Lecture 25 Granites

Wednesday, May 4th, 2005

Chapters 17 & 18: Granitoid Rocks

“Granitoids” (*sensu lato*): loosely applied to a wide range of felsic plutonic rocks (granite *(sensu stricto),* granodiorite, tonalite

- Associated volcanics occur and have same origin, but are frequently eroded away
- Typically associated with diorites and gabbros in granitic batholiths
- Granitoids are the most abundant plutonic rocks in the upper continental crust
- Origins are diverse and very controversial!

Chapter 18: Granitoid Rocks

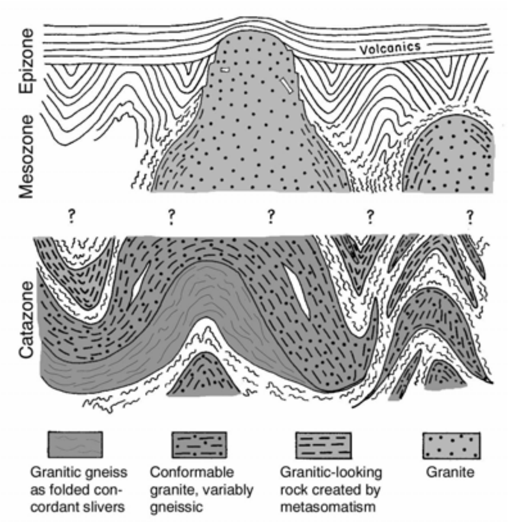
A few broad generalizations:

1) Most granitoids of significant volume occur in areas where the continental crust has been thickened by orogeny, either continental arc subduction or collision of sialic masses. Many granites, however, may post-date the thickening event by tens of millions of years.
2) Because the crust is solid in its normal state, some thermal disturbance is required to form granitoids
3) Most workers are of the opinion that the majority of granitoids are derived by crustal anatexis, but that the mantle may also be involved. The mantle contribution may range from that of a source of heat for crustal anatexis, or it may be the source of material as well

Granite Classifications

- MODAL – relatively easy but tells us little about the origins
- DEPTH – location of granite within the crust
- CHEMICAL – attempts to relate composition and mineralogy to the origin
- TECTONIC – uses tectonic regime to make deductions about origin

Buddington's Depth Zones



Epizonal Granite

Mesozonal Granite

Catazonal Granite

Figure 4-31. **a.** General characteristics of plutons in the epizone, mesozone, and catazone. From Buddington (1959), *Geol. Soc. Amer. Bull.*, **70**, 671-747.

Chemical Classification

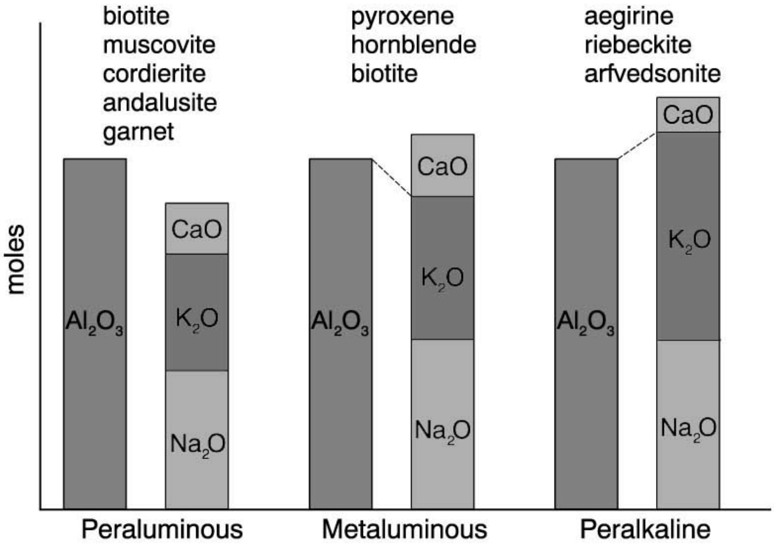
Table 18-3. The S-I-A-M Classification of Granitoids

Type	SiO_2	K_2O/Na_2O	Ca, Sr	A/(C+N+K)*	Fe^{3+}/Fe^{2+}	Cr, Ni	$\delta^{18}O$	$^{87}Sr/^{86}Sr$	Misc	Petrogenesis
M	46-70%	low	high	low	low	low	< 9‰	< 0.705	Low Rb, Th, U Low LIL and HFS	Subduction zone or ocean-intraplate Mantle-derived
I	53-76%	low	high in mafic rocks	low: metaluminous to peraluminous	moderate	low	< 9‰	< 0.705	high LIL/HFS med. Rb, Th, U hornblende magnetite	Subduction zone Infracrustal Mafic to intermed. igneous source
S	65-74%	high	low	high metaluminous	low	high	> 9‰	> 0.707	variable LIL/HFS high Rb, Th, U biotite, cordierite Als, Grt, Ilmenite	Subduction zone Supracrustal sedimentary source
A	high → 77%	Na_2O high	low	var peralkaline	var	low	var	var	low LIL/HFS high Fe/Mg high Ga/Al High REE, Zr High F, Cl	Anorogenic Stable craton Rift zone

* *molar* $Al_2O_3/(CaO+Na_2O+K_2O)$

Data from White and Chappell (1983), Clarke (1992), Whalen (1985)

M = mantle derived
I = Melting of igneous source material
S = melting of sediment source material
A = occur in anorogenic regions – origin controversial



S-Type I-Type A-Type

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.

These analyses of granitic rocks are on p. 347 in your textbook. Those of you with granitic "pet rocks" may find it useful to plot some of these analyses with your own data.

