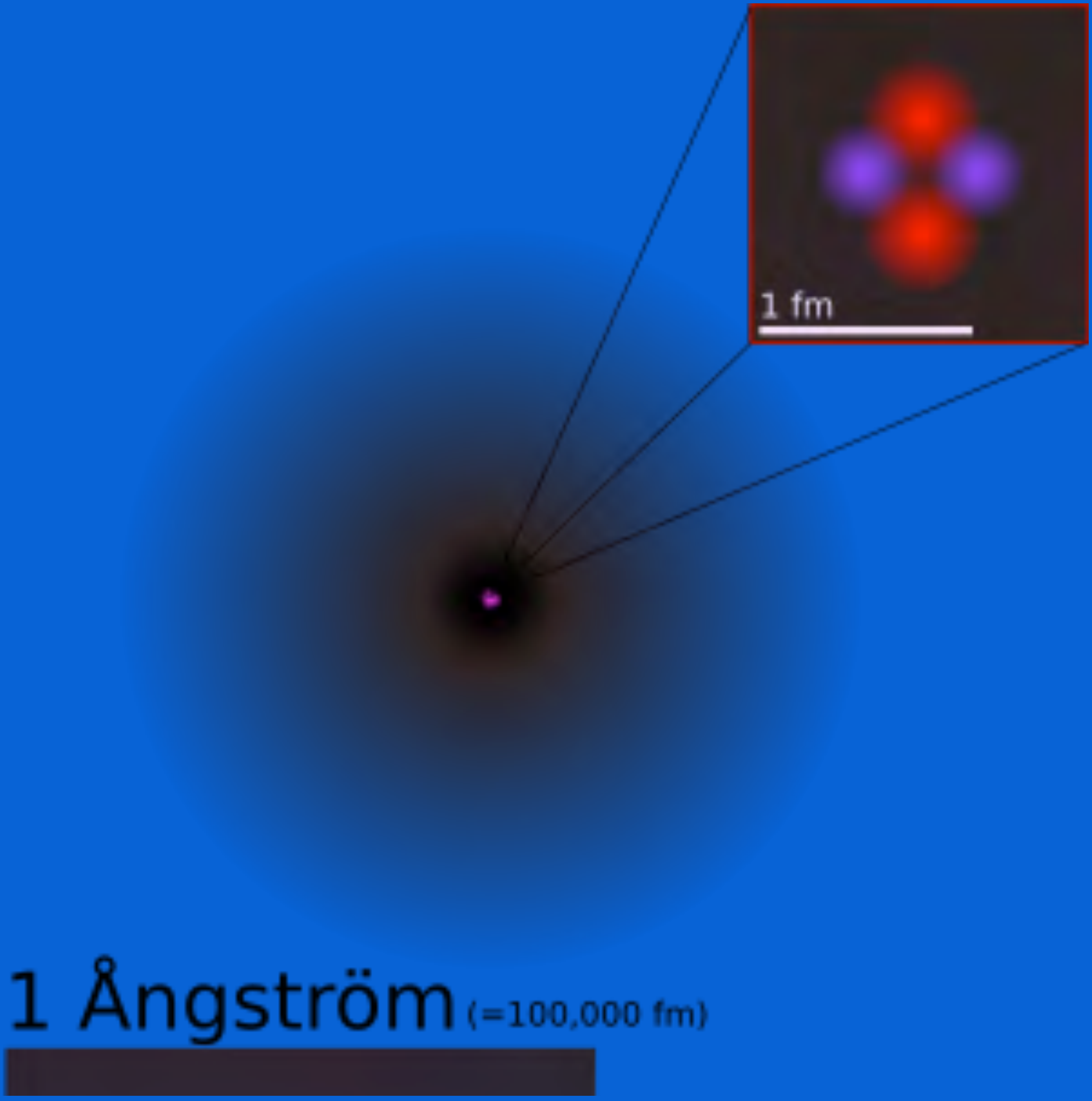
Compounds?

Minerals?

Rocks?

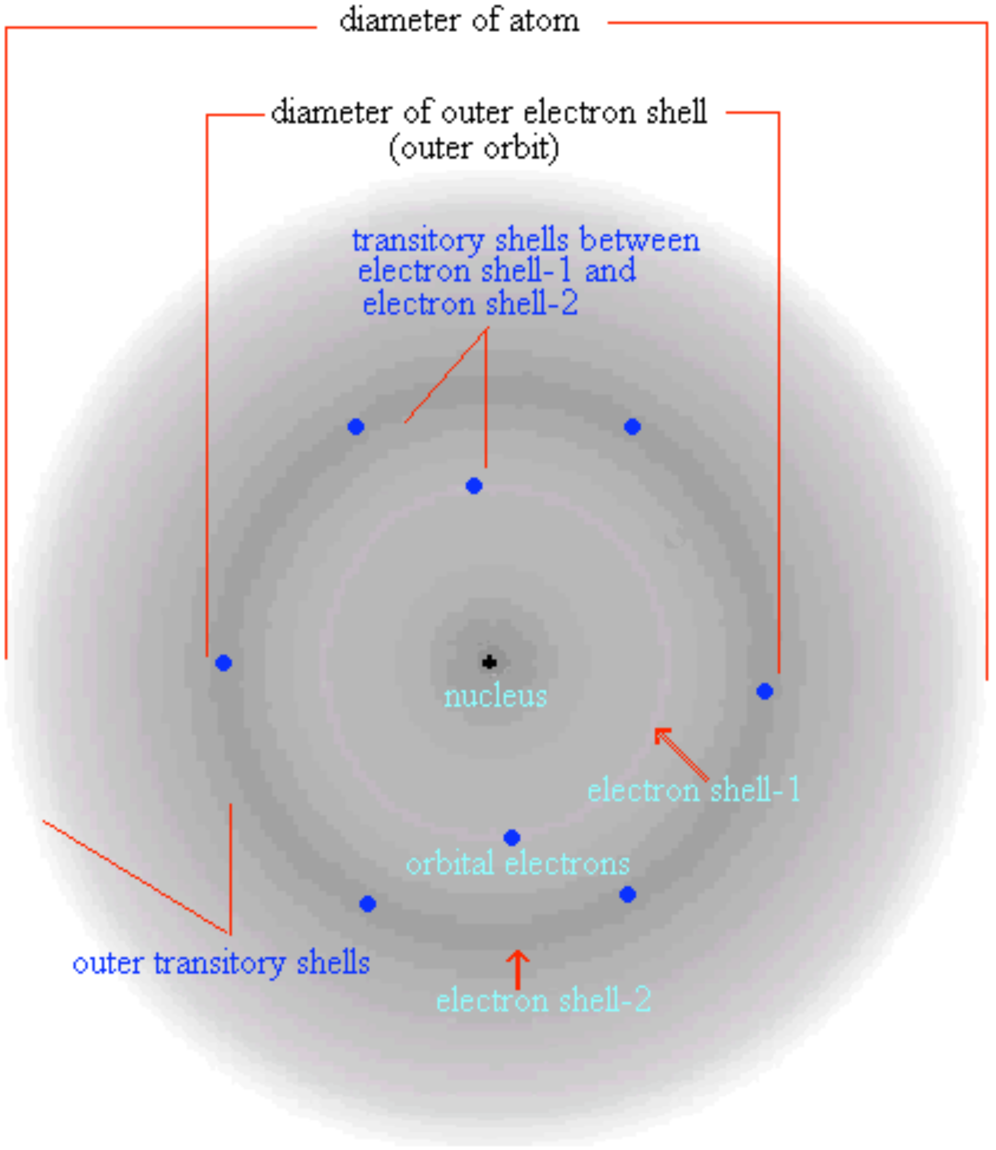
What is going on here?

One Illustrated Helium Atom



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

One Oxygen Atom



Cross sectional diagram of an oxygen atom

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

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

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

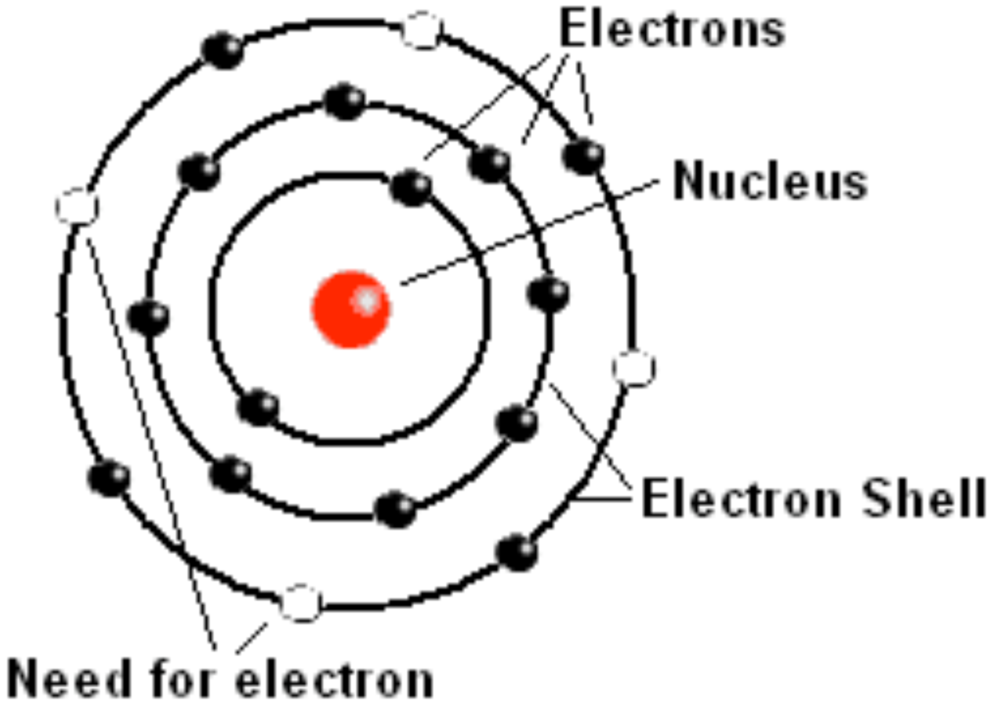
b) Buoyant force exerted on the electrons by space matter in the atom

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

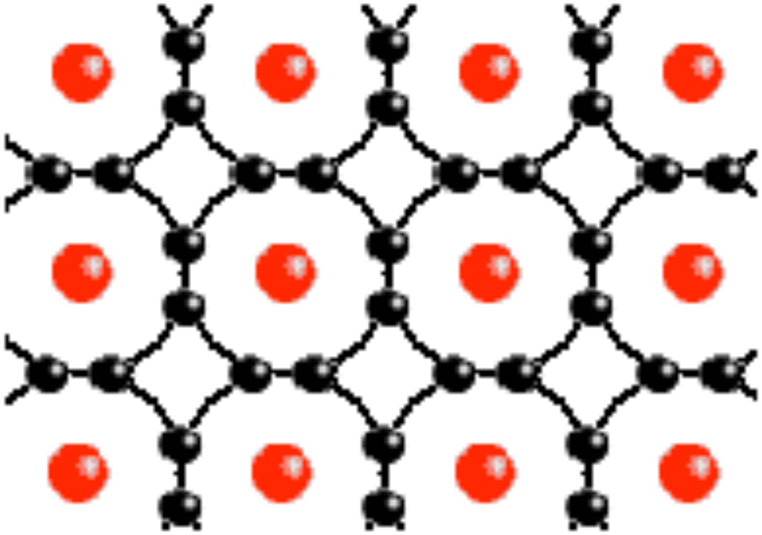
Since the incredibly constant density and elasticity of space matter at every fixed distance from the center of the nucleus of an atom, each of that region of space matter act as resonant columns with unique natural frequencies. Since the density of space matter decreases with the increasing of the distance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

http://physics-edu.org/Chemical_Energy.htm

One Silicon Atom



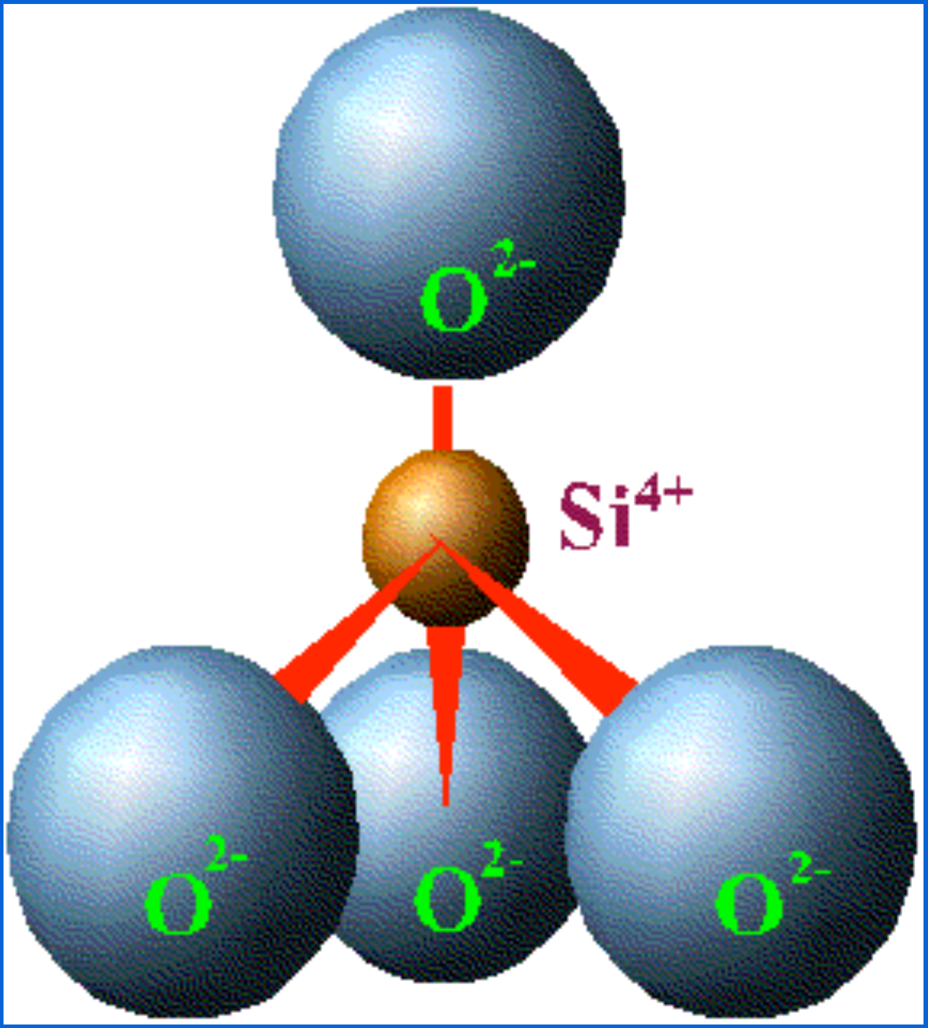
12 Silicon Atoms



Silicon Atoms sharing electrons to make each other happy.

http://electronics-for-beginners.com/pages/page/3/

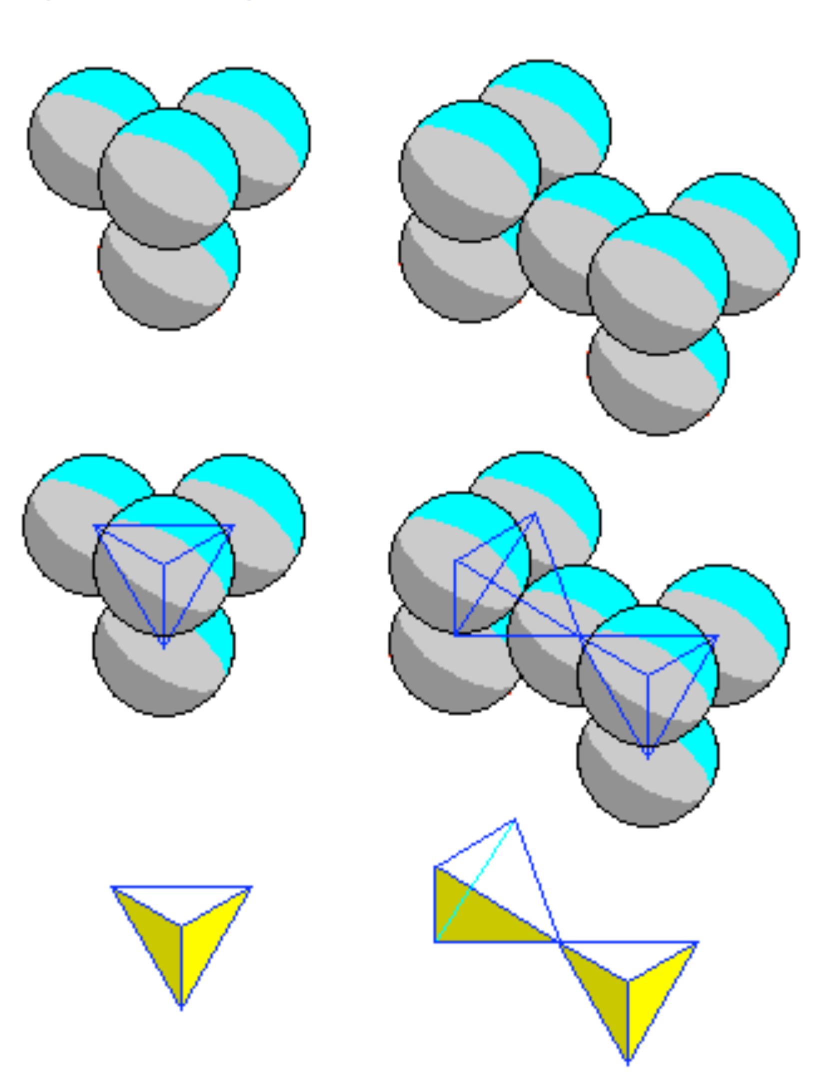
Silicon Tetrahedron: the building block of most minerals



http://pubpages.unh.edu/~harter/Tetra.gif

Nesosilicate:

