Partial melting of the continental crust

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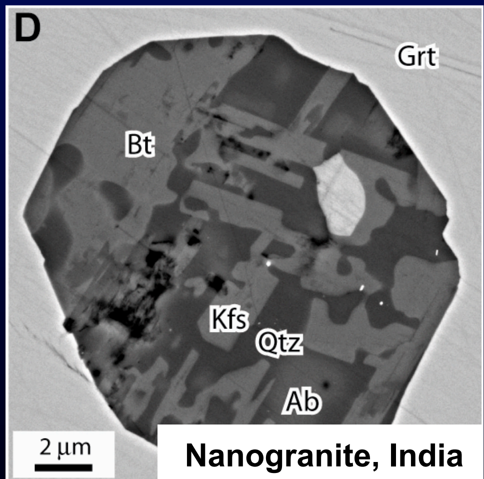

Nanogranite, India


Migmatites-granulites, S Spain

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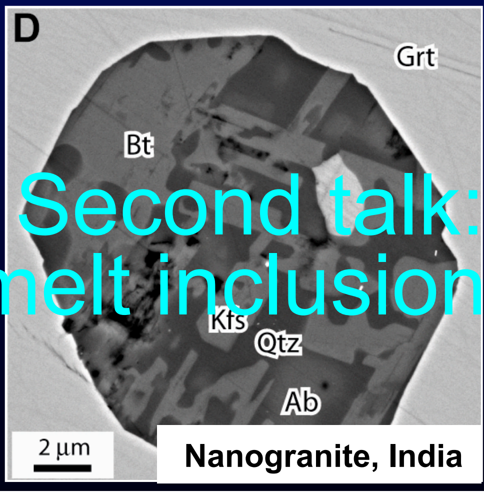
First talk: the continental crust and crustal anatexis

Migmatites-granulites, S Spain

Second talk: melt inclusions



Nanogranite, India

Definition/nature of the continental crust

- *Continental crust: defined based on seismic studies (Mohorovicic, P-waves).*

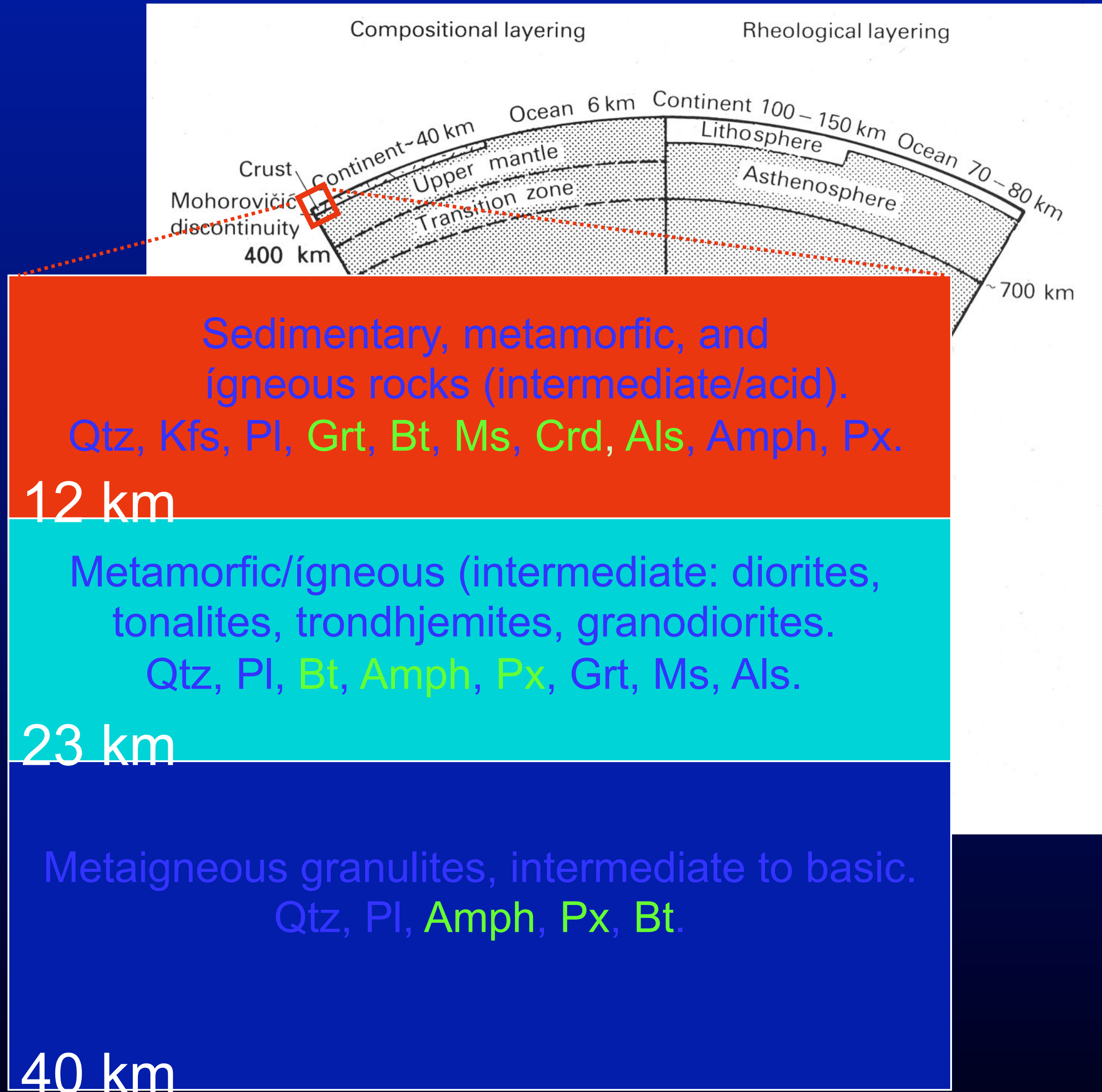
- *Composition: andesitic, with compositional features similar to subduction zones.*

- *Thickness: 20-60 km (40 km). Divided in three parts (seismics):*

1.Upper continental crust: intermediate to acid (granodioritic).

2. Middle continental crust: intermediate (andesitic).

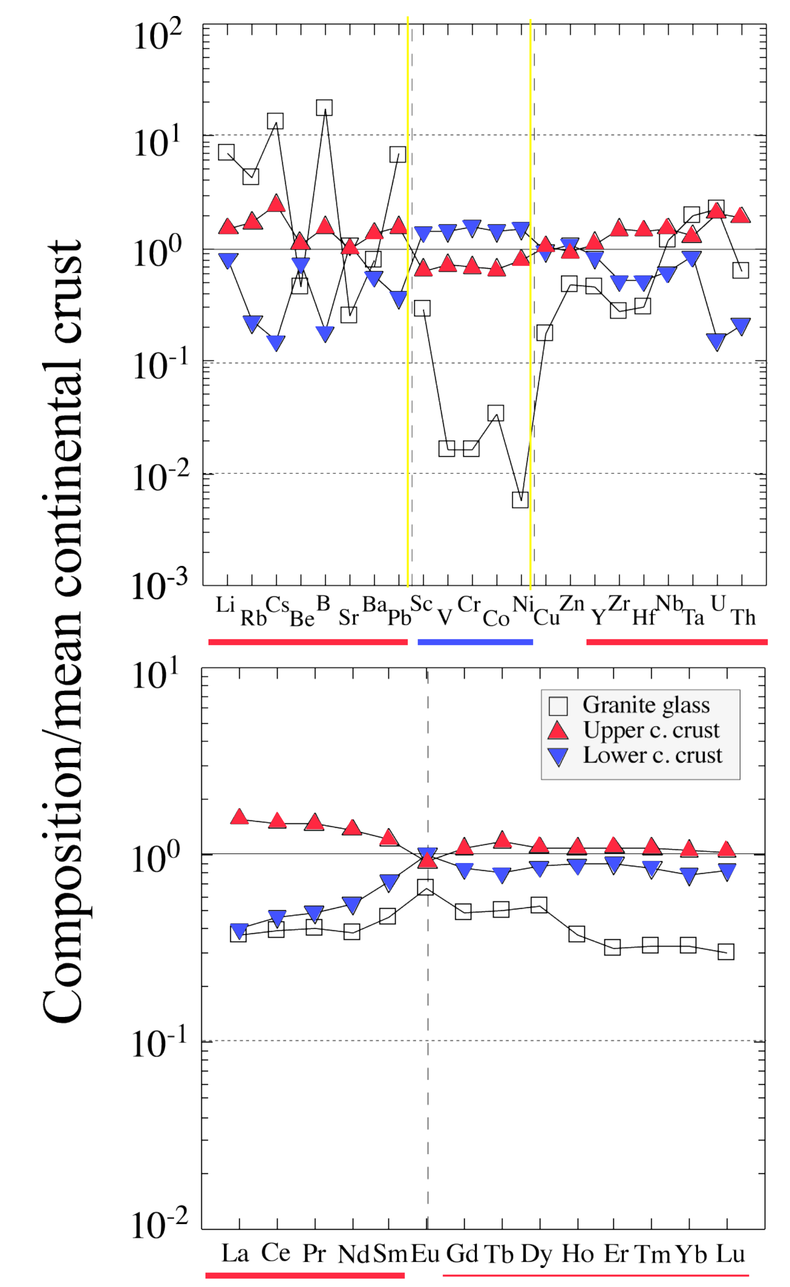
3. Lower continental crust: intermediate to basic (andesitic to basaltic).



Data from Rudnick & Gao (2013)

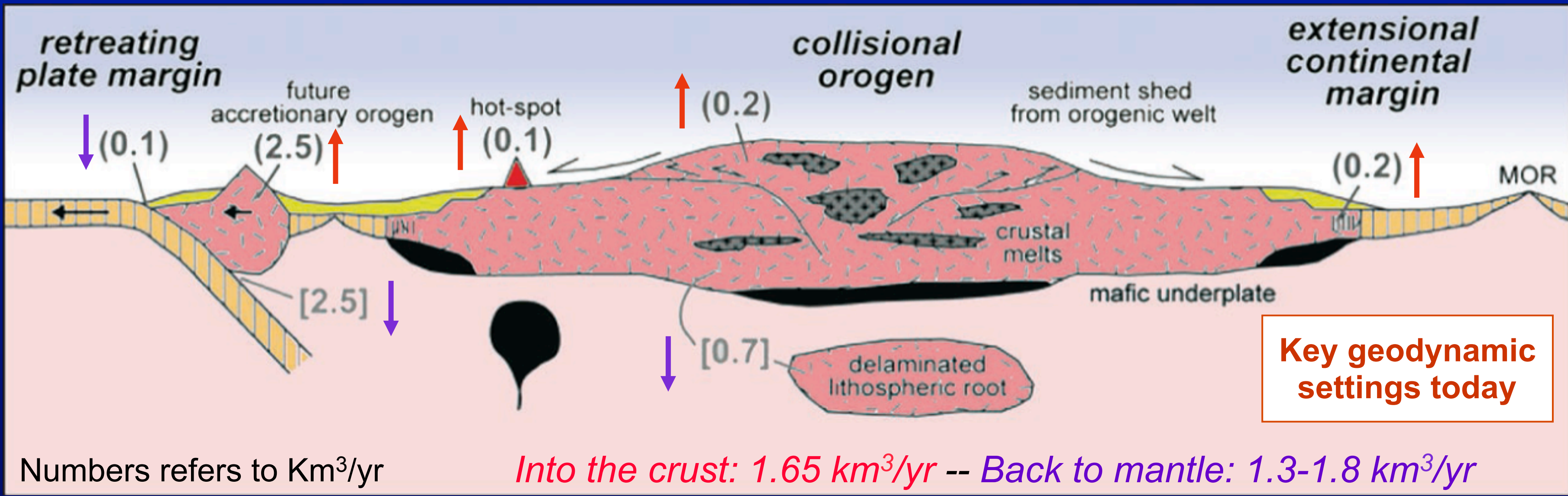
Composition of the continental crust

	Upper	Middle	Lower
SiO_2	66.6	63.5	54.3
TiO_2	0.64	0.69	0.97
Al_2O_3	15.4	15.0	16.1
FeO_t	5.04	6.02	10.6
MgO	2.48	3.59	6.28
CaO	3.59	5.25	8.48
Na_2O	3.27	3.39	2.79
K_2O	2.80	2.30	0.64
ASI	1.03	0.85	0.78



Data from Rudnick & Gao (2003)

Generation of continental crust

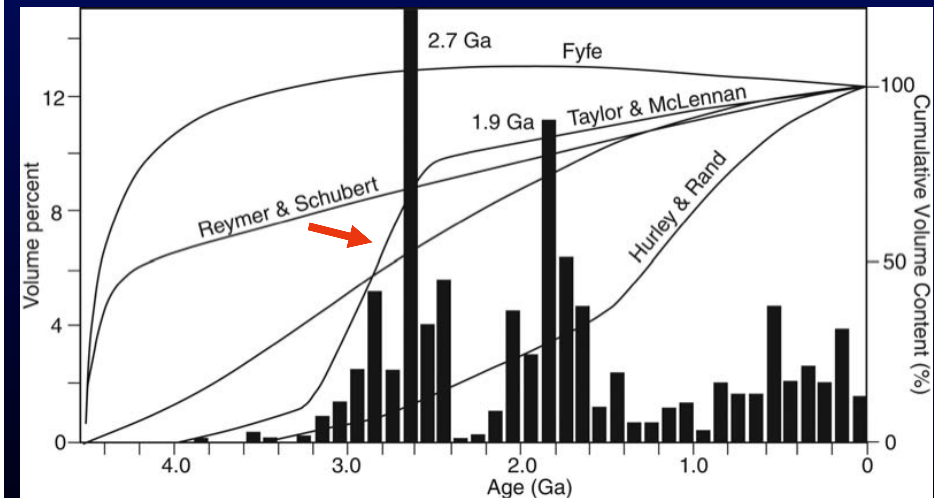


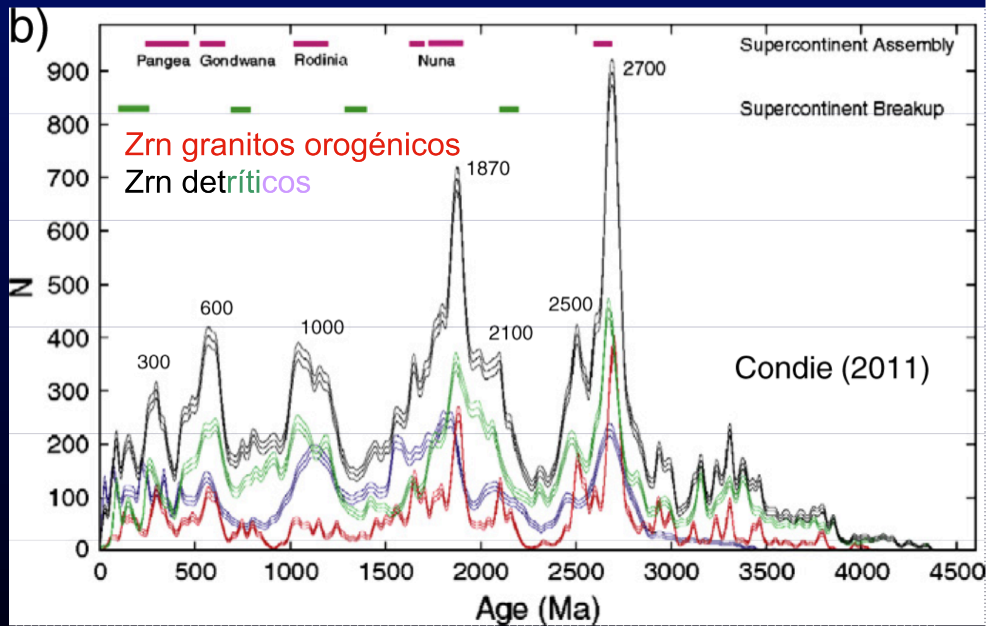
Hawkesworth et al. (2010)