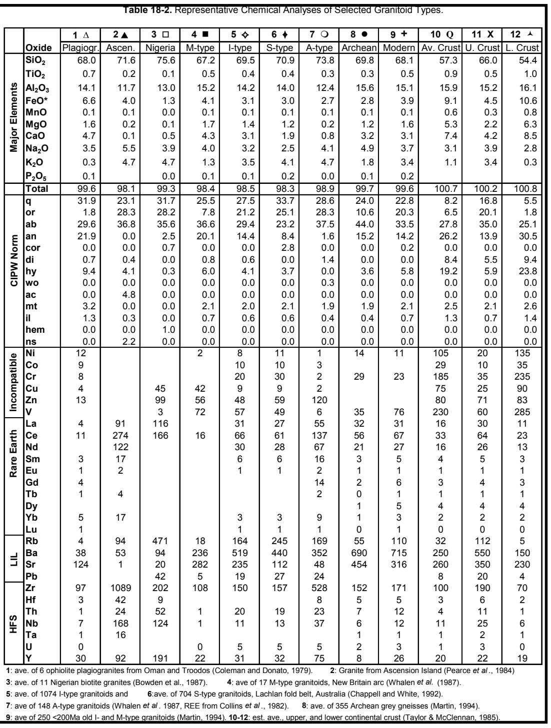


Table 18-2. Representative Chemical Analyses of Selected Granitoid Types.

		1 △	2 ▲	3 □	4 ■	5 ✧	6 ⧫	7 ❍	8 ●	9 +	10 Q	11 X	12 ⅄
	Oxide	Plagiogr.	Ascen.	Nigeria	M-type	I-type	S-type	A-type	Archean	Modern	Av. Crust	U. Crust	L. Crust
Major Elements	**SiO_2**	68.0	71.6	75.6	67.2	69.5	70.9	73.8	69.8	68.1	57.3	66.0	54.4
	TiO_2	0.7	0.2	0.1	0.5	0.4	0.4	0.3	0.3	0.5	0.9	0.5	1.0
	Al_2O_3	14.1	11.7	13.0	15.2	14.2	14.0	12.4	15.6	15.1	15.9	15.2	16.1
	FeO*	6.6	4.0	1.3	4.1	3.1	3.0	2.7	2.8	3.9	9.1	4.5	10.6
	MnO	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.6	0.3	0.8
	MgO	1.6	0.2	0.1	1.7	1.4	1.2	0.2	1.2	1.6	5.3	2.2	6.3
	CaO	4.7	0.1	0.5	4.3	3.1	1.9	0.8	3.2	3.1	7.4	4.2	8.5
	Na_2O	3.5	5.5	3.9	4.0	3.2	2.5	4.1	4.9	3.7	3.1	3.9	2.8
	K_2O	0.3	4.7	4.7	1.3	3.5	4.1	4.7	1.8	3.4	1.1	3.4	0.3
	P_2O_5	0.1		0.0	0.1	0.1	0.2	0.0	0.1	0.2			
	Total	99.6	98.1	99.3	98.4	98.5	98.3	98.9	99.7	99.6	100.7	100.2	100.8
CIPW Norm	**q**	31.9	23.1	31.7	25.5	27.5	33.7	28.6	24.0	22.8	8.2	16.8	5.5
	or	1.8	28.3	28.2	7.8	21.2	25.1	28.3	10.6	20.3	6.5	20.1	1.8
	ab	29.6	36.8	35.6	36.6	29.4	23.2	37.5	44.0	33.5	27.8	35.0	25.1
	an	21.9	0.0	2.5	20.1	14.4	8.4	1.6	15.2	14.2	26.2	13.9	30.5
	cor	0.0	0.0	0.7	0.0	0.0	2.8	0.0	0.0	0.2	0.0	0.0	0.0
	di	0.7	0.4	0.0	0.8	0.6	0.0	1.4	0.0	0.0	8.4	5.5	9.4
	hy	9.4	4.1	0.3	6.0	4.1	3.7	0.0	3.6	5.8	19.2	5.9	23.8
	wo	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0
	ac	0.0	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	mt	3.2	0.0	0.0	2.1	2.0	2.1	1.9	1.9	2.1	2.5	2.1	2.6
	il	1.3	0.3	0.0	0.7	0.6	0.6	0.4	0.4	0.7	1.3	0.7	1.4
	hem	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ns	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Incompatible	**Ni**	12			2	8	11	1	14	11	105	20	135
	Co	9				10	10	3			29	10	35
	Cr	8				20	30	2	29	23	185	35	235
	Cu	4		45	42	9	9	2			75	25	90
	Zn	13		99	56	48	59	120			80	71	83
	V			3	72	57	49	6	35	76	230	60	285
Rare Earth	**La**	4	91	116		31	27	55	32	31	16	30	11
	Ce	11	274	166	16	66	61	137	56	67	33	64	23
	Nd		122			30	28	67	21	27	16	26	13
	Sm	3	17			6	6	16	3	5	4	5	3
	Eu	1	2			1	1	2	1	1	1	1	1
	Gd	4						14	2	6	3	4	3
	Tb	1	4					2	0	1	1	1	1
	Dy								1	5	4	4	4
	Yb	5	17			3	3	9	1	3	2	2	2
	Lu	1				1	1	1	0	1	0	0	0
LIL	**Rb**	4	94	471	18	164	245	169	55	110	32	112	5
	Ba	38	53	94	236	519	440	352	690	715	250	550	150
	Sr	124	1	20	282	235	112	48	454	316	260	350	230
	Pb			42	5	19	27	24			8	20	4
HFS	**Zr**	97	1089	202	108	150	157	528	152	171	100	190	70
	Hf	3	42	9				8	5	5	3	6	2
	Th	1	24	52	1	20	19	23	7	12	4	11	1
	Nb	7	168	124	1	11	13	37	6	12	11	25	6
	Ta	1	16						1	1	1	2	1
	U	0			0	5	5	5	2	3	1	3	0
	Y	30	92	191	22	31	32	75	8	26	20	22	19

1: ave. of 6 ophiolite plagiogranites from Oman and Troodos (Coleman and Donato, 1979). **2**: Granite from Ascension Island (Pearce *et al*., 1984)
3: ave. of 11 Nigerian biotite granites (Bowden et al., 1987). **4**: ave of 17 M-type granitoids, New Britain arc (Whalen *et al.* (1987).
5: ave. of 1074 I-type granitoids and **6**:ave. of 704 S-type granitoids, Lachlan fold belt, Australia (Chappell and White, 1992).
7: ave of 148 A-type granitoids (Whalen *et al* . 1987, REE from Collins *et al*., 1982). **8**: ave. of 355 Archean grey gneisses (Martin, 1994).
9: ave of 250 <200Ma old I- and M-type granitoids (Martin, 1994). **10-12**: est. ave., upper, and lower continental crust (Taylor & McClennan, 1985).

