Studies of Arc Volcanism and Mantle Behavior in Subduction Zones Using COMSOL

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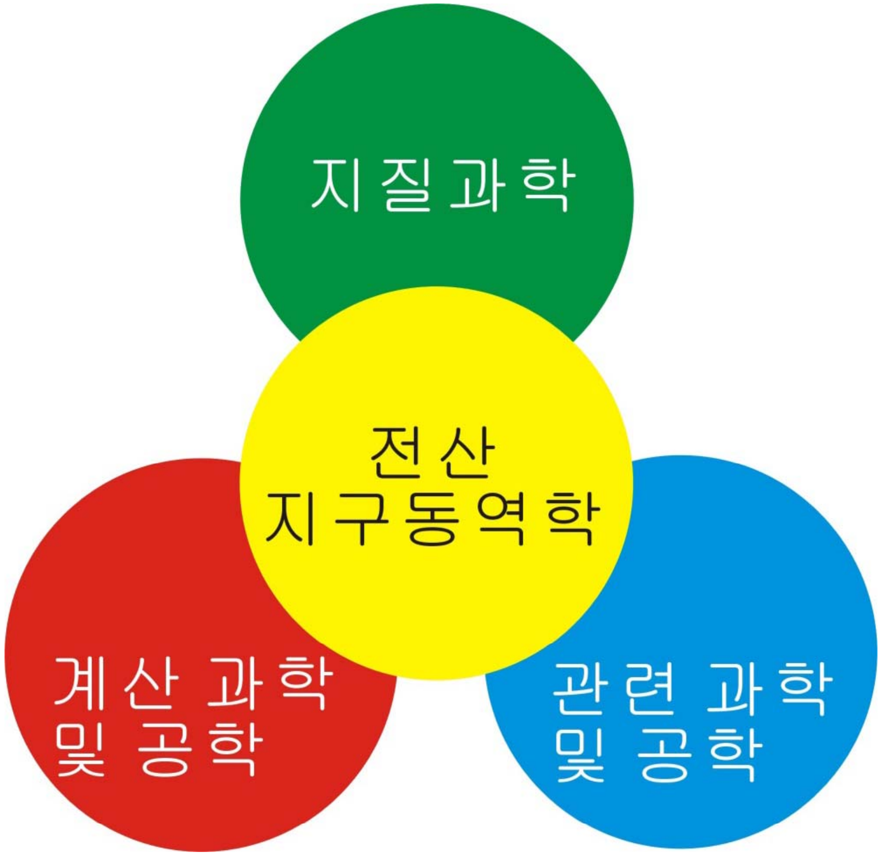
Computational Geodynamics?



- What is it?

  A branch of geology to understand the planetary evolution in space and time. e.g., mantle plume and subduction

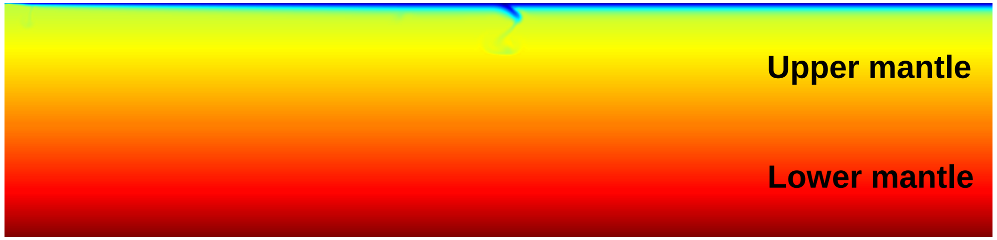
- An integrated study

  1) geology (e.g., petrology, geochemistry, and geophysics)