Arndt & Davaille (2013)

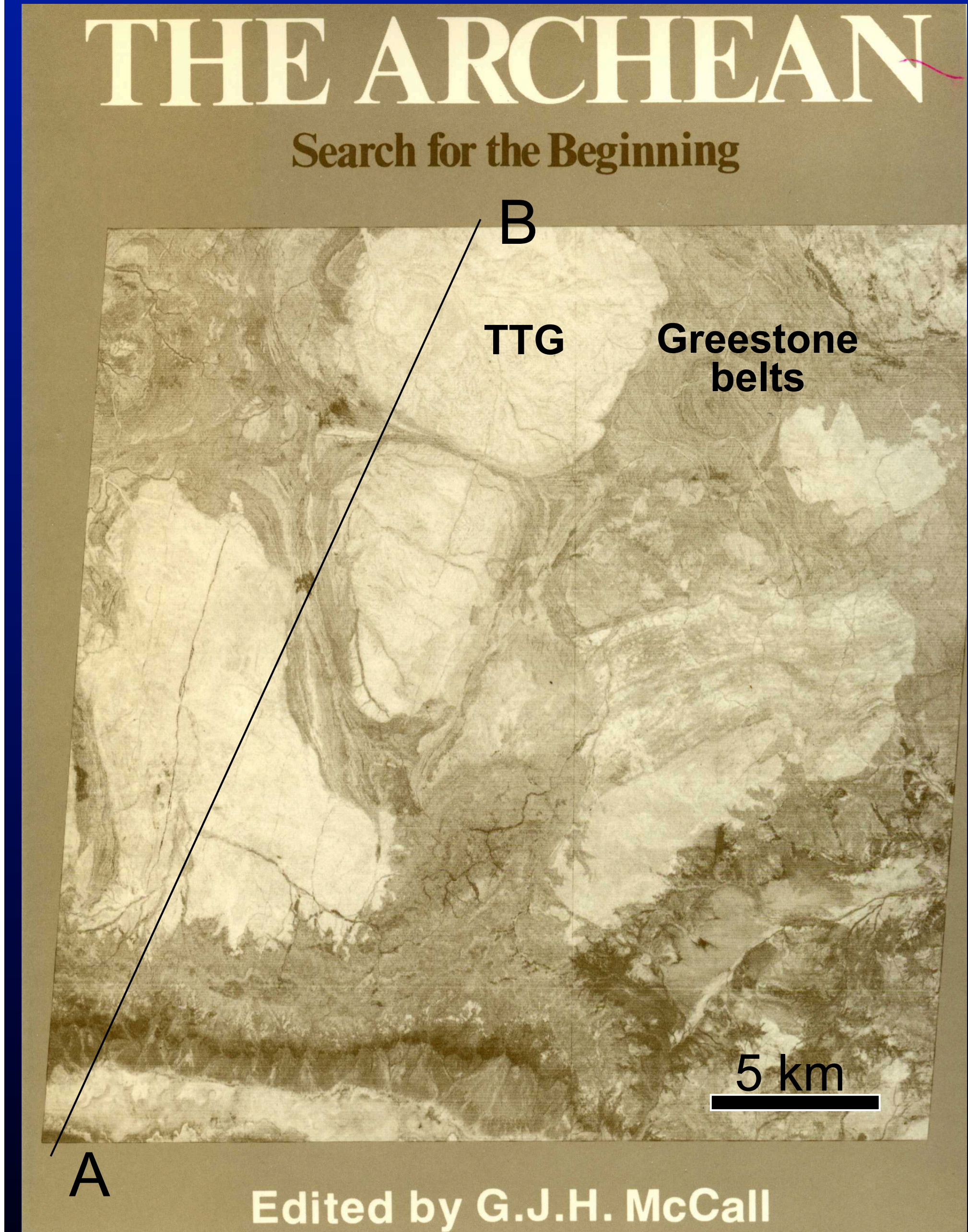
Back in time

Cawood et al. (2009)

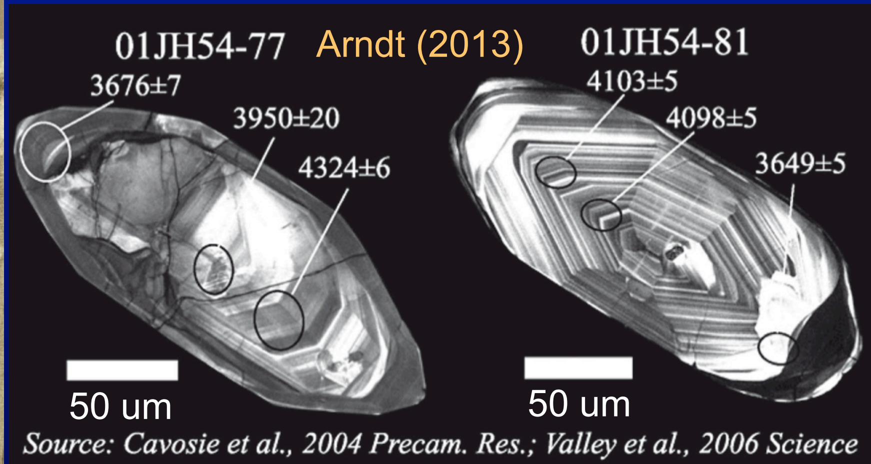




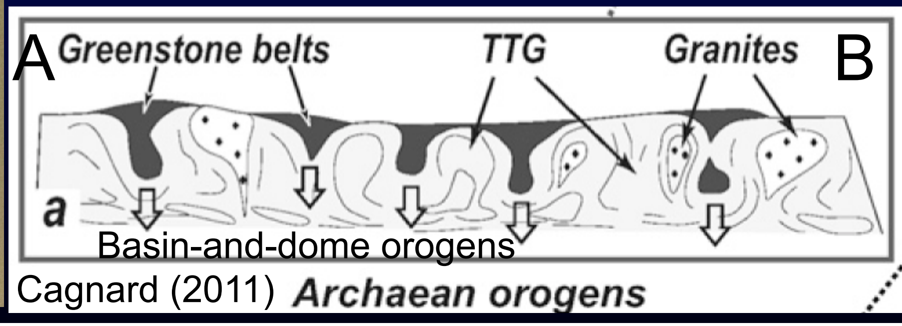
Early continental crust



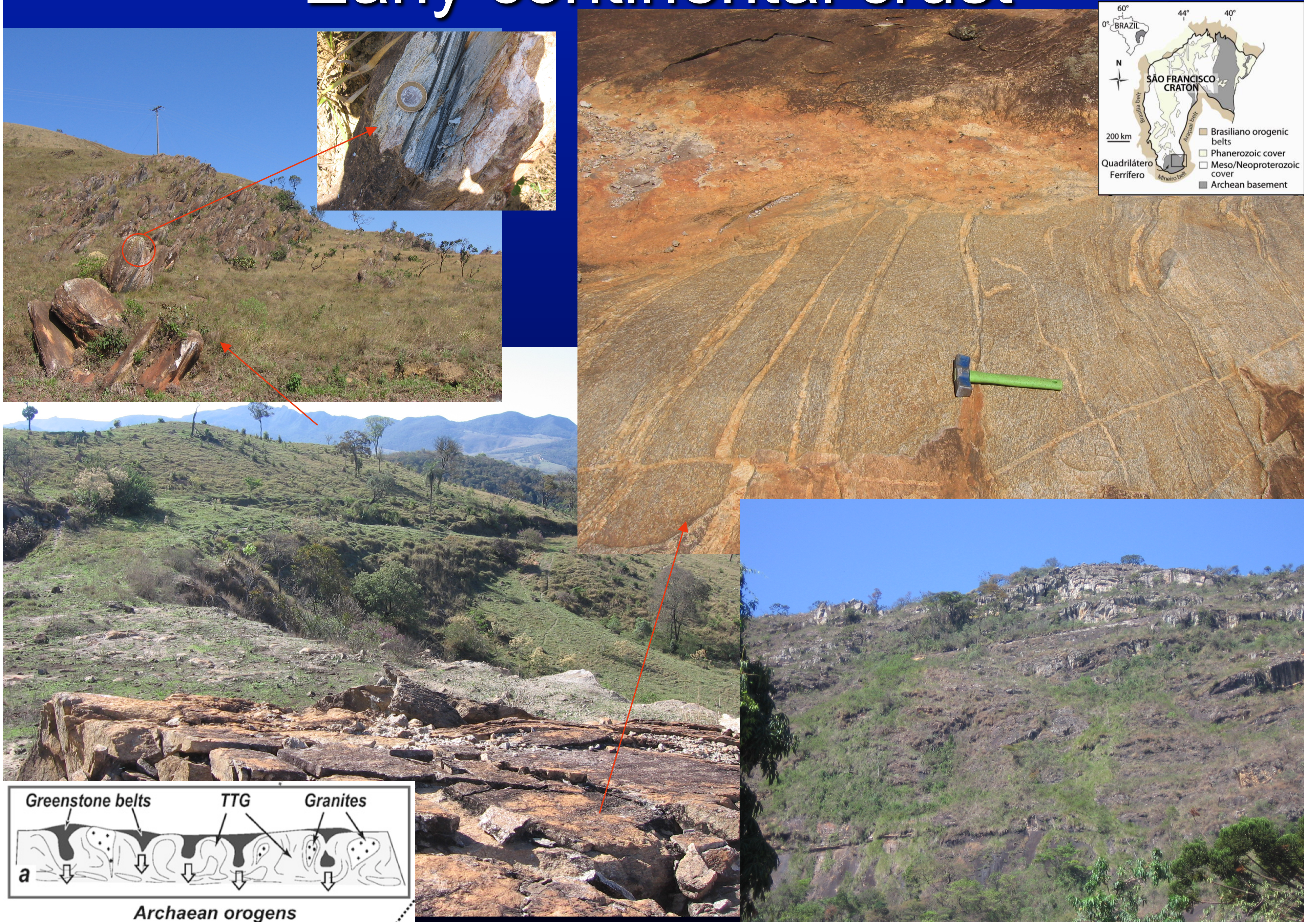
Oldest continental crust: zircons in metasedimentary sequences, Jack Hills, Australia (≈4.4-4.2 Ga), and some TTG, Acasta orthogneiss, Canada (≈4.2-4.0 Ga)



Greenstone belts: supracortical sequences of komatiites-basalts and metasediments-metavulcanites; G-UHTM, hot weak lithosp.
TTG: intermediate to acid Na gneisses, rich in LREE and Sr, poor in HREE, Y; Ep, 8-10 Kb



Early continental crust



Origin of early continental crust

2a

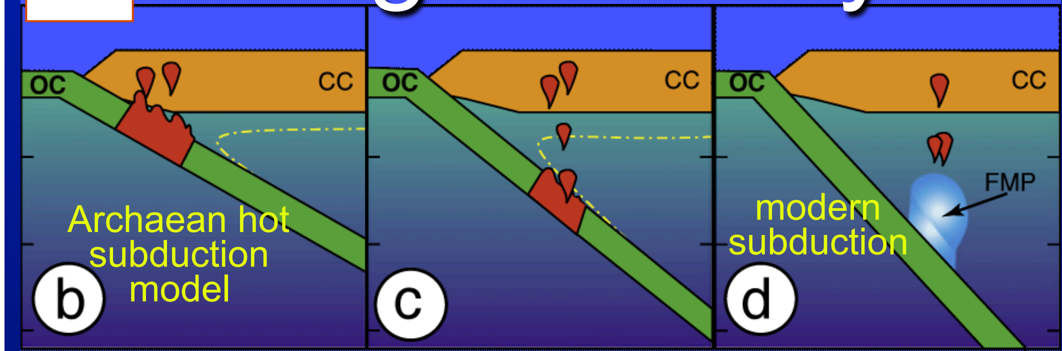
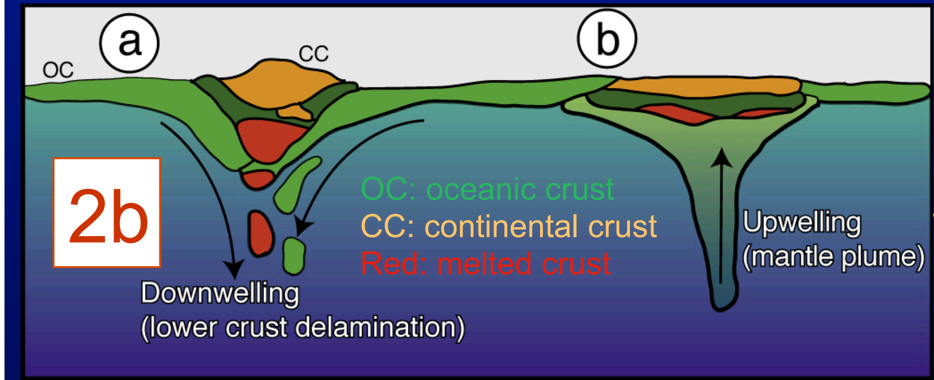
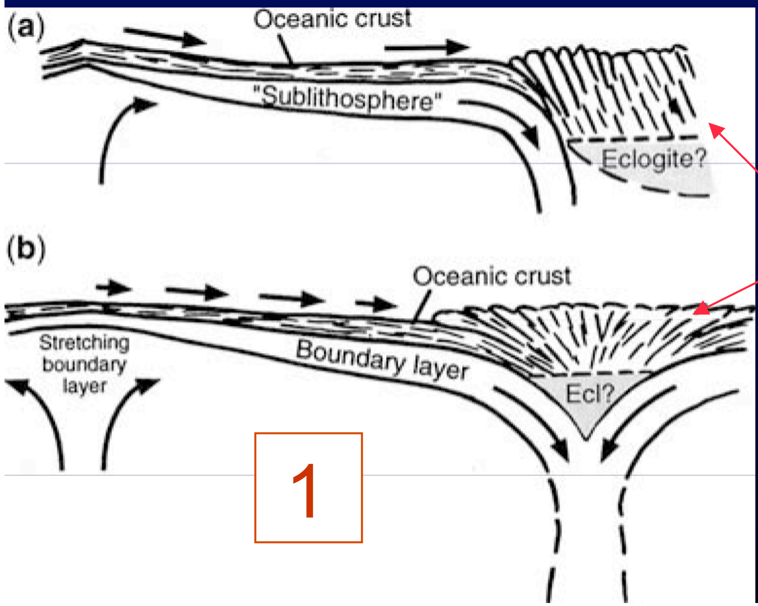


PLATE TECTONIC REGIME-2a

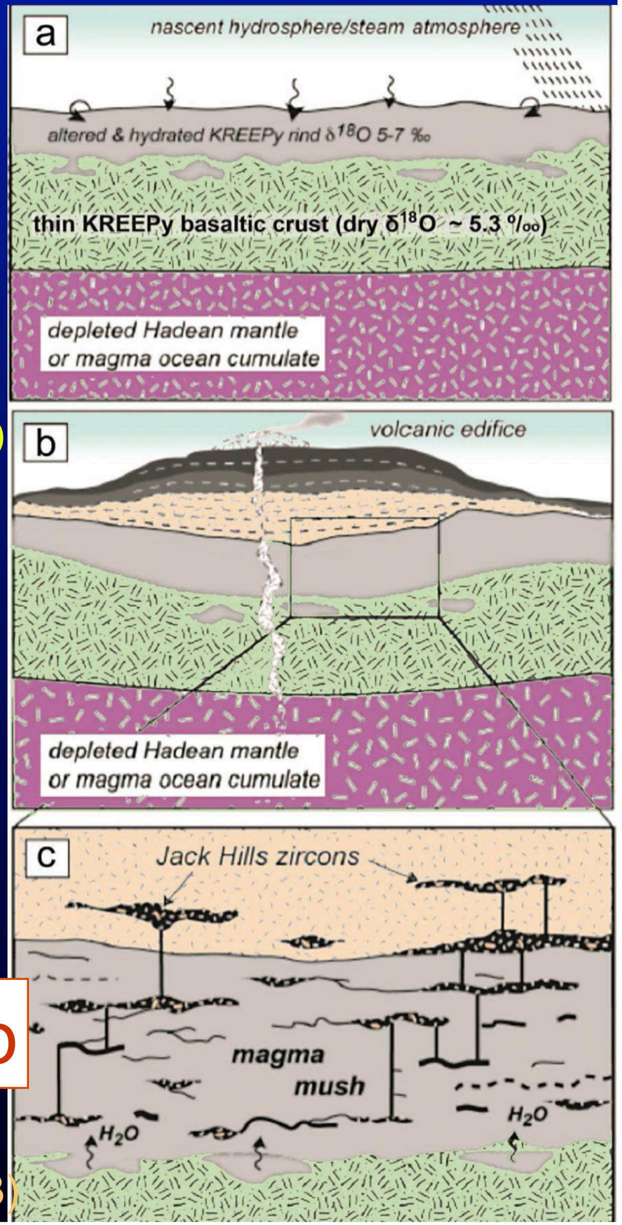


Moyen and Martin (2012)

STAGNANT LID REGIME-2b



¿First nuclei of continental crust?