Table 18-2. Representative Chemical Analyses of Selected Granitoid Types. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Chapter 18: Granitoid Rocks

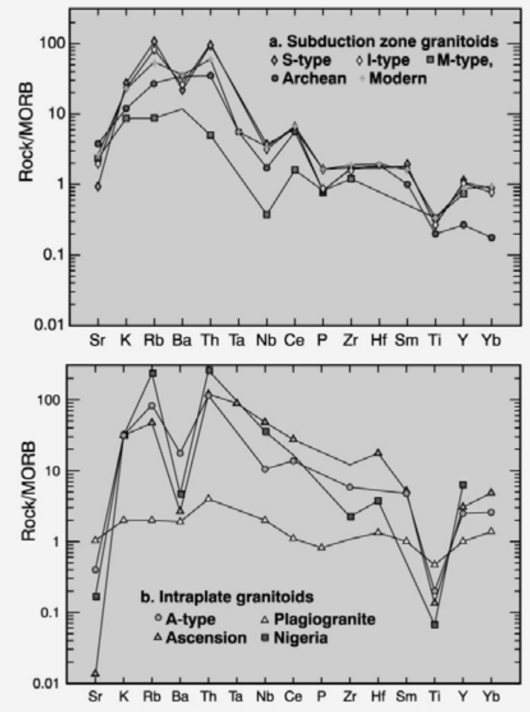
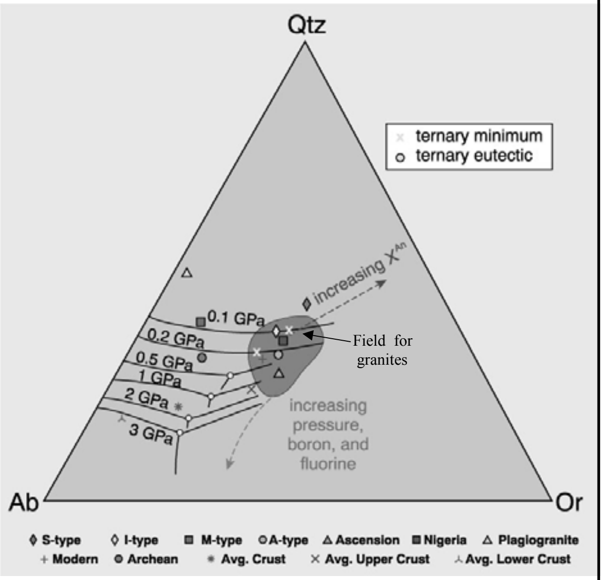


Figure 18-4. MORB-normalized spider diagrams for the analyses in Table 18-2 . From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Melting or Fractional Crystallization?

Both processes will produce SiO_2 – rich melts around the cotectics and eutectic minima in this system



Field for granites

Figure 18-3. The Ab-Or-Qtz system with the ternary cotectic curves and eutectic minima from 0.1 to 3 GPa. Included is the locus of most granite compositions from Figure 11-2 (shaded) and the plotted positions of the norms from the analyses in Table 18-2. Note the effects of increasing pressure and the An, B, and F contents on the position of the thermal minima. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Crustal melting
Note that the zircon has a rounded core (detrital sediment) surrounded by euhedral zones (magmatic origin)

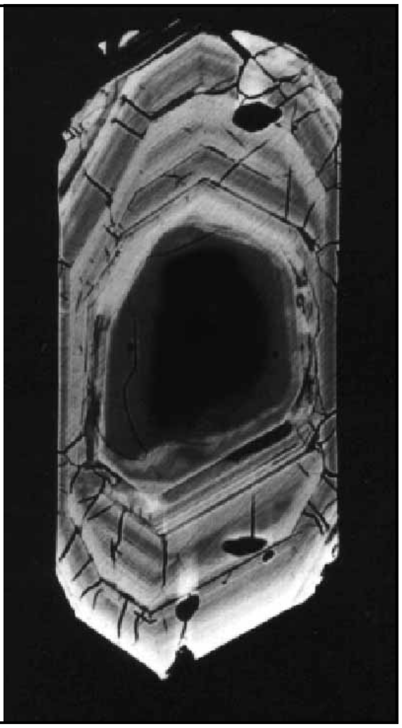


Figure 18-1. Backscattered electron image of a zircon from the Strontian Granite, Scotland. The grain has a rounded, un-zoned core (dark) that is an inherited high-temperature non-melted crystal from the pre-granite source. The core is surrounded by a zoned epitaxial igneous overgrowth rim, crystallized from the cooling granite. From Paterson *et al*. (1992), *Trans. Royal. Soc. Edinburgh.* 83, 459-471. Also *Geol. Soc. Amer. Spec. Paper,* 272, 459-471.

1. Melting of water-saturated metamorphosed sediments will be initiated at a, b, c depending on P/T but insufficient melt is produced
2. Breakdown of muscovite at (1) produces <10% melt – sufficient for migmatites
3. Only after breakdown of biotite at 760^{0}C (2) is there sufficient melt to produce a mobile granitic magma
4. Continued melting of anhydrous phases may produce up to 60% melt
5. Refractory residue left behind is termed RESTITE