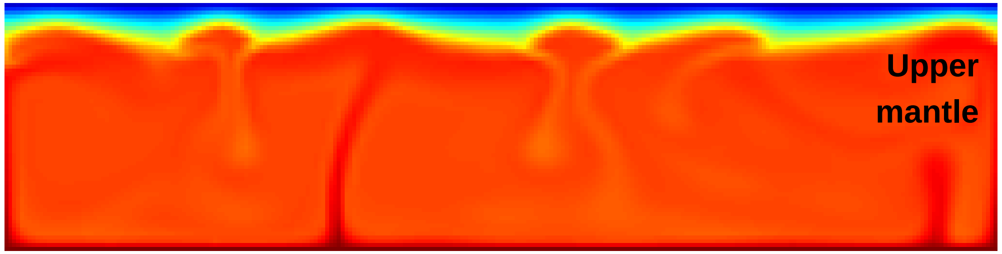
  2) computational sciences (e.g., coding, and numerical analysis)

  3) other sciences and engineering (e.g., fluid dynamics, and thermodynamics)

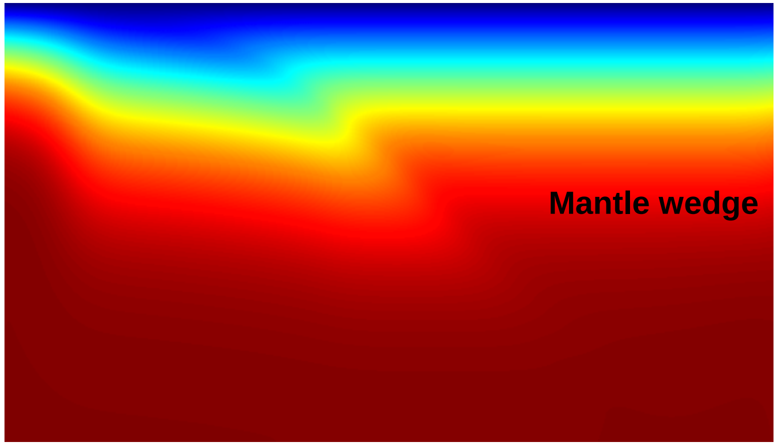
Examples



Slab buckling (Lee and King, 2011)



Mantle convection in Venus (Lee, 2014)



Subduction in Eastern Aleutians
(Kim and Lee, 2014)

Example:

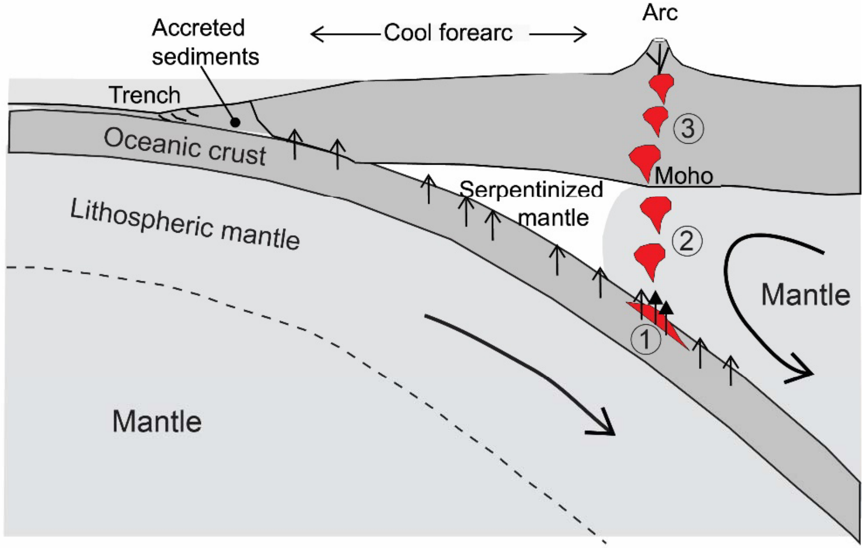
Plume-Slab Interaction

Using

COMSOL Multiphysics

Genesis of Adakite in Subduction Zone

Melting in the Subduction Zones
(modified from Hyndman and Peacock, 2003)



