More Island Arc Magmas

Friday, May 6th, 2005

The Story So Far!

- Simple model of melting subducted oceanic crust appears untenable. Basalts are quite common, and HREE do not indicate role for garnet in melting eclogite (basalt crust).
- Flat HREE (similar to MORB) suggests involvement of shallow MORB mantle (peridotite).
- Elevated LIL (relative to HFS) implies involvement of fluids (water) in formation of arc magmas.

Isotopes

- New Britain, Marianas, Aleutians, and South Sandwich volcanics plot within a surprisingly limited range of DM
- Implies similar source as MORB

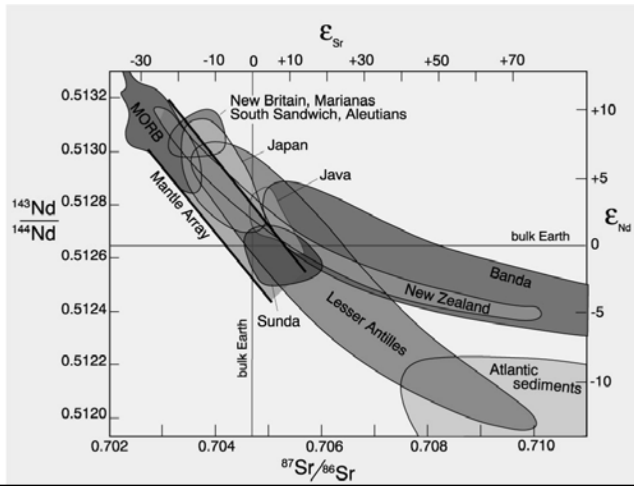
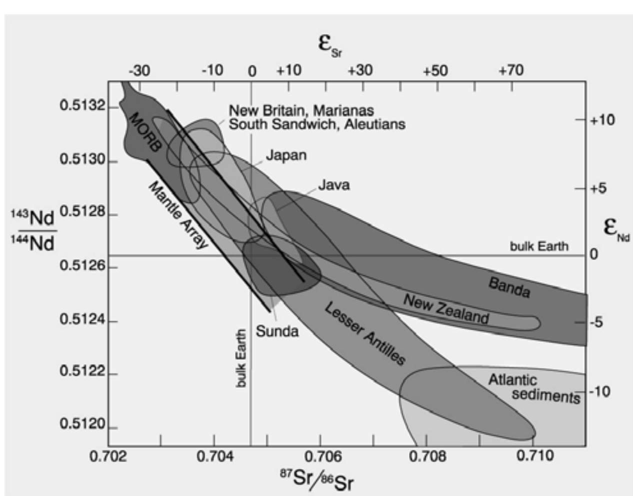


Figure 16-12. Nd-Sr isotopic variation in some island arc volcanics. MORB and mantle array from Figures 13-11 and 10-15. After Wilson (1989), Arculus and Powell (1986), Gill (1981), and McCulloch *et al*. (1994). Atlantic sediment data from White *et al*. (1985).

- Lesser Antilles project towards Atlantic sediments
- Banda, New Zealand project towards Pacific Sediments
- Implications – Arc magmas produced from depleted MORB mantle and subducted sediments



Pb isotopes emphasize the role of subducted sediments in the generation of arc magmas. But when did this occur? Long ago (OIBS) or more recently?

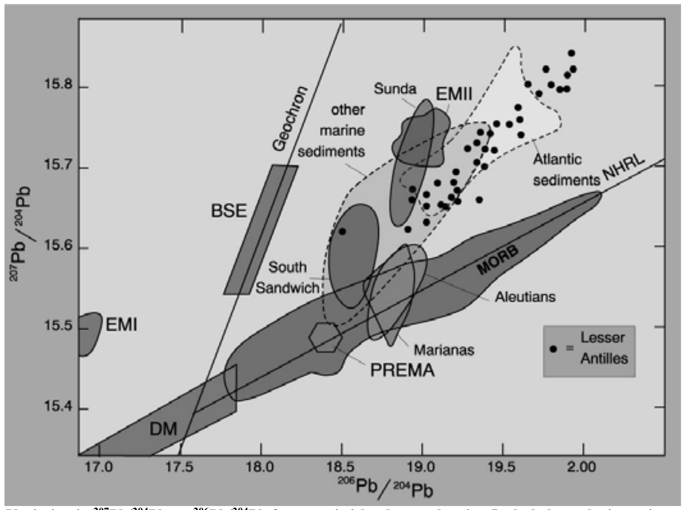


Figure 16-13. Variation in $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ for oceanic island arc volcanics. Included are the isotopic reservoirs and the Northern Hemisphere Reference Line (NHRL) proposed in Chapter 14. The geochron represents the mutual evolution of $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ in a single-stage homogeneous reservoir. Data sources listed in Wilson (1989).