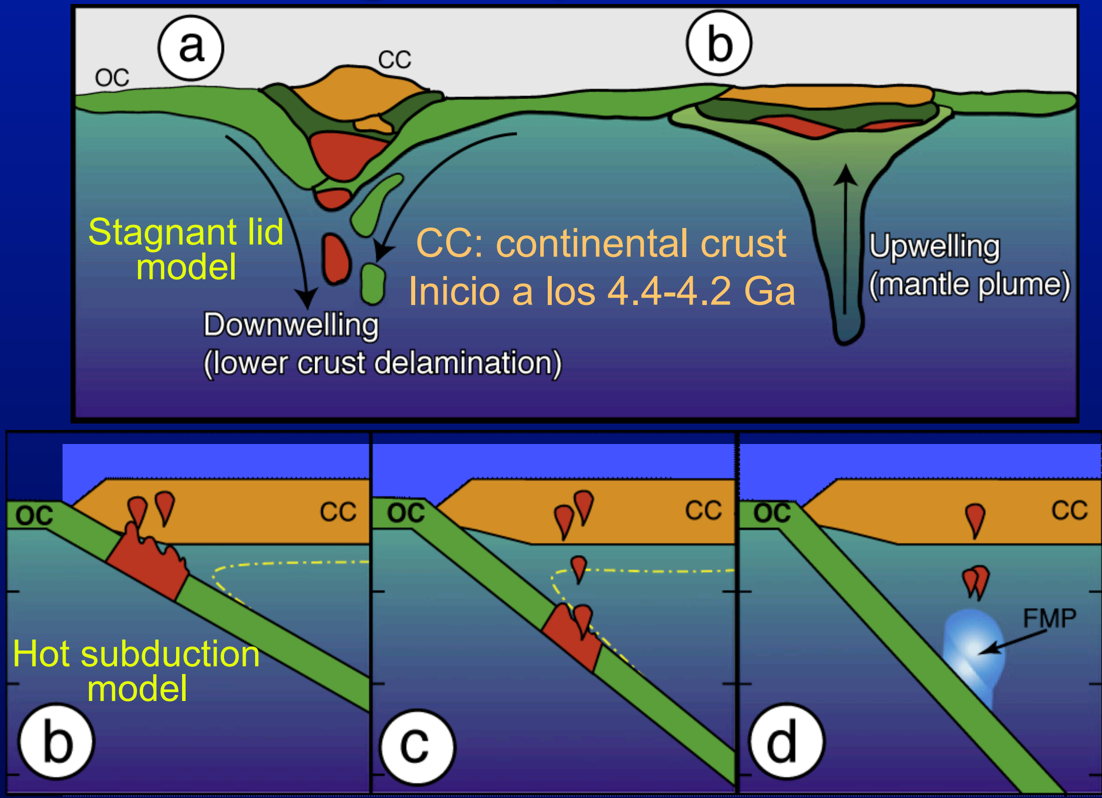


Davies (1992)

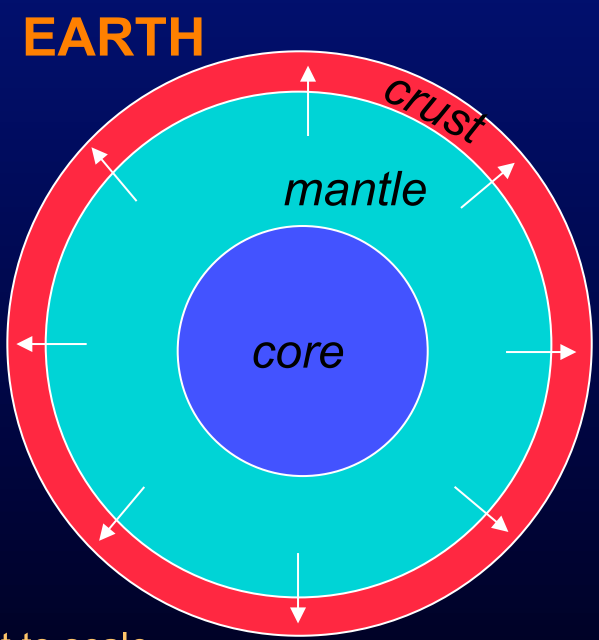
Arndt (2013)

Why is partial melting important?

Partial melting: key process in the evolution of the Earth.



Moyen and Martin (2012)



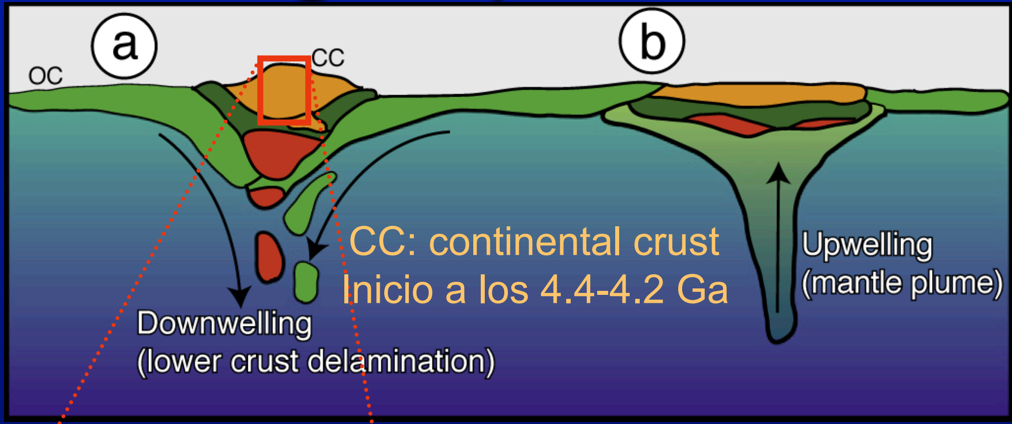
Not to scale

Continental crust: produced by partial melting of the mantle since the Archean (4.4-4.2 Ga), and hence is key to understand the evolution of Earth.

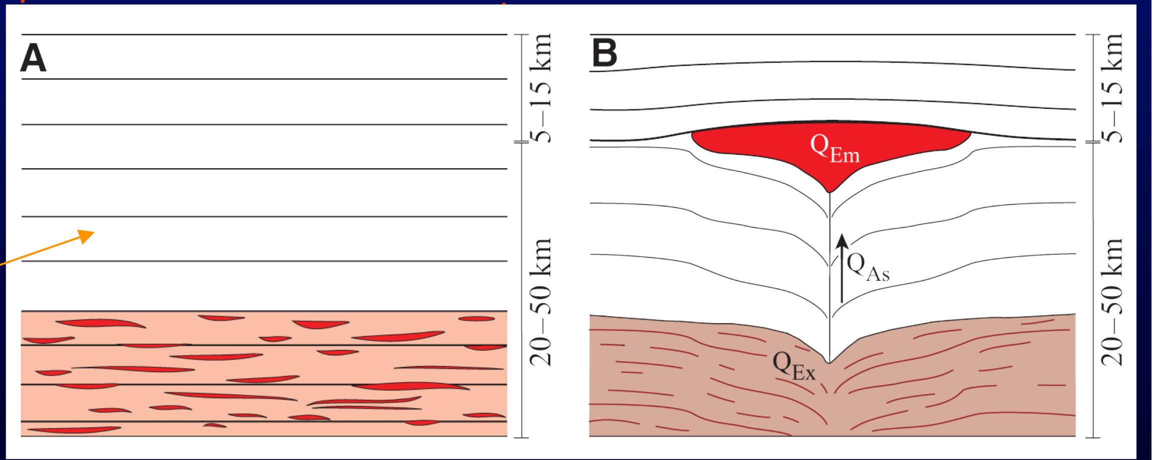
Why is crustal melting important?

- *Importance of the study of origin of continental crust (4.4-4.2 Ga): formed progressively since the very beginning of the Earth: key to understand the history and geochemical evolution of the planet.*

- *The continental crust is not static, but changes/evolves/is reproccessed, after its generation. Compositional differentiation (vertical evolution in composition). Hence to know its origin it is necessary to characterize its evolution in time, and crustal melting (ANATEXIS), together with melt extraction and ascent, is thought to be one of the main processes producing compositional evolution.*

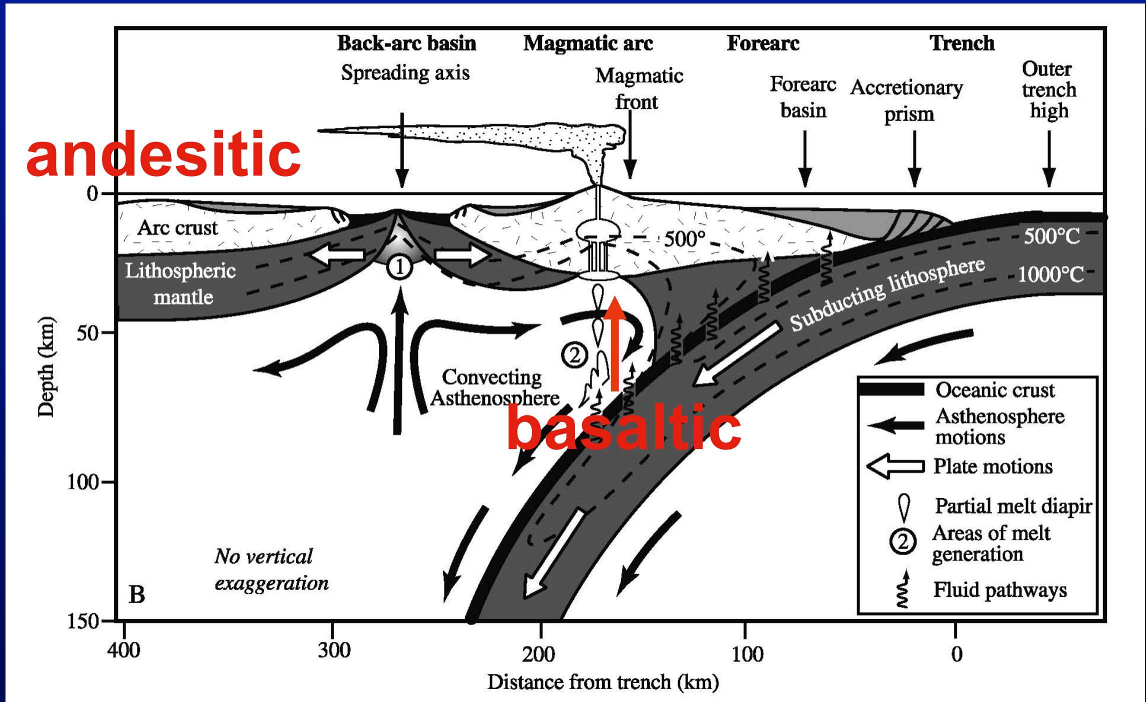


Moyen and Martin (2012)

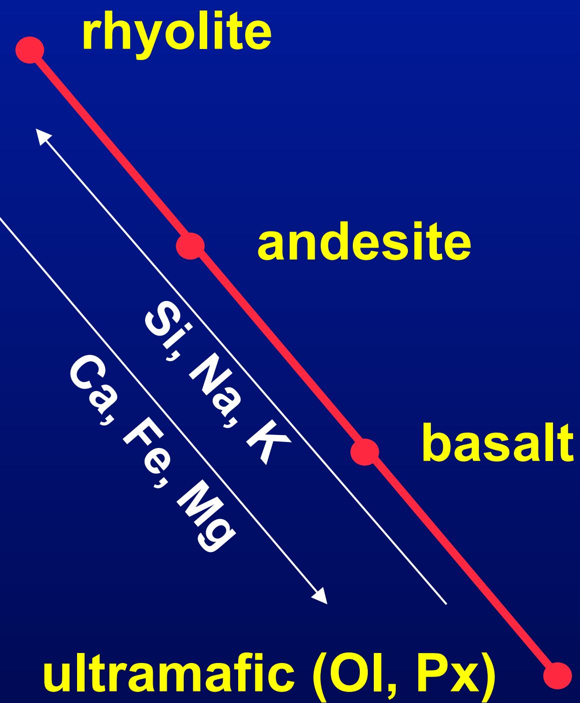


Brown (2013)

Problems genesis of continental crust



modified from Stern (2002)



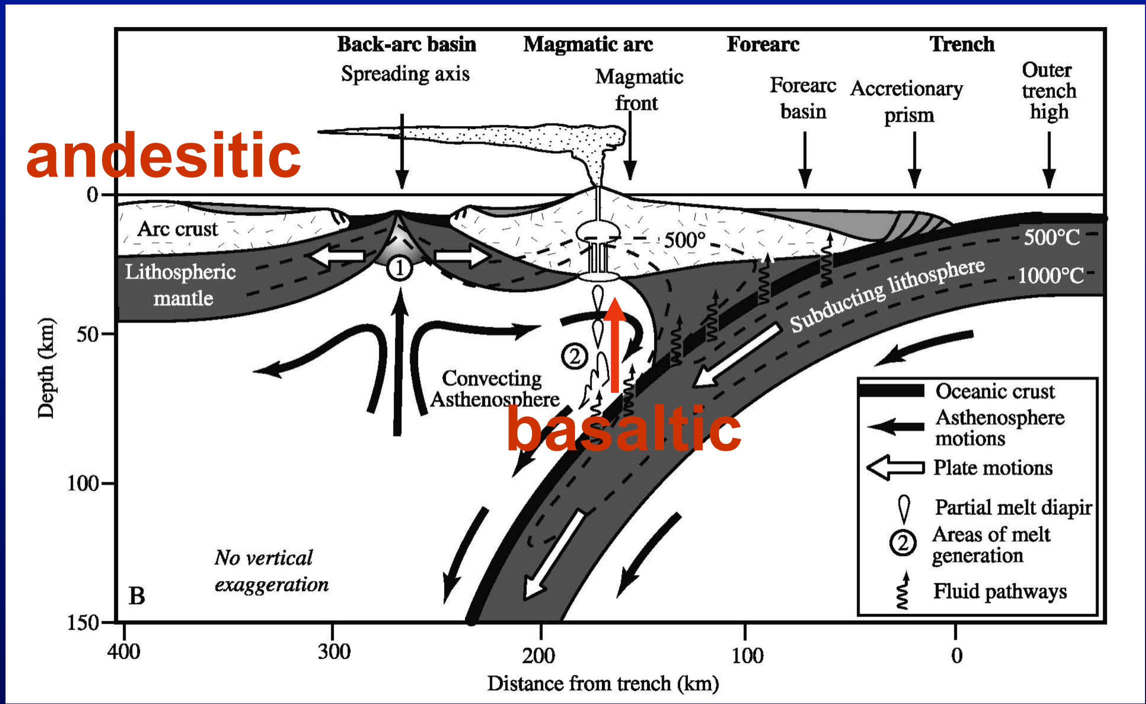
❑ *Continental crust: formed by partial melting of, and melt extraction from the mantle through geologic time, mean andesitic composition (Taylor & McLennan, 1985; Rudnick & Gao, 2003).*

❑ *Genetic models:*

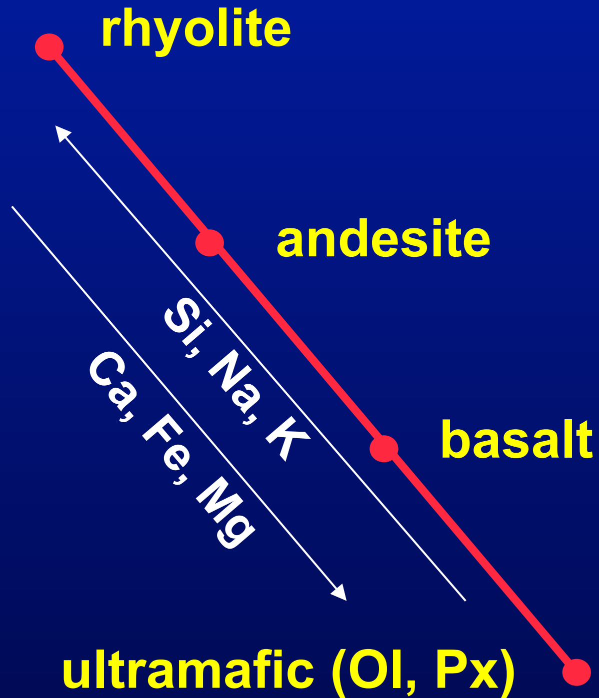
1. "Andesite model": addition of andesites in subduction zones (Taylor, 1967).