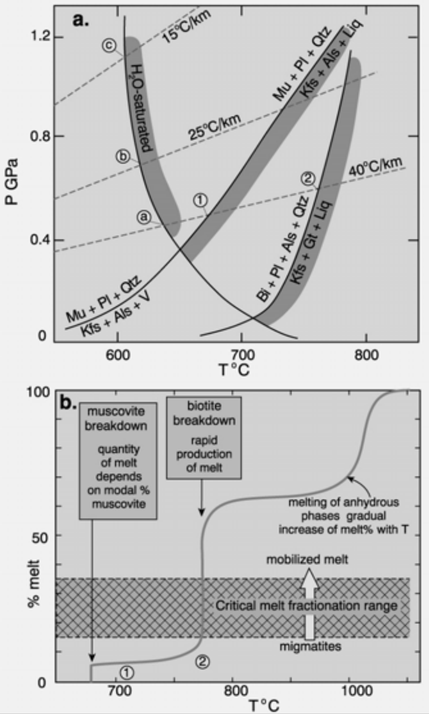


Figure 18-5. a. Simplified P-T phase diagram and b. quantity of melt generated during the melting of muscovite-biotite-bearing crustal source rocks, after Clarke (1992) *Granitoid Rocks*. Chapman Hall, London; and Vielzeuf and Holloway (1988) *Contrib. Mineral. Petrol.*, 98, 257-276. Shaded areas in (a) indicate melt generation. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

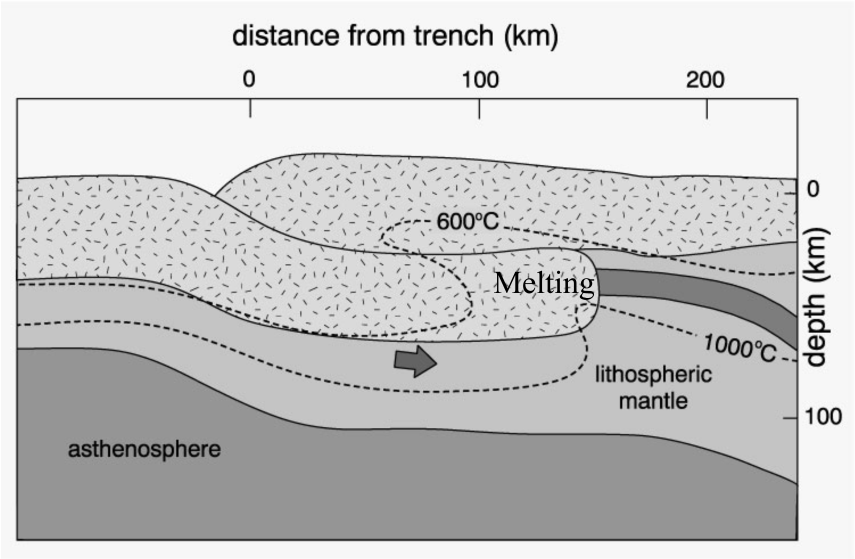
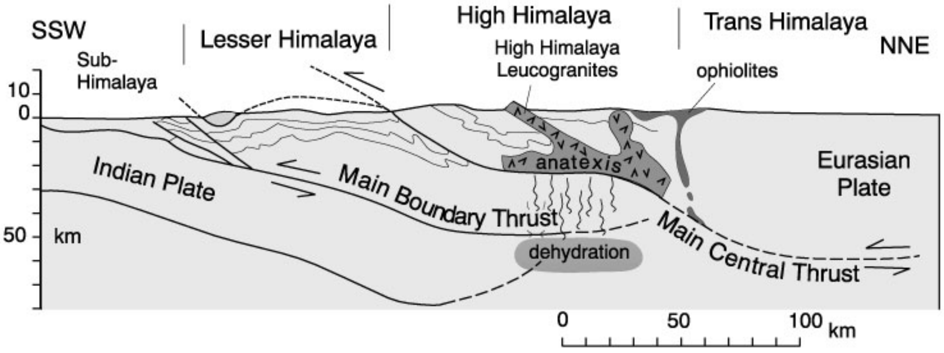


Figure 18-6. A simple modification of Figure 16-17 showing the effect of subducting a slab of continental crust, which causes the dip of the subducted plate to shallow as subduction ceases and the isotherms begin to "relax" (return to a steady-state value). Thickened crust, whether created by underthrusting (as shown) or by folding or flow, leads to sialic crust at depths and temperatures sufficient to cause partial melting. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.



Crustal melting may also be enhanced by dehydration of the lower under-thrust crust

Figure 18-7. Schematic cross section of the Himalayas showing the dehydration and partial melting zones that produced the leucogranites. After France-Lanord and Le Fort (1988) *Trans. Roy. Soc. Edinburgh*, 79, 183-195. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Continental Arc Magmatism

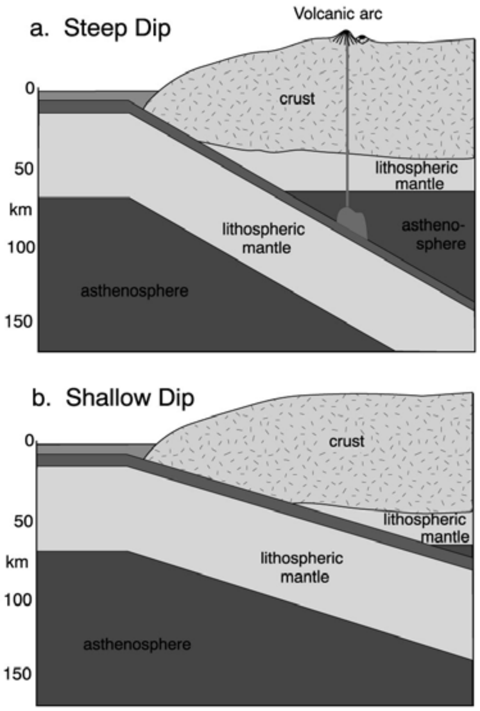
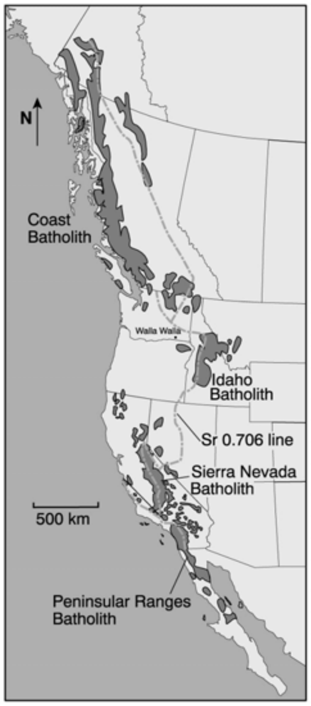
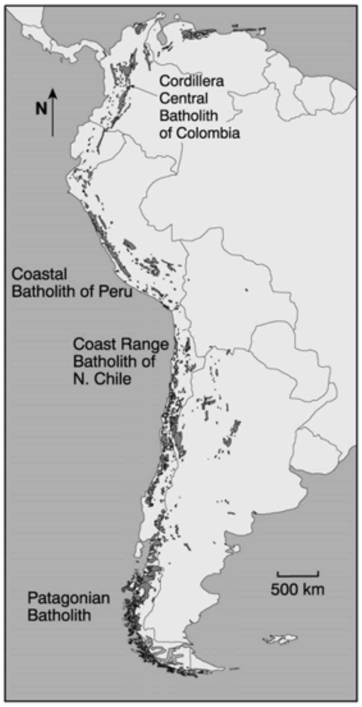