↑ : Dewatering and dehydration of subducting slab
↑ : Ascending slab melts
① : Slab melting (sediments and basaltic crust)
② : Flux melting (mantle peridotite)
③ : Crust melting (continental or oceanic crust)

- Genesis of Adakite:

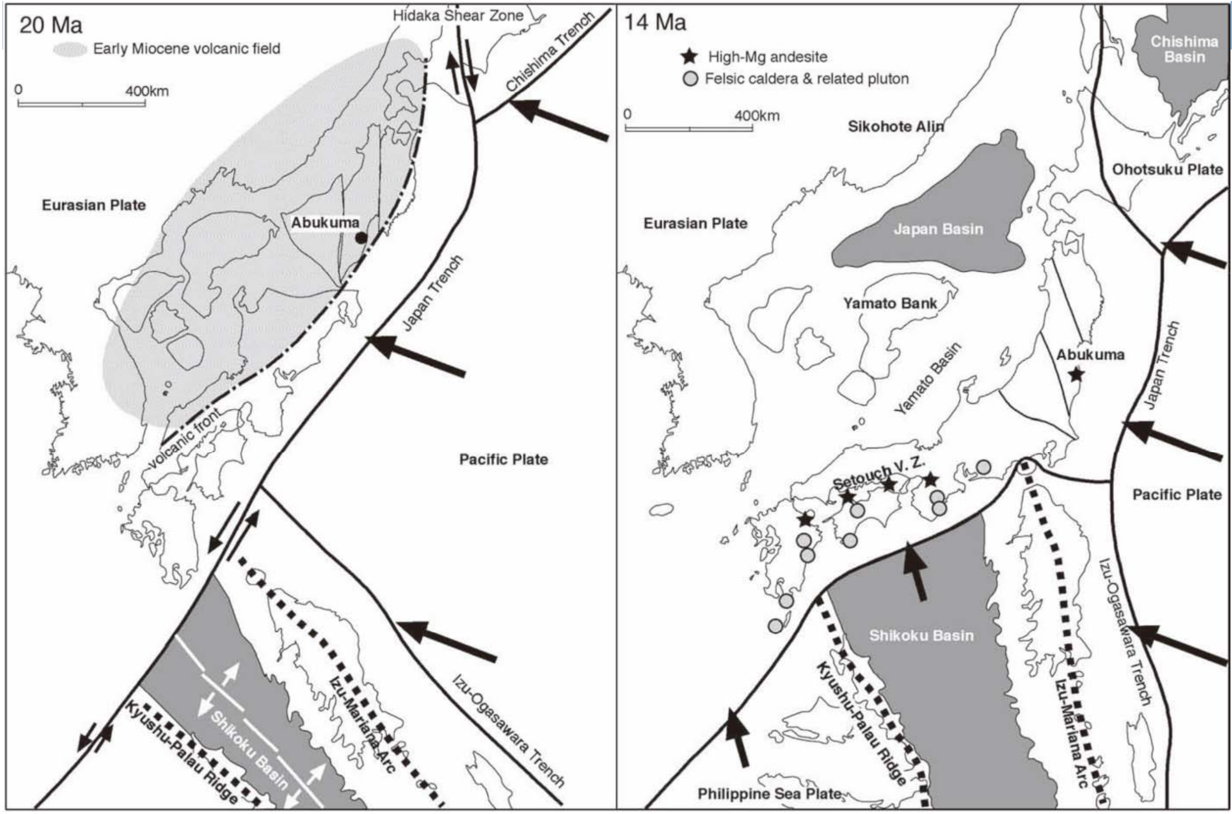
  1) partial melting of eclogited oceanic crust (e.g., young slab or ridge subduction)

  2) partial melting of lower crust (thick crust, > 50 km)

  3) partial melting of flat or very shallow slab (e.g., Chile)

  4) cold-plume ascending from subducting slab surface due to Rayleigh-Taylor instability

