Lecture 12

COMPLEX MELTING MODELS

(see books by Shaw, Trace Elements in Magmas (2006)

and Zou, Quantitative Geochemistry (2007))

Thus far we have considered two end-member melting models, batch melting and fractional melting; incremental melting is an intermediate model between these two extreme models. Before adding more complexities to melting models, it is instructive to consider why rocks melt.

    A. Why do rocks melt? There are three major processes:

        1. Heating

        2. Lowering of solidus by addition of volatiles

        3. Decompression

Although **Heating** is the most familiar process causing materials to melt, e.g., determining the melting temperature of NaCl or in terms of experimental petrology, heating a mineral assemblage in a furnace. This mechanism for inducing melting of natural rocks is uncommon in the present-day earth. However, heating as a result of high energy impact events occurs on the moon and is undoubtedly an important process during the high frequency impacts occurring early in the formation of planets.

The lowering of the solidus by addition of **Volatiles**, i.e. inducing a melting point depression such as adding salt to ice, is believed to be the principal mechanism leading to arc volcanoes which result from subduction of cold but water-rich oceanic plates. We will discuss details of this process in a seminar on "Arc Volcanism".

The third mechanism **"Decompression"** is the principal cause of magma formation in the present-day earth; e.g., the ascent of mantle material resulting from the plate divergence that creates new oceanic crust at spreading ridges.

Consider the effects of decompression during upwelling of a mantle diapir Assume an adiabatic path, i.e., no heat exchange with its surroundings. The diapir intersects the solidus at some depth and melting occurs and temperature decreases because heat is required to melt. As the material ascends, the extent of melting increases. Note that the total amount of melting depends upon the depth that the diapir intersects the solidus and the depth where ascent stops (lithosphere?). This subject is discussed clearly and in detail in Langmuir et al. (1992); this paper is a primer for understanding volcanism at spreading ridges, i.e., the location of diverging plates.

B. The Melting Process

    1) Important Questions to Address:

        (a) How is the melt distributed on grain boundaries; is it at triple junctions between minerals; is it interconnected (see Kohlstedt, 1992)?

        (b) How does melt aggregate and segregate and on what time scales?

        (c) Does the melt equilibrate with residue when it is formed and to what extent does melt re-equilibrate with wall-rock during magma ascent?

    2) In regard to question (b) there are two end-member models for melt migration (see Figure 39)

(a) Fractures/channels (dikes and conduits).

Geologic observations of eroded volcanoes, and ophiolites demonstrates the importance of dikes ascending through fractures. We also have numerous examples of gabbroic and pyroxenite dikes and layers in mantle peridotites. These layers are often mineralogically zoned and a hypothesis is that "cumulates" precipitated on cool wall-rocks serve to isolate magma from wall-rocks.

(b) Porous Flow

A stage where melt is confined within a solid matrix, like a sponge with water, is believed to be the first process in melt formation and migration; at this point we expect extensive interaction between melt and wall-rocks. This process is described by the equations for batch melting (e.g., Ribe, 1985). An unresolved question is – over what depth region is this an important process? Specifically do melts during ascent interact with wall-rocks that are initially not in equilibrium with the melt? How important is interaction between the wall-rock and ascending melt?
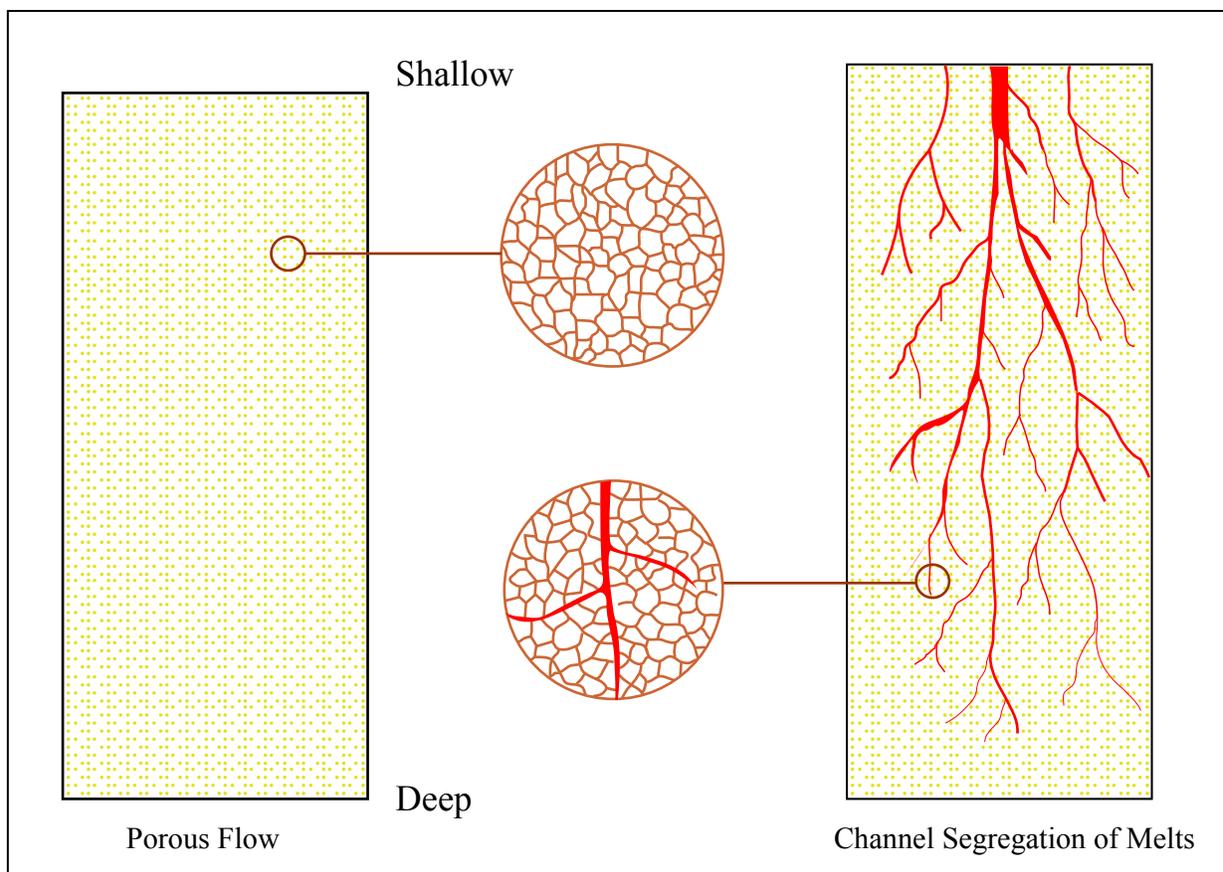
Shallow