Figure 17-2. Schematic diagram to illustrate how a shallow dip of the subducting slab can pinch out the asthenosphere from the overlying mantle wedge. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Granite Batholiths along Continental Arcs





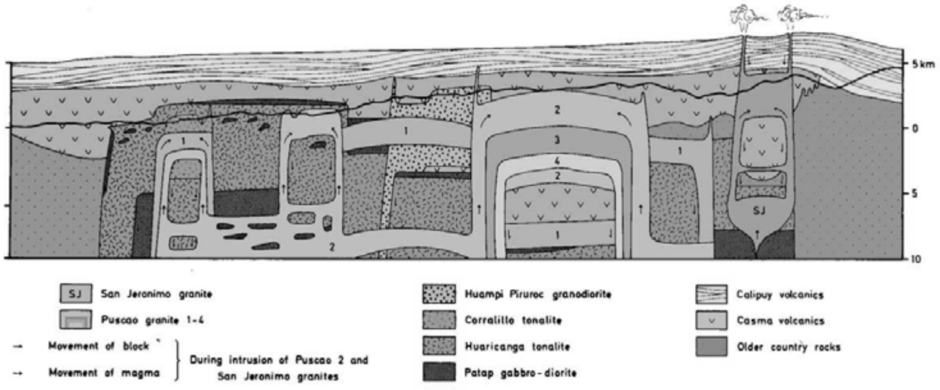
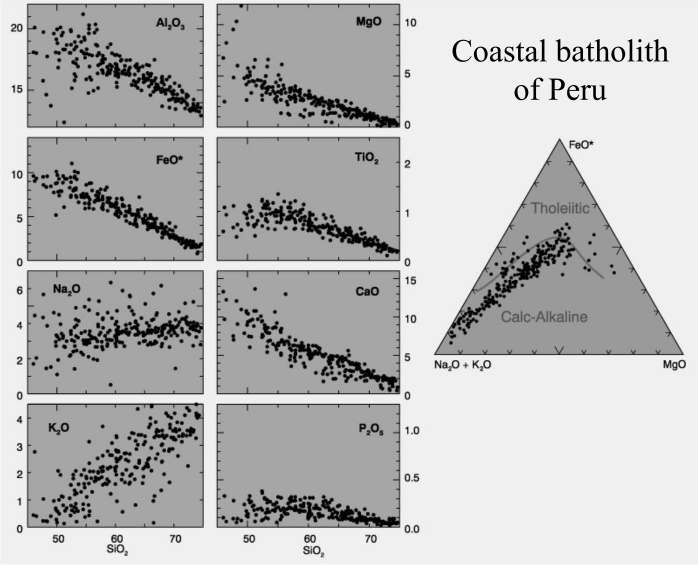


Figure 17-16. Schematic cross section of the Coastal batholith of Peru. The shallow flat-topped and steep-sided "bell-jar"-shaped plutons are stoped into place. Successive pulses may be nested at a single locality. The heavy line is the present erosion surface. From Myers (1975) *Geol. Soc. Amer. Bull.*, 86, 1209-1220.

Coastal batholith of Peru



Note typical calc-alkaline trend and range from gabbro to granite

Figure 17-17. Harker-type and AFM variation diagrams for the Coastal batholith of Peru. Data span several suites from W. S. Pitcher, M. P. Atherton, E. J. Cobbing, and R. D. Beckensale (eds.), *Magmatism at a Plate Edge. The Peruvian Andes*. Blackie. Glasgow. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Batholith plutonic rocks are compositionally similar to the associated volcanics

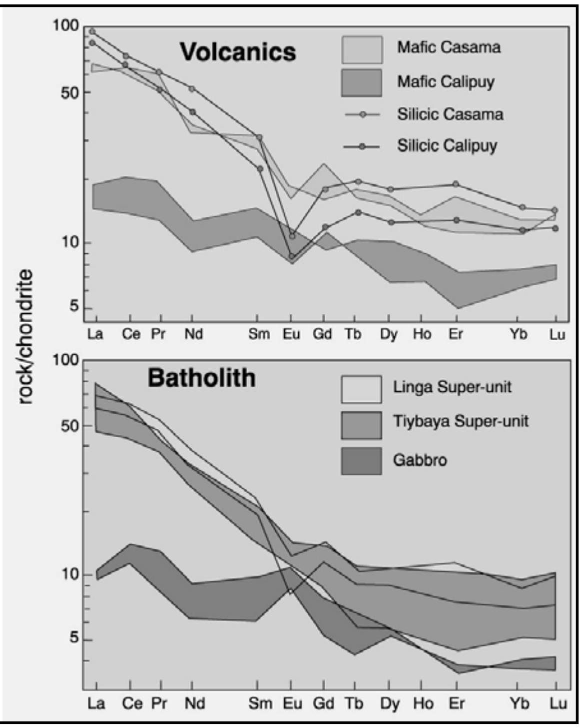


Figure 17-18. Chondrite-normalized REE abundances for the Linga and Tiybaya super-units of the Coastal batholith of Peru and associated volcanics. From Atherton *et al*. (1979) In M. P. Atherton and J. Tarney (eds.), *Origin of Granite Batholiths: Geochemical Evidence*. Shiva. Kent. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

How do they form?