Evidence from Beryllium (Be) and Boron (B)

^{10}Be created by cosmic rays + oxygen and nitrogen in upper atmosphere.

- Fall to Earth by precipitation & readily incorporated into clay-rich oceanic sediments
- Half-life is only 1.5 Ma (long enough to be subducted, but quickly lost to mantle systems). After about 10 Ma ^{10}Be is no longer detectable
- $^{10}Be/^{9}Be$ averages about 5000 x 10^{-11} in the uppermost oceanic sediments
- In mantle-derived MORB and OIB magmas, & continental crust, ^{10}Be is below detection limits (<1 x 10^{6} atom/g) and $^{10}Be/^{9}Be$ is <5 x 10^{-14}

Boron (B) is a stable element

- Very brief residence time deep in subduction zones
- B in recent sediments is high (50-150 ppm), but has a greater affinity for altered oceanic crust (10-300 ppm)
- In MORB and OIB it rarely exceeds 2-3 ppm

$^{10}Be/Be_{total}$ vs. B/Be_{total} diagram (Be$_{total}$ ≈ ^{9}Be since ^{10}Be is so rare)

The important point here is that one needs **young** ocean sediments to explain the arc magma data. Otherwise there would be no ^{10}Be left.

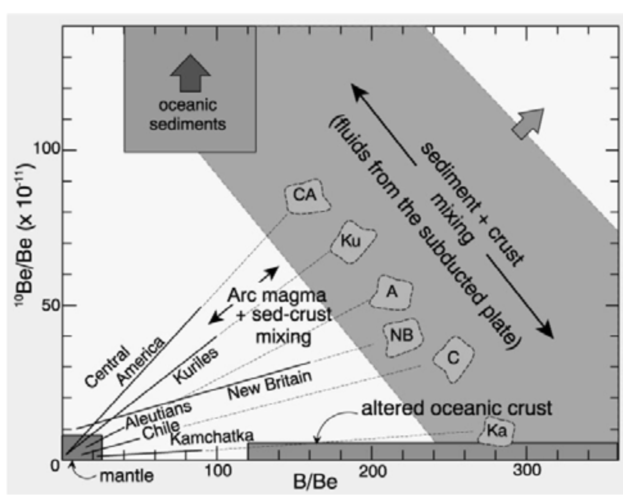


Figure 16-14. $^{10}Be/Be(total)$ vs. B/Be for six arcs. After Morris (1989) *Carnegie Inst. of Washington Yearb.*, 88, 111-123.

Petrogenesis of Island Arc Magmas

- HFS elements suggest involvement of a MORB source.
- LIL elements indicate role for hydrous fluids
- Isotopes indicate both MORB source and sediments
- Be isotopes indicate young subducted sediments

So, how can we produce magmas in a subduction zone?

We need to consider the thermal regime

Of the many variables that can affect the isotherms in subduction zone systems, the main ones are:

1) the rate of subduction
2) the age of the subduction zone
3) the age of the subducting slab
4) the extent to which the subducting slab induces flow in the mantle wedge

Other factors, such as:

- ☞ dip of the slab
- ☞ frictional heating
- ☞ endothermic metamorphic reactions
- ☞ metamorphic fluid flow

are now thought to play only a minor role

- Typical thermal model for a subduction zone
- Isotherms will be higher (i.e. the system will be hotter) if
  - a) the convergence rate is slower
  - b) the subducted slab is young and near the ridge (warmer)
  - c) the arc is young (<50-100 Ma according to Peacock, 1991)

yellow curves = mantle flow

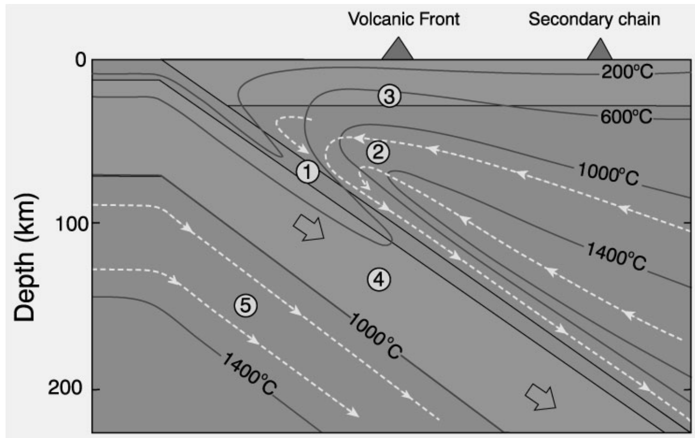
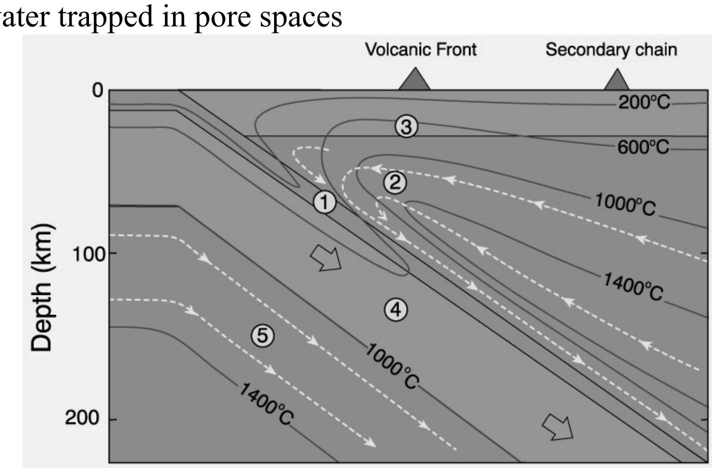


Figure 16-15. Cross section of a subduction zone showing isotherms (red-after Furukawa, 1993, *J. Geophys. Res.*, 98, 8309-8319) and mantle flow lines (yellow- after Tatsumi and Eggins, 1995, *Subduction Zone Magmatism*. Blackwell. Oxford).

The principal source components for Island Arc magmas

1. The crustal portion of the subducted slab
   - 1a Altered oceanic crust (hydrated by circulating seawater, and metamorphosed in large part to greenschist facies)
   - 1b Subducted oceanic and forearc sediments
   - 1c Seawater trapped in pore spaces



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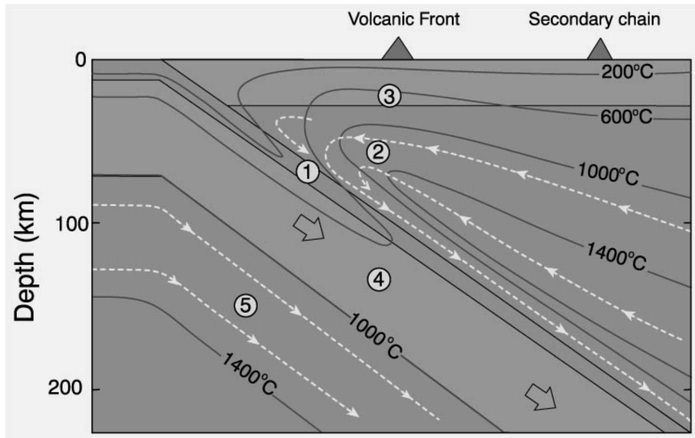
The principal source components for Island Arc magmas

2. The mantle wedge between the slab and the arc crust (OK)
3. The arc crust (not likely)
4. The lithospheric mantle of the subducting plate (not likely)
5. The asthenosphere beneath the slab (not likely)