Deep

Porous Flow

Channel Segregation of Melts

Figure 39. Two end-member models for migration and segregation of melts. Left: Porous flow, whereby melt is distributed and connected throughout a three-dimensional solid; Stipples (dots) indicate melt distribution. Right: aggregation of porous melts into channels or dikes that provide pathways for melt to segregate from the residual solid. Figure is adapted from Eggins (1992). See also Hart (1993).

(c) Models that Address these Complexities (Appendix 1 is a listing of relevant papers on complex melting process).

Williams and Gill (1989) present various models for channel segregation. The two end-member models are Batch Melting and Fractional Melting (Figure 40). The difference between these two models is how readily does melt segregate relative to how fast melt is created. The 1984 paper of McKenzie was instrumental in showing that silicate melts can segregate from their residues at low melt fractions. As emphasized in the 1985 paper by McKenzie and in a 1989 paper by Hunter and McKenzie melt viscosity is an important parameter.

It seems intuitive that there must be a critical porosity whereby melts do not segregate until they reach this porosity but at this porosity they segregate readily. The Kohlsted (1992) paper reviews this subject.

C. Complex Melting Models That Incorporate Residual Porosity (Figure 40)

1) Continuous Melting: To model the concept of a critical porosity Williams and Gill (1989) used a model of Continuous Melting which is fractional melting with a constant proportion of residual melt. In this model the solid has a finite porosity during the melting process. For example, consider a non-porous solid prior to melting; in this model melting proceeds without melt segregation until a critical porosity, melt fraction or volume, is attained. This could correspond to formation of a three-dimensional interconnected melt network. Subsequent formation of melt results in immediate melt segregation

(continuous melt segregation) because the residual solid always maintains the critical porosity.

This model is similar to fractional melting except that there is always a melt fraction that remains in the residual solid. Note that this residual melt fraction can be treated as another residual phase with a D value of unity. Therefore, in this case all incompatible elements have higher D values when there is a critical porosity. Just as in fractional melting, which is the end-member case where residual porosity (ϕ) is zero, in Continuous Melting (CM) there is a Continuous Melt which is the melt extracted at any given total F and an accumulated (average) melt fraction which is the aggregate of all continuous melts (ACM).