Garnet
Fosterite
Fayalite
Kyanite
Olivine
Sillimanite
Sphene
Topaz
Zircon

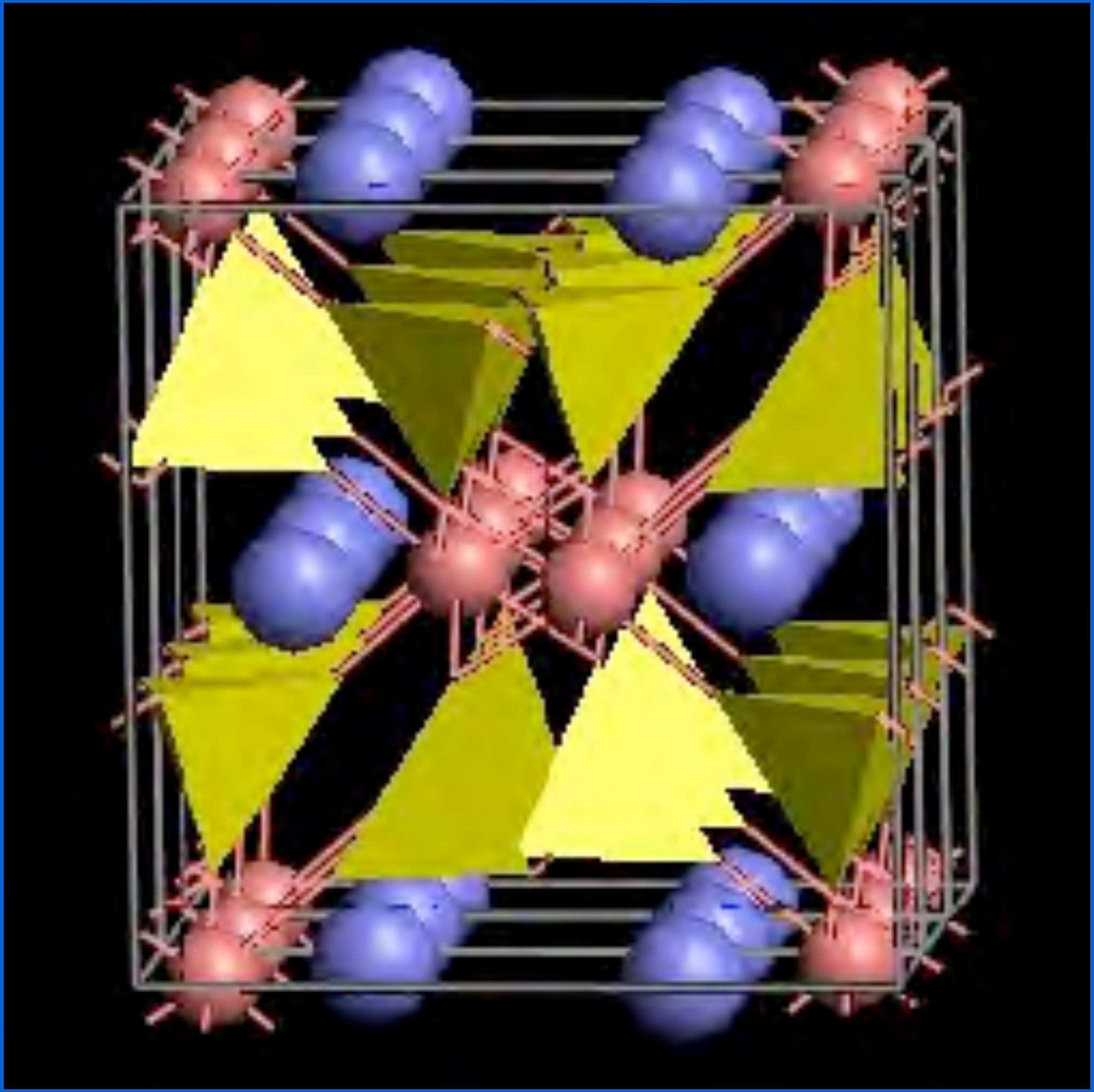


Sorosilicate

Epidote
Zoisite
Bertrandite
Idocrase

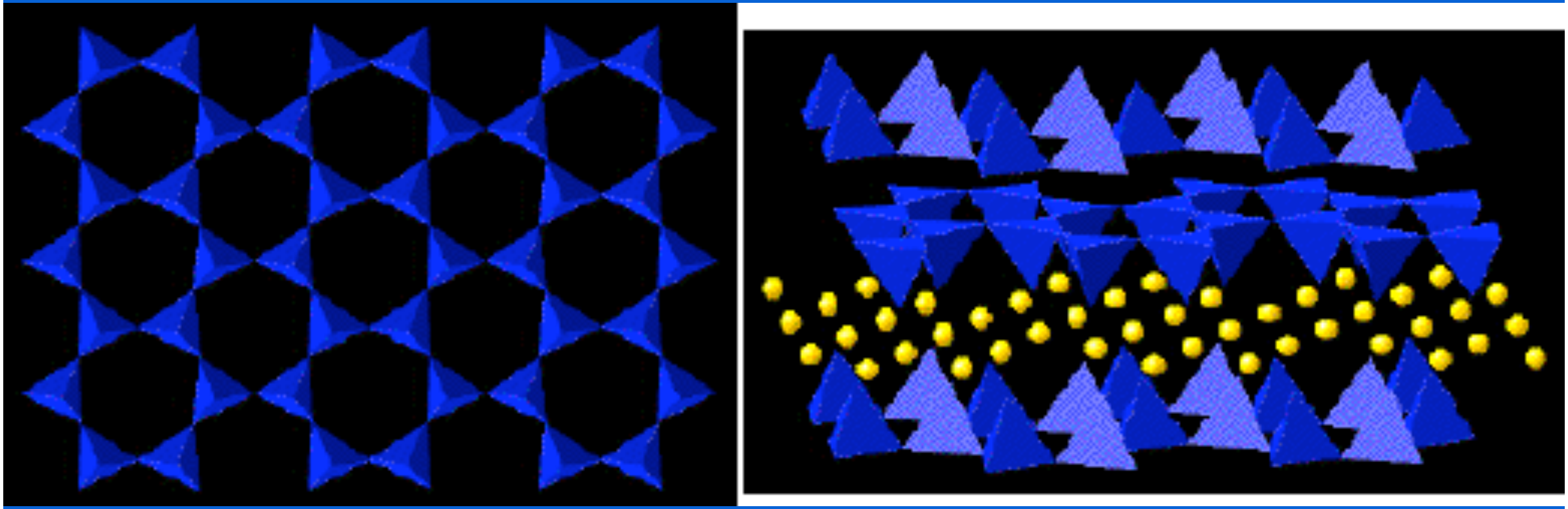
http://www.uwsp.edu/geo/projects/geoweb/participants/dutch/PETROLGY/NesoSoro.HTM

Single Chain: Pyroxenes (Augite, Diopside, Enstatite, Jadite)



http://www.earth.ox.ac.uk/~davewa/pt/pt02_px.html

Double Chains: Amphiboles (Hornblende, Riebeckite, Tremolite)

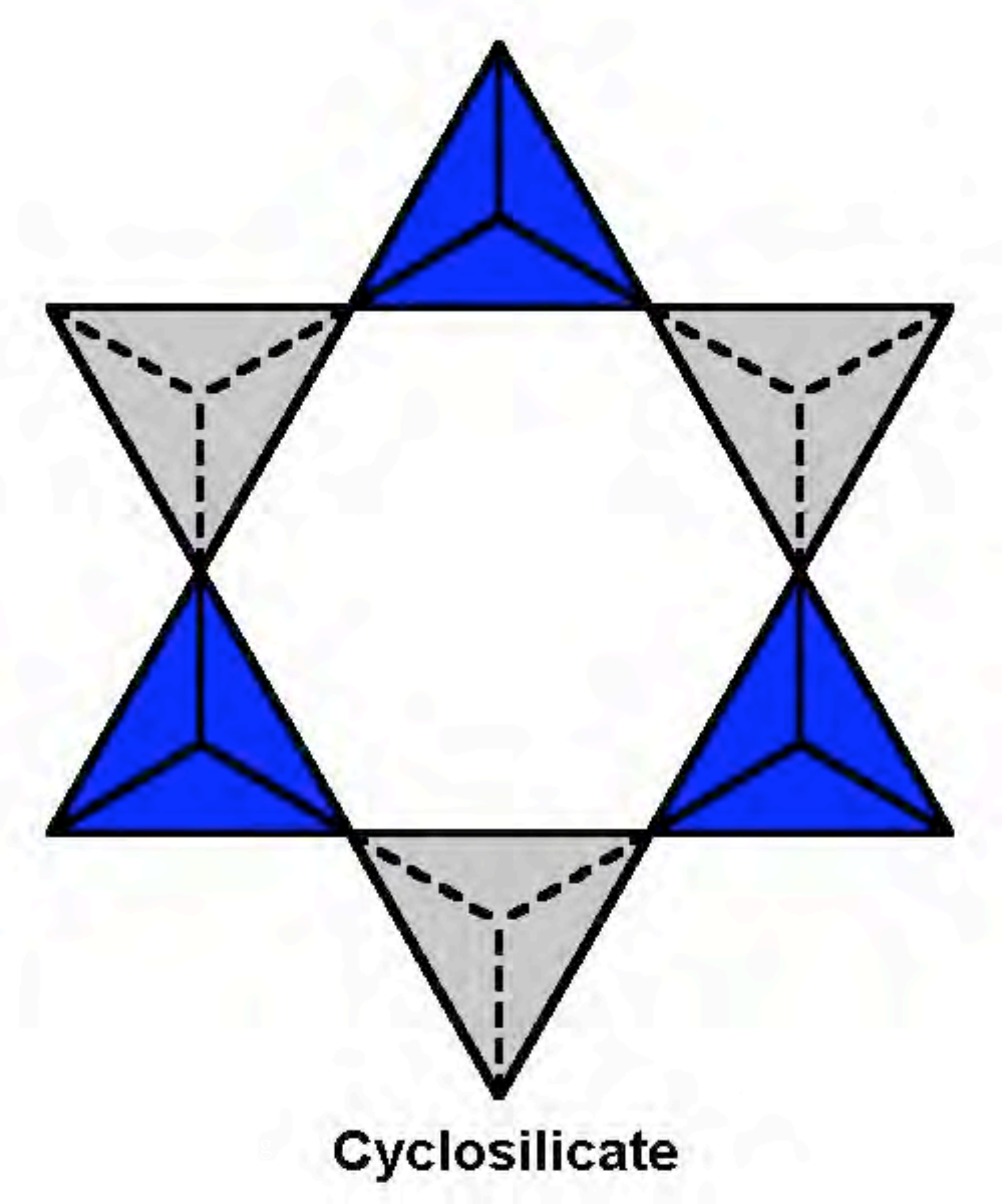


http://www.chem.ox.ac.uk/icl/heyes/structure_of_solids/Lecture4/SilP3.gif

Cyclosilicate

Tourmalines

Beryl

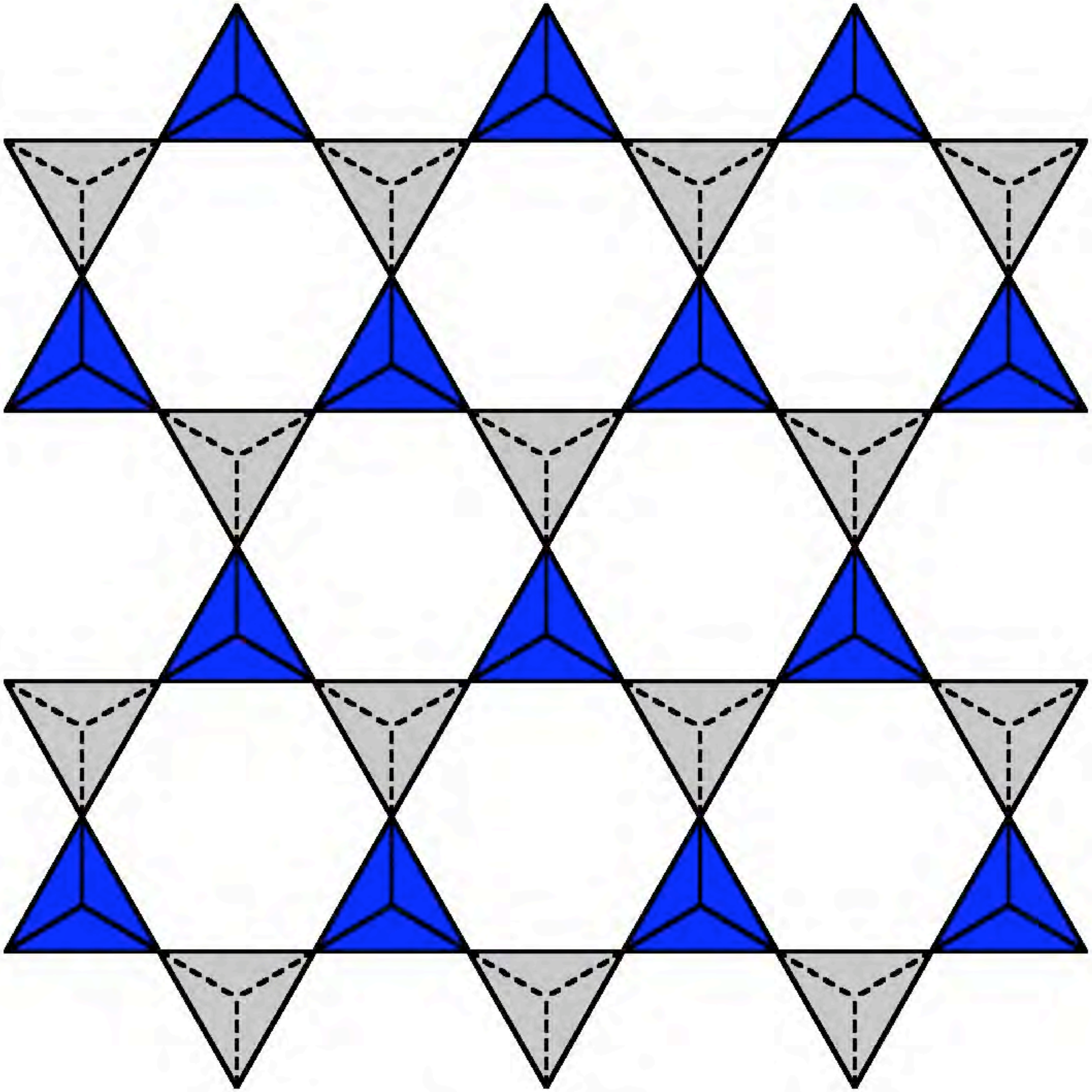

Cyclosilicate

http://www.uraniumminerals.com/Tutorials/S

Phylosilicates

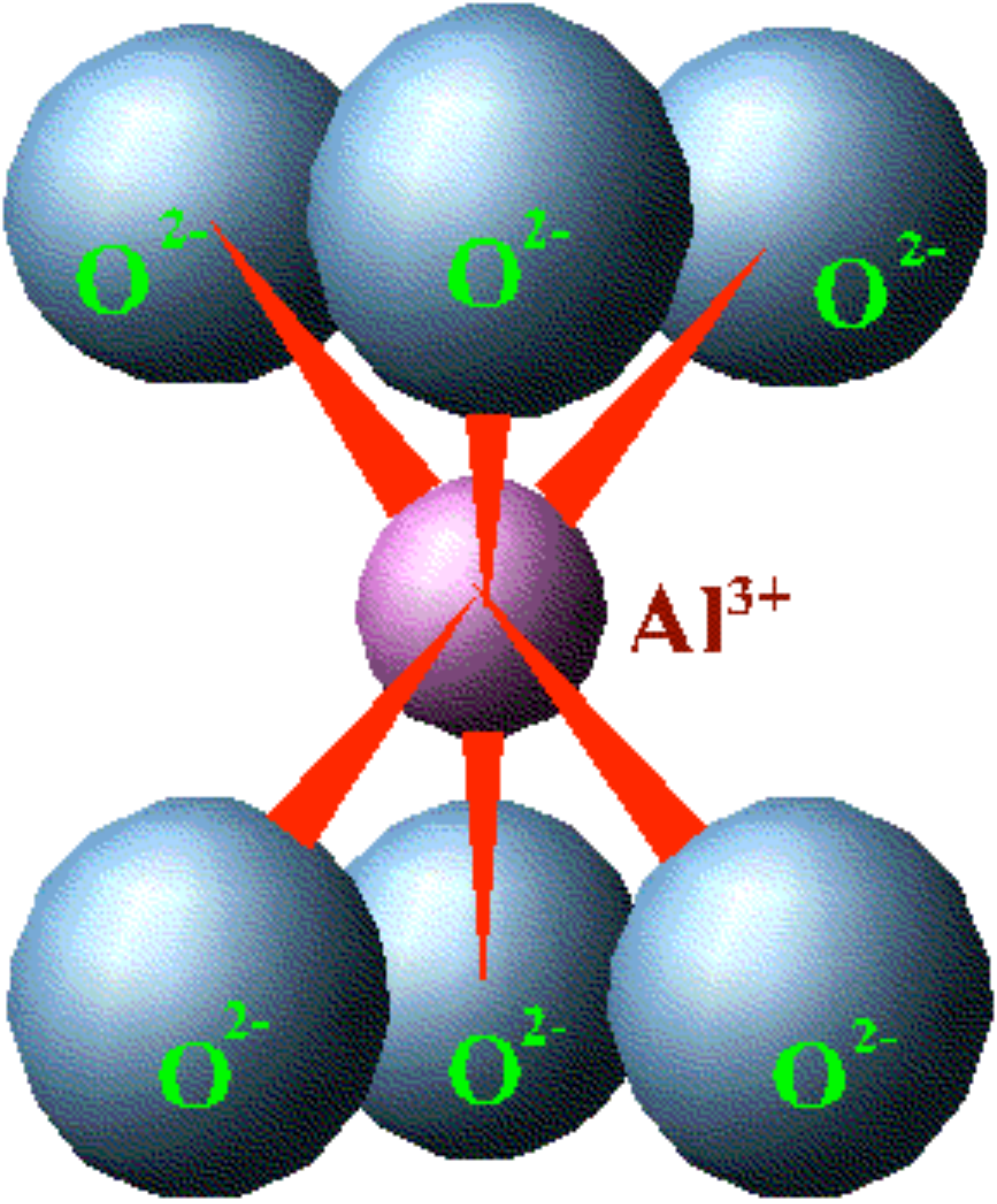
- Micas
  - Biotite
  - Muscovite
  - Lepidolite
  - Phlogopite
- Clays
  - Chlorite Clay
  - Kaolinite
  - Pyrophyllite
  - Talc
- Prehnite
- Serpentine

http://www.uraniumminerals.com/Tutorials/Sil

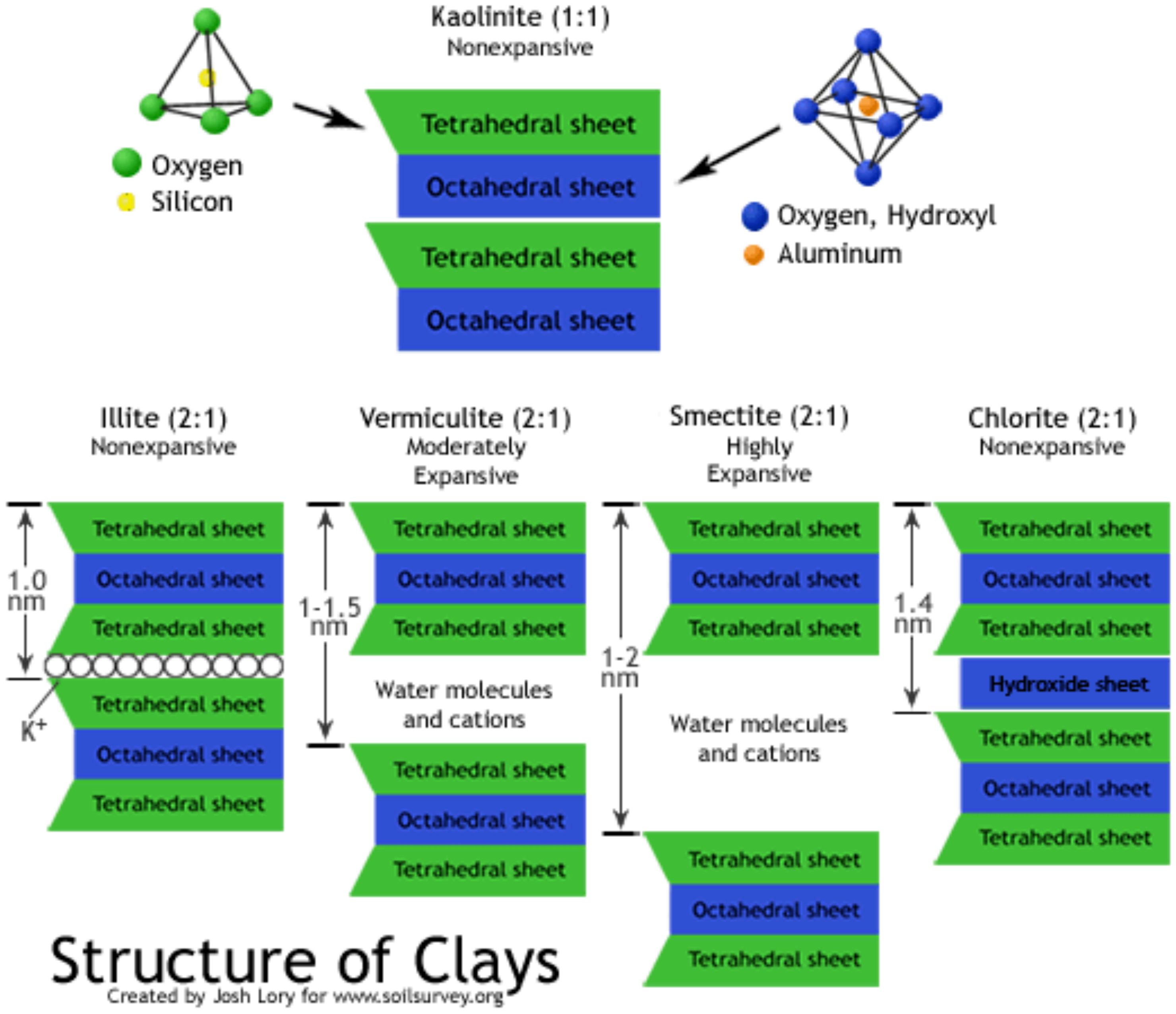


Phyllosilicate

Aluminum Octahedron: A major component of clay minerals



http://pubpages.unh.edu/~harter/crystal.htm



Structure of Clays

Created by Josh Lory for www.soilsurvey.org

Magmatism produces these major element averages:

Chemical analyses of some representative Igneous Rocks

	Ultra-Basic	**Basic**	**Intermed**	**Felsic**	**Intermed**
	Peridotite	Basalt	Andesite	Rhyolite	Phonolite
SiO2	42.26	49.20	57.94	72.82	56.19
TiO2	0.63	1.84	0.87	0.28	0.62
Al2O3	4.23	15.74	17.02	13.27	19.04
Fe2O3	3.61	3.79	3.27	1.48	2.79
FeO	6.58	7.13	4.04	1.11	2.03
MnO	0.41	0.20	0.14	0.06	0.17
MgO	31.24	6.73	3.33	0.39	1.07
CaO	5.05	9.47	6.79	1.14	2.72
Na2O	0.49	2.91	3.48	3.55	7.79
K2O	0.34	1.10	1.62	4.30	5.24
H2O+	3.91	0.95	0.83	1.10	1.57
Total	98.75	99.06	99.3	99.50	99.23

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

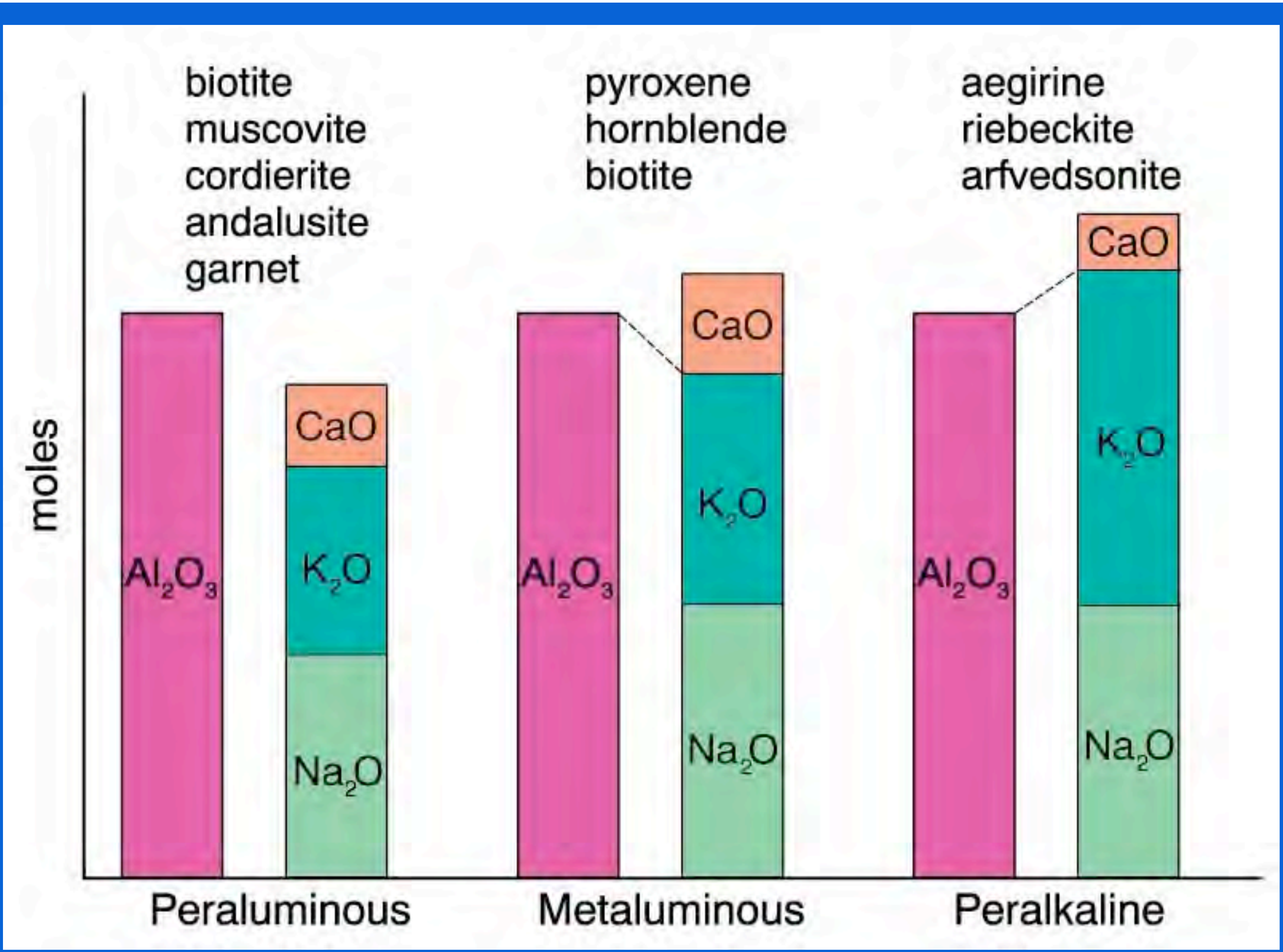
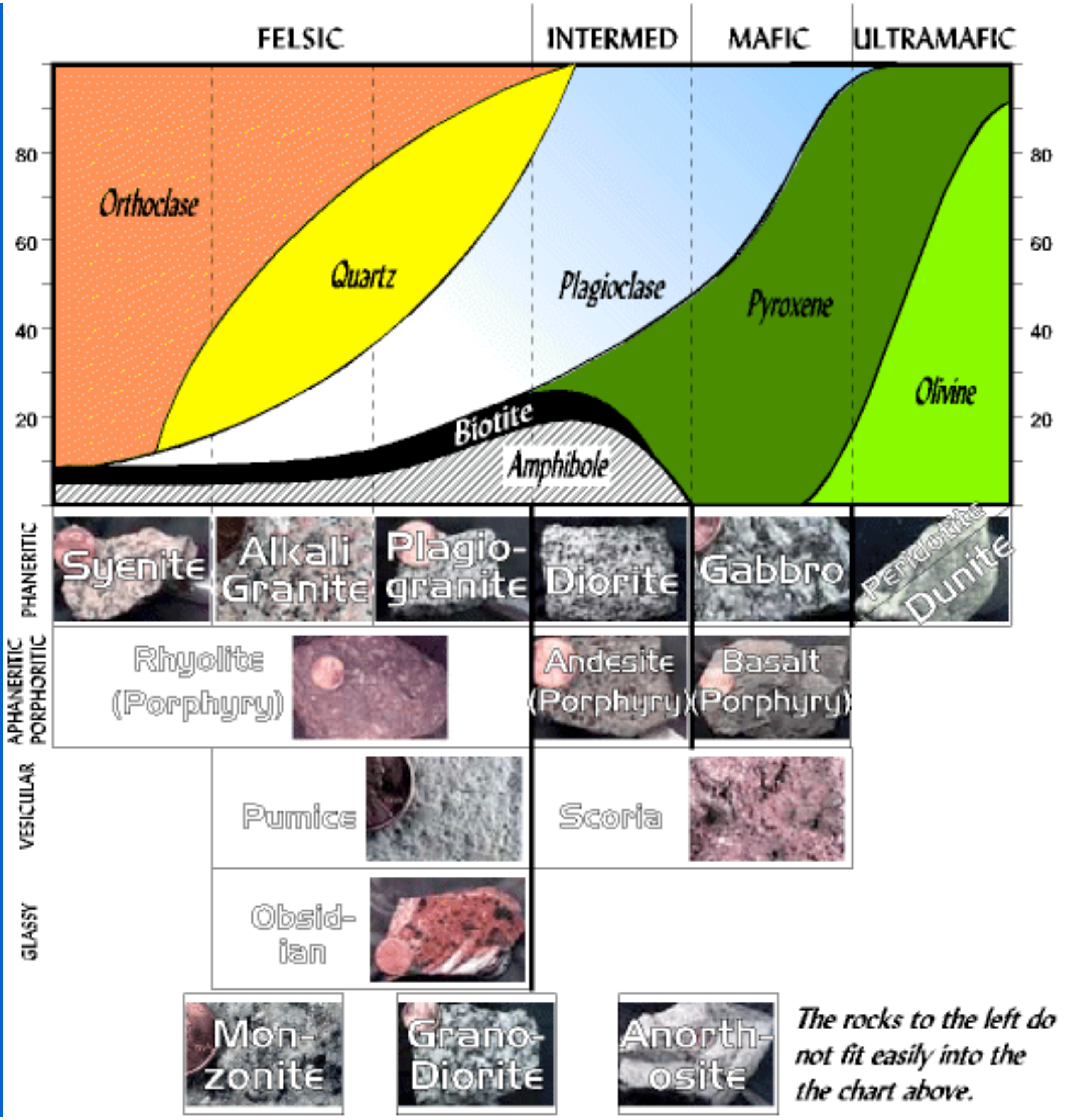
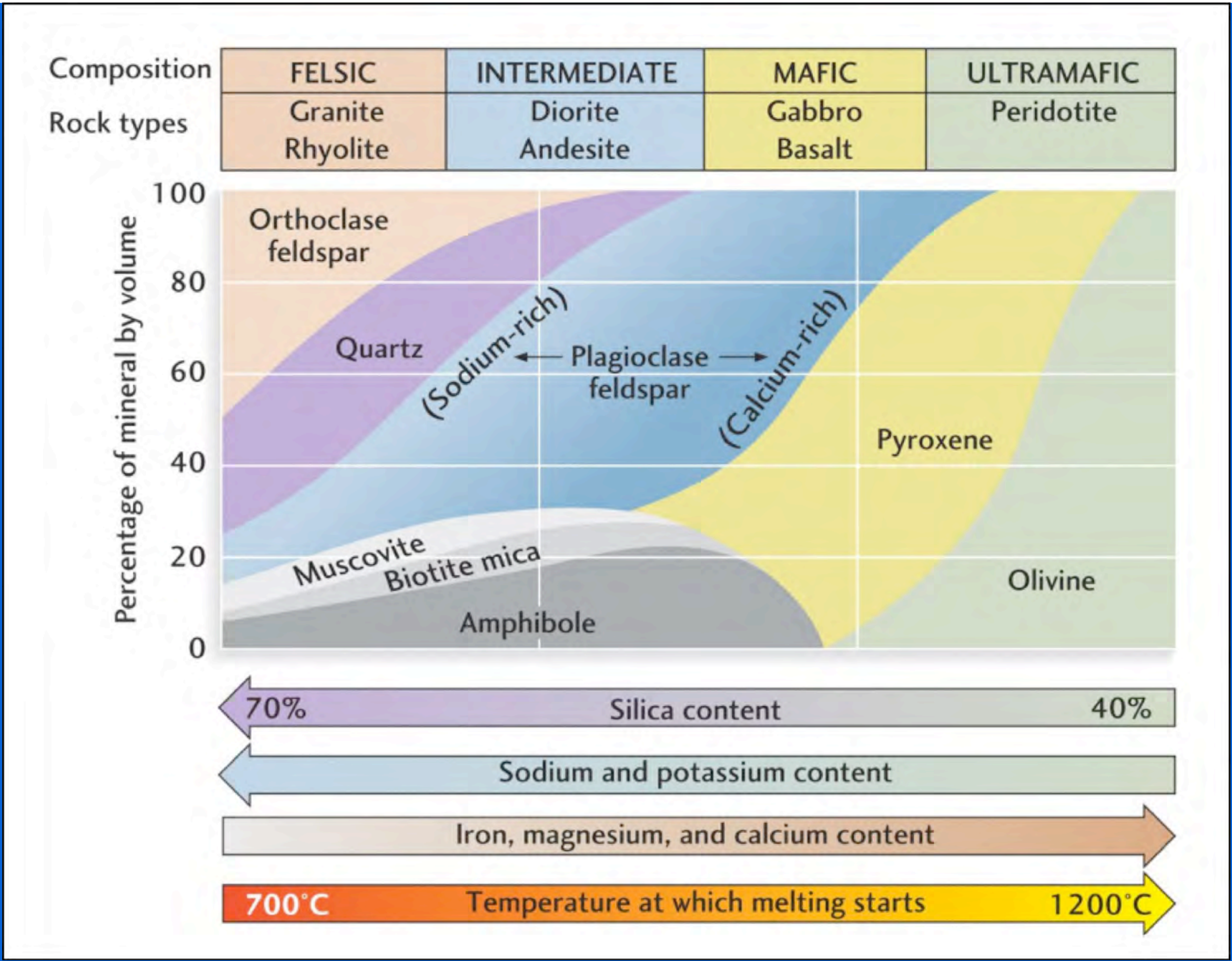


Figure 18-2. Alumina saturation classes based on the *molar* proportions of $Al_2O_3/(CaO+Na_2O+K_2O)$ ("A/CNK") after Shand (1927). Common non-quartzo-feldspathic minerals for each type are included. After Clarke (1992). Granitoid Rocks. Chapman Hall.



The rocks to the left do not fit easily into the chart above.

http://csmres.jmu.edu/geollab/
fichter/IgnRx/HTMLimag/igclsht2.gif



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

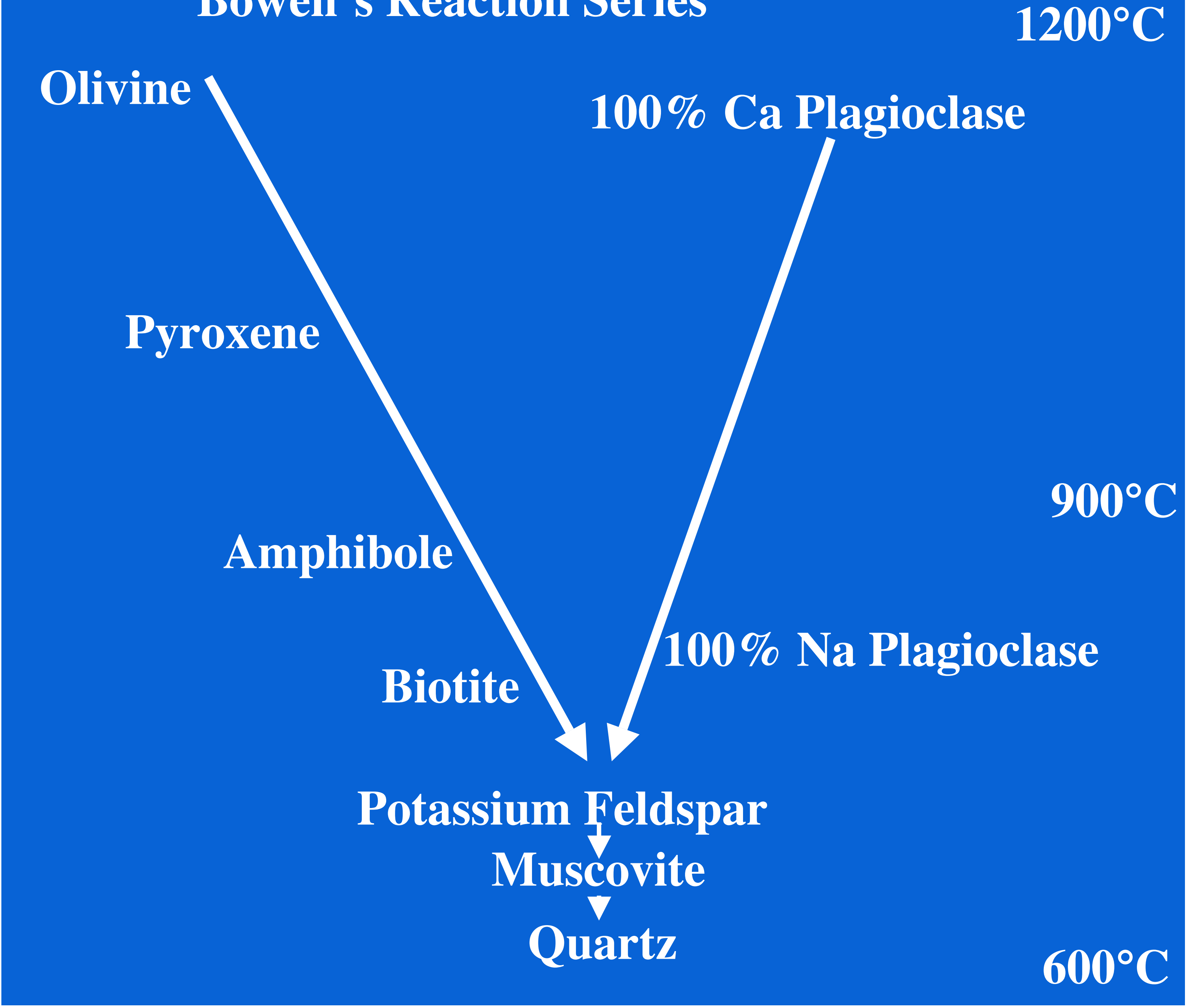
Compounds-made of elements

Minerals-mostly silicates

Rocks-made of minerals

How do we get different magmas from a single melt?

Bowen’s Reaction Series



1200°C

Olivine

100% Ca Plagioclase

Peridotite

Pyroxene

Basaltic

900°C

Amphibole

100% Na Plagioclase

Andesitic

Biotite

Potassium Feldspar

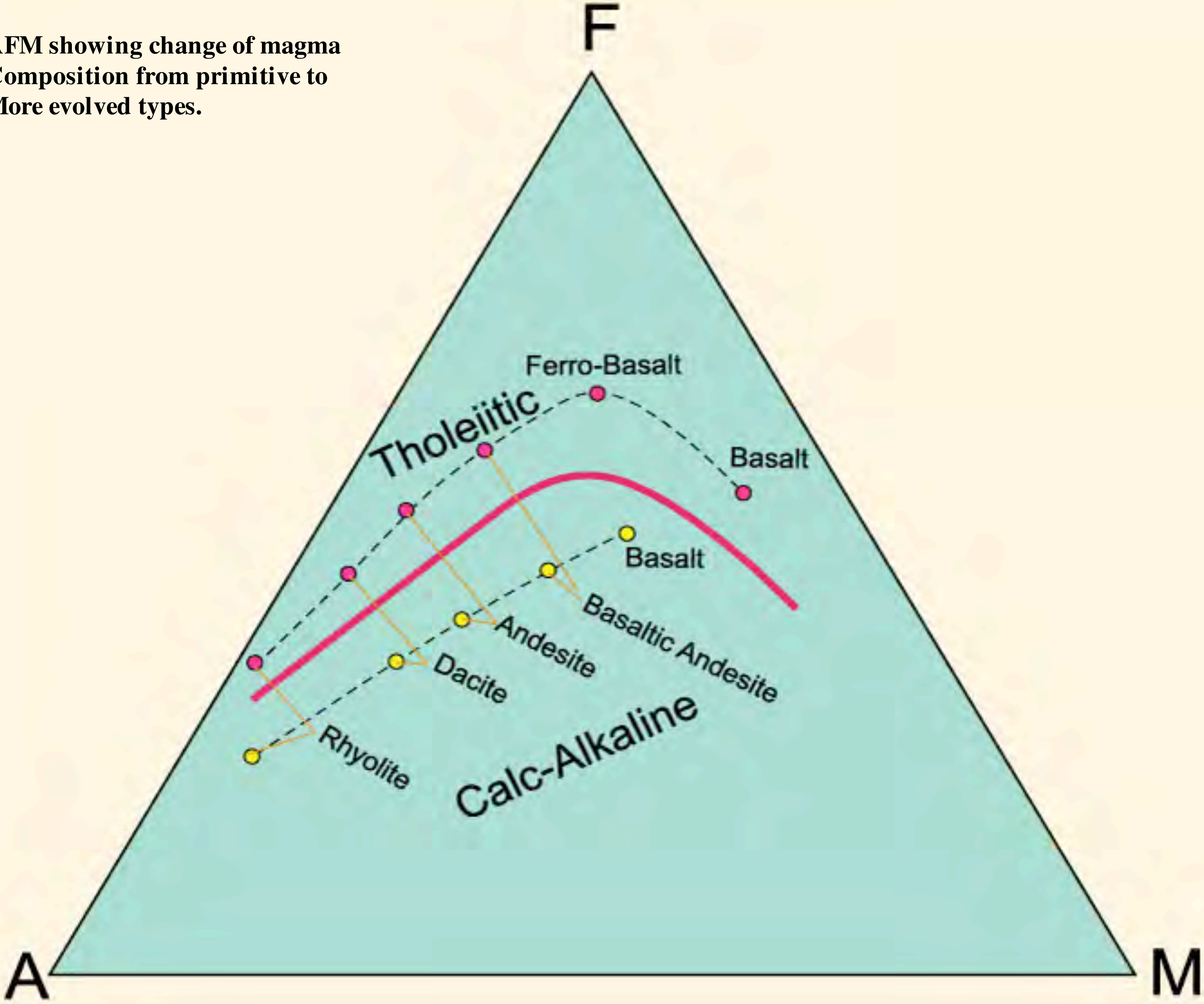
Muscovite

Quartz

Granite

600°C

AFM showing change of magma
Composition from primitive to
More evolved types.



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

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.