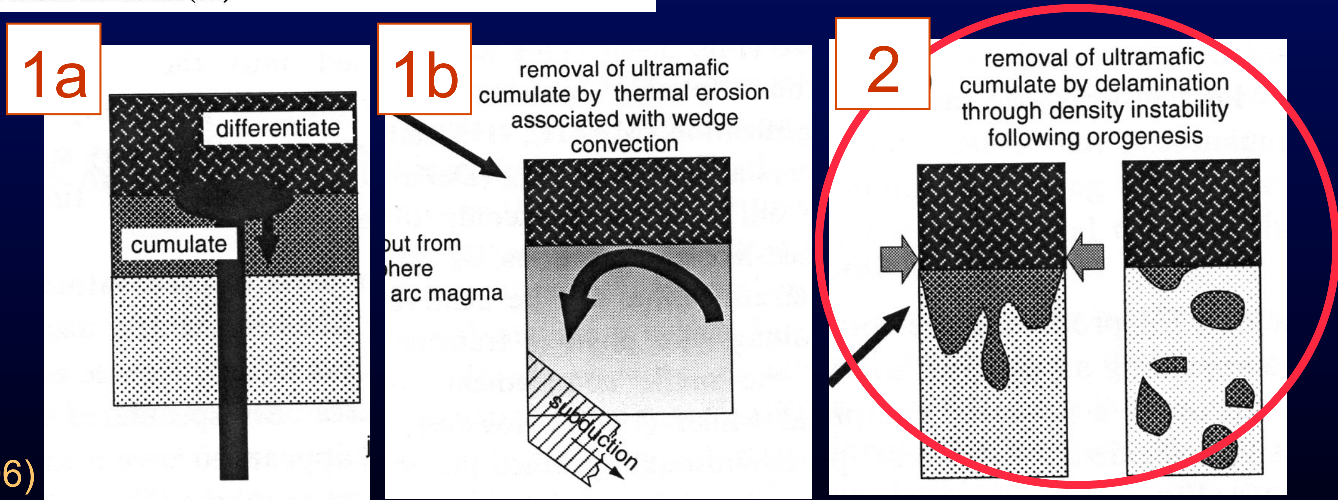
2. "Basalt imput model": addition of basalts in subduction zones, plus reprocessing of the basaltic material to make it andesitic (Davidson & Arculus 2006).

Problems genesis of continental crust



modified from Stern (2002)





Davidson & Arculus (2006)

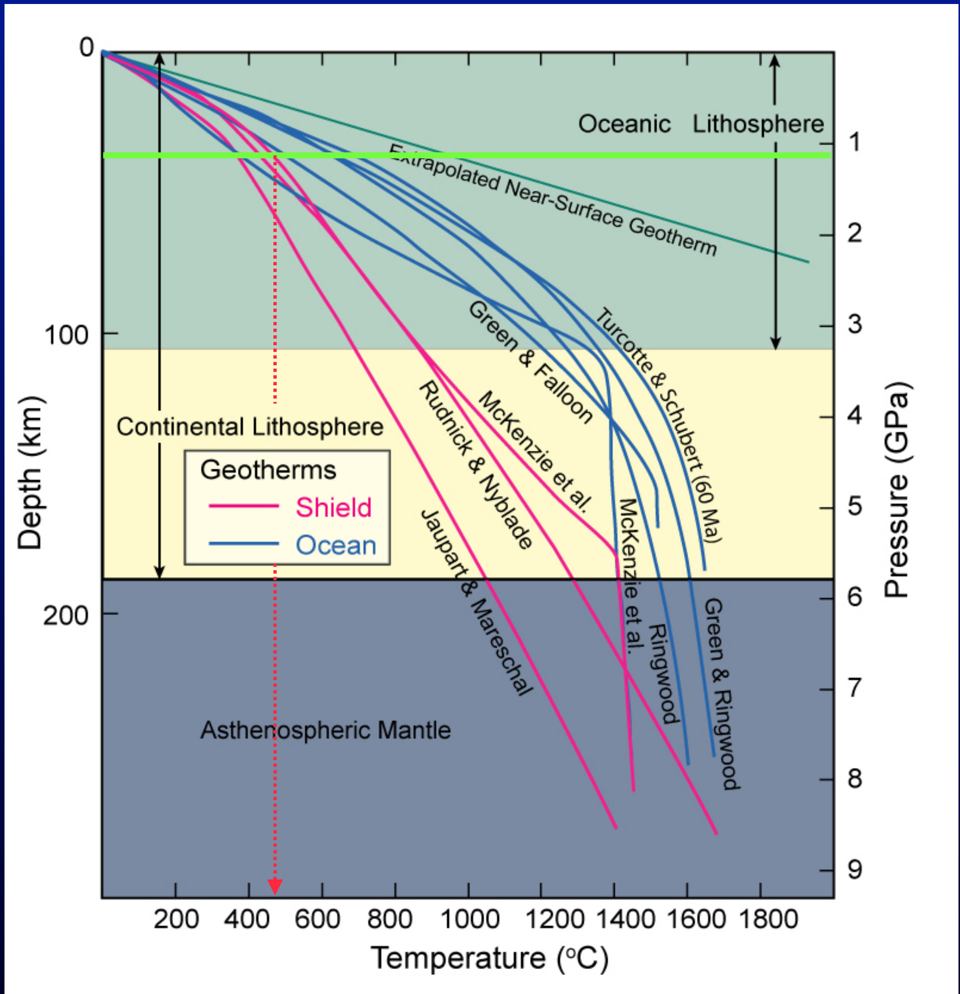
Crustal anatexis

- Crustal anatexis (=partial melting of the continental crust):
  1. Where, when, why?
  2. How, i.e. mechanisms of anatexis: protoliths, melting reactions, P-T-X_{H2O} conditions.
  3. Mechanisms of segregation, extraction, ascent and emplacement.
  4. Melt composition, extent of melt-solid (=residue) equilibration.
  5. Connection between anatectic terranes-crustal granites: nature and intensity of crustal differentiation, role of mantle (heat-mass: crustal differentiation to crustal growth ratio).

- Sources of information:
  1. Anatectic terranes and enclaves in volcanic rocks: field, petrology and geochemical studies.
  2. Experimental petrology.
  3. Thermal-thermodynamic-thermomechanic modeling.

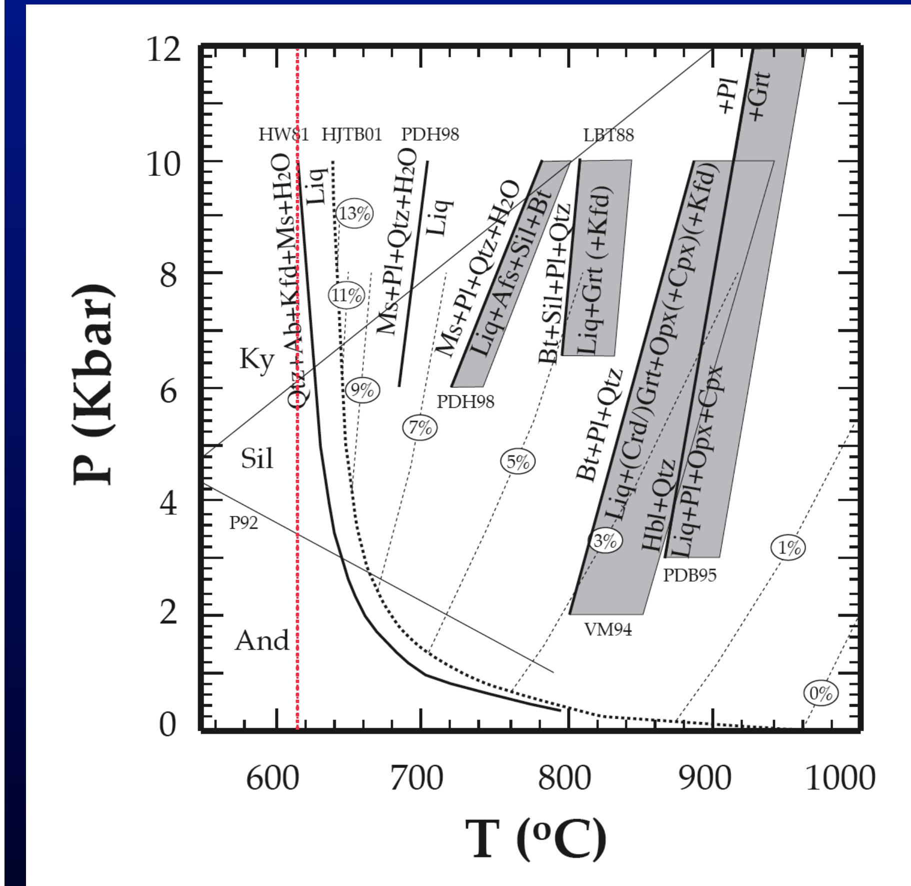
When does the continental crust melt?

The geothermal gradient



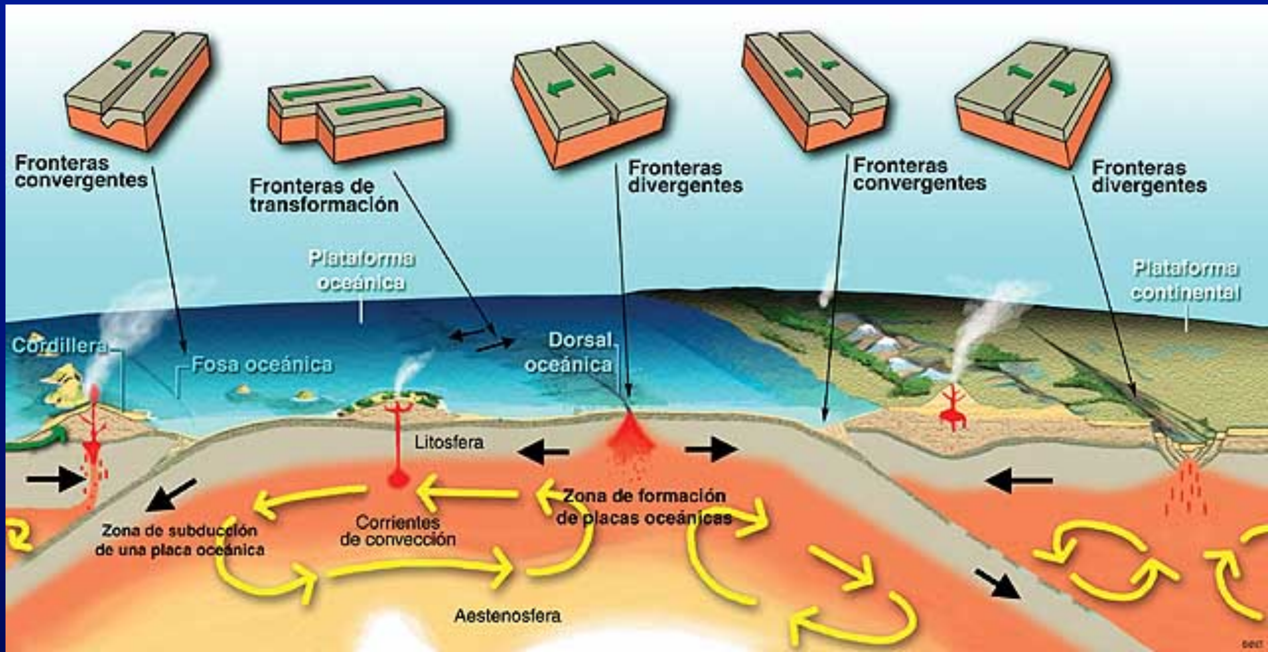
Anatexis does not happen in old and stable continental crust, e.g. cratons

Melting reactions in the continental crust

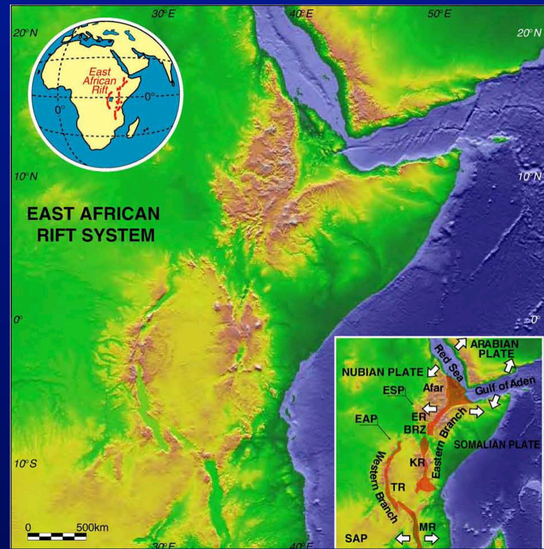


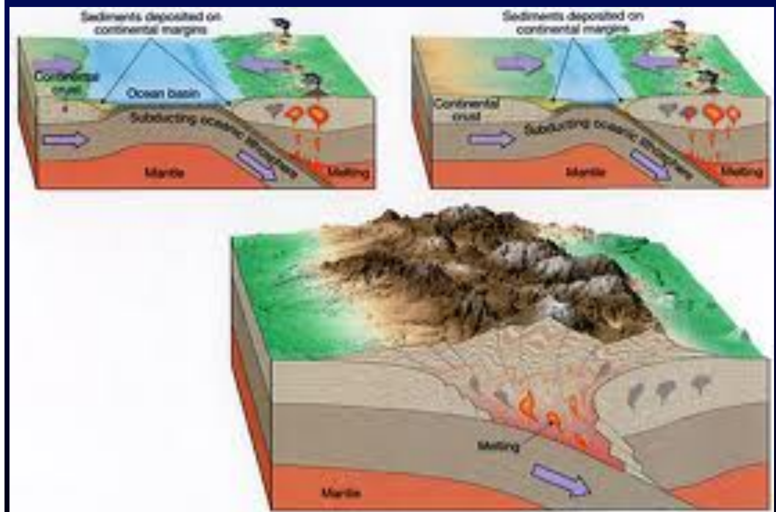
Clemens (2006) and references therein

When does the continental crust melt?