2) Dynamic Melting: Continuous melting is a static model without matrix movement, so to model melting during ascent Williams and Gill (1989) consider a process of Dynamic Melting (see also McKenzie, 1985). Dynamic melting is analogous to continuous melting in that there is always trapped melt, but here matrix and interstitial melt are moving upward together with new fertile material entering the system at the bottom and refractory residues leaving the system at top. The magma composition varies with depth because F varies with depth. In this model, as presented by Williams and Gill, melt extraction is assumed to be via a channel (dike) which taps melt from all depth levels. The equations describing Continuous and Dynamic Melting Models are identical (see eqns. A-12 of Williams and Gill (1989) or eqn. 5 of Eggins (1999)).
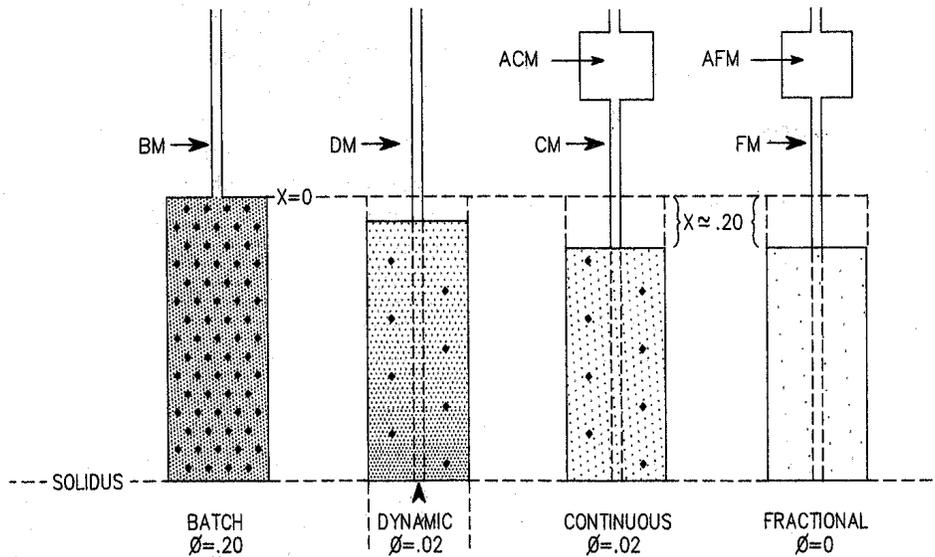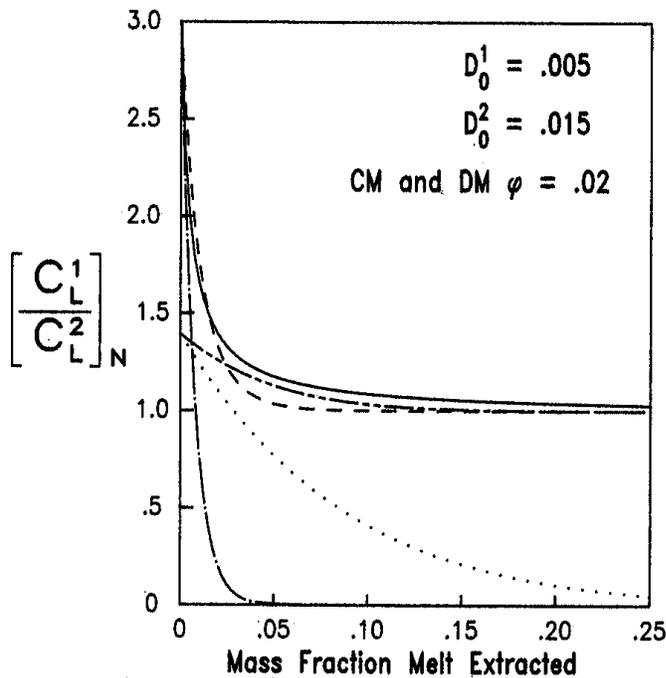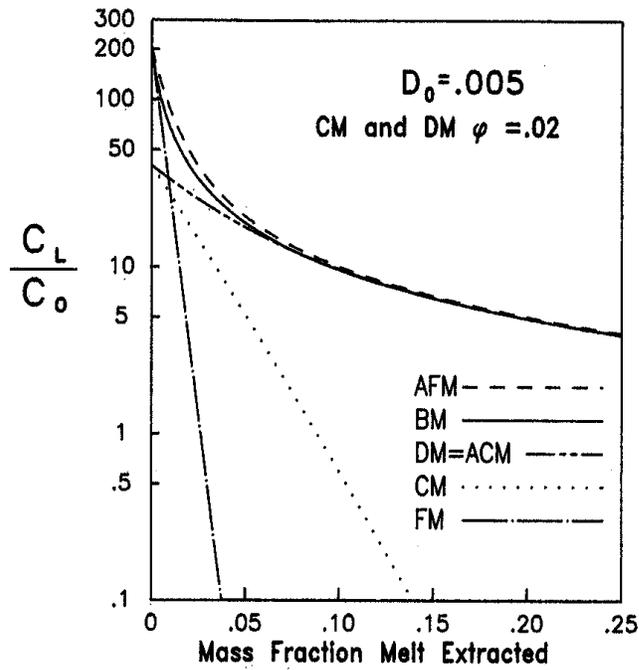
Figure 40.   The four rectangles represent mantle source regions that are subject to melting by different processes.