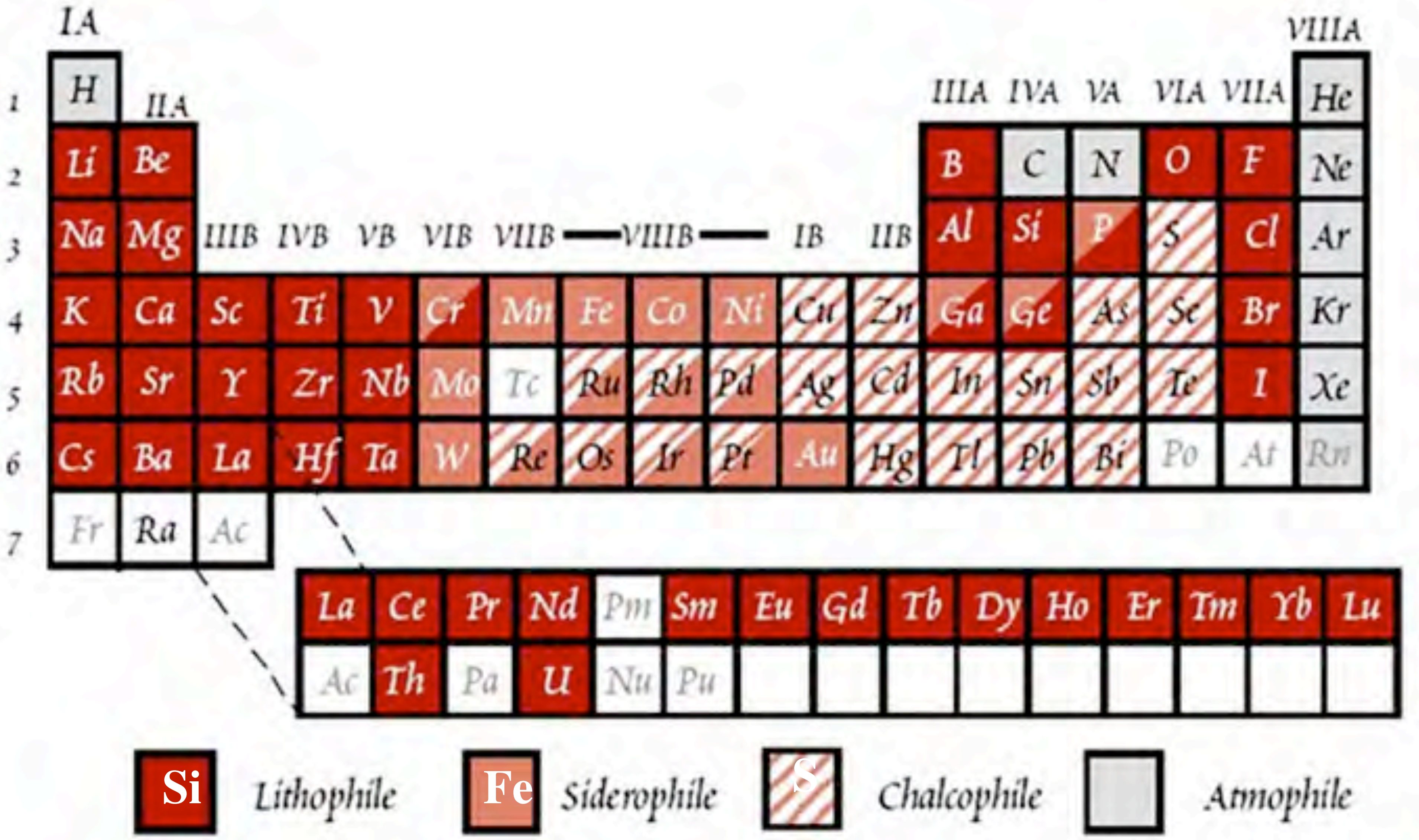
Solid Primitive Mantle
1-compatible element
2-compatible element
3-compatible element
4-incompatible element
5-incompatible element
6-incompatible element

Partial Melting

Solid Depleted Mantle
1-compatible element
2-compatible element
3-compatible element

The Melt
4-incompatible element
5-incompatible element
6-incompatible element

Which elements are “compatible” with each other?



	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Ac															

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu									

Si Lithophile

Fe Siderophile

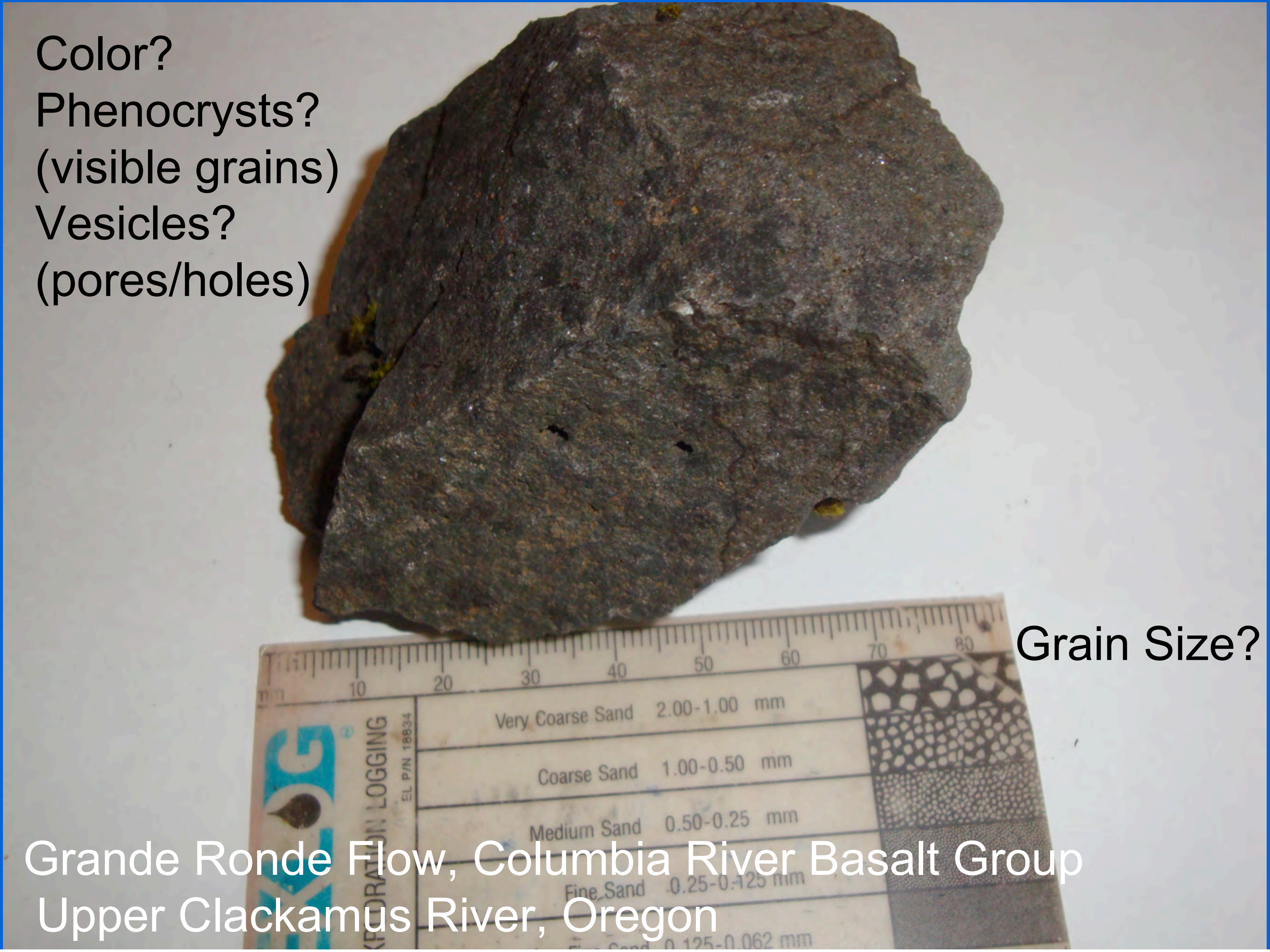
S Chalcophile

▢ Atmophile

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)

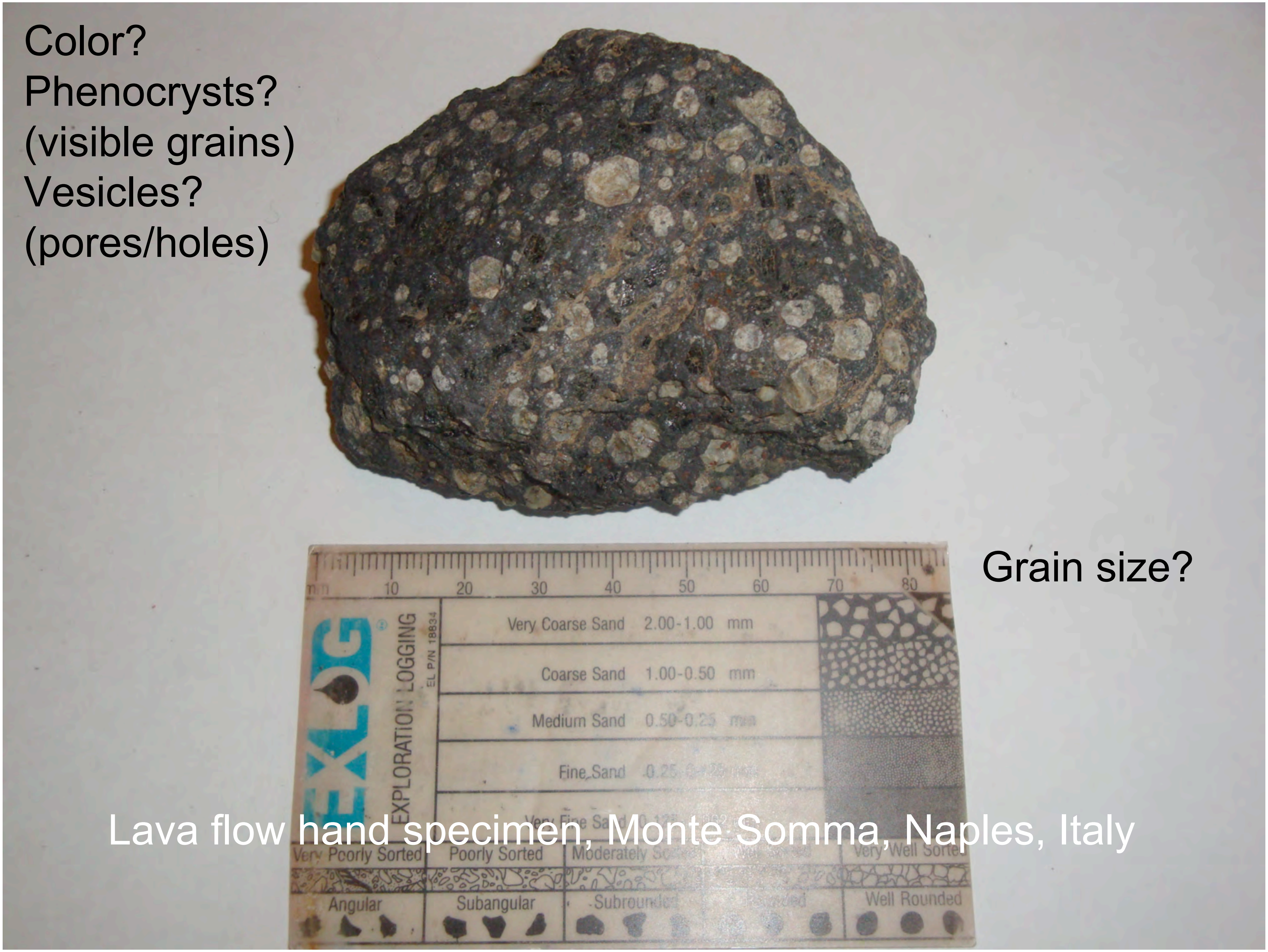
Grain Size?

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)

Grain size?

Lava flow hand specimen, Monte Somma, Naples, Italy

Medium to dark grey leucite basalt porphery

Lava flow hand specimen, Monte Somma, Naples, Italy

Color?
Phenocrysts
Vesicles?

Grain size?

Hand specimen lava flow, Craters of the Moon, Arco, Idaho

Dark reddish grey
Vesicular basalt

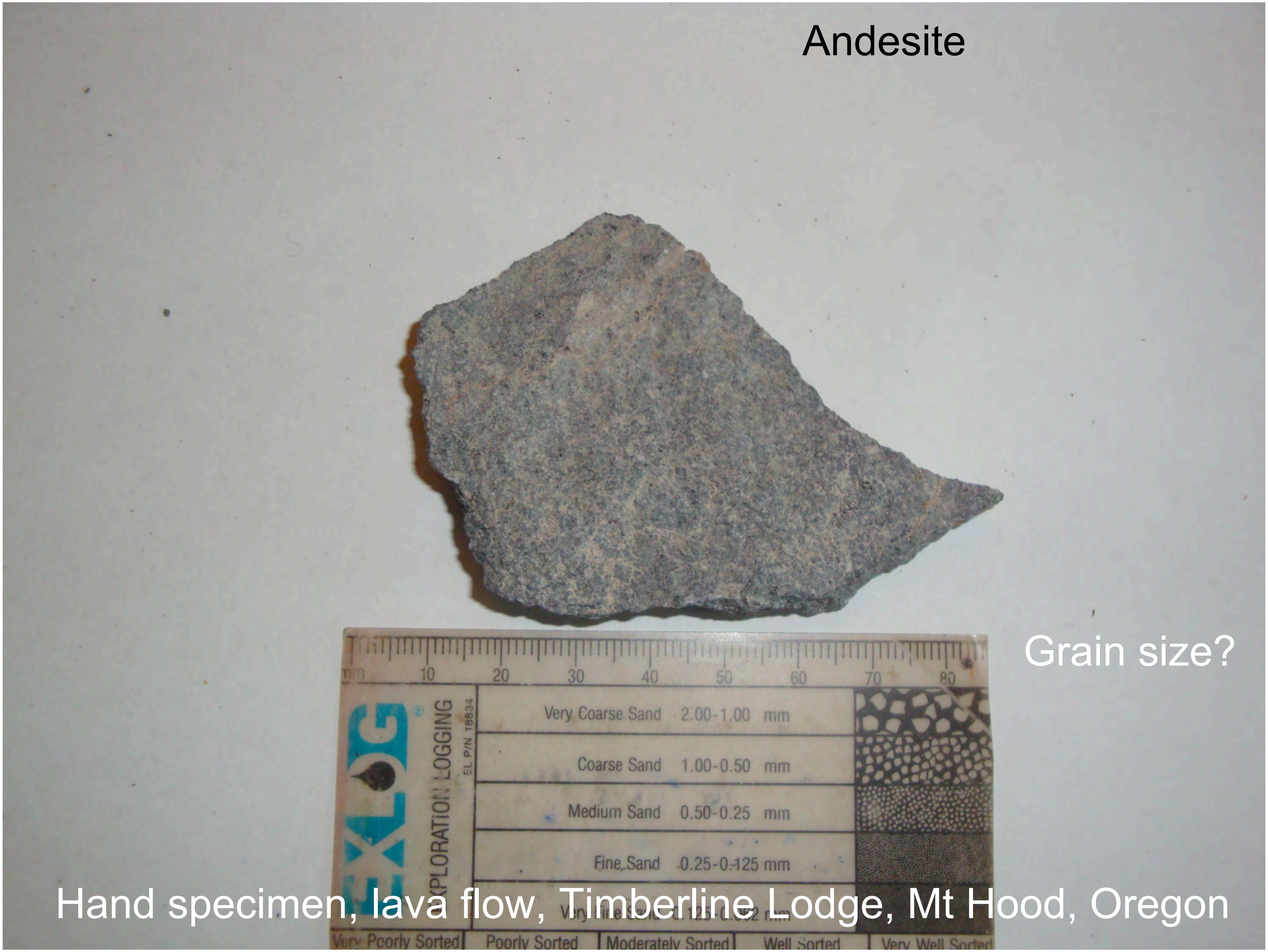
Hand specimen lava flow, Craters of the Moon, Arco, Idaho

Color?
Phenocrysts?
Vesicles?

Grain size?

Hand specimen, lava flow, Timberline Lodge, Mt Hood, Oregon

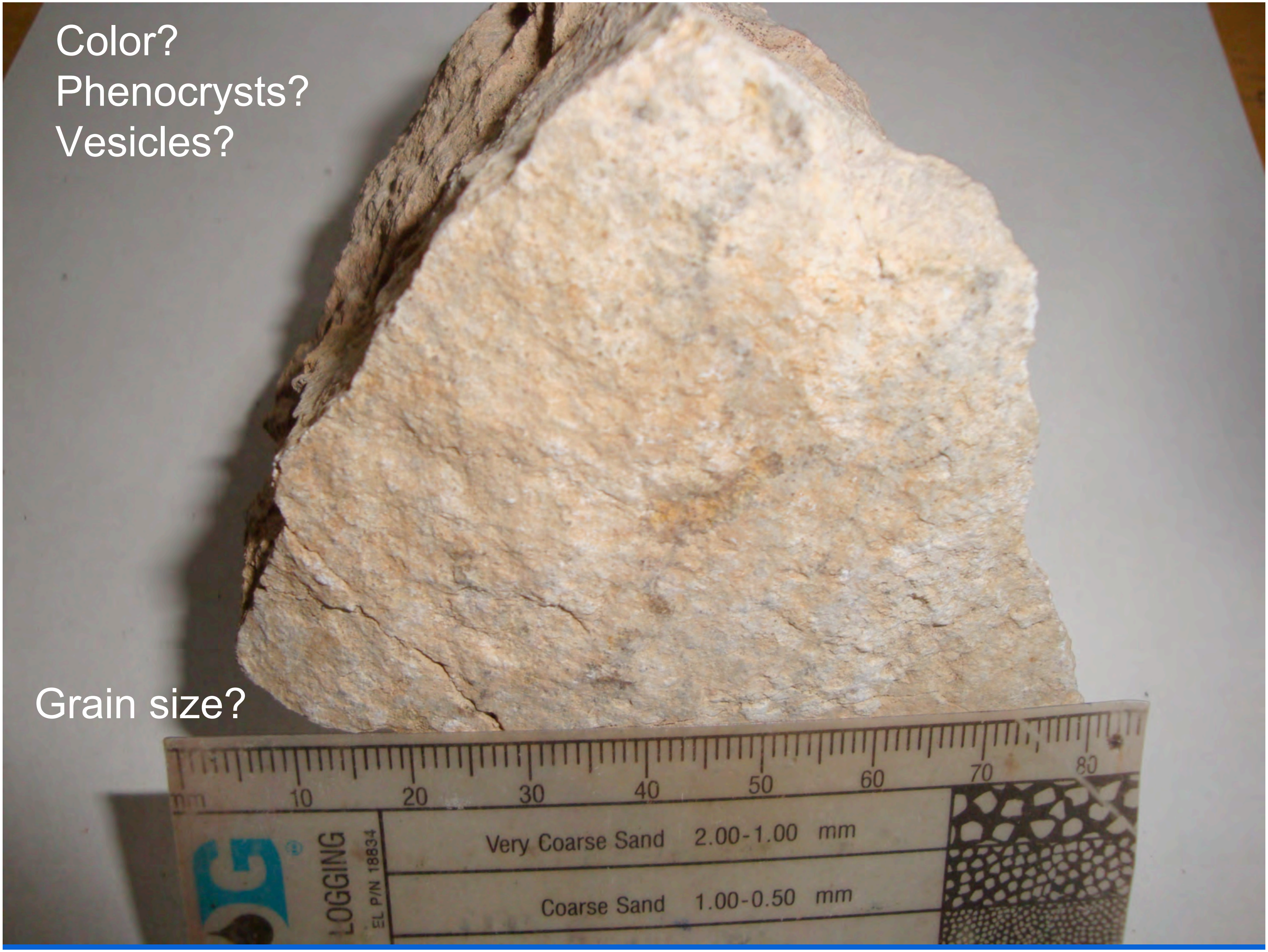
Andesite



Grain size?

Hand specimen, lava flow, Timberline Lodge, Mt Hood, Oregon

Do your labels distinguish these four samples?



Color?