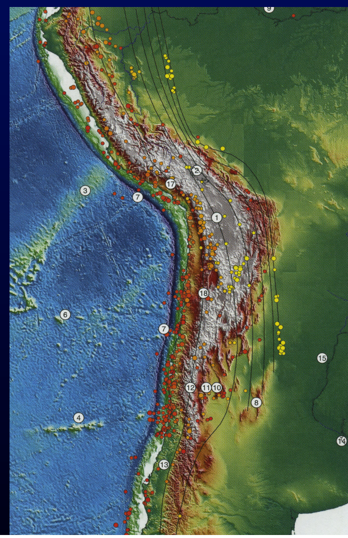
East African
Continental rifts





Himalaya
collisional belt

we need
particular
situations
for anatexis



Los Andes
orogenic arc

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Field, petrology of anatectic terranes

Migmatite (Sawyer 2008):
Rock in medium-, high-grade area, heterogeneous at micro-, macro-scale, consisting of two petrographically different parts. One formed by anatexis. All parts petrogenetically related by partial melting and segregation from the solid fraction.
It is a genetic-, partial melting-based definition.
The anatectic part is light-colored, larger in grain size, and rich in Qtz and feldspars; the other petrographic part is dark-colored and rich in ferromagnesian minerals.

Types (morphology, funct. % melt and effect/interplay of deformation):
Metatexites and diatexites.

Brown (2013)

Acosta-Vigil et al. (2014)

Field, petrology of anatectic terranes

Sawyer (2008)

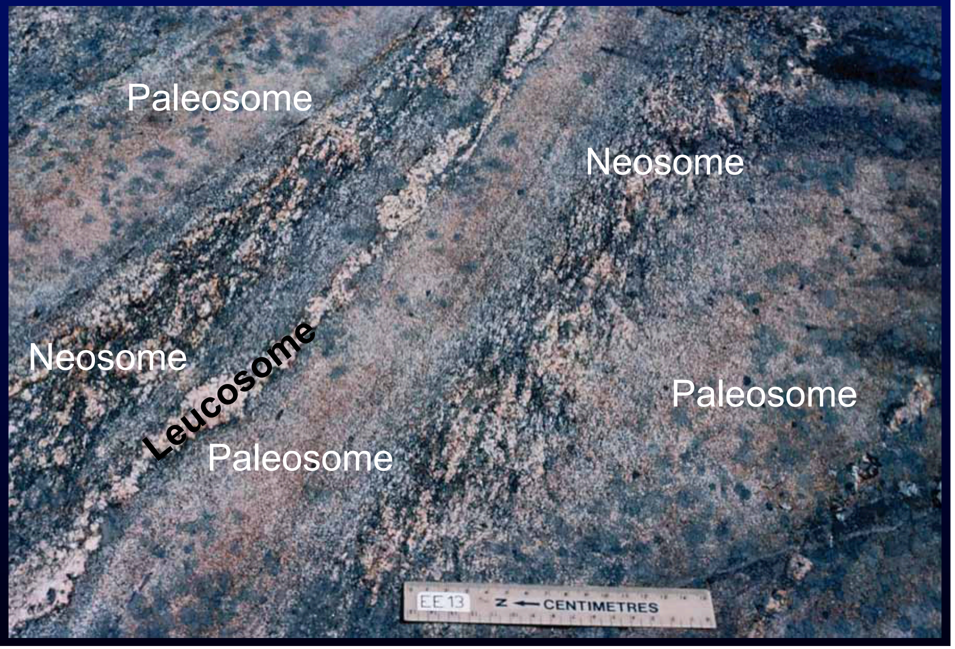
Parts of migmatite (Sawyer 2008):
Neosome: part newly formed by partial melting. May or may not Have undergone segregation.

Protolith: rock out of the anatectic area that will become neosome.

Paleosome, resister: non-neosome part of a migmatite.

Residuum: solid fraction part of the Neosome, left after melt extraction.

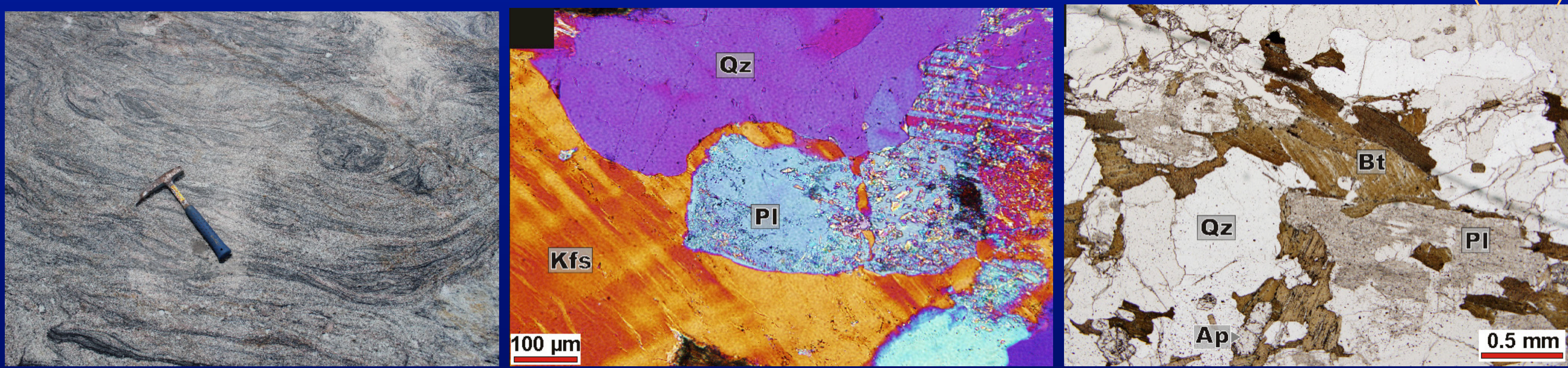
Leucosome: part of the migmatites Derived from the segregated melt. May not have the composition of the primary melt. In situ, in source, leucocratic vein or dike.



Field, petrology of anatectic terranes

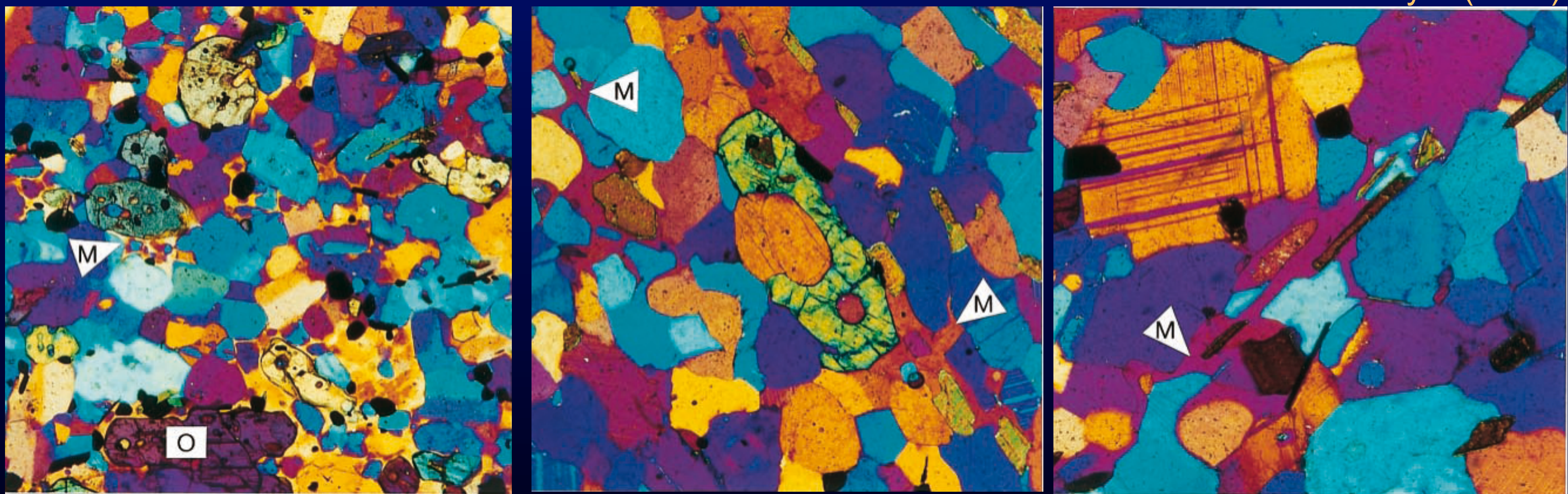
2. Mechanisms of anatexis: protoliths, melting reactions, P-T-X_{H2O} conditions

Carvalho et al. (2016)



Qtz + Pl + Kfs + H_2O = melt; 730 ºC, 0.5-0.6 GPa; Archean TTG, Brazil

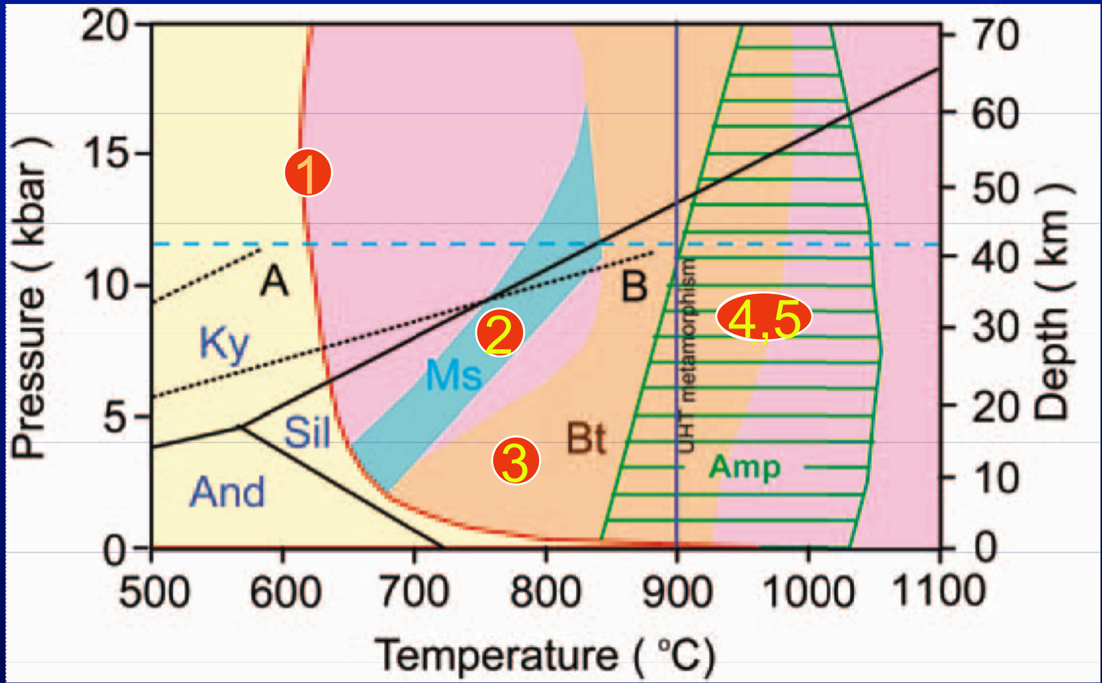
Sawyer (2001)



Qtz + Pl + Bt = Opx + Ilm + melt; Archean metagreywacke, Canada

Experimental petrology

4. Melting reactions, melt composition, equilibrium conditions, melt distribution



Sawyer et al. (2011)

P-T: 700-900 ºC at 4-15 kbar, dehydration-melting or fluid absent reactions.
2 Ms+Pl+Qtz→Melt+Als+Kfd+Bt
3 Bt+Pl+Als+Qtz→Melt+Crd/Grt±Kf
4 Bt+Pl+Qtz→Melt+Opx±Ilm
5 Hbl+Pl→Melt+Grt ±Cpx±Ilm
HP-UHP: 900-1000 ºC at 15-50 kbar; UHT: 900-1100 ºC at 10 kbar
Fluid present: 650 ºC
1 Qtz+Pl+Kfd+Ms+H_2O→Fundido

Crustal anatexis

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Field, petrology of anatectic terranes

3. Mechanisms of segregation, extraction, ascent and emplacement

In order to differentiate the continental crust during crustal anatexis, melt must separate from solid residuum and ascend to upper crustal levels.

Field studies: Migmatites separate deeper levels of residual granulites with rare leucosomes, from shallower levels rich in allochthonous granites.
Migmatite terranes are complex, polygenetic, in that they represent levels where melting has occurred, from which melt has been drained, in which melt has accumulated, and through which melt has transferred (Brown 2013).

With field and petrology studies we may recognize the presence of melt at the microscopic and macroscopic scale, and start to understand how melt segregate and ascend from melt production sites, and emplace into upper crustal levels.

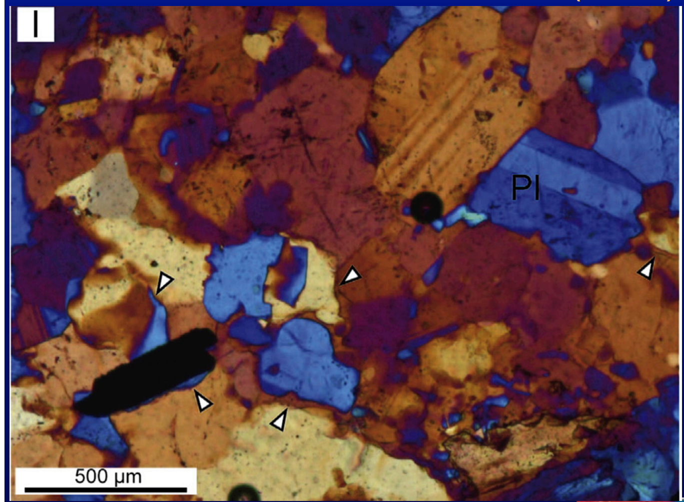
Field, petrology of anatectic terranes

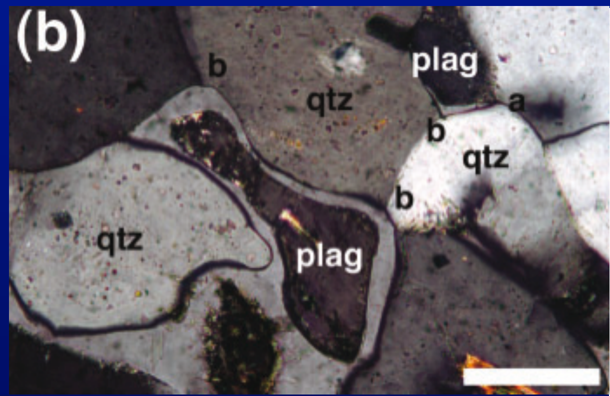
3. Mechanisms of segregation, extraction, ascent and emplacement

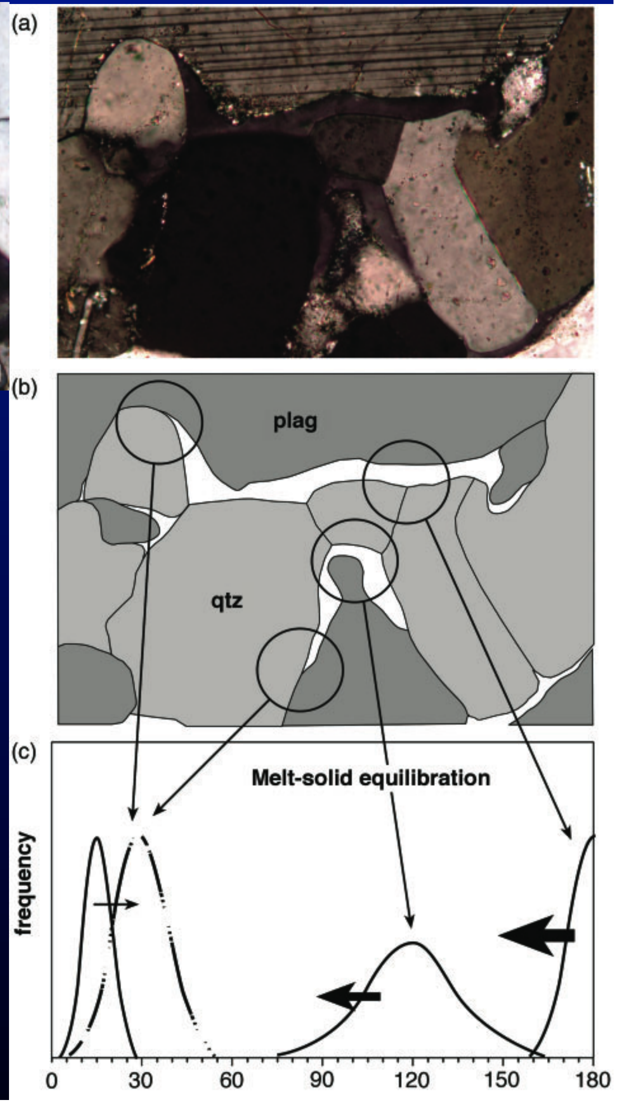
Low melt fractions at the microscopic scale: pore pseudomorphs, shown by melt films, cuspate terminations.