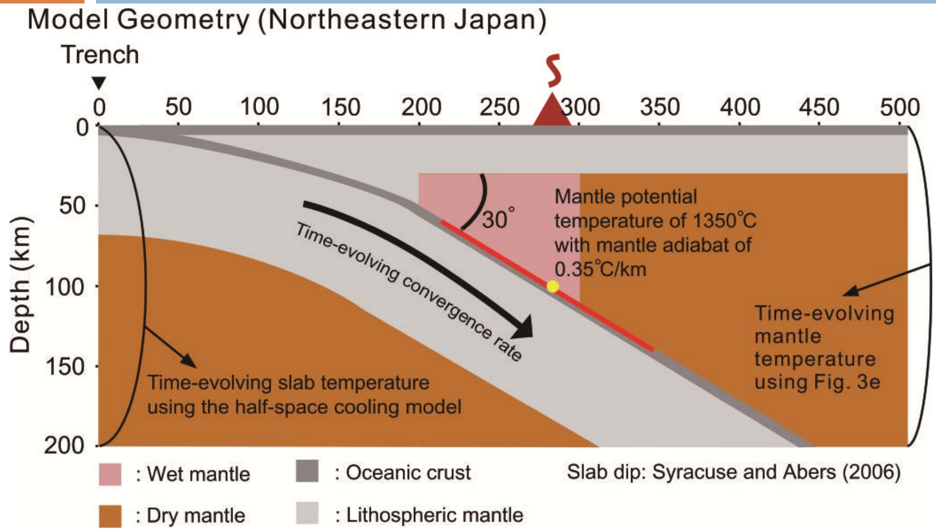
A Pulse of Abukuma Adakite, NE Japan

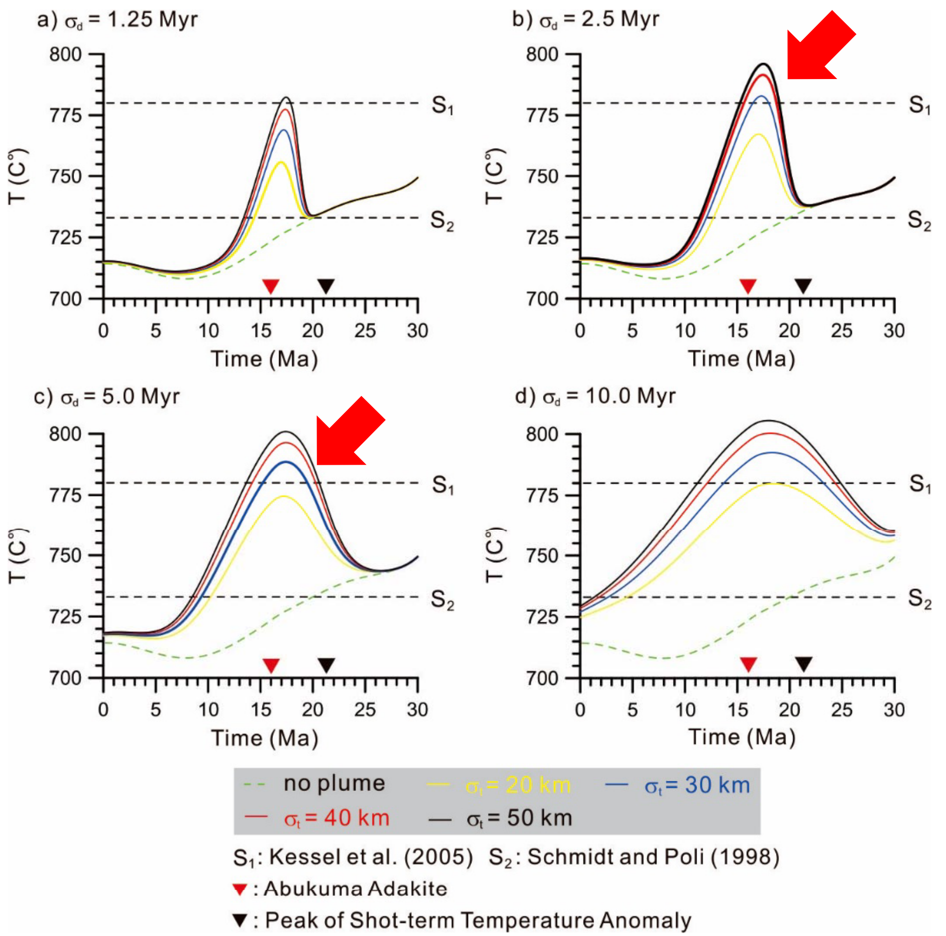


Yamamoto & Hoang (2009)

- Tenmyosan basalt: ~20 Ma, low Sr/Y (common island arc lava)
- Ryozen dacite: ~16 Ma, high Sr/Y (typical adakite) – a pulse of adakite
- Nodegamiyama High Mg Andesite: ~14 Ma, low Sr/Y (common island arc lava)