Model # 1

1. Underplating of crust by suduction zone mafic magmas
2. Melting of underplate to produce tonalite magmas
3. Differentiation of tonalite (or crustal assimilation) to produce granites

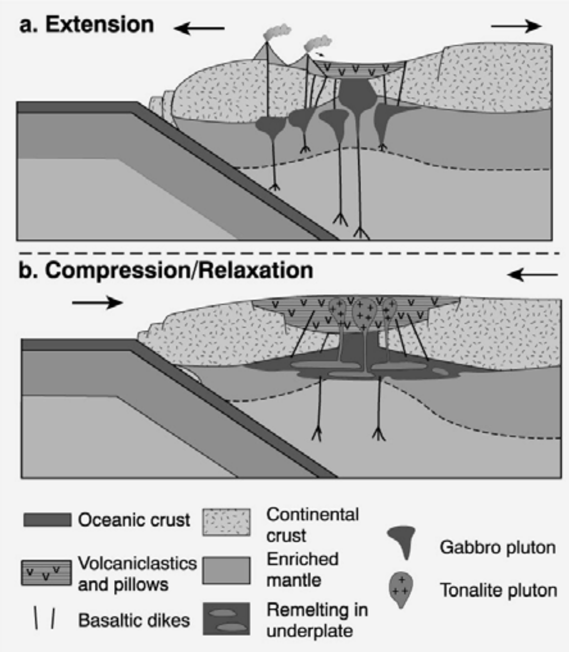


Figure 17-20. Schematic diagram illustrating (a) the formation of a gabbroic crustal underplate at an continental arc and (b) the remelting of the underplate to generate tonalitic plutons. After Cobbing and Pitcher (1983) in J. A. Roddick (ed.), *Circum-Pacific Plutonic Terranes*. *Geol. Soc. Amer. Memoir*, 159. pp. 277-291.

Model # 2

1. Underplating of crust by subduction zone mafic magmas
2. But also extensive fractionation of mafic magma accompanied by assimilation and melting of crust and homogenization
3. MASH = melting, assimilation, storage and homogenization

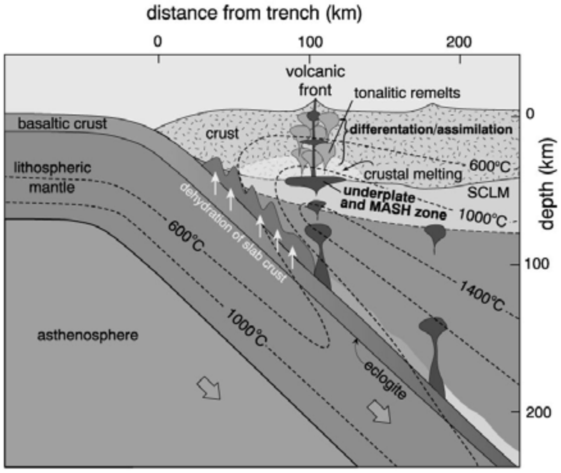


Figure 17-23. Schematic cross section of an active continental margin subduction zone, showing the dehydration of the subducting slab, hydration and melting of a heterogeneous mantle wedge (including enriched sub-continental lithospheric mantle), crustal underplating of mantle-derived melts where MASH processes may occur, as well as crystallization of the underplates. Remelting of the underplate to produce tonalitic magmas and a possible zone of crustal anatexis is also shown. As magmas pass through the continental crust they may differentiate further and/or assimilate continental crust. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

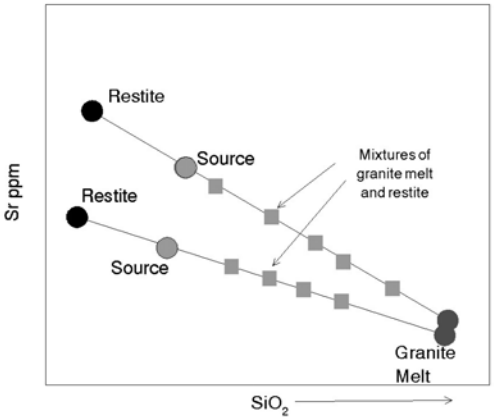
Magma Mixing versus the Restite Model

Many granites contain mafic inclusions such as those shown here. Generally the more mafic the granite the more mafic inclusions it contains

What's the Problem?

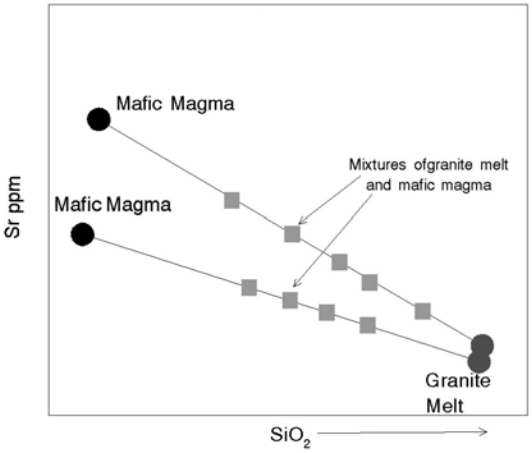
1. Are these inclusions blobs of mafic magma that was liquid at the same time as the granite?
2. Are they the refractory residua (restite) remaining after crustal rocks (or underplated gabbros) have been melted to produce granite?