Holness & Sawyer (2007)

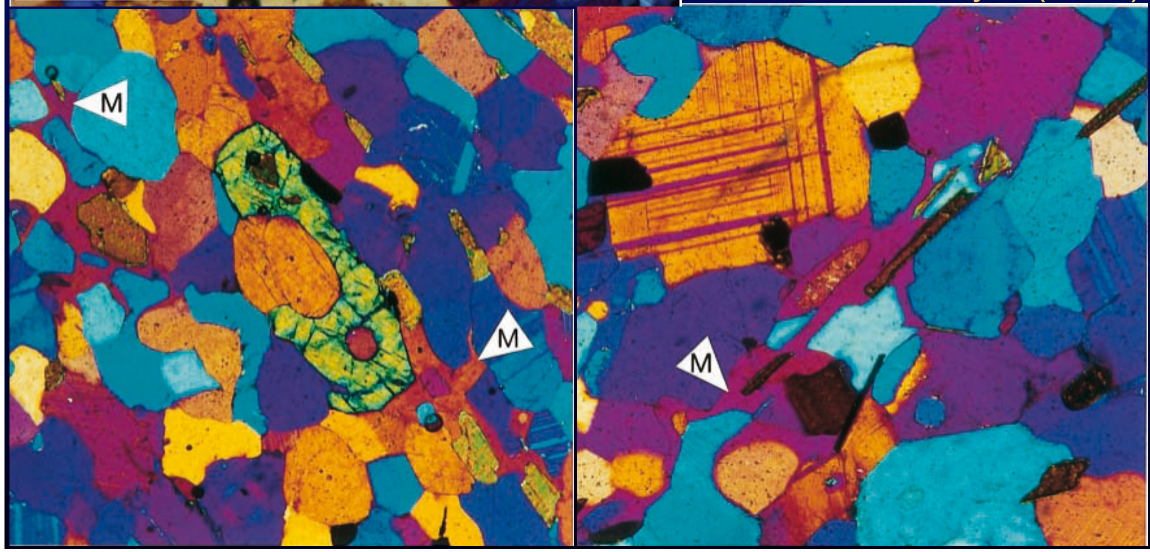
Barich et al. (2014)







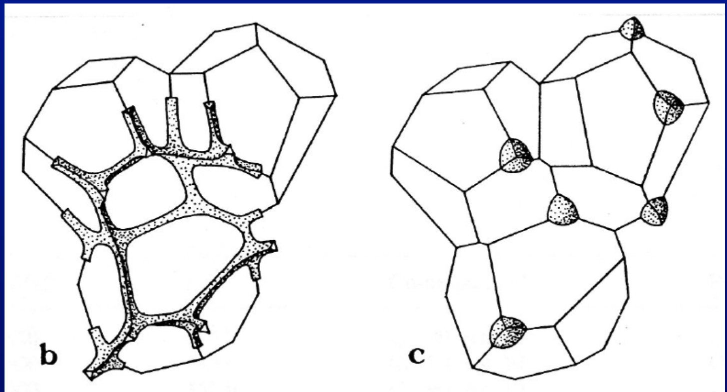
Sawyer (2001)



Experimental petrology

3. Mechanisms of segregation, extraction, ascent and emplacement

Laporte et al. (1997), Holness (2011)



Laporte y Provost (2000)

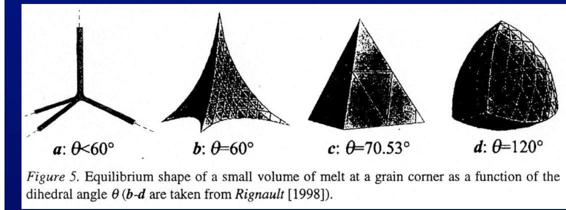
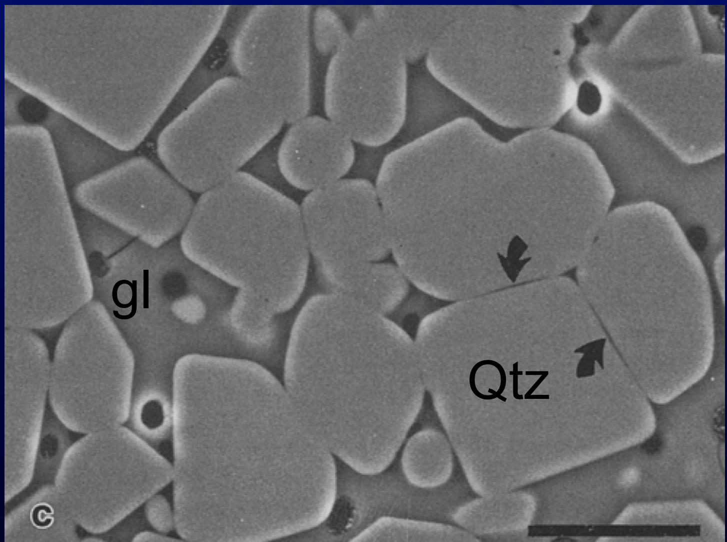
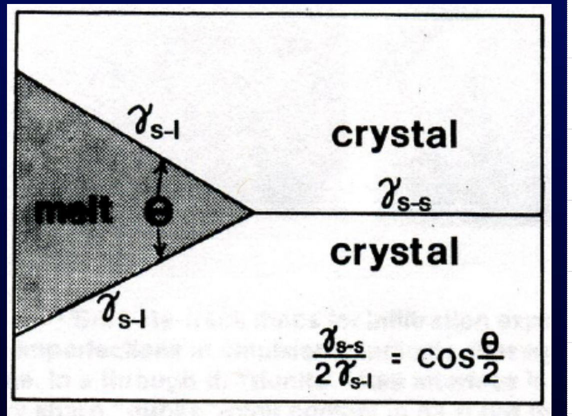


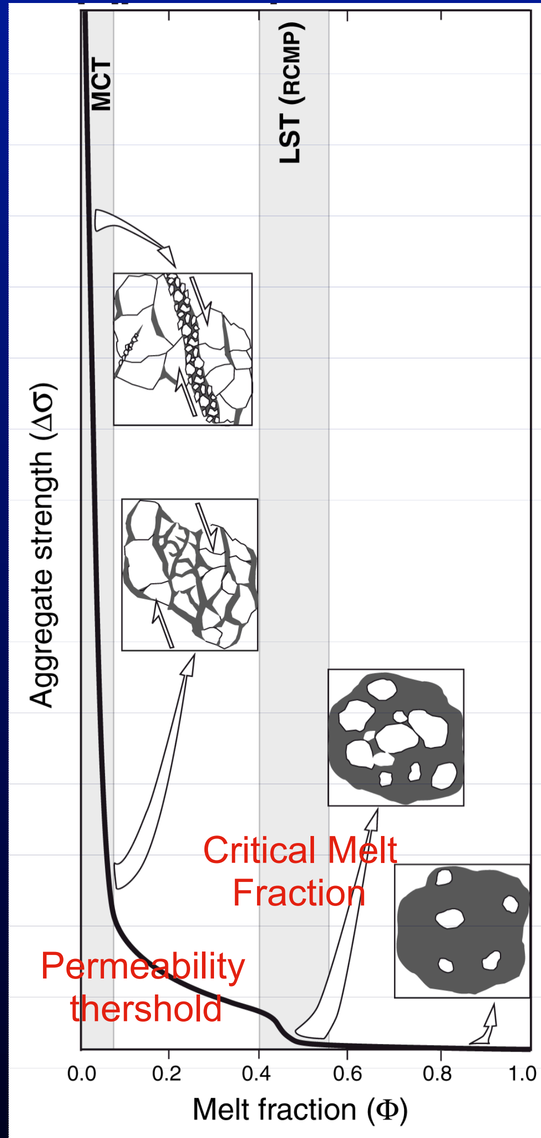
Figure 5. Equilibrium shape of a small volume of melt at a grain corner as a function of the dihedral angle θ (*b-d* are taken from *Rignault* [1998]).



Laporte (1994)

Dihedral angle





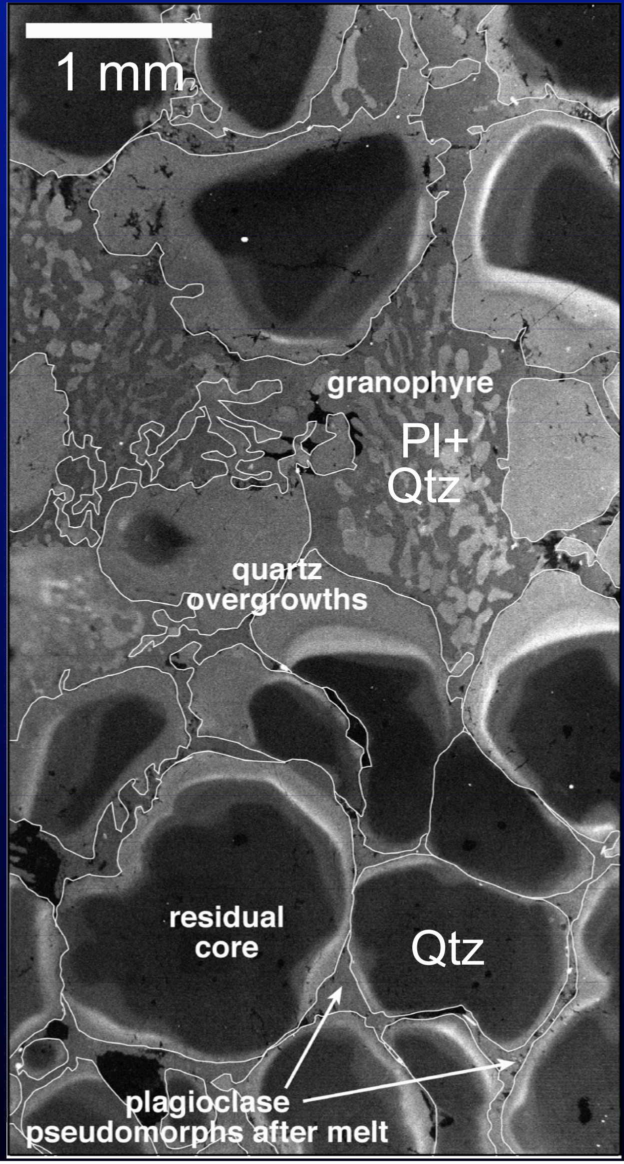
Rosemberg y Handy (2005)

Field, petrology of anatectic terranes

3. Mechanisms of segregation, extraction, ascent and emplacement

Low melt fractions at the microscopic scale: pore pseudomorphs

Migmatite

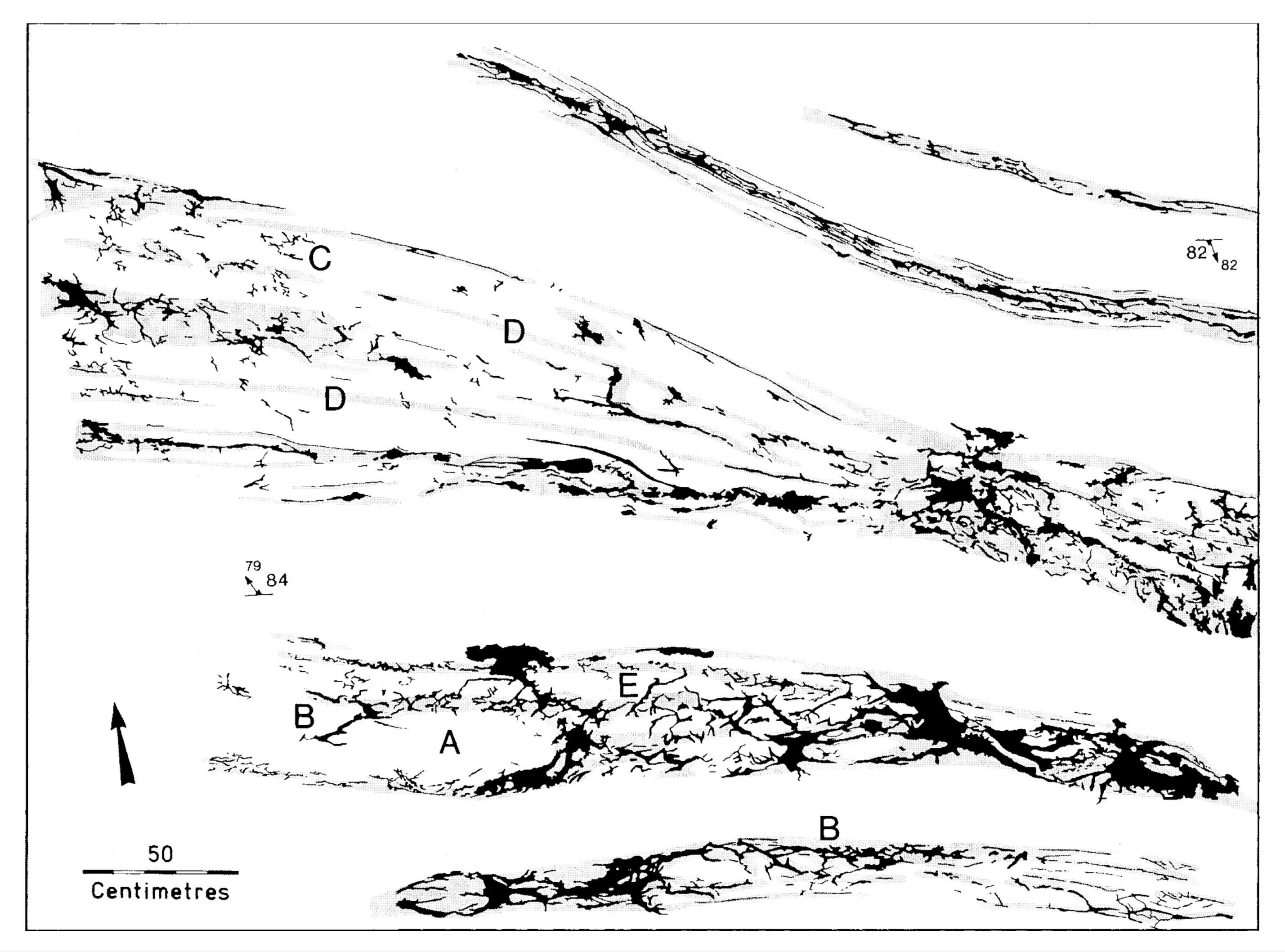


Holness (2008)

Field, petrology of anatectic terranes

3. Mechanisms of segregation, extraction, ascent and emplacement

It is easy to recognize and map melt distribution at the macroscopic scale once melt has amalgamated into cm-, dm-, m-scale leucosomes.