2-D Numerical Subduction Model

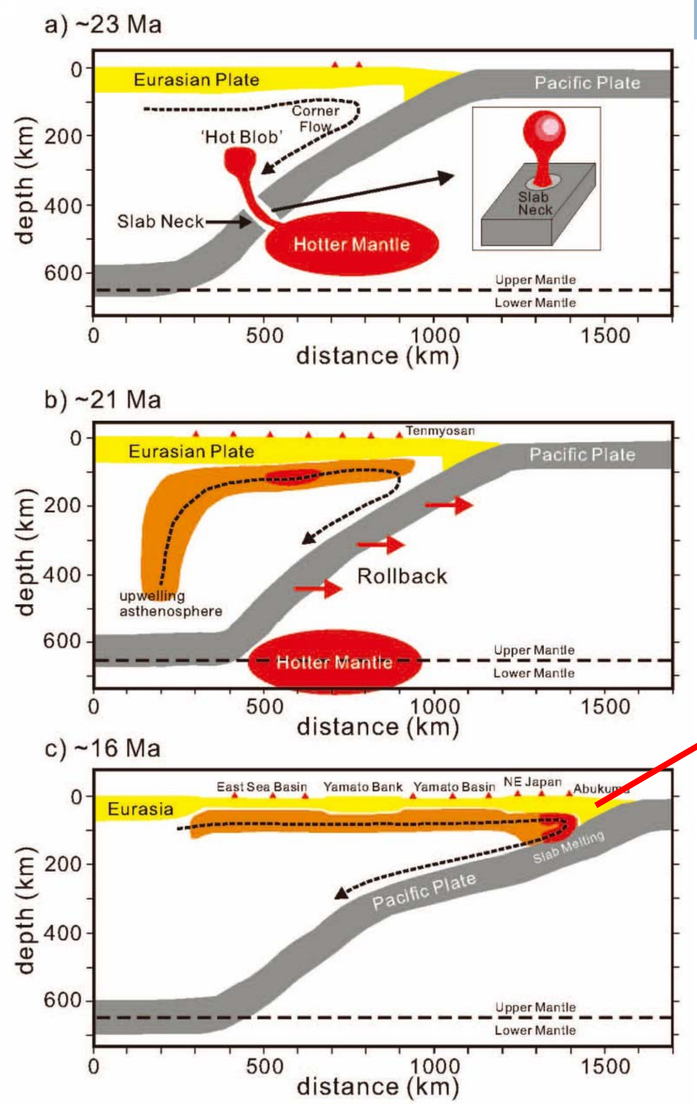




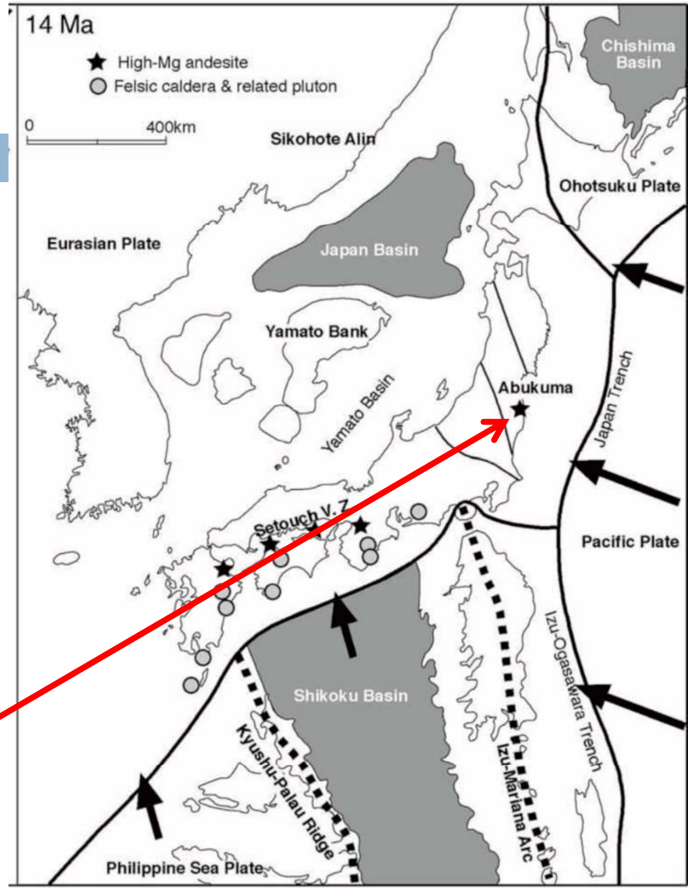
- 2-D Numerical Model Study:
  1) Injection of hot mantle blob into the mantle wedge