Model # 3 The Restite Model



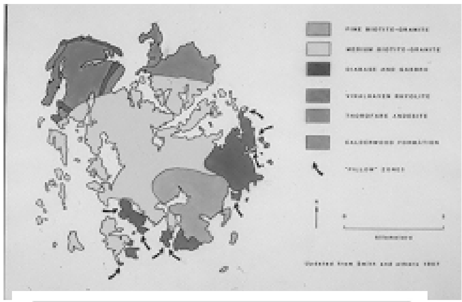
1. Melting of source produces a granite melt
2. Source can be sedimentary (S-type granites) or igneous (I-type granites)
3. Restite represented by mafic inclusions
4. Range in composition (granite to granodiorite) results from mixtures of granite melt and restite

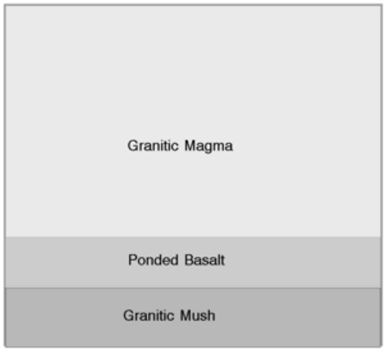
Model # 4 Magma Mixing Model



1. Melting of crust produces a granitic melt
2. Invasion of mafic magma into granitic magma reservoir results in mixing and formation of mixed magmas ranging from granite to granodiorite

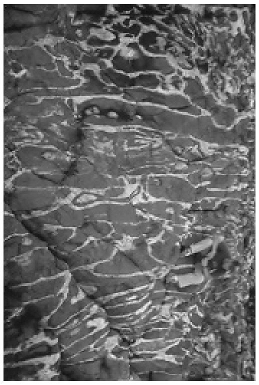
Vinalhaven – an example of magma mixing





Mafic magma (red) has ponded on top of a crystal mush of granitic magma on the floor of the magma chamber

At nearby Isle au Haut this process has been repeated about six times!



Mingling and mixing of coexisting liquid granitic and basaltic magma produces pillows of basalt in granite

Further confirmation that both magmas were simultaneously liquid is provided by these pipes of granite in the gabbro.

The less dense granite mush was lighter than the overlying basalt magma and therefore rose as pipes through the liquid basalt.

Problem!

Although mingling and mixing of graniite and mafic magmas can be clearly demonstrated. The compositional range is very limited and does not account for the compositional range found in many granitic batholiths

Classification according to tectonic setting

Table 18-4. A classification of granitoid rocks based on tectonic setting

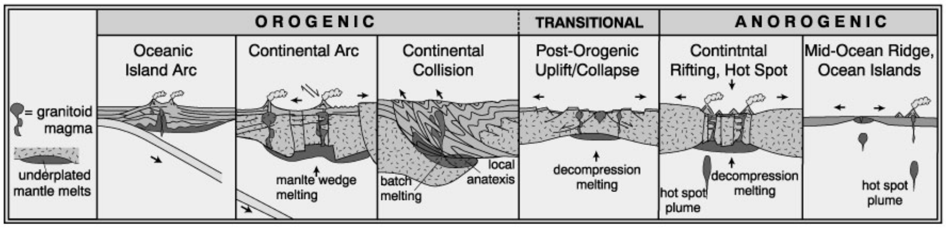


Table 18-4. A Classification of Granitoid Rocks Based on Tectonic Setting. After Pitcher (1983) in K. J. Hsü (ed.), *Mountain Building Processes*, Academic Press, London; Pitcher (1993), *The Nature and Origin of Granite*, Blackie, London; and Barbarin (1990) *Geol. Journal*, 25, 227-238. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

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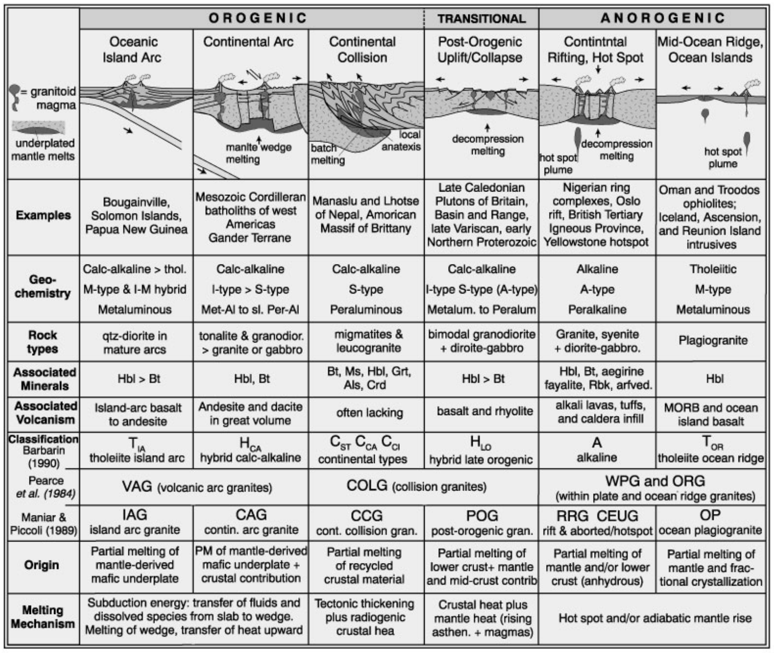