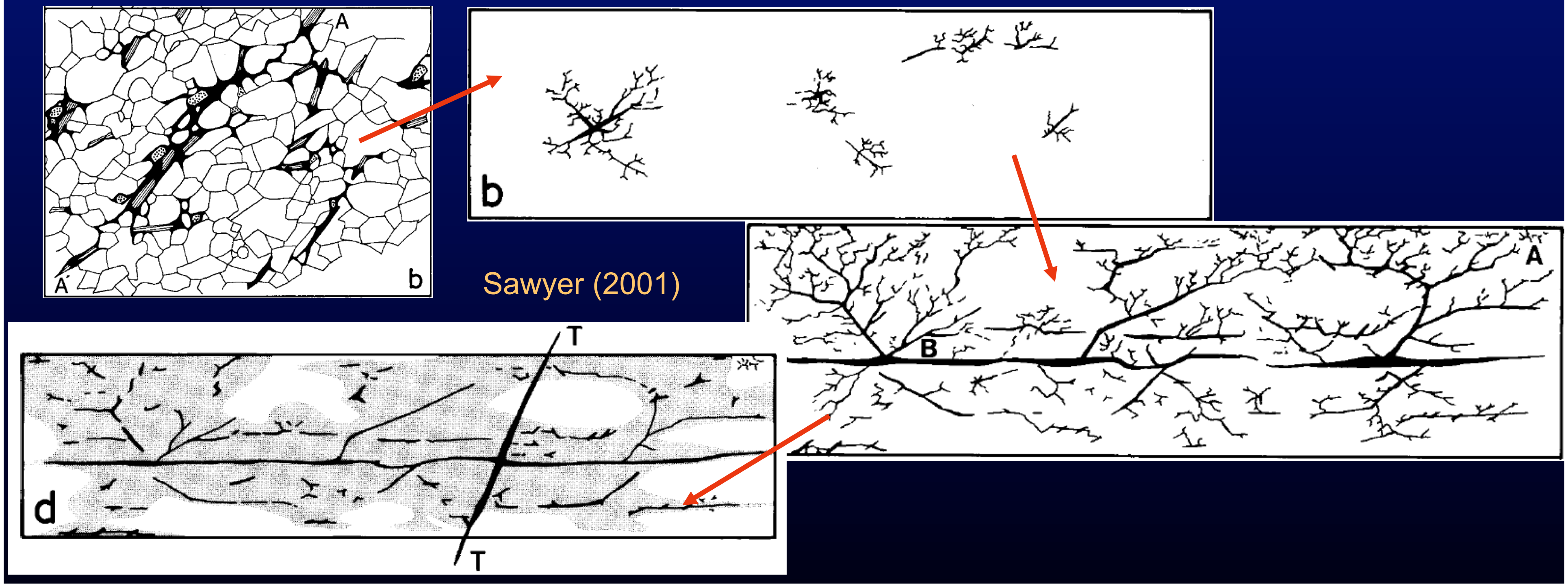


Sawyer (2001)

Field, petrology of anatectic terranes

3. Mechanisms of segregation, extraction, ascent and emplacement

Leucosomes typically form a network that changes form in the direction of melt movement. At melt production sites, small scattered paches of <u>in situ</u> leucosomes. Next, they link together to feed into wider, longer leucosomes, commonly along foliation planes or shear bands, to form <u>in source</u> leucosomes. These connect with discordant planar/circular structures that extract the melt from the anatectic terrane. Driving force for melt segregation: P gradients during differential stress on heterogenous crust (Sawyer 2014).



Sawyer (2001)

Field, petrology of anatectic terranes

3. Mechanisms of segregation, extraction, ascent and emplacement

Driving force for melt ascent:

Differences in density (e.g. Brown 2010).

Brown (2004)

Brown (2013)

Brown (2004)

Field, petrology of anatectic terranes

3. Mechanisms of segregation, extraction, ascent and emplacement

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Differences in density (e.g. Brown 2010).

Brown (2013)

Brown (2004)

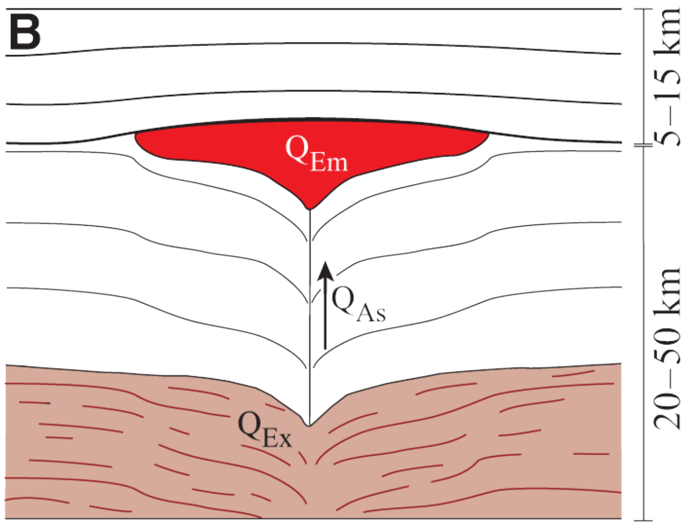
Brown (2007)

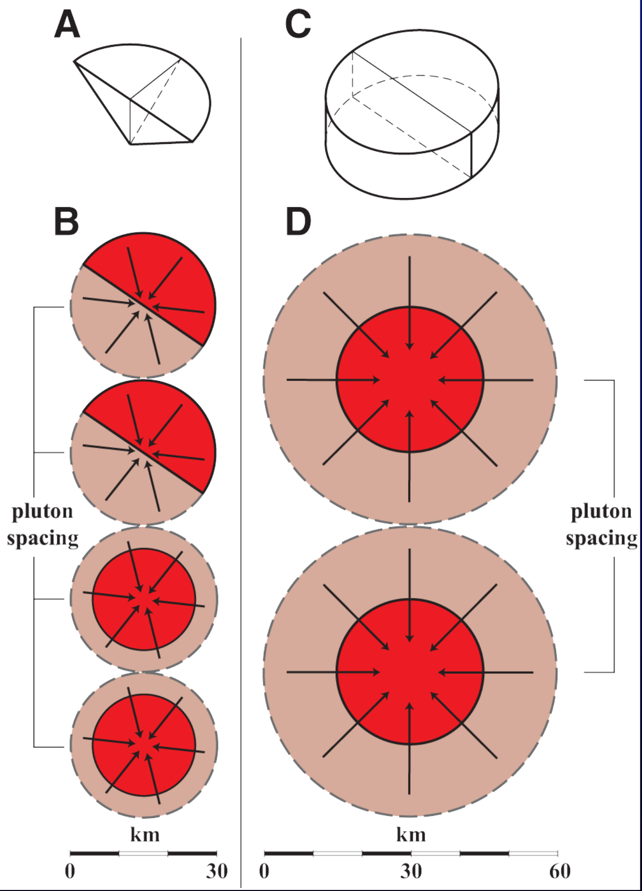
Field, petrology of anatectic terranes

3. Mechanisms of segregation, extraction, ascent and emplacement

Plutons (10^3-10^4 Km^3) by addition of many magma batches, emplaced while the previously intruded magma is partially crystallized (mush), hence contacts between batches are cryptic. Melt is extracted periodically. Plutons form in 10^6-10^7 yrs: end product. Processes is balanced at crustal scale.

Brown (2013)





Field, petrology of anatectic terranes

4. Melt composition, extent of melt-solid (=residue) equilibration

Leucosomes are the part of migmatite that today approach more closely to the melt during anatexis, whereas melanosomes are those that approach more closely to the residuum. Hence, in order to obtain melt compositions, we analyze leucosomes; and to check the extent of equilibrium, we compare leucosomes with minerals in melanosomes.

However, this approach has problems associated with nature of migmatites:

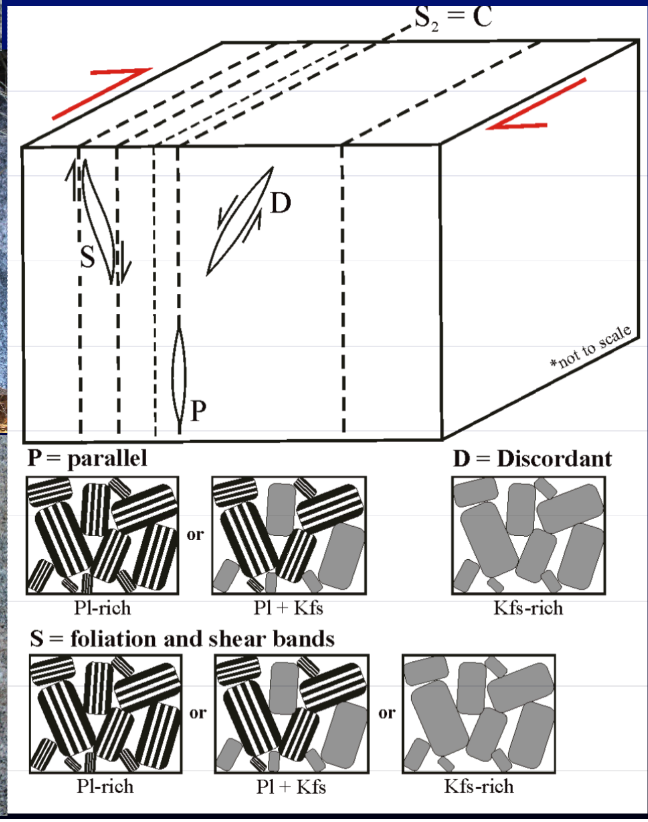
- Leucosomes rarely represent pure melts, particularly primary melts.
- Fractional crystallization, melt segregation: cumulates, evolved melts.
- Upon cooling, melt-residue reaction, e.g. by diffusion through melt.

The way to partially solve these problems: thorough and systematic petrological-geochemical study of the anatectic terrane (Sawyer 1998, Carvalho et al. 2016).

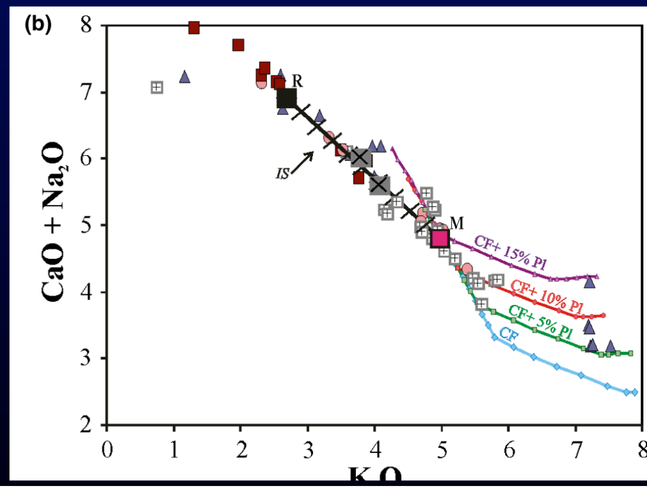
Field, petrology of anatectic terranes

4. Melt composition, extent of melt-solid (=residue) equilibration

Understanding processes operating during anatexis. Anatexis of a TTG gneiss. Melt segregated before and during crystallization, producing the variety of lithologies. GD are residual. L primary and fractionated. Level of exposure: has gained melt.



Carvalho et al. (2016)



Field, petrology of anatectic terranes

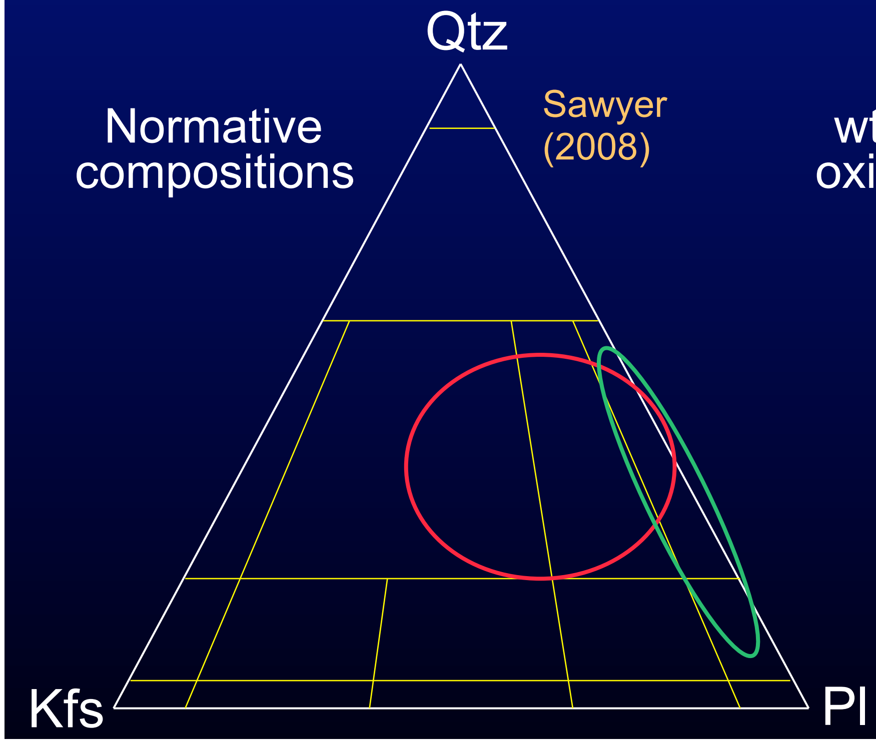
4. Melt composition, extent of melt-solid (=residue) equilibration

Leucosomes in metatexites from metasediments (pelites, greywackes) range in composition from monzogranites to tonalites, though in most cases are monzogranites and granodiorites.

Leucosomes in mafic metatexites range from monzodiorites to tonalites.

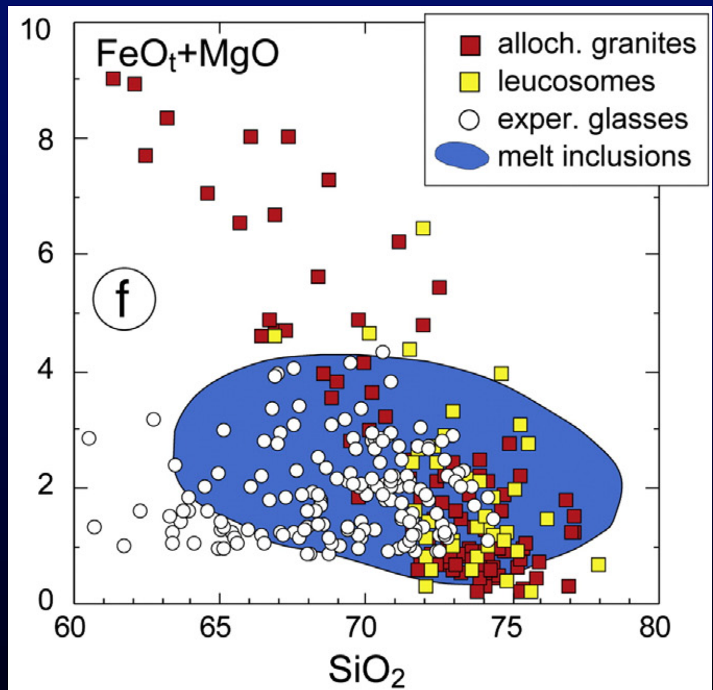
Leucosomes from metasedimentary rocks are too leucocratic (low in Fe, Mg, Ti) to be the source of many crustal granites (mafic S-type granites).