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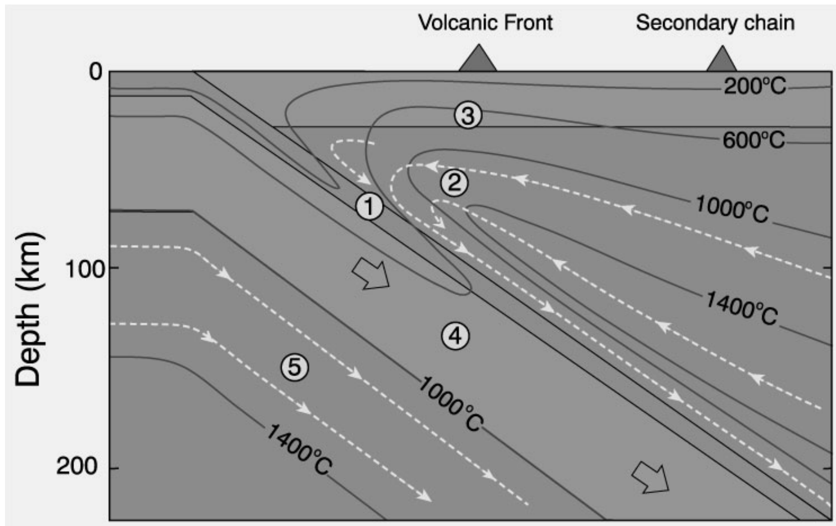
- Left with the subducted crust and mantle wedge
- The trace element and isotopic data suggest that both contribute to arc magmatism. How, and to what extent?
  - Dry peridotite solidus too high for melting of anhydrous mantle to occur anywhere in the thermal regime shown
  - Dry basalt crust would not begin melting until depths of several hundred km (remember h!)
  - LIL/HFS ratios of arc magmas indicate water plays a significant role in arc magmatism

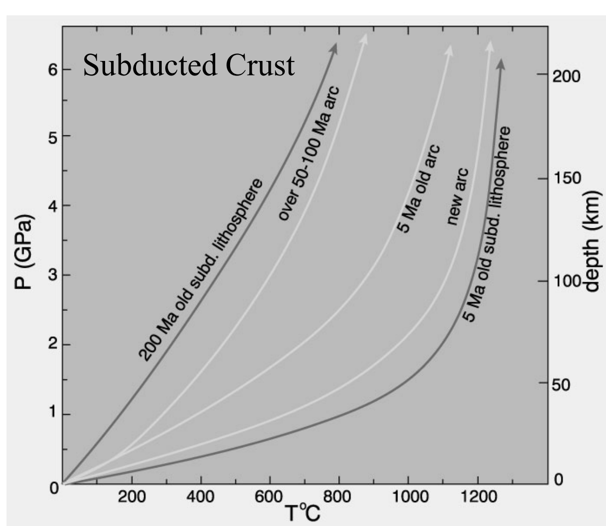
- The sequence of pressures and temperatures that a rock is subjected to during an interval such as burial, subduction, metamorphism, uplift, etc. is called a pressure-temperature-time or P-T-t path



- P-T-t paths for the subducted crust in a variety of arc scenarios numerically modeled by Peacock (1990, 1991)
- All curves are based on a subduction rate of 3 cm/yr, so the length of each curve represents about 15 Ma

The yellow P-T-t paths represent various arc ages

Figure 16-16. Subducted crust pressure-temperature-time (P-T-t) paths for various situations of arc age (yellow curves) and age of subducted lithosphere (red curves, for a mature ca. 50 Ma old arc) assuming a subduction rate of 3 cm/yr (Peacock, 1991, *Phil. Trans. Roy. Soc. London*, 335, 341-353).