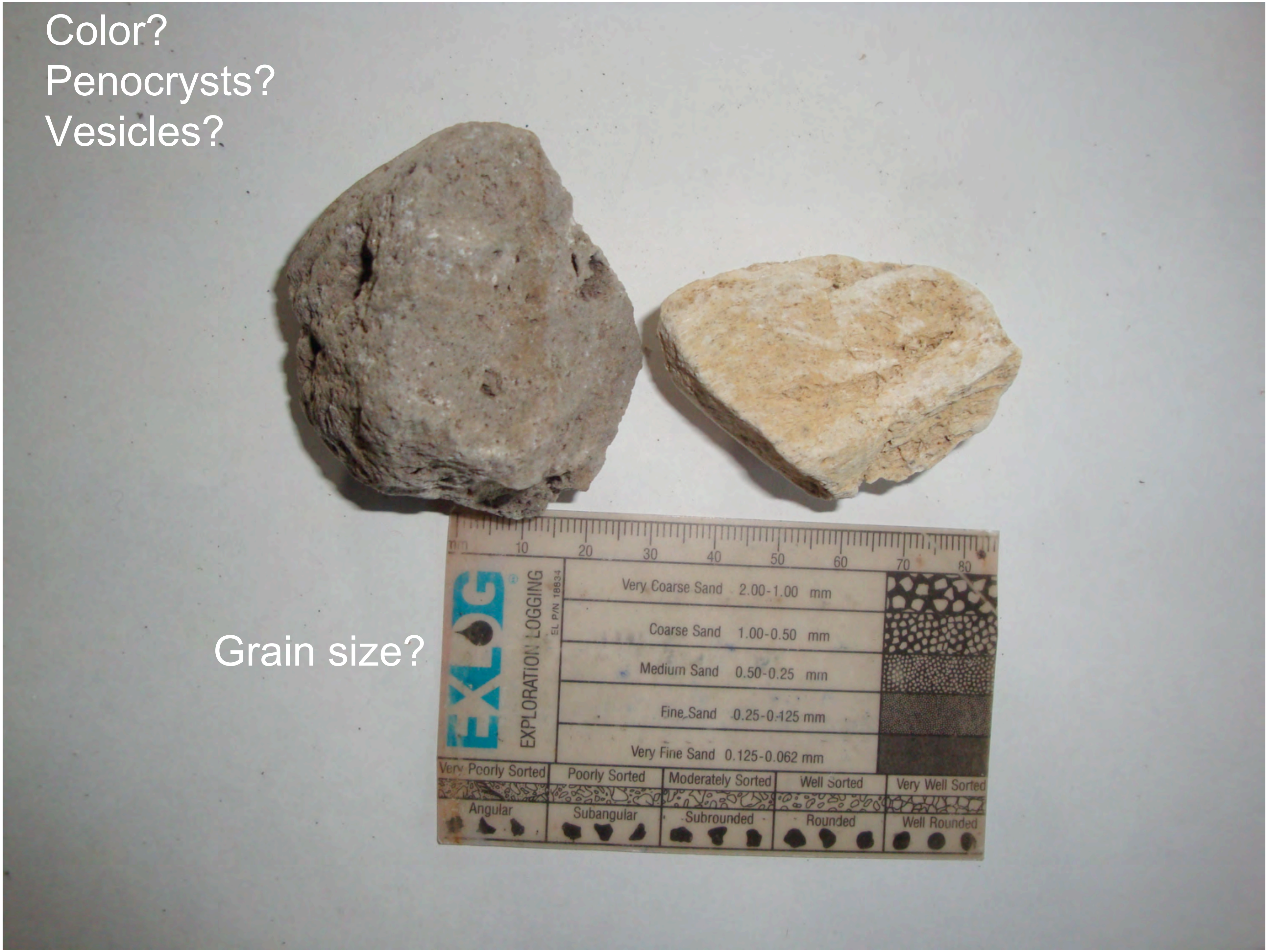
Phenocrysts?

Vesicles?

Grain size?

Air Fall Tuff

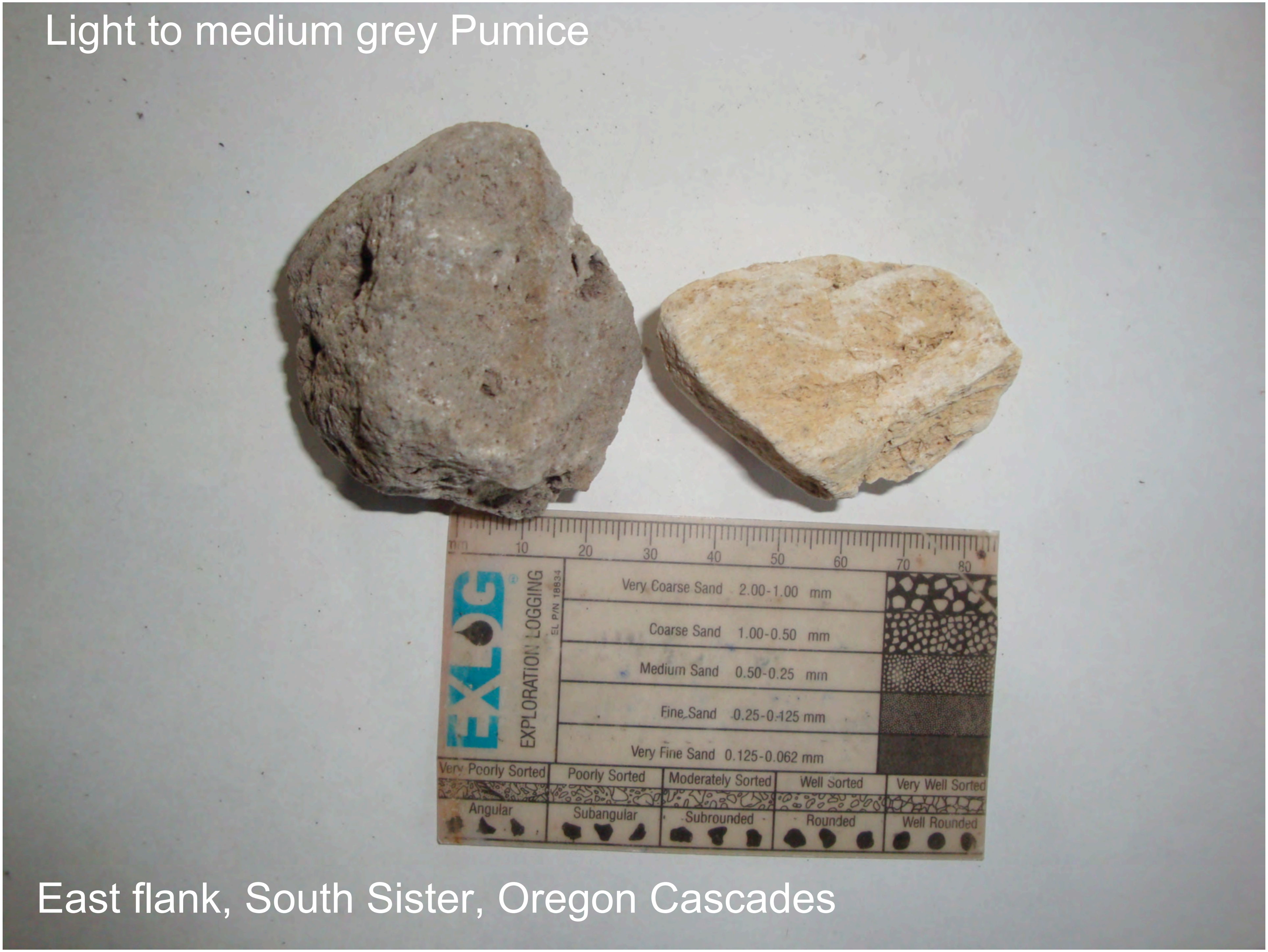
Coldwater Canyon, Mount St Helens, Washington



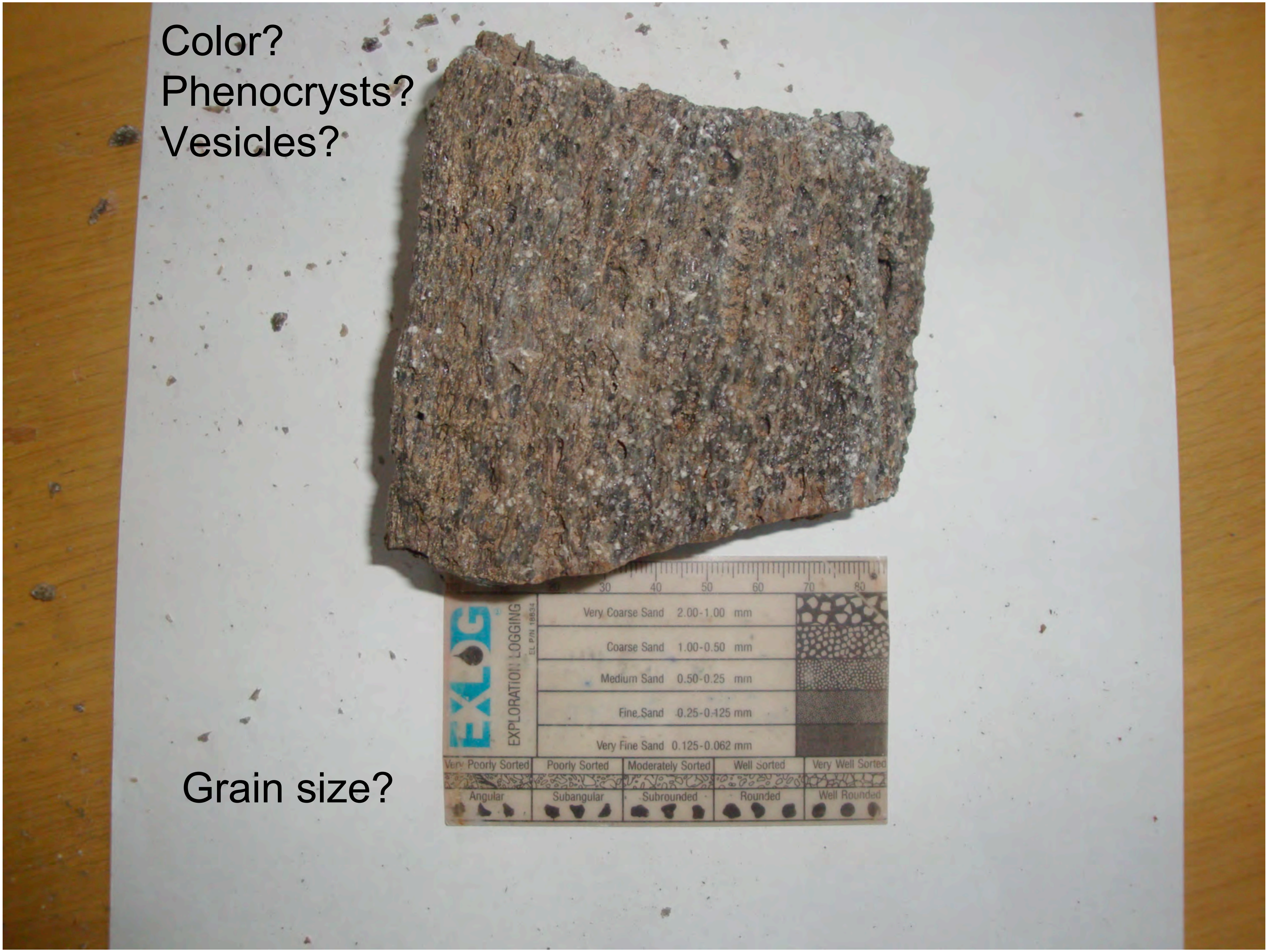
Color?
Penocrysts?
Vesicles?

Grain size?

Light to medium grey Pumice



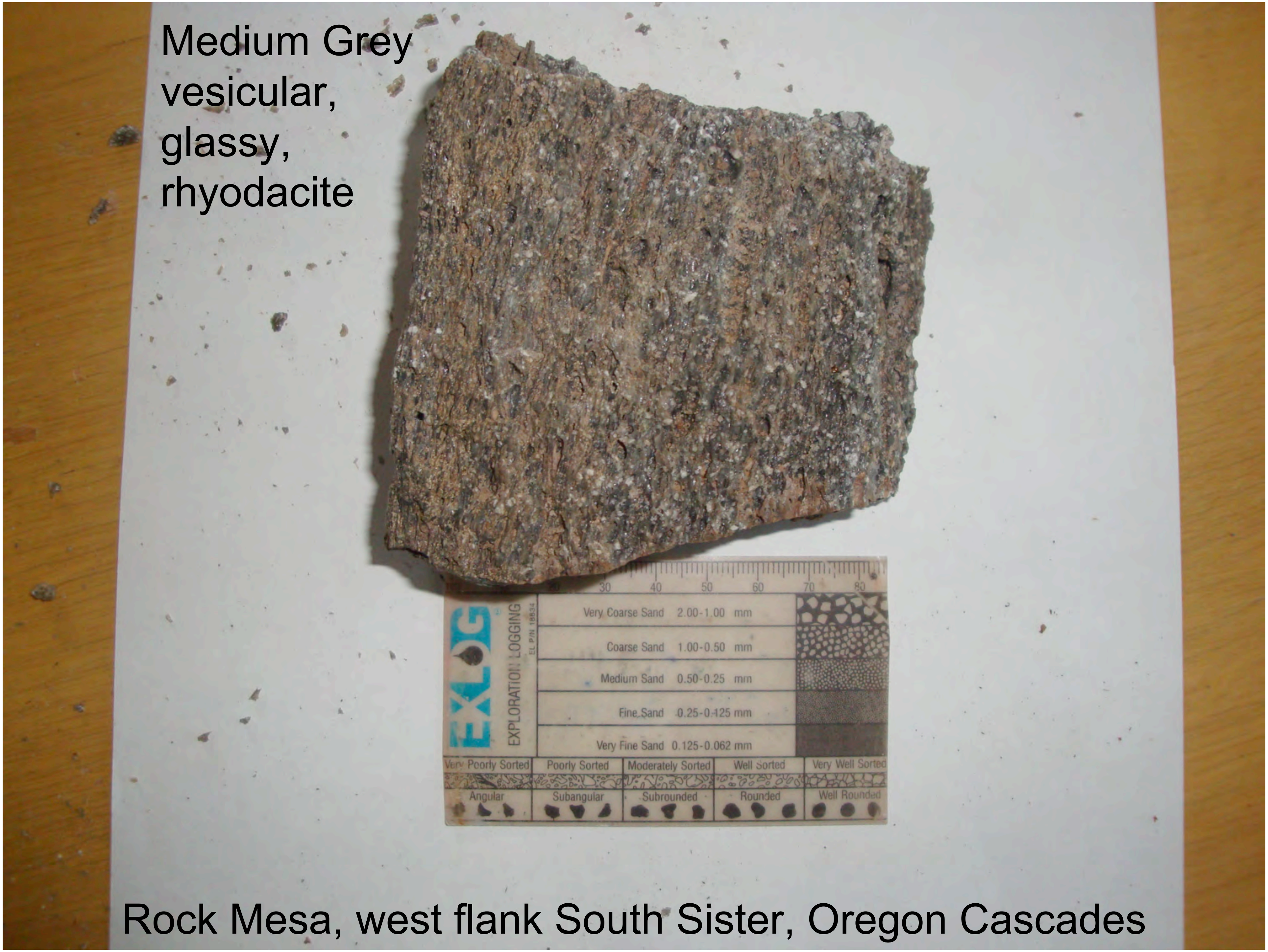
East flank, South Sister, Oregon Cascades



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" volcaniclastic debris deposit;

(3) Ellittico eruptive products;

(4) Valle del Bove centers eruptive products;

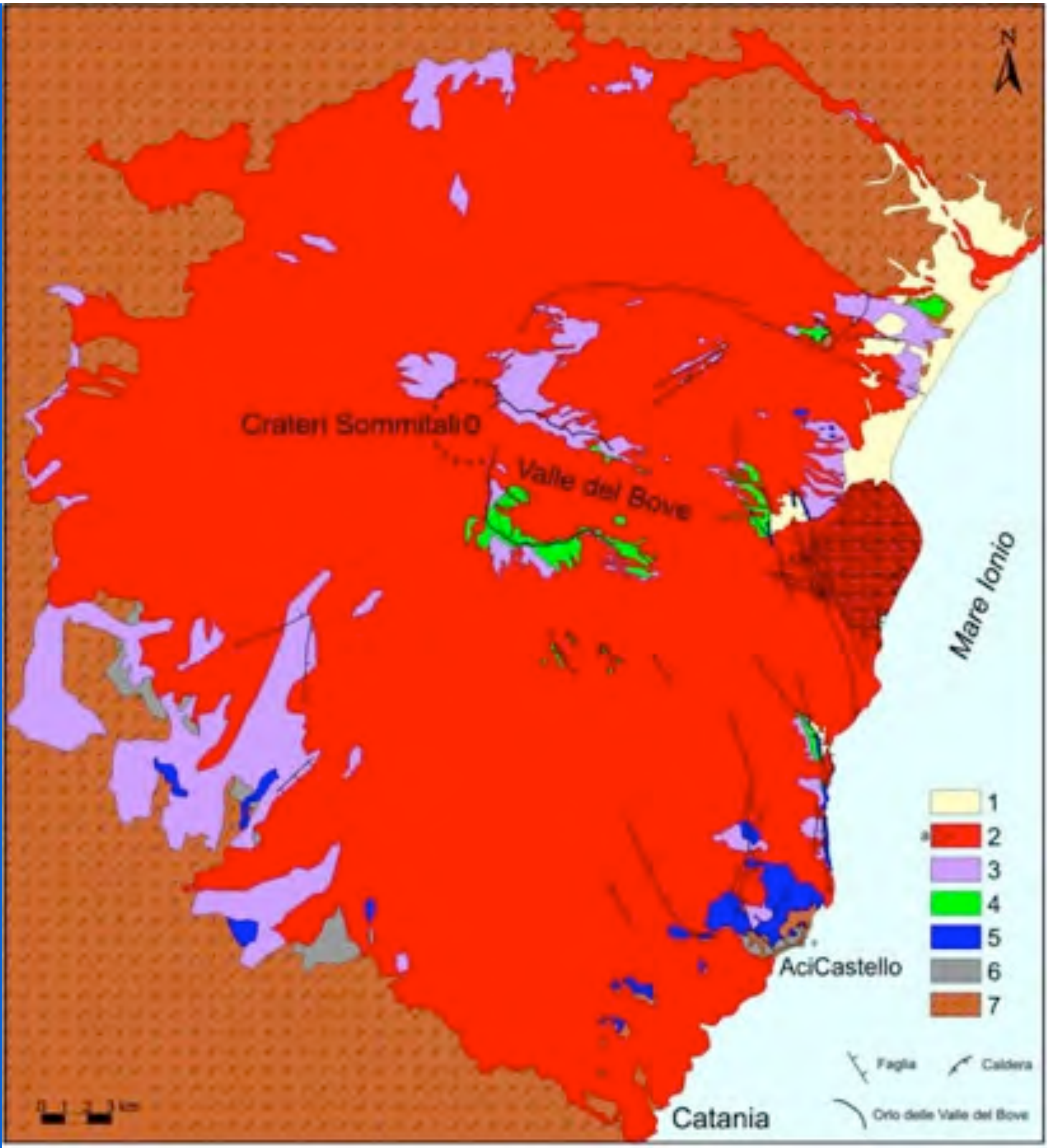
(5) Timpe phase eruptive products;