BM = Batch Melt; DM = Dynamic Melt; CM and ACM = continuous and accumulated continuous melt, respectively; FM and AFM = fractional and accumulated (average) fractional melt, respectively. The maximum degree of melting in each case is 20%, and the concentration of incompatible elements remaining in the source (the fertility) is shown by the density of the dots. The fraction of liquid present, or porosity (ϕ), shown by the black diamonds, varies between 20% for batch melting (the liquid has not yet been extracted) and 0% for fractional melting. The porosity for the dynamic and continuously melting source regions is arbitrarily set at 2%. This is Figure 1 of Williams and Gill (1989).

Figure 41a compares C_L/C_o results calculated for each melting model (batch (BM), fractional (FM and AFM), continuous (CM and ACM), and dynamic (DM). Note the following important results:

(a) As seen before (Figure 36) the trajectory for BM and AFM are nearly identical reaching the 1/D limit as F→ o.

(b) Instantaneous fractional melts are rapidly depleted in incompatible element as F increases (also shown in Figure 36).

(c) The continuous melt is not as depleted as the fractional melt because the 2% residual porosity is akin to having a trapped melt in the residue with D = 1; hence when there is a critical porosity, in this example 2% melt that cannot be extracted, all incompatible elements are slightly more compatible than if there is no critical porosity.

(d) The DM and ACM melts are identical since these models are described by the same equations. Again because of the 2% critical porosity (i.e. 2% melt retained in the solid residue) incompatible elements are not as enriched in the melt as for porosity equal zero models (BM and AFM).

Figure 41b shows that the ratio of two incompatible elements in melts created by BM, FM and AFM models can be changed by a maximum as F → o that is given by the ratio of partition coefficients, hence in this example, 0.015/0.005 = 3. However, the melts created by DM and ACM have a smaller change in element ratio and melts created by CM and FM have the surprising characteristic of relative depletion in the more incompatible element.

$D_0 = .005$

CM and DM $\varphi = .02$

$\dfrac{C_L}{C_0}$

AFM — — — — —
BM ————
DM=ACM —·—·—
CM ·········
FM —·—··—

Mass Fraction Melt Extracted

$\left[\dfrac{C_L^1}{C_L^2}\right]_N$

$D_0^1 = .005$

$D_0^2 = .015$

CM and DM $\varphi = .02$

Mass Fraction Melt Extracted

7ci fhYgmcZ 9`gYj ]Yfž =bWž \Hnd. ##k k k "gWJYbWYX]fYVVn'Vta "ˉl gYX k ]h\ `dYfa]gg]cb"

Figure 41. a) The concentrations of an incompatible element with a bulk partition coefficient of 0.005 in liquids produced by different melting processes. (C_L) is normalized to the initial source composition (C_0) and plotted versus the mass fraction of melt extracted (X, or degree of melting). Note that fraction of melt extracted is not equal to F if there is a critical porosity. The critical porosity in the CM and DM source region is 2%. b) The ratio of a more incompatible element ($D_0 = 0.005$) to a less incompatible element ($D_0 = 0.05$) normalized to the ratio in the initial source is plotted versus mass fraction of melt extraction. The different melting processes are shown by the different line styles as in (a). This is Figure 2 of Williams and Gill (1989).

9

Appendix 1. Some references for complex melting models:

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9) Hunter and McKenzie, The equilibrium geometry of carbonate melt in rocks of mantle composition, *EPSL*, *92*, 347-356, 1989.

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11) Kohlsted, Structure, rheology and permeability of partially molten rocks at low melt fractions, *AGU Geophysical Monograph 71*, 103-122, 1992.

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14) Spiegelman and Kenyon, The requirements for chemical disequilibrium during magma migration, *EPSL*, *109*, 611-620, 1992.

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19) Maaloe, Geochemical aspects of primary magma accumulation from extended source regions, *Geochim. Cosmochim. Acta*, 59, 5091-5101, 1995.

20) Kelemen et al., A review of melt migration processes in the adiabatically upwelling mantle beneath oceanic spreading ridges, *Phil. Trans. R. Soc. London A*, *355*, 283-318, 1997.

21) Zou, Trace element fractionation during modal and non-modal dynamic melting: A mathematical treatment, *Geochim. Cosmochim. Acta*, *62*, 1937-1945, 1998.

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23) Zou, H. and Reid, M.R., Quantitative modeling of trace element fractionation during incongruent dynamic melting. *Geochim. Cosmochim. Acta*, 65, 153-162, 2001.

24) Faul, U.H., Melt retention and segregation beneath mid-ocean ridges. *Nature*, 410, 920-923, 2001.

25) Spiegelman and Kelemen, Extreme chemical variability as a consequence of channelized melt transport, *Geochemistry, Geophysics, Geosystems*, 4(7), 1055; doi:10.1029/2002GC000336, 2003.

12.479 Trace-Element Geochemistry

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