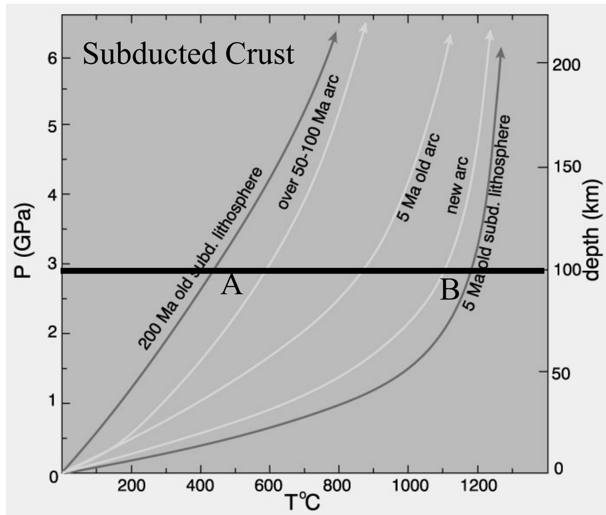


Red curves = age of the subducted slab

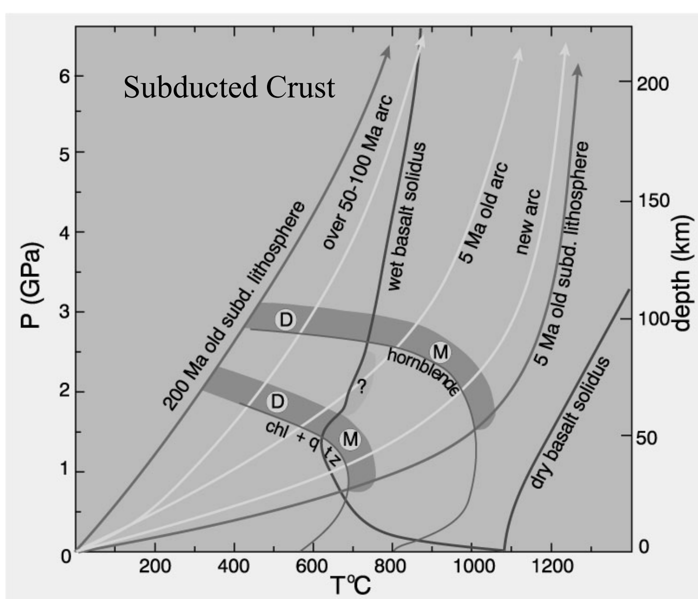
Consider T at 100 km

A – old cool lithosphere subducted below old mature arc at ~ 400-500 °C

B – young hot lithosphere subducted below young arc at ~ 1100 °C



Now add the solidi for dry and water-saturated melting of basalt to see what might happen.



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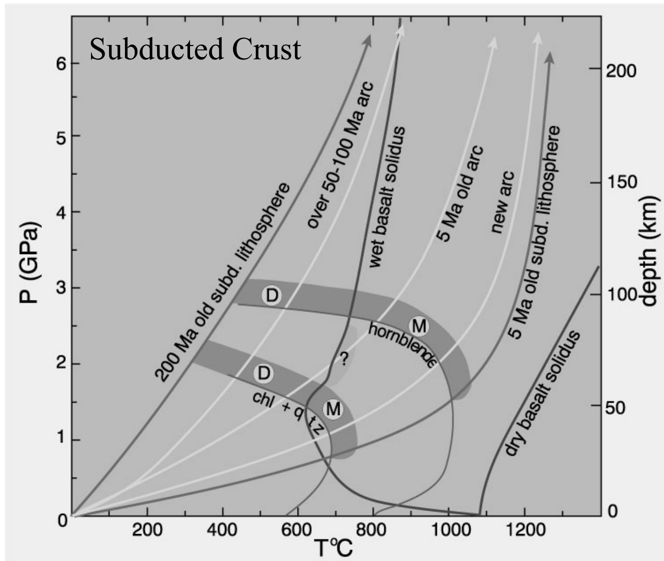
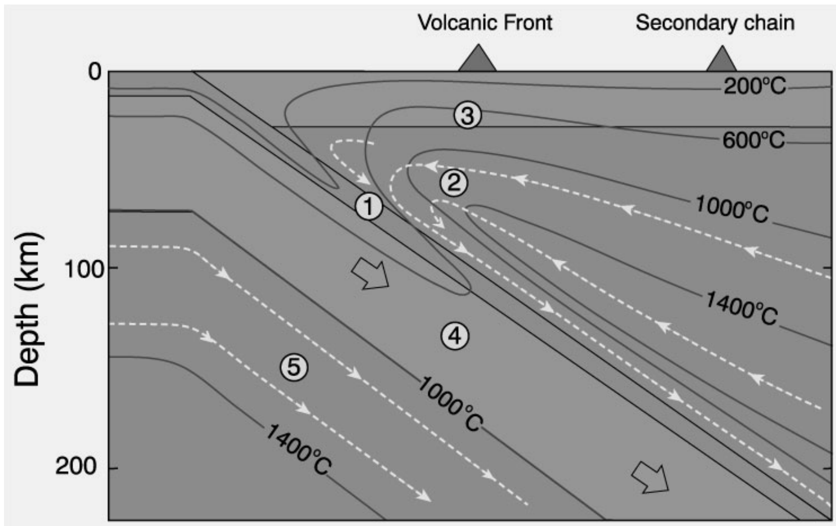
1. Dehydration D and liberation of water takes place (mature arcs with lithosphere > 25 Ma old). But no melting!