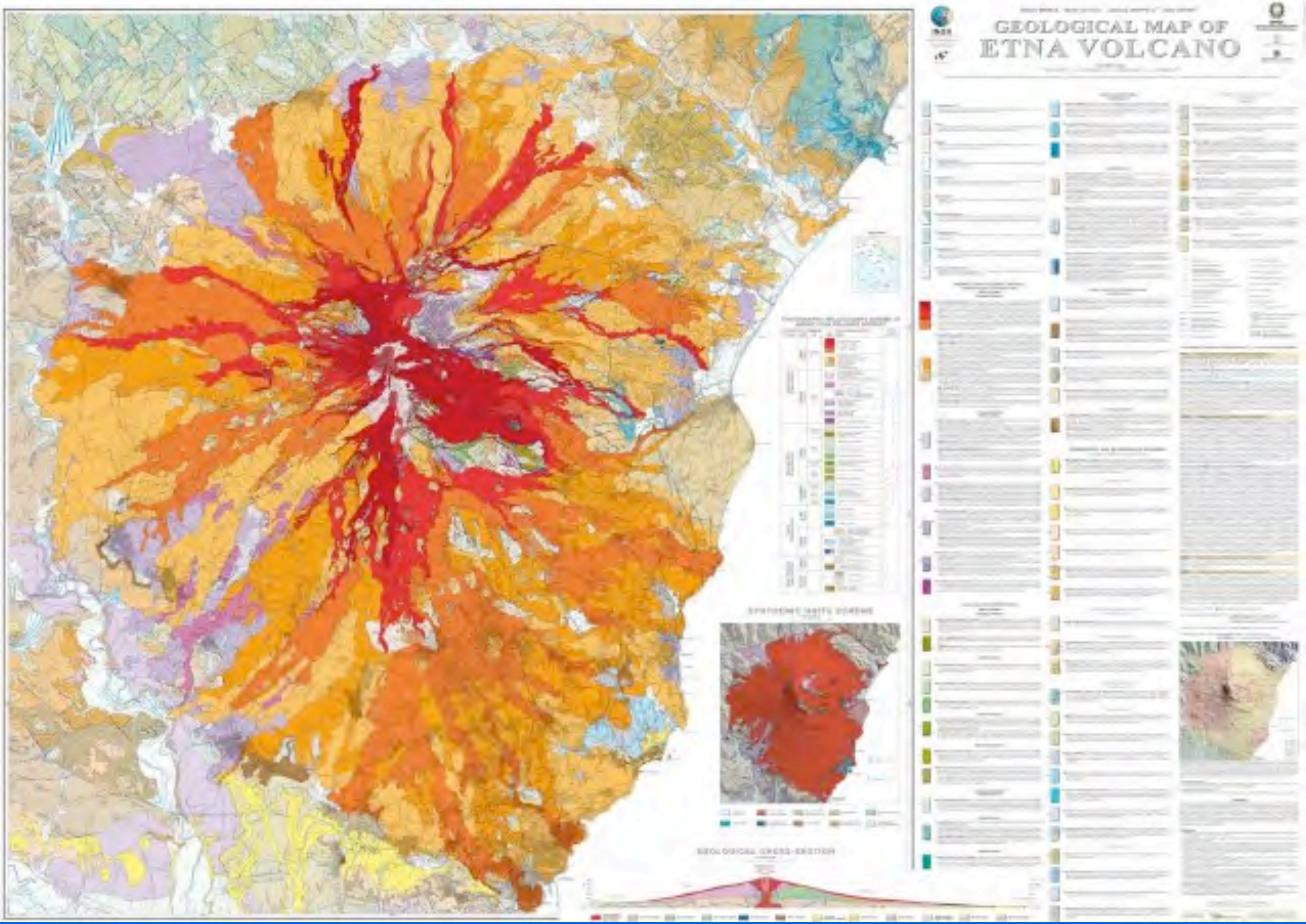
(6) Basal Tholeiites;

(7) Sedimentary basement;

"Faglia" = fault,

"Orlo della Valle del Bove" = Valle del Bove rim; "Crateri Sommitali" = Summit craters




GEOLOGICAL MAP OF
ETNA VOLCANO
SYNTHEMIC UNITS SCHEME
GEOLOGICAL CROSS-SECTION

Monte Etna Cross-Section

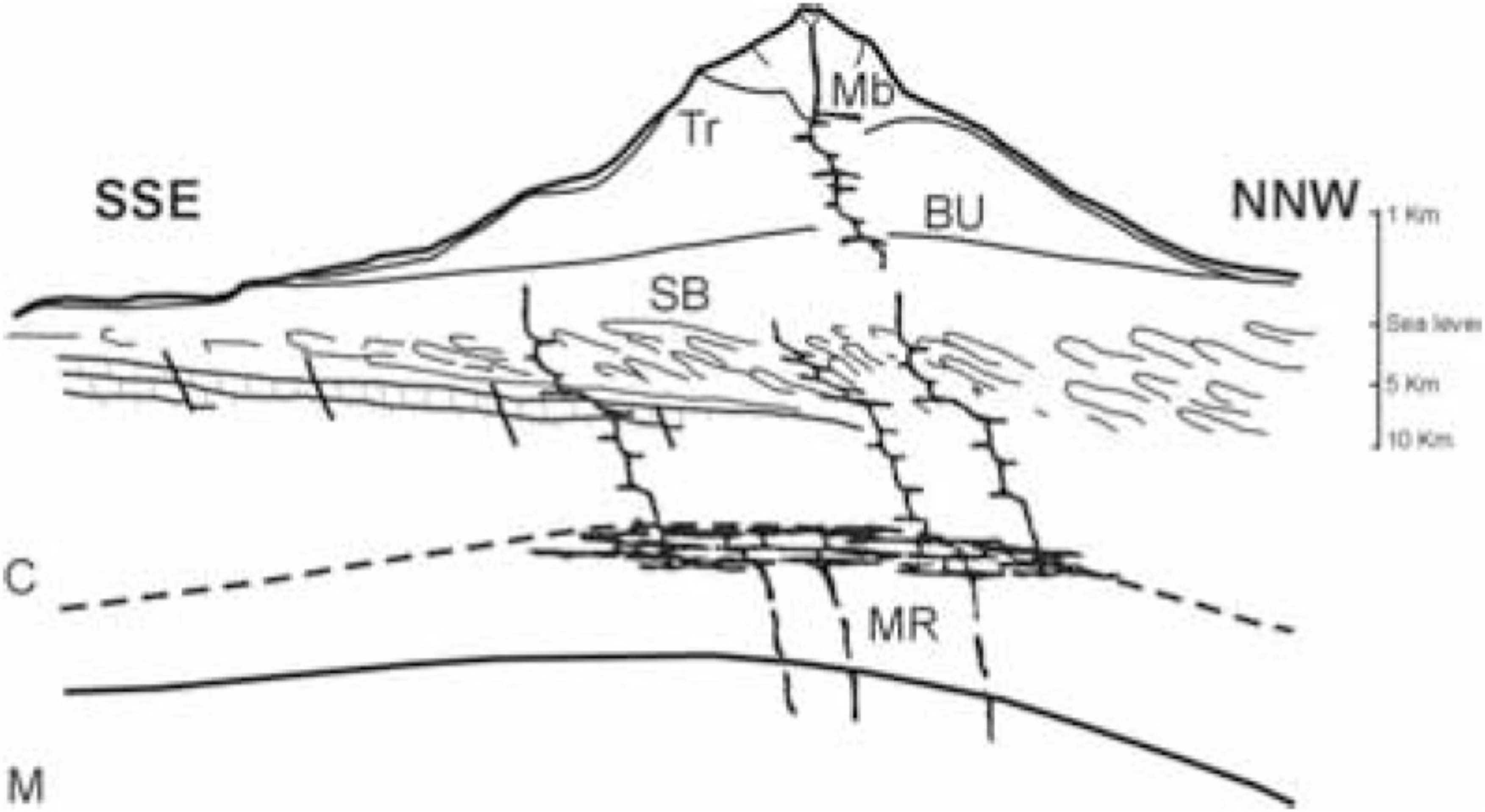


Figure 2 - Cross-section sketch, NNW-SSE (Randazzo – Summit area - Acireale) of Mount Etna, showing the relationship between the main units within the volcanic sequence and the underlying basement. Note the different scale of elevations above and below sea level (lm). Mb: Mongibello Unit; TR: Trifoglietto Unit; BU: Basal volcanic Units (older than 80 ka); SB: Sedimentary Basement Successions; MR: Main agma reservoirs; C: Continental crust; M: Mantle.

Modified after COLTELLI et al., (1994)		Modified after ROMANO (1982)	
Syntheme	Lithosomatic Unit	Unit	Centre (Edifice)
Il Piano		MONGIBELLO	Recent Mongibello
Le Concazze	Ellittico Pomiciaro Tripodo		Ellittico
Cuvigghiuni		TRIFOGLIETTO	Vavalaci
Giannicola	Salifizio Giannicola Grande Trifoglietto		Trifoglietto 2
	Rocca Capra	ANC. ALK. CENTRES	Trifoglietto 1
			Calanna

Table 1 - Tentative correlation between UBS Units and earlier ones for the Etnean succession more recent than about

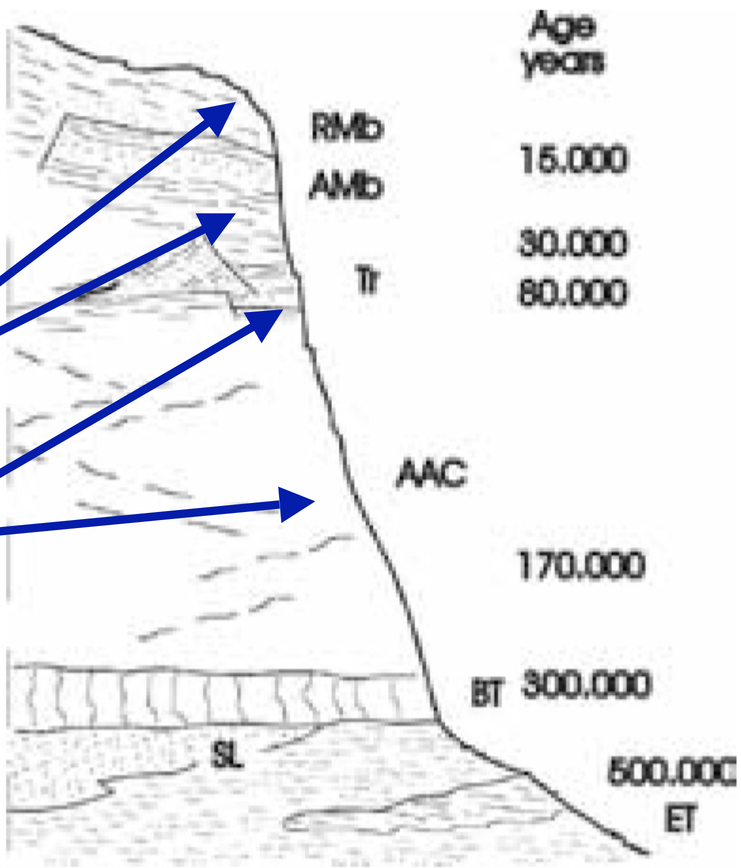


Figure 1 - Schematic representation of the Etnean succession (modified after Cristofolini and Romano, 1982). RM: Recent Mongibello; AM: Ancient Mongibello; TR: Trifoglietto Unit; AAC: Ancient Alkaline Centres; BT: Basal Tholeiitic to transitional lavas (mostly subaerial); ET: Earliest Tholeiites (submarine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

Ash from vents F3 & F5 on Piano de Lago, Mt Etna

Photo taken by Giuseppe Scarpinati on 22 July 2001

http://www.ct.ingv.it/index.php?option=com_content&view=article&id=
406%3A10-years-ago-the-july-august-2001-eruption-of-etna&catid=102%3Aetna&lang=en

July 2001 Eruption

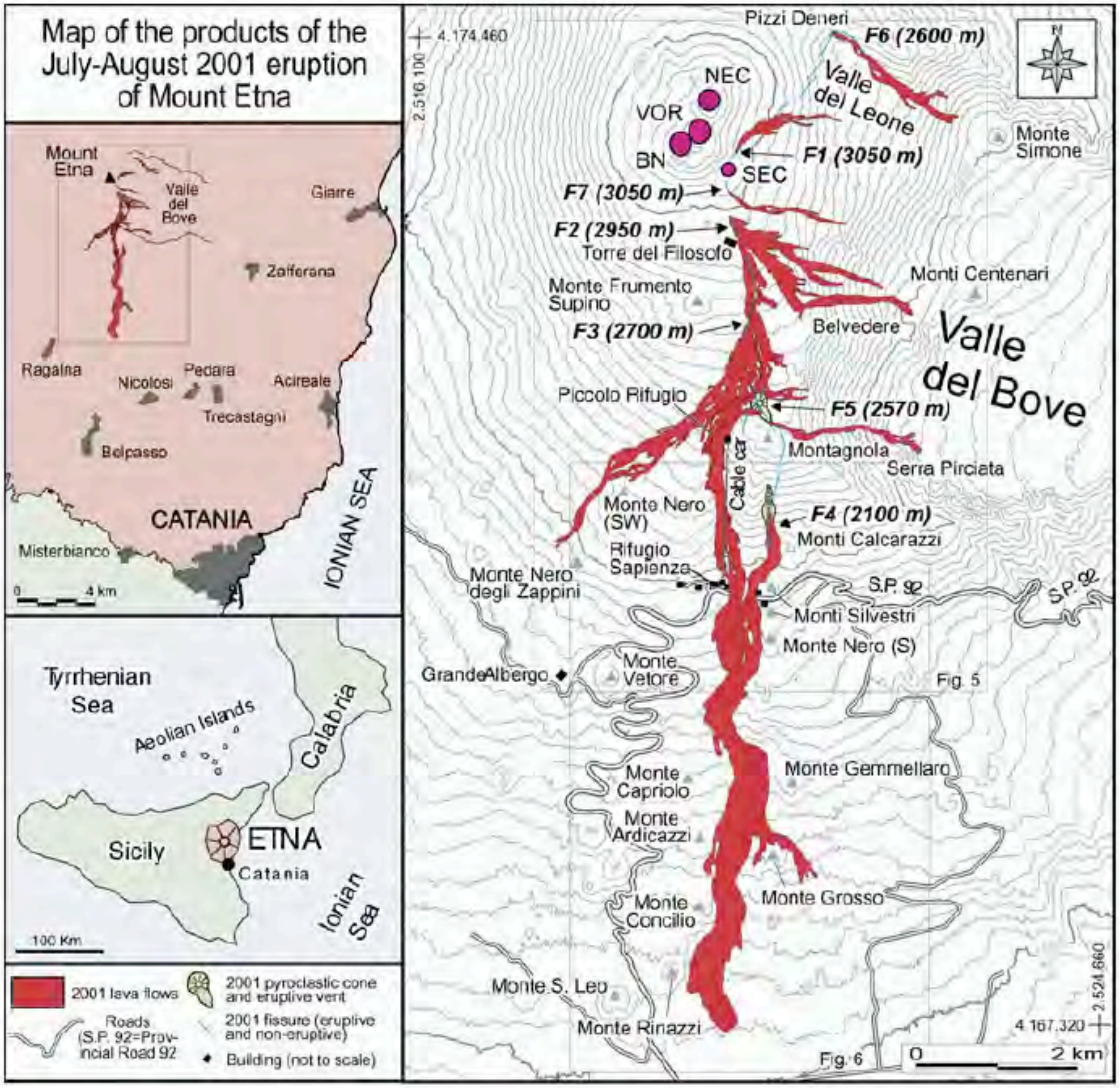
July 28 Piano del lago

July 22, 2001

July 28

http://www.ct.ingv.it/index.php?option=com_content&view=article&id=406%3A10-years-ago-the-july-august-2001-eruption-of-etna&catid=102%3Aetna&lang=en

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 flowfields and major population centers in the SE sector of Mt. Etna. Location of volcano is indicated in *inset at lower left*. Contours in metres



Behncke and Neri 2003

Behncke and Neri 2003

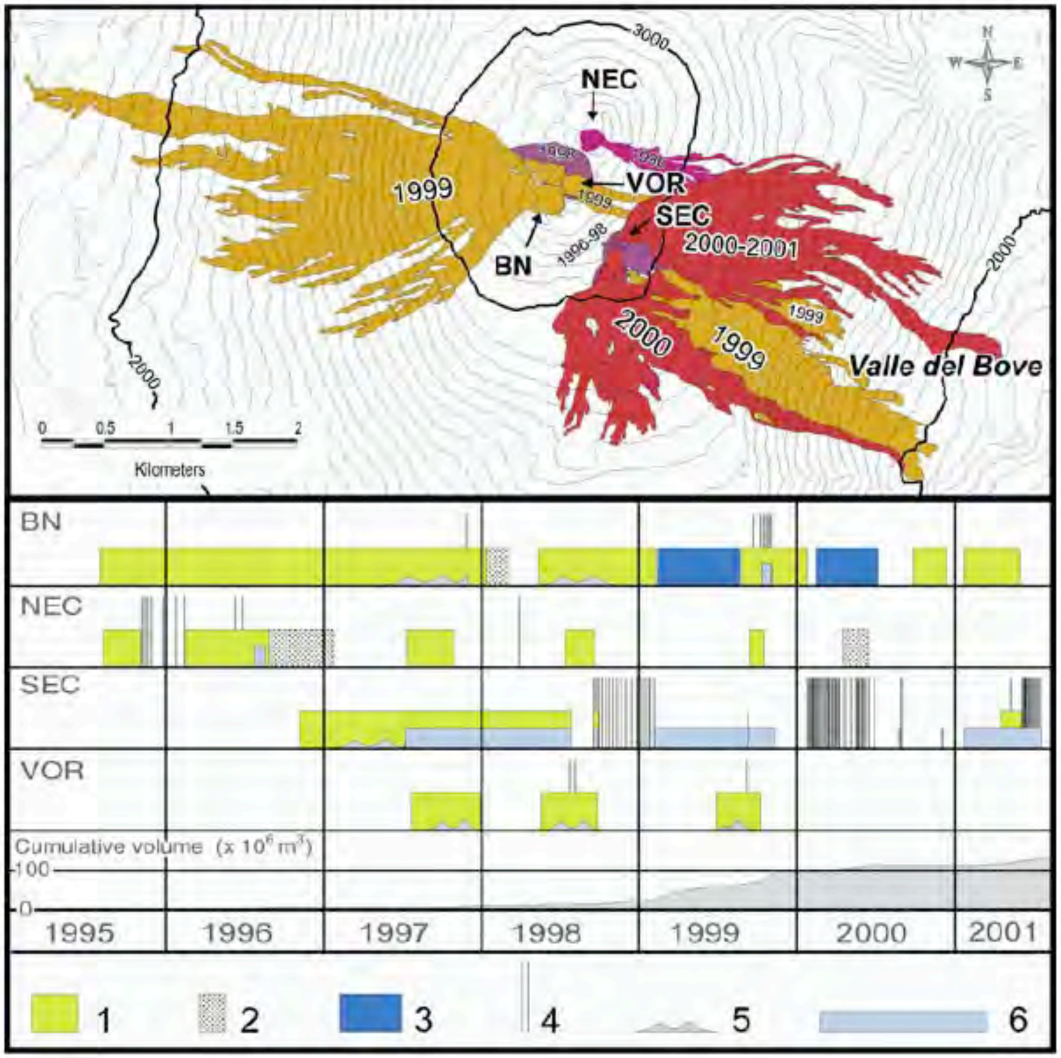


Fig. 2 **a** Lava flows produced by 1995–2001 eruptions of summit craters of Mt. Etna. Contours in metres. **b** Sequence and character of eruptive events at the summit craters, 1995–2001. *First four rows* contain qualitative information regarding time, duration, and style of eruptive activity, and 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