	OROGENIC			TRANSITIONAL	ANOROGENIC	
	Oceanic Island Arc	Continental Arc	Continental Collision	Post-Orogenic Uplift/Collapse	Contintntal Rifting, Hot Spot	Mid-Ocean Ridge, Ocean Islands
= granitoid magma underplated mantle melts		manlte wedge melting	batch melting local anatexis	decompression melting	hot spot plume decompression melting	hot spot plume
Examples	Bougainville, Solomon Islands, Papua New Guinea	Mesozoic Cordilleran batholiths of west Americas Gander Terrane	Manaslu and Lhotse of Nepal, Amorican Massif of Brittany	Late Caledonian Plutons of Britain, Basin and Range, late Variscan, early Northern Proterozoic	Nigerian ring complexes, Oslo rift, British Tertiary Igneous Province, Yellowstone hotspot	Oman and Troodos ophiolites; Iceland, Ascension, and Reunion Island intrusives
Geo-chemistry	Calc-alkaline > thol. M-type & I-M hybrid Metaluminous	Calc-alkaline I-type > S-type Met-Al to sl. Per-Al	Calc-alkaline S-type Peraluminous	Calc-alkaline I-type S-type (A-type) Metalum. to Peralum	Alkaline A-type Peralkaline	Tholeiitic M-type Metaluminous
Rock types	qtz-diorite in mature arcs	tonalite & granodior. > granite or gabbro	migmatites & leucogranite	bimodal granodiorite + diroite-gabbro	Granite, syenite + diorite-gabbro.	Plagiogranite
Associated Minerals	Hbl > Bt	Hbl, Bt	Bt, Ms, Hbl, Grt, Als, Crd	Hbl > Bt	Hbl, Bt, aegirine fayalite, Rbk, arfved.	Hbl
Associated Volcanism	Island-arc basalt to andesite	Andesite and dacite in great volume	often lacking	basalt and rhyolite	alkali lavas, tuffs, and caldera infill	MORB and ocean island basalt
Classification Barbarin (1990)	T_{IA} tholeiite island arc	H_{CA} hybrid calc-alkaline	C_{ST} C_{CA} C_{CI} continental types	H_{LO} hybrid late orogenic	A alkaline	T_{OR} tholeiite ocean ridge
Pearce *et al. (1984)*	VAG (volcanic arc granites)		COLG (collision granites)		WPG and ORG (within plate and ocean ridge granites)	
Maniar & Piccoli (1989)	IAG island arc granite	CAG contin. arc granite	CCG cont. collision gran.	POG post-orogenic gran.	RRG CEUG rift & aborted/hotspot	OP ocean plagiogranite
Origin	Partial melting of mantle-derived mafic underplate	PM of mantle-derived mafic underplate + crustal contribution	Partial melting of recycled crustal material	Partial melting of lower crust+ mantle and mid-crust contrib	Partial melting of mantle and/or lower crust (anhydrous)	Partial melting of mantle and frac-tional crystallization
Melting Mechanism	Subduction energy: transfer of fluids and dissolved species from slab to wedge. Melting of wedge, transfer of heat upward		Tectonic thickening plus radiogenic crustal hea	Crustal heat plus mantle heat (rising asthen. + magmas)	Hot spot and/or adiabatic mantle rise	

After Pitcher (1983, 1993), Barbarin (1990)

Use of trace elements as tectonic discriminants

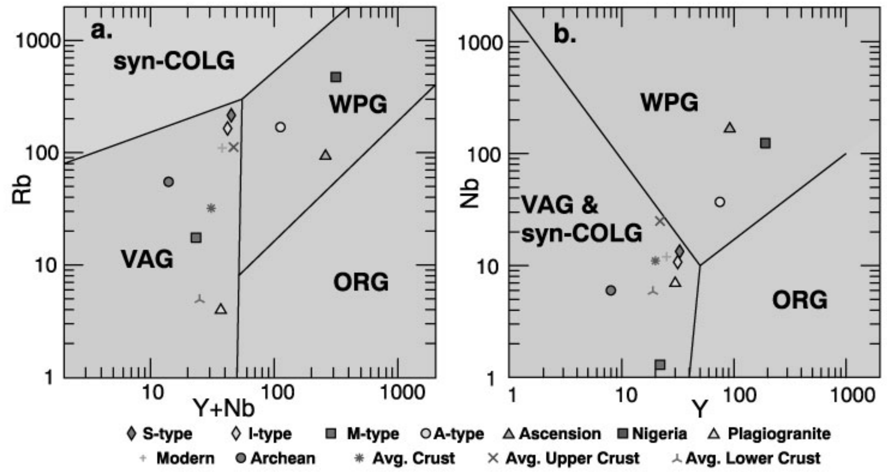

Figure 18-9. Examples of granitoid discrimination diagrams used by Pearce *et al*. (1984, *J. Petrol.*, 25, 956-983) with the granitoids of Table 18-2 plotted. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

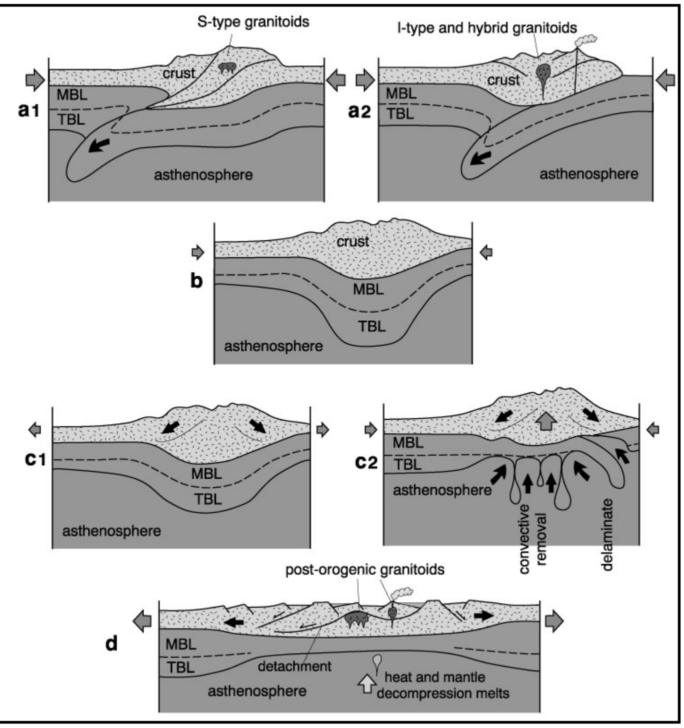

Figure 18-8. Schematic models for the uplift and extensional collapse of orogenically thickened continental crust. Subduction leads to thickened crust by either continental collision (a1) or compression of the continental arc (a2), each with its characteristic orogenic magmatism. Both mechanisms lead to a thickened crust, and probably thickened mechanical and thermal boundary layers ("MBL" and "TBL") as in (b) Following the stable situation in (b), either compression ceases (c1) or the thick dense thermal boundary layer is removed by delamination or convective erosion (c2). The result is extension and collapse of the crust, thinning of the lithosphere, and rise of hot asthenosphere (d). The increased heat flux in (d), plus the decompression melting of the rising asthenosphere, results in bimodal post-orogenic magmatism with both mafic mantle and silicic crustal melts. Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.