2. Slab melting M occurs at arcs subducting young lithosphere, as dehydration of chlorite or amphibole release water above the wet solidus to form Mg-rich andesites directly.



- The LIL/HFS trace element data underscore the importance of slab-derived water and a MORB-like mantle wedge source
- The flat HREE pattern argues against a garnet-bearing (eclogite) source
- Thus modern opinion has swung toward the non-melted slab for most cases

Mantle Wedge P-T-t Paths



- Amphibole-bearing hydrated peridotite should melt at ~ 120 km
- Phlogopite-bearing hydrated peridotite should melt at ~ 200 km
  → second arc behind first?

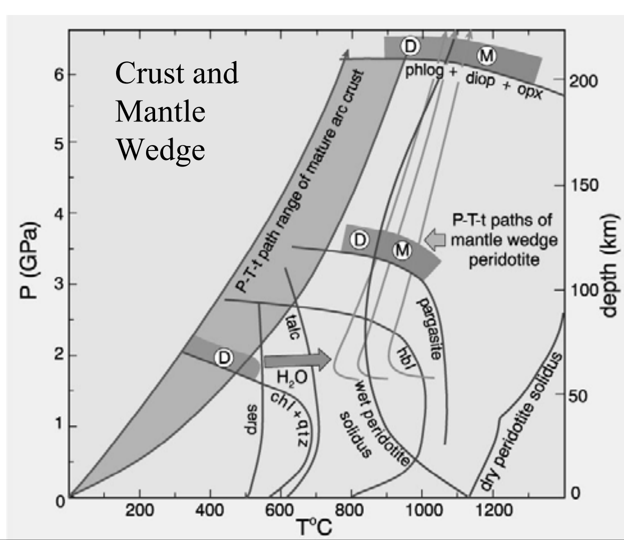


Figure 16-18. Some calculated P-T-t paths for peridotite in the mantle wedge as it follows a path similar to the flow lines in Figure 16-15. Included are some P-T-t path range for the subducted crust in a mature arc, and the wet and dry solidi for peridotite from Figures 10-5 and 10-6. The subducted crust dehydrates, and water is transferred to the wedge (arrow). After Peacock (1991), Tatsumi and Eggins (1995). Winter (2001). An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Island Arc Petrogenesis

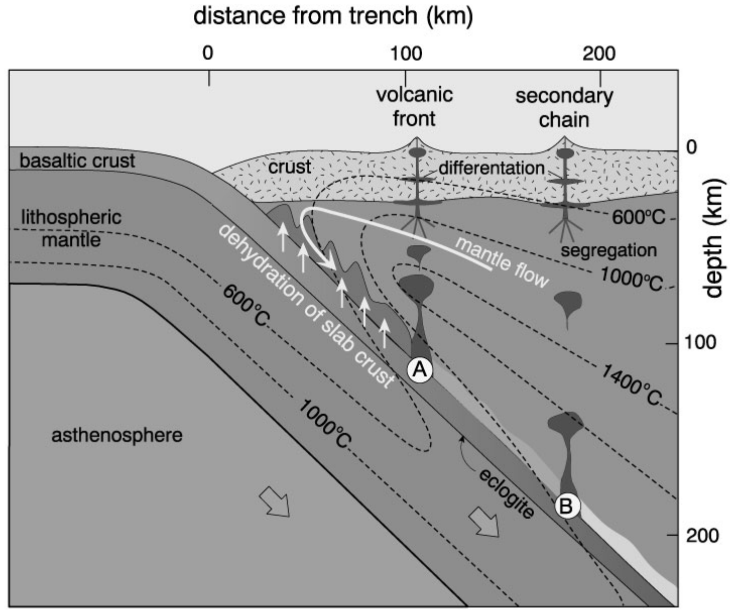
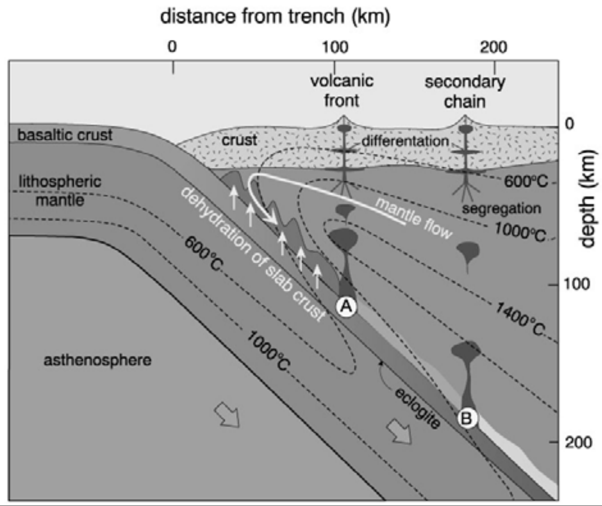