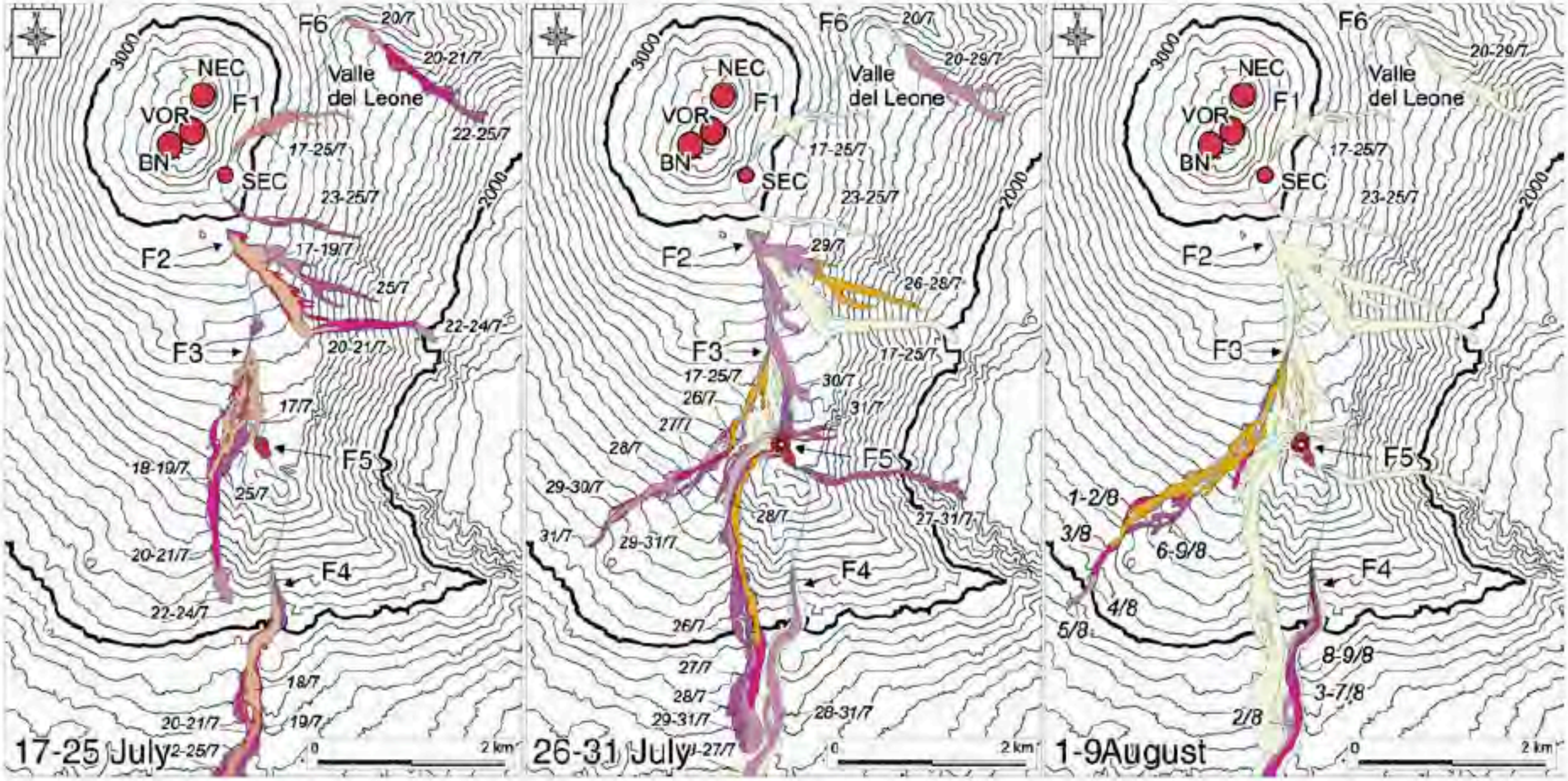


Fig. 5 Comparative maps showing evolution of lava flow-fields produced by F1–F3 and F5–F7. *17–25 July* All lava fields grow mainly downslope, but new lateral branches develop on 25 July below F2 and F3. *26–31 July* Several distinct lava flows extend from F5 toward S and E, a new branch of lava extends 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

Behncke and Neri 2003

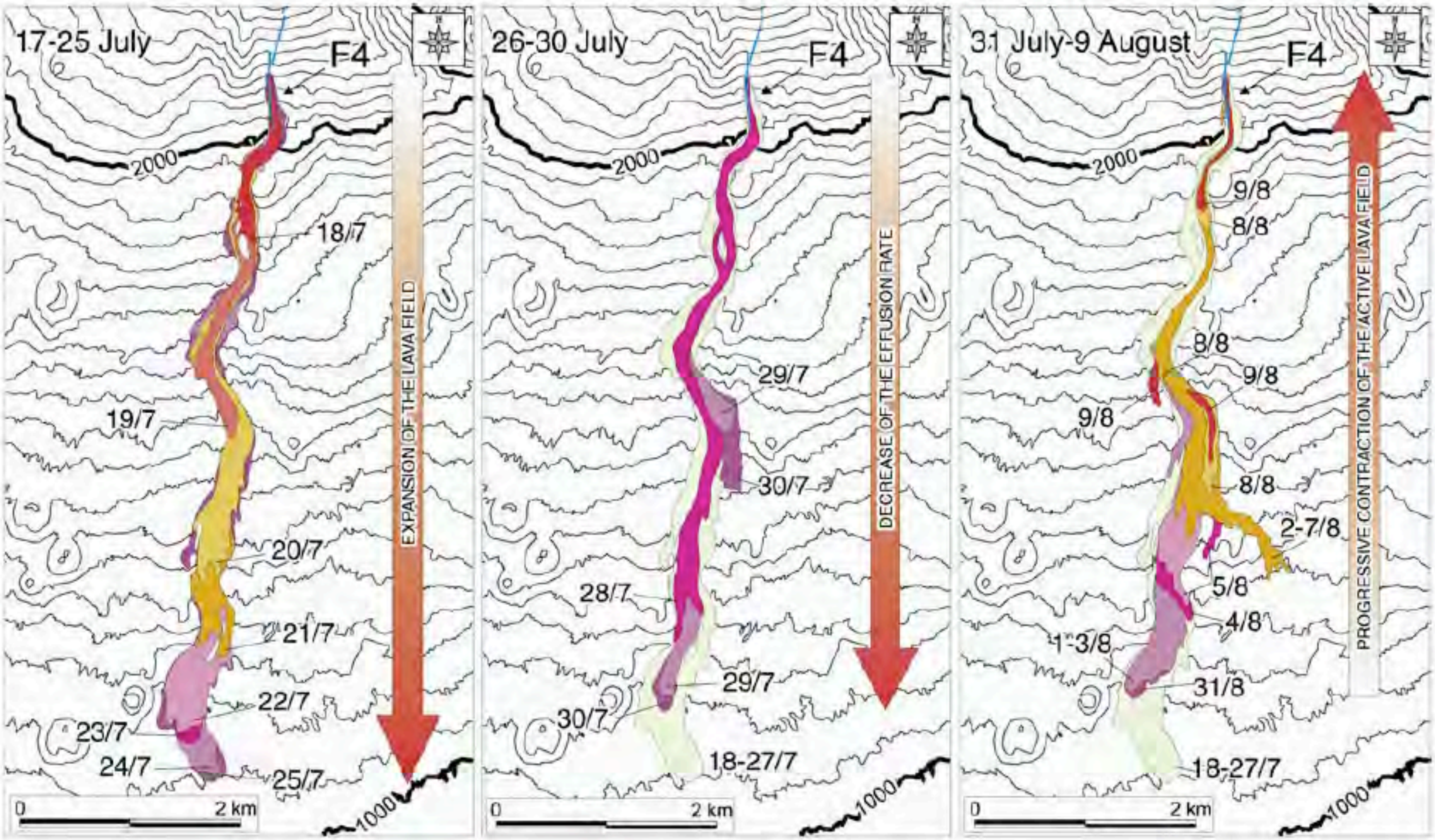


Fig. 6 Comparative maps showing evolution of lava flow-field produced by F4. *17–25 July* First major lava surge between 18 and 25 July generates the longest single flow unit of the entire eruption. *26–30 July* Advance of the second lava surge (28–30 July). Note that during this period negligible net 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 km^2, compared to a total area of 2.4 km^2. Lava flows from F3 and F5 in the map area are not shown for clarity

Behncke and Neri 2003

Behncke and Neri 2003

Fig. 8 Simplified block diagram (not to scale) illustrating the assumed geometric relationships between the two different, independent lateral and eccentric magma pathways established before and during the 2001 eruption

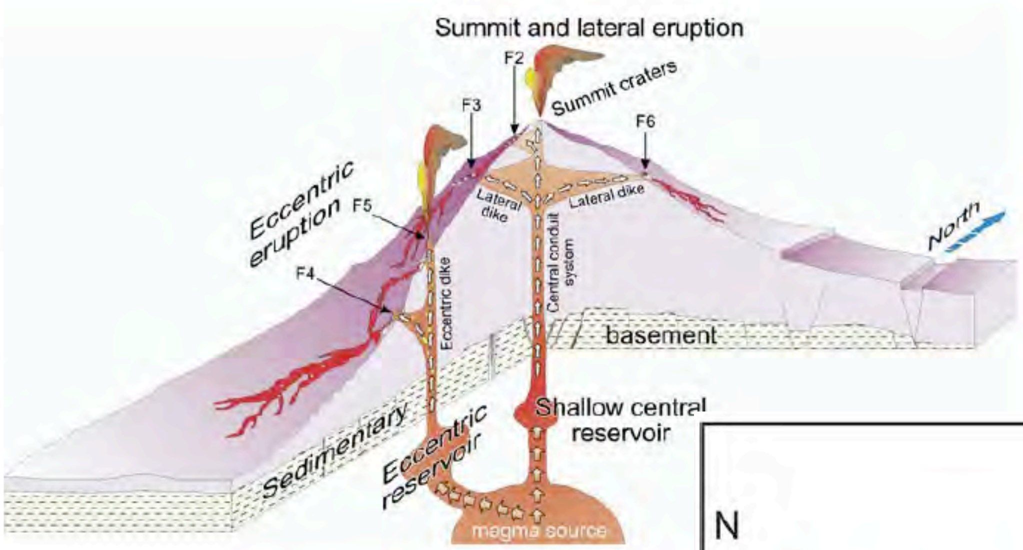
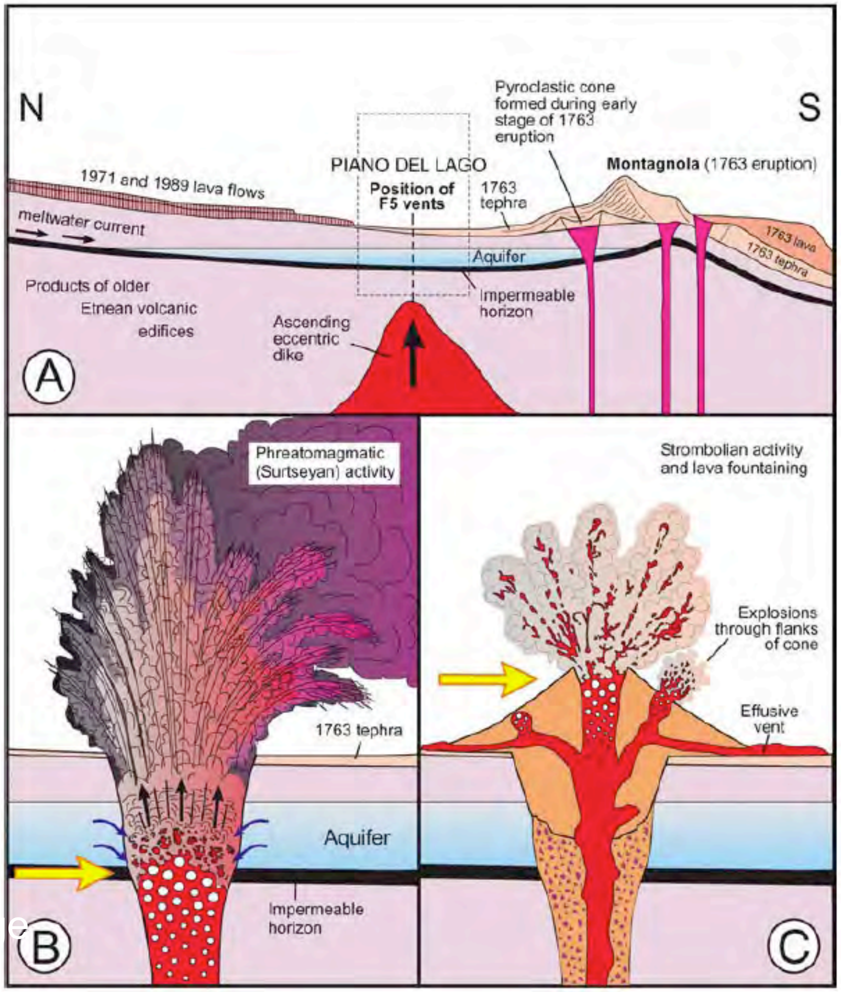


Fig. 9 A Hypothetical N–S section across the Piano del Lago–Montagnola area, showing possible stratigraphic relationships and inferred Position of a shallow aquifer on top of an impermeable horizon, fed by meltwater currents from the summit area. Box indicates area enlarged in B and C. B Cartoon depicting 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

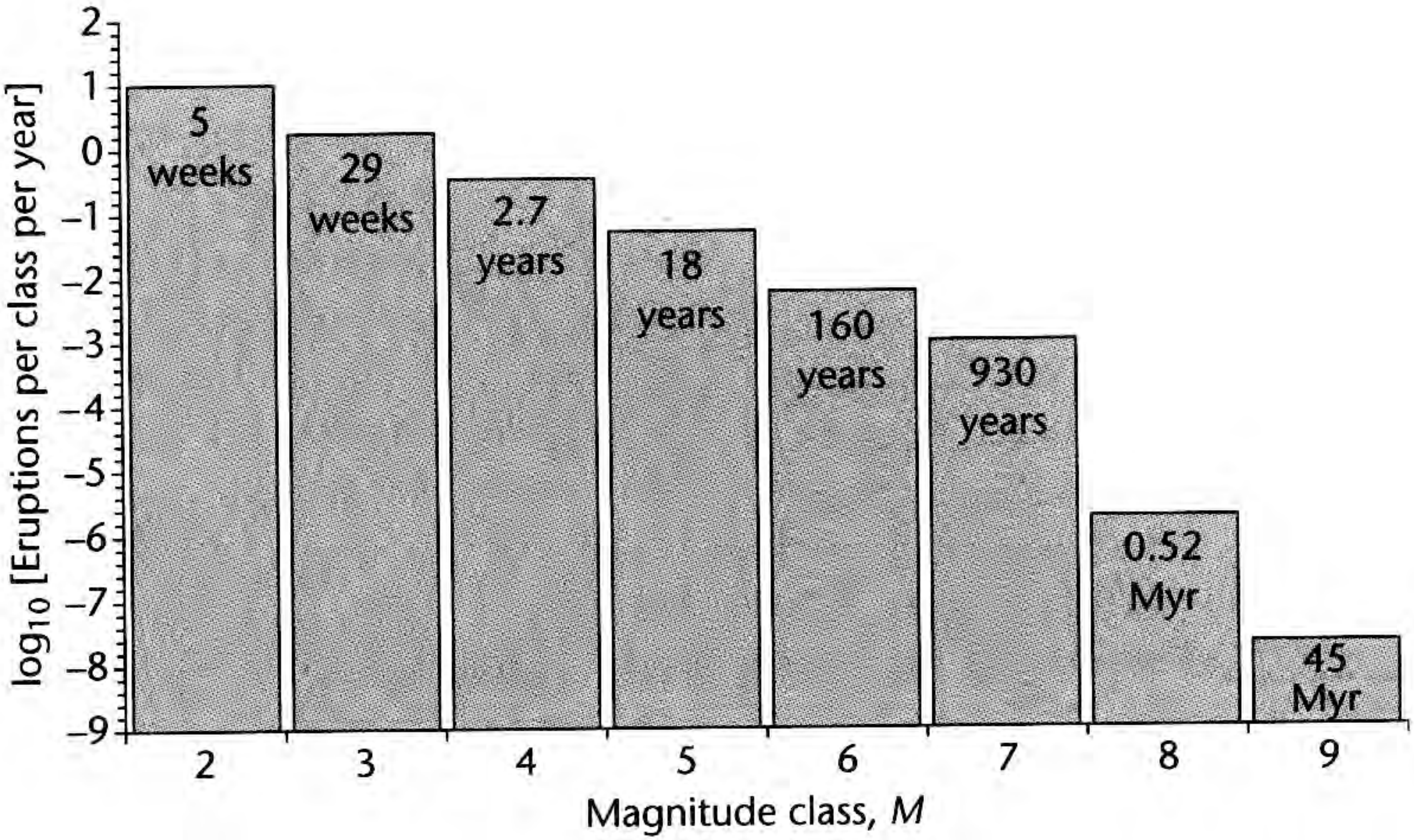
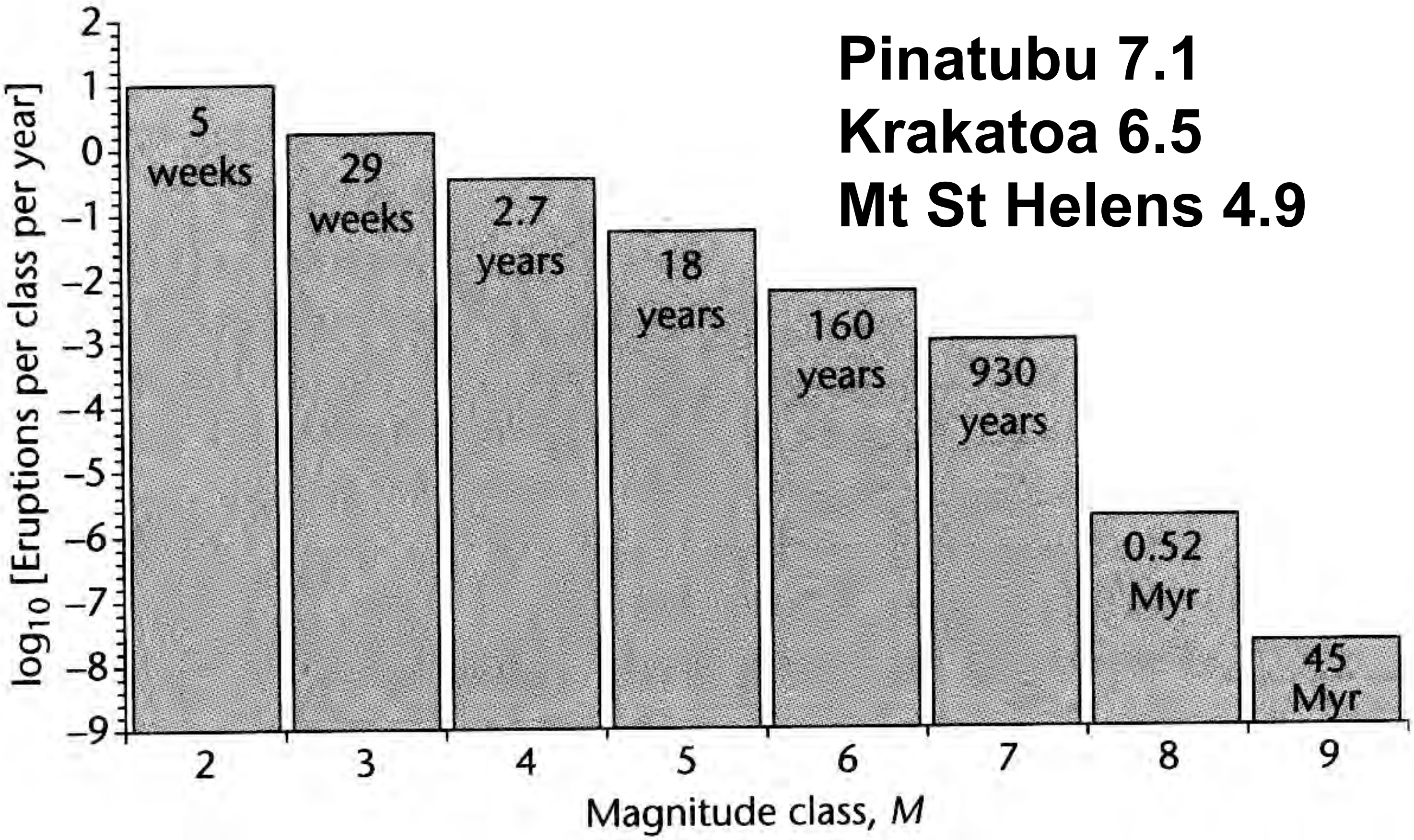


Fig. 5.5 Magnitude–frequency plot for subaerial volcanic eruptions based on records for last 300 yr for $2 \leq M < 6$; last 2 kyr for $6 \leq M < 8$; and for all known 'super-eruptions' of the past 45 Myr for $M \geq 8$. Note that extrapolation of the more or less reliable record for the past 300 years 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 very cautiously. Data from D. Pyle and B. Mason.