  2) Dragged hot mantle blob into the mantle wedge increases slab surface temperatures.

Lee and Lim (2014, EPSL)

Hypothesis of Adakite



Lee and Lim (2014, EPSL)



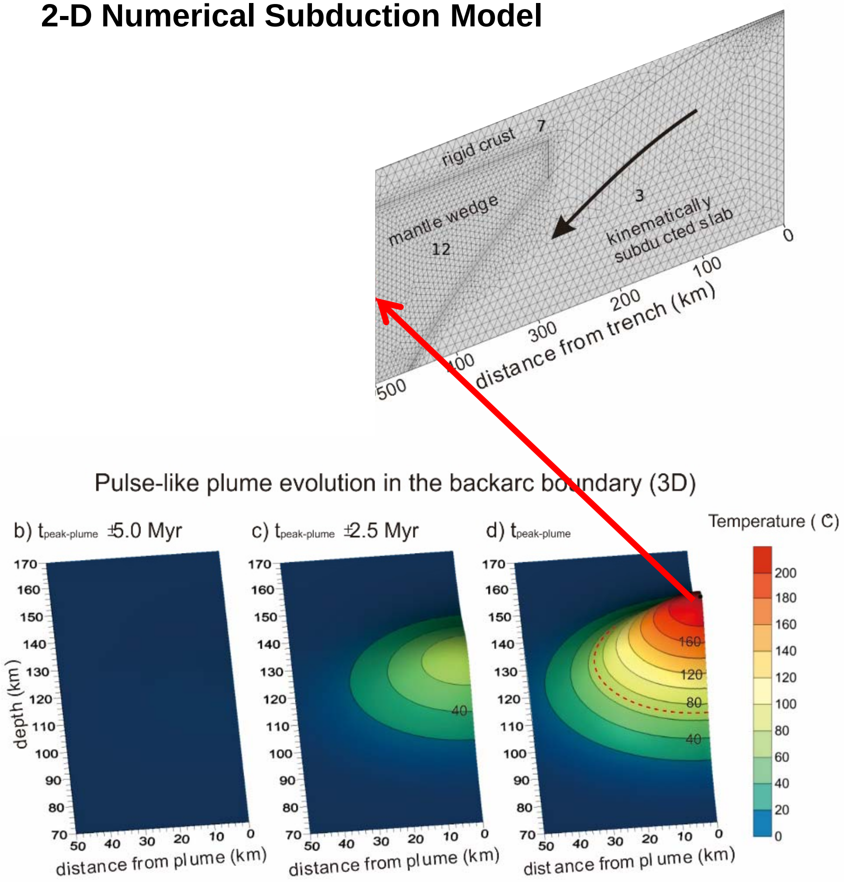
- Genesis of Abukuma adakite:

  Injection of 'hot plume blob' into the mantle wedge resulted in short-term slab melting generating the Abukuma adakite

3-D Numerical Subduction Model

3-D Numerical Subduction Model

2-D Numerical Subduction Model



Lee and Lim (GR, accepted)

- Limitation of 2-D subduction model:
  Short-term eruption of adakite should be localized at the Abukuma region (diameter: ~30 km). 2-D model cannot consider along-arc direction.
- 3-D numerical subduction model:
  Injection of '3-D plume blob' into the mantle wedge with realistic rheology
- 3-D injection of plumb blob:
  Modified distribution function of duration (σ_d), width (σ_w) and thickness (σ_t) of the plume blob

$$T = T_{mantle} + T_{plume} \exp\left\{-\frac{(t-t_p)^2}{(\sigma_d)^2}\right\} \exp\left\{-\frac{(y-y_p)^2}{(\sigma_t)^2}\right\} \exp\left\{-\frac{(z-z_p)^2}{(\sigma_w)^2}\right\}$$

Governing Equations

- Continuity equation:

  Boussinesq approximation (no density change with time and space)

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot (\mathbf{u}) = 0$$

- Navier-Stokes equations:

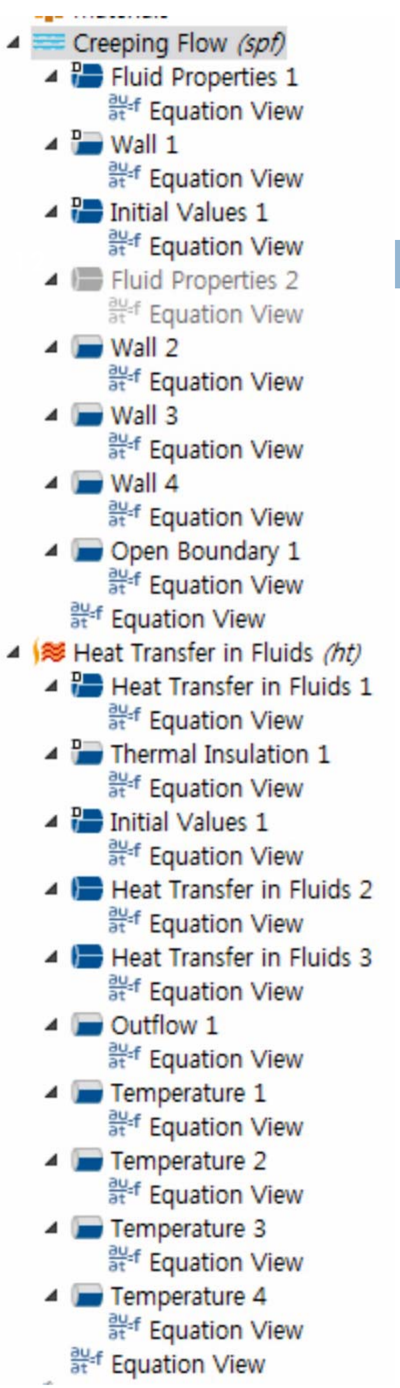
  Calculate the behaviors of the mantle wedge and subducted slab by neglecting buoyancy.

$$\rho \frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \left[-p\mathbf{I} + \mu \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right] + \mathbf{F}$$

- Energy equation:

  Calculates the heat transfer by convection and diffusion.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T)$$