Figure 16-11b. A proposed model for subduction zone magmatism with particular reference to island arcs. Dehydration of slab crust causes hydration of the mantle (violet), which undergoes partial melting as amphibole (A) and phlogopite (B) dehydrate. From Tatsumi (1989), *J. Geophys. Res.*, 94, 4697-4707 and Tatsumi and Eggins (1995). *Subduction Zone Magmatism*. Blackwell. Oxford.

A multi-stage, multi-source process

- Dehydration of the slab provides the LIL, ^{10}Be, B, etc. enrichments + enriched Nd, Sr, and Pb isotopic signatures
  - These components, plus other dissolved silicate materials, are transferred to the wedge in a fluid phase (or melt?)
- The mantle wedge provides the HFS and other depleted and compatible element characteristics

- Phlogopite is stable in ultramafic rocks beyond the conditions at which amphibole breaks down
- P-T-t paths for the wedge reach the phlogopite-2-pyroxene dehydration reaction at about 200 km depth



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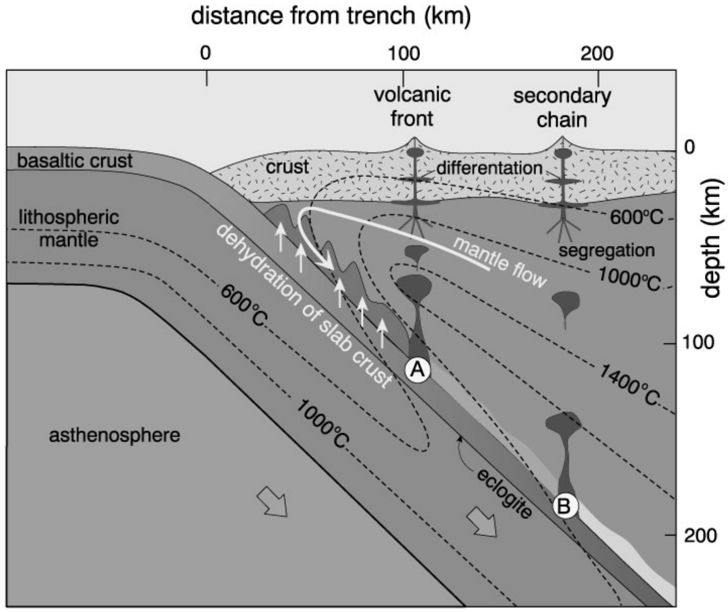
- The parent magma for the calc-alkaline series is a high alumina basalt, a type of basalt that is largely restricted to the subduction zone environment, and the origin of which is controversial
- Some high-Mg (>8wt% MgO) high alumina basalts may be primary, as may some andesites, but most surface lavas have compositions too evolved to be primary
- Perhaps the more common low-Mg (< 6 wt. % MgO), high-Al (>17wt% Al_2O_3) types are the result of somewhat deeper fractionation of the primary tholeiitic magma which ponds at a density equilibrium position at the base of the arc crust in more mature arcs

- Fractional crystallization thus takes place at a number of levels



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