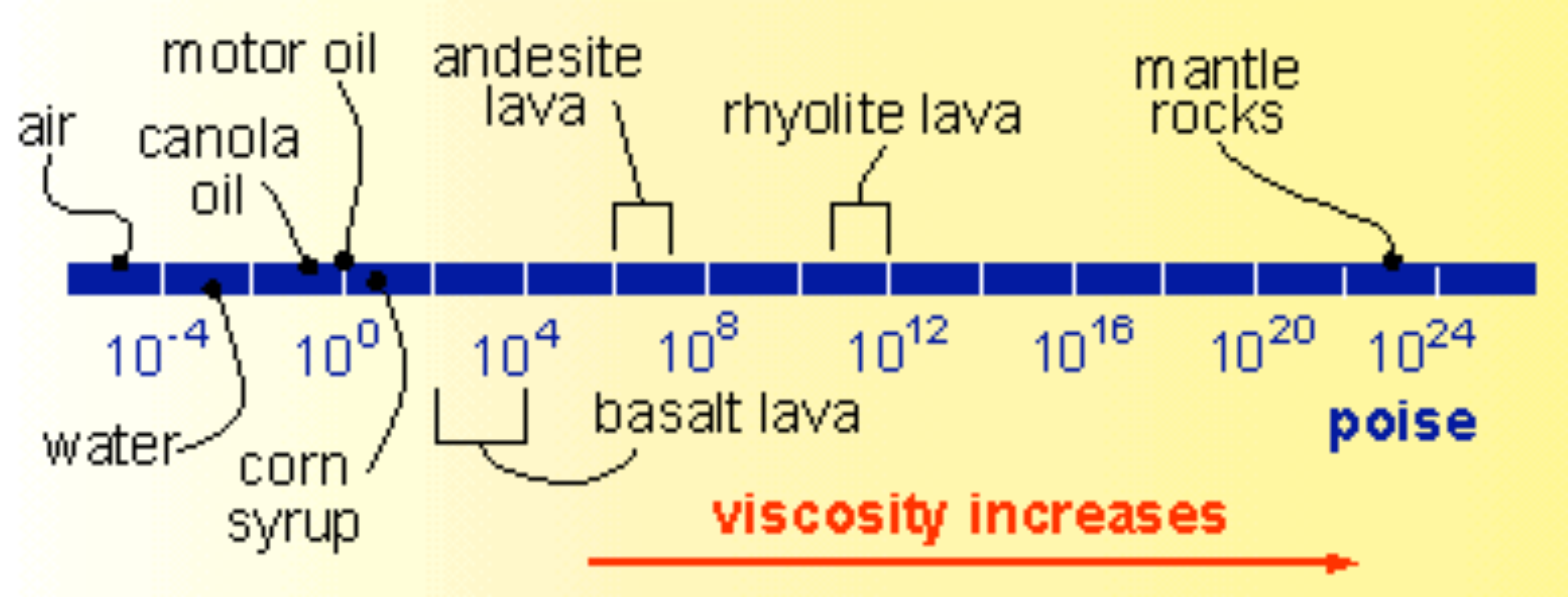
Pinatubu 7.1
Krakatoa 6.5
Mt St Helens 4.9

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 very cautiously. Data from D. Pyle and B. Mason.

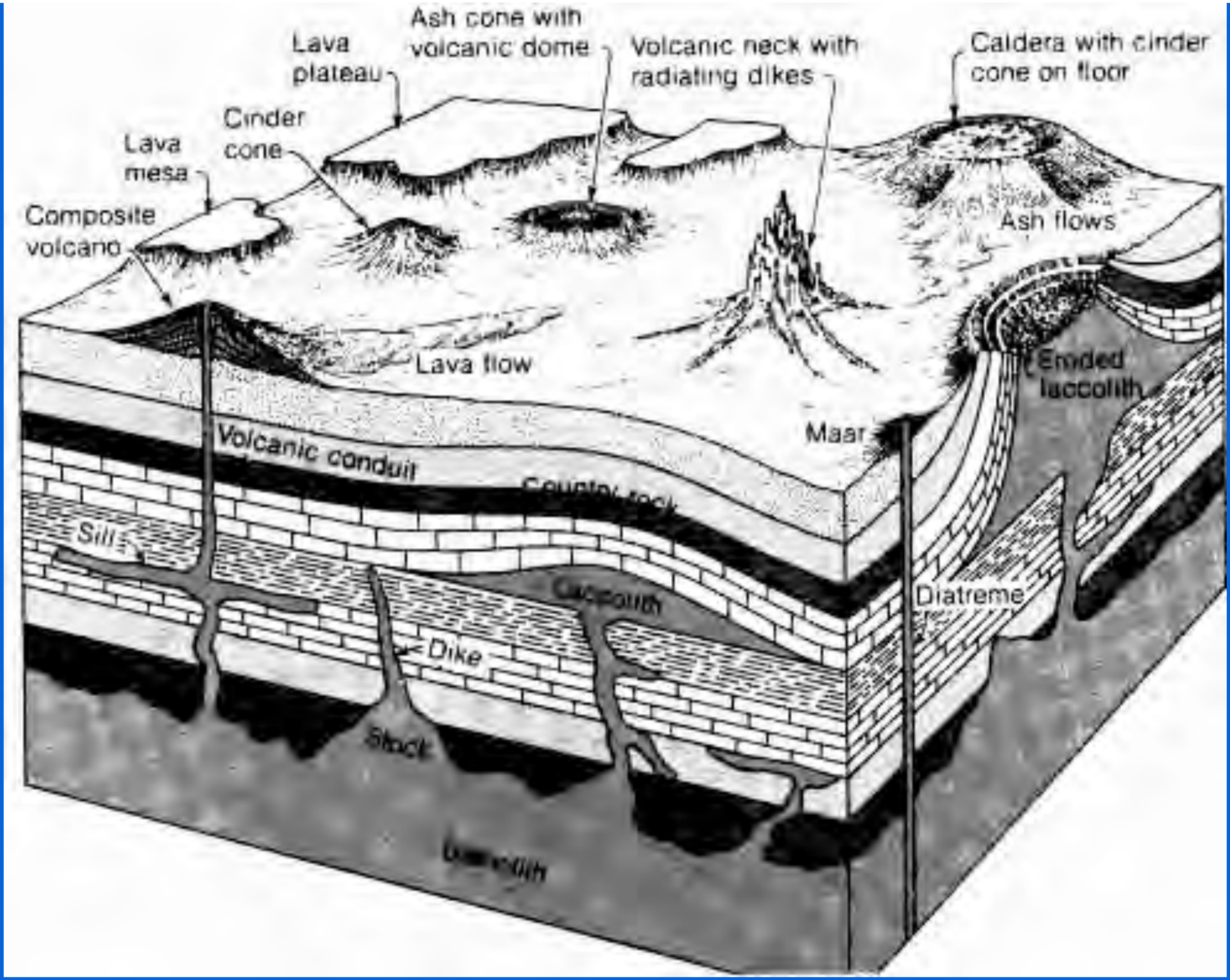
A Simplified Volcanic Activity Classification

- 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



http://disc.sci.gsfc.nasa.gov/geomorphology/GEO_3/GEO_CHAPTER_3.shtml

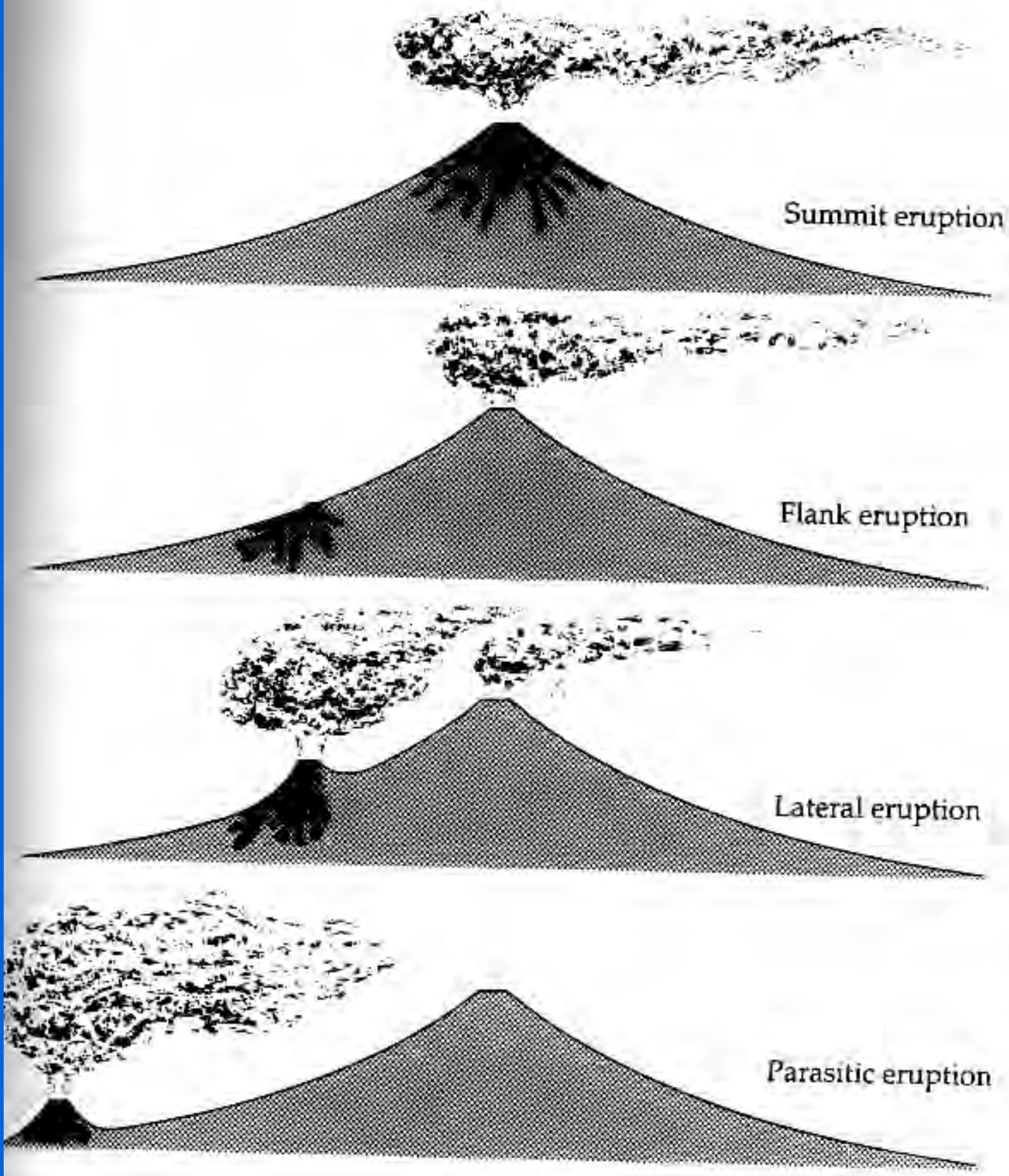
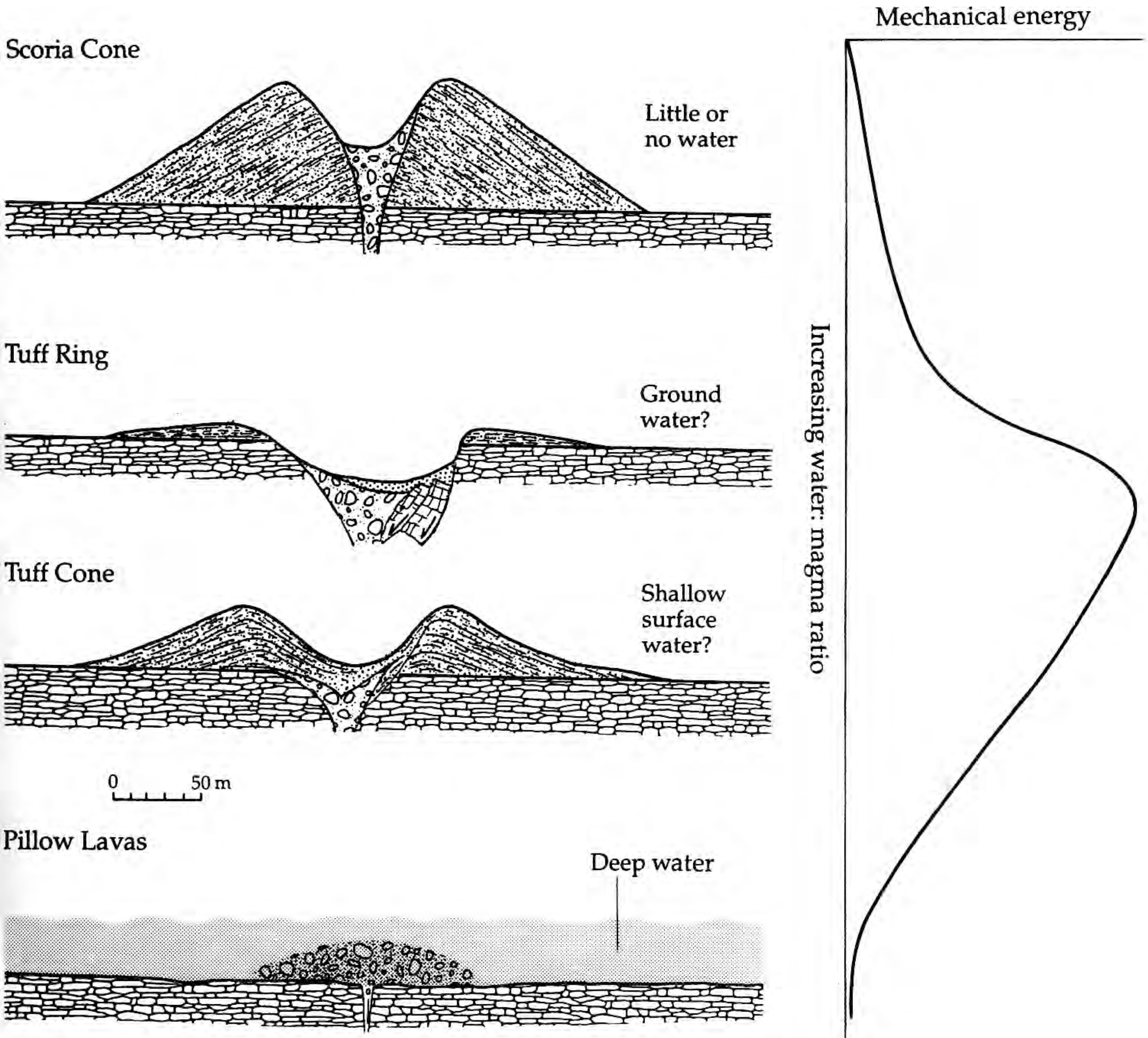


Fig. 5.2 Some terms commonly used in describing the sites of eruptions relative to a simple conical volcano. Flank eruptions commonly commence with summit activity, but activity shifts to lower levels where most lava emerges. 'Lateral' eruptions are similar, but may involve only minimal summit activity.

Francis and Oppenheimer 2004

Impact of water on small basaltic eruptions



Francis and Oppenheimer 2004)

Formation of Crater Lake
Howell Williams (1941)

(reproduced in Francis and Oppenheimer 2004)

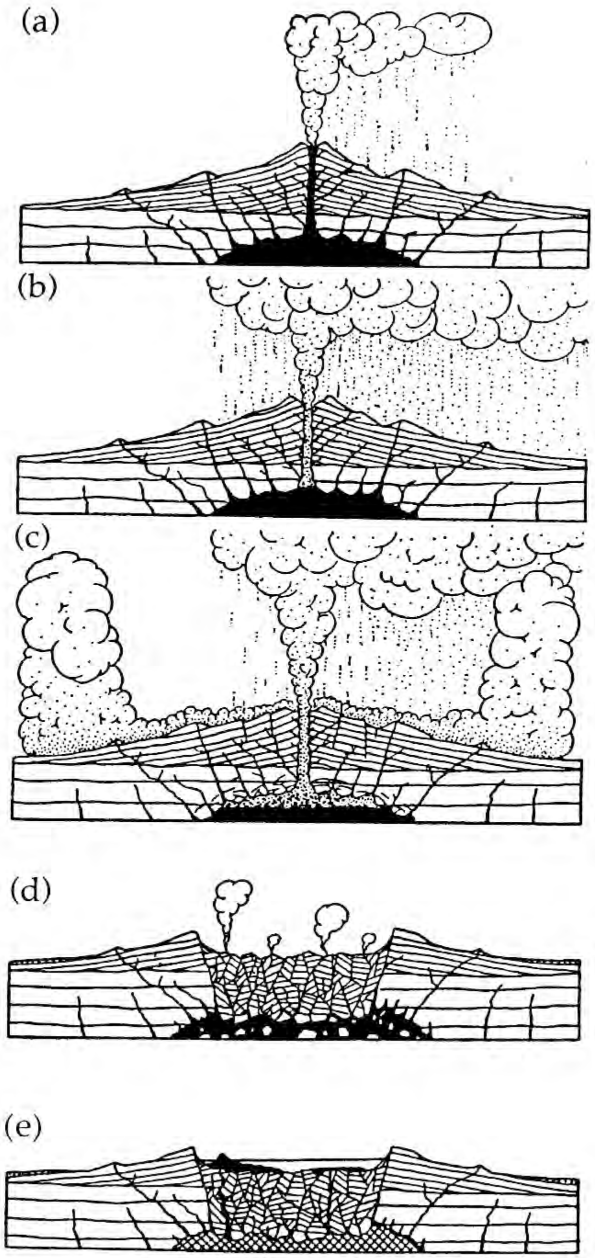


Fig. 11.5 Howel Williams's classic diagrams illustrating the formation of Crater Lake caldera Oregon [13]. His original

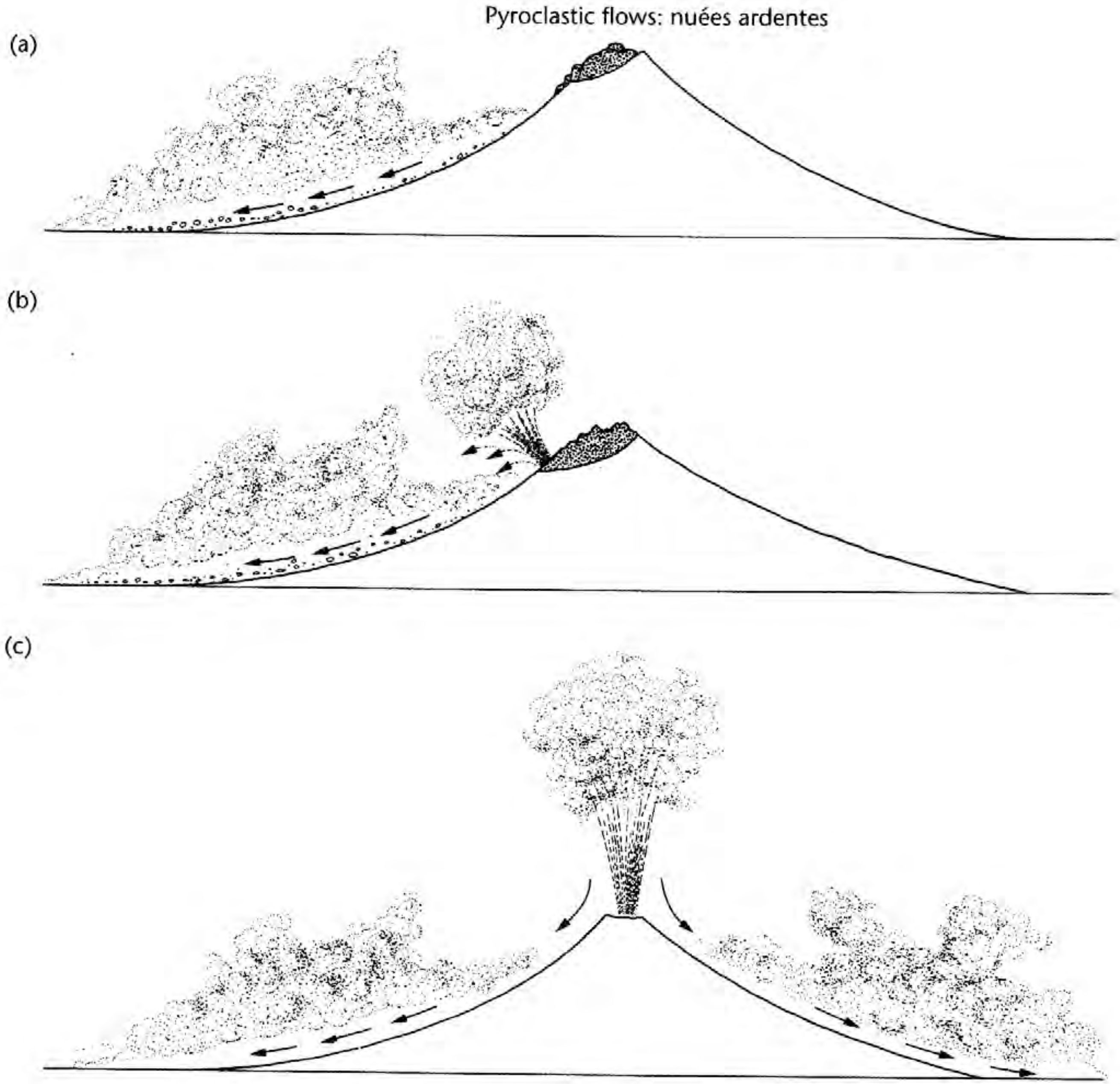


Fig. 9.7 Three common mechanisms for generating PDCs. (a) Simple gravitational collapse of a growing lava dome or flow on a volcano (merapi type). (b) Explosive disruption of growing lava dome (peléean type). (c) Collapse from eruption column (soufrière type).

Francis and Oppenheimer 2004)