Normative compositions



Sawyer (2008)

wt % oxides

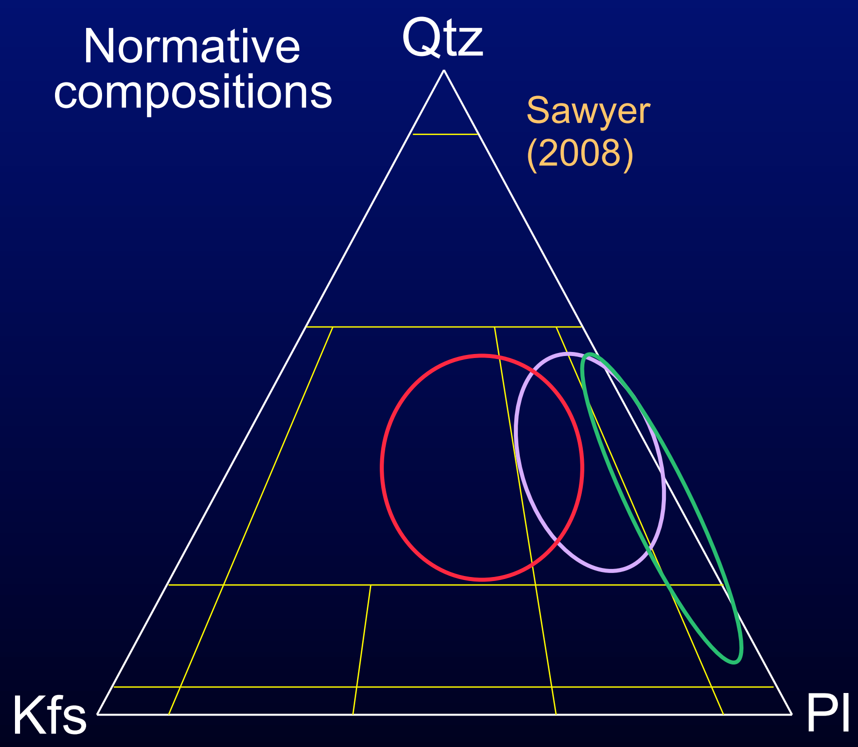


Cesare et al. (2008)

Experimental petrology

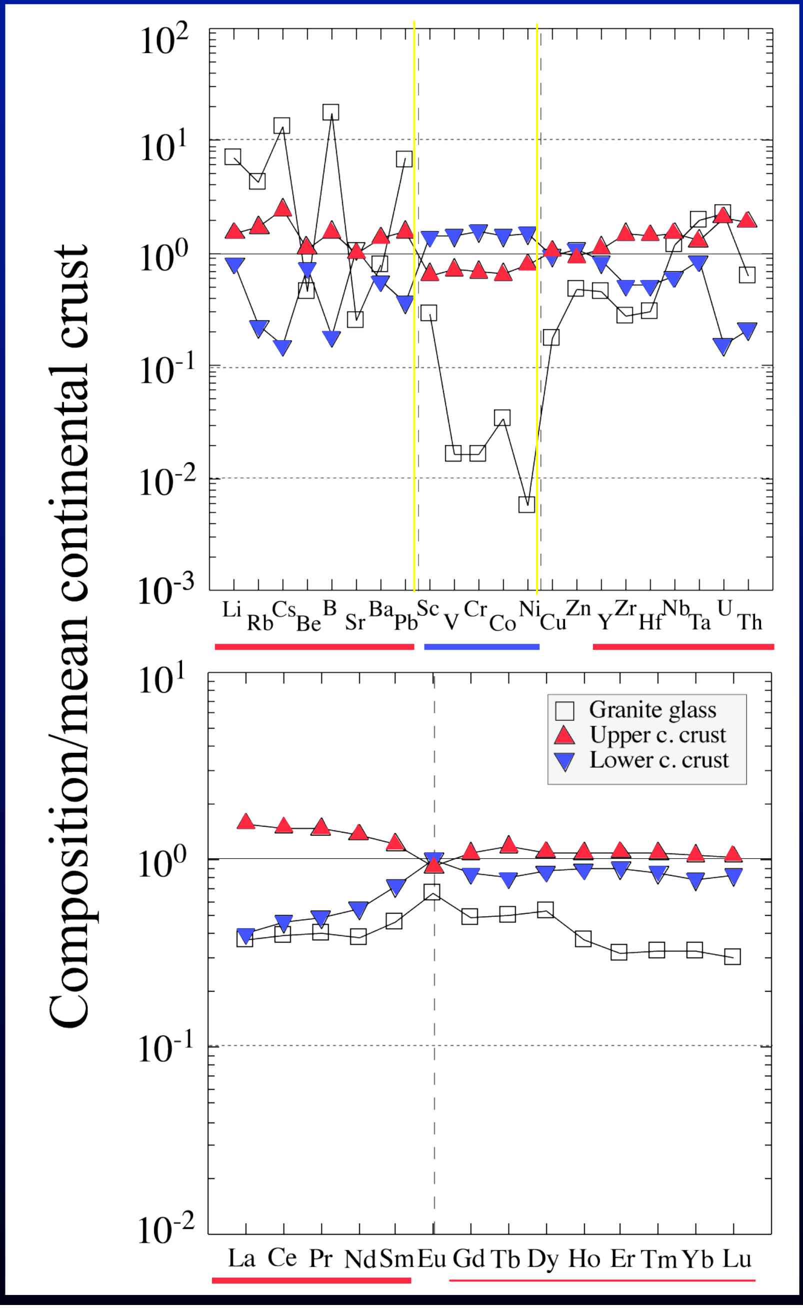
4. Melting reactions, melt composition, equilibrium conditions, melt distribution

Dehydration melting metasediments
Dehydration melting-fluxed melting mafic rocks
Fluxed melting metasediments



Composition of the continental crust

	Upper	Middle	Lower
SiO_2	66.6	63.5	54.3
TiO_2	0.64	0.69	0.97
Al_2O_3	15.4	15.0	16.1
FeO_t	5.04	6.02	10.6
MgO	2.48	3.59	6.28
CaO	3.59	5.25	8.48
Na_2O	3.27	3.39	2.79
K_2O	2.80	2.30	0.64
ASI	1.03	0.85	0.78

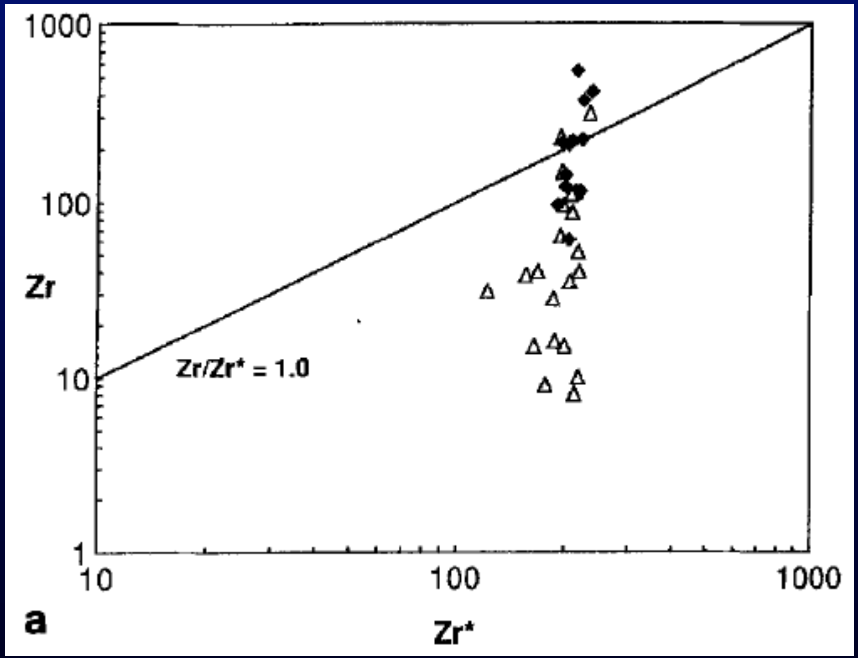


Data from Rudnick & Gao (2003)

Field, petrology of anatectic terranes

4. Melt composition, extent of melt-solid (=residue) equilibration

Extent of equilibrium mostly (only?) calculated regarding the trace elements controlled by accessory minerals (Zrn: Zr; Mnz: LREE, Th).
In most cases, disequilibrium has been reported, implying rapid segregation of melt from its residuum (10^2-10^4 yrs).
Much more difficult to establish equilibrium regarding major minerals/oxides.



Watt et al. (1996), Montel (1993), Bea (1996), Watson (1996)

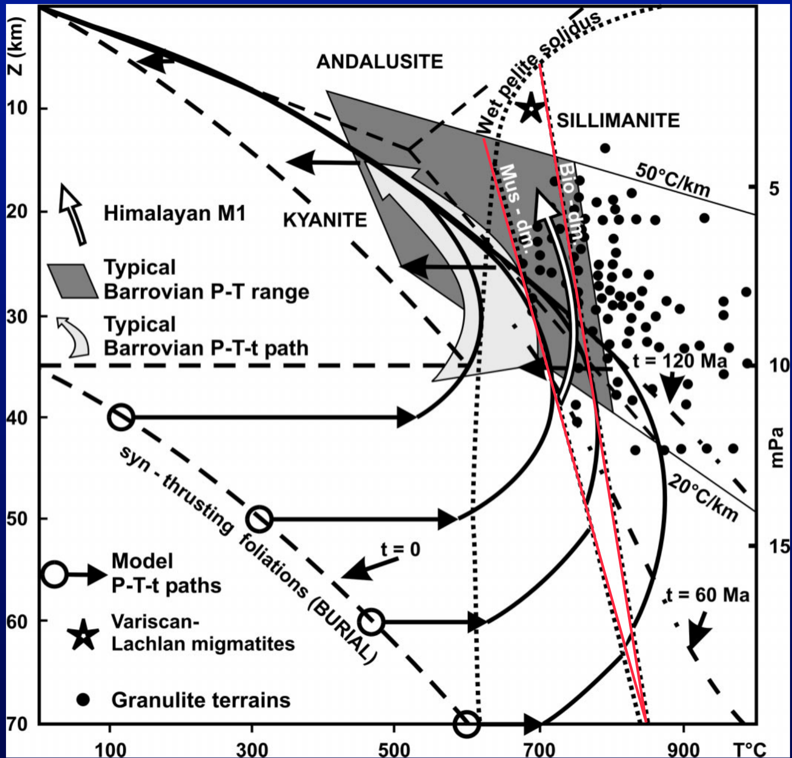
Crustal anatexis

- Crustal anatexis (=partial melting of the continental crust):
  1. Where, when, why?
  2. How, i.e. mechanisms of anatexis: protoliths, melting reactions, P-T-X_{H2O} conditions.
  3. Mechanisms of segregation, extraction, ascent and emplacement.
  4. Melt composition, extent of melt-solid (=residue) equilibration.
  5. Connection between anatectic terranes-crustal granites: nature and intensity of crustal differentiation, role of mantle (heat-mass: crustal differentiation to crustal growth ratio).

- Sources of information:
  1. Anatectic terranes and enclaves in volcanic rocks: field, petrology and geochemical studies.
  2. Experimental petrology.
  3. Thermal-thermodynamic-thermomechanic modeling.

Thermal modeling colisional orogens

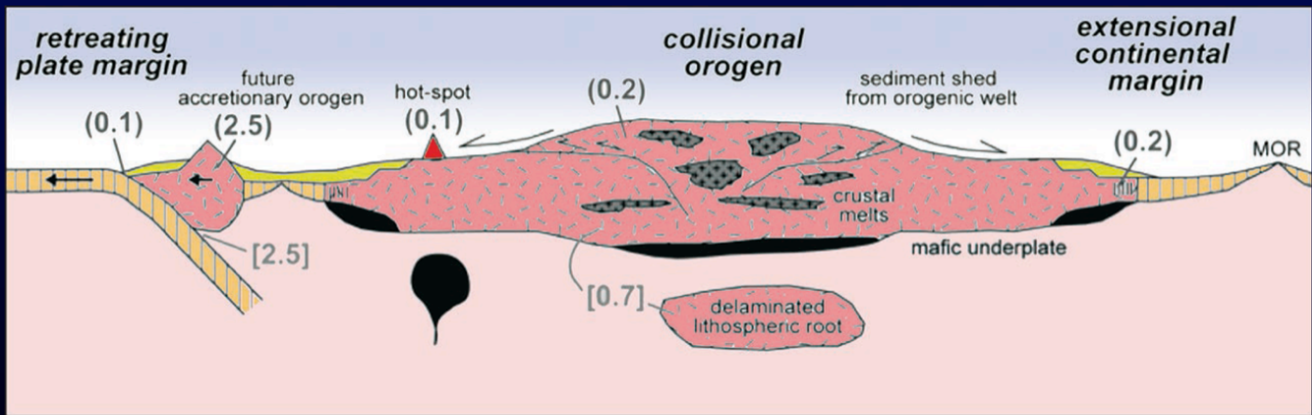
Collins (2000)



5. Connection migmatites-crustal granites
- Nature/intensity of crustal differentiation,
- Role of mantle, crustal differentiation/ crustal growth ratio.

Not a simple answer, depends on:
- Geodynamic setting: subduction, collision, extension, and
- Associated granite type: S-, I-, A-type.

Hawkesworth et al. (2010)



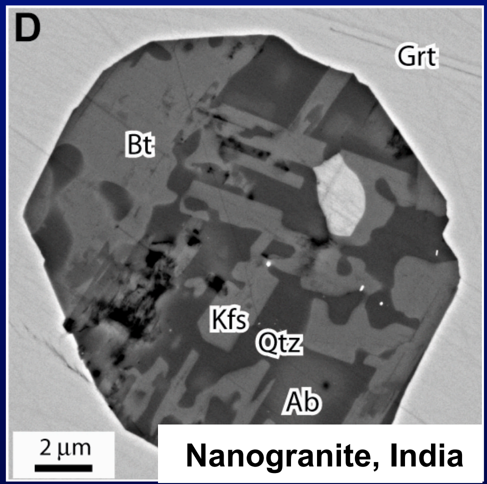
Granite types, mantle role

S- and I-types (Chappell & White 1974):
S-type: setimentary protolith, low Na, ASI>1.1, mostly felsic, irregular trends.
I-type (cordilleran): igneous protolith, high Na, ASI<1.1, mafic to felsic, linear trends.
Peraluminous leucogranites, two-mica granites (e.g. Barbarin 1999; Patiño-Douce 1999): S-type low in Fe, Mg and Ti, abundant primary Ms.
Mafic S-types, peraluminous S-type granites (e.g. Montel & Viezeuf 1997):
S-type high in Fe, Mg, Ti, high ASI, rich in Crd and/or Opx (higher T, lower P).
A-type (anorogenic, anhydrous) granites (e.g. Eby 1990):
High in Si, Na+K, Fe/Mg, Zr, Nb, Ga, Y, Ce, low in Ca,and Sr.

Pro-mantle role in I-type and mafic S-types:
Collins (1996, 2000), Kemp et al. (2007, 2009): geochemistry, bulk rock isotopes, O-Hf isotopes of Zrn.
Patiño-Douce (1999): experiments and geochemical modeling.

Pro-crust role in I-type:
Chappell et al. (1987, 2004), Chappell (1996): petrology, geochemistry.
Clemens et al. (2011): petrology, geochemistry.

Second talk: melt inclusions



Nanogranite, India