Rheology and Relevant Modules

- Viscosity equation:

  Diffusion creep of the mantle depending pressure and temperature

$$\mu = A^{-1} d_g^{\ m} \exp[\frac{E + PV}{RT}]$$

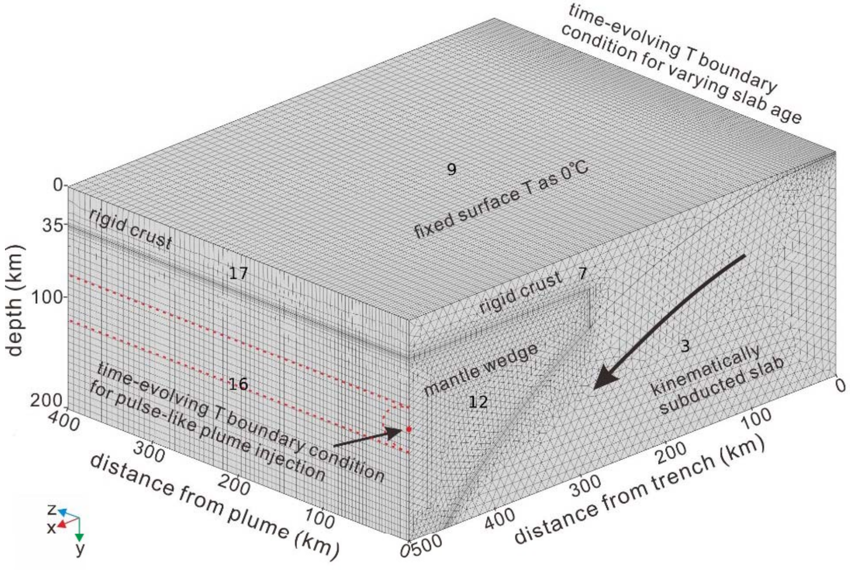
A: constant, *d*: grain size, *m*: grain parameter, *E*: activation energy, *P*: pressure, *V*: activation volume, *R*: gas constant, *T*: temperature (K)

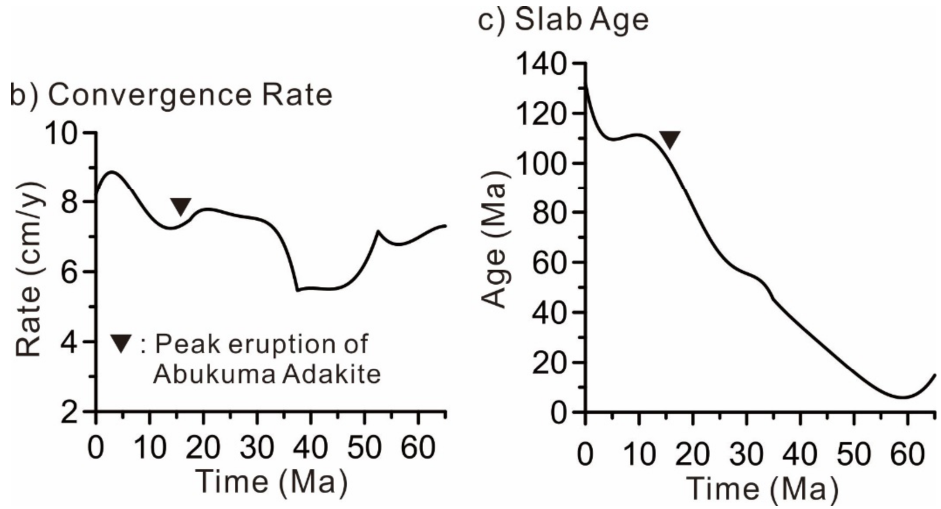
- Relevant physics:

  1. Creeping Flow for the continuity and Navier-Stokes equations.
  2. Heat Transfer in Fluids for the energy equation.

  All the governing equations can be modelled by using the CFD module.

Boundary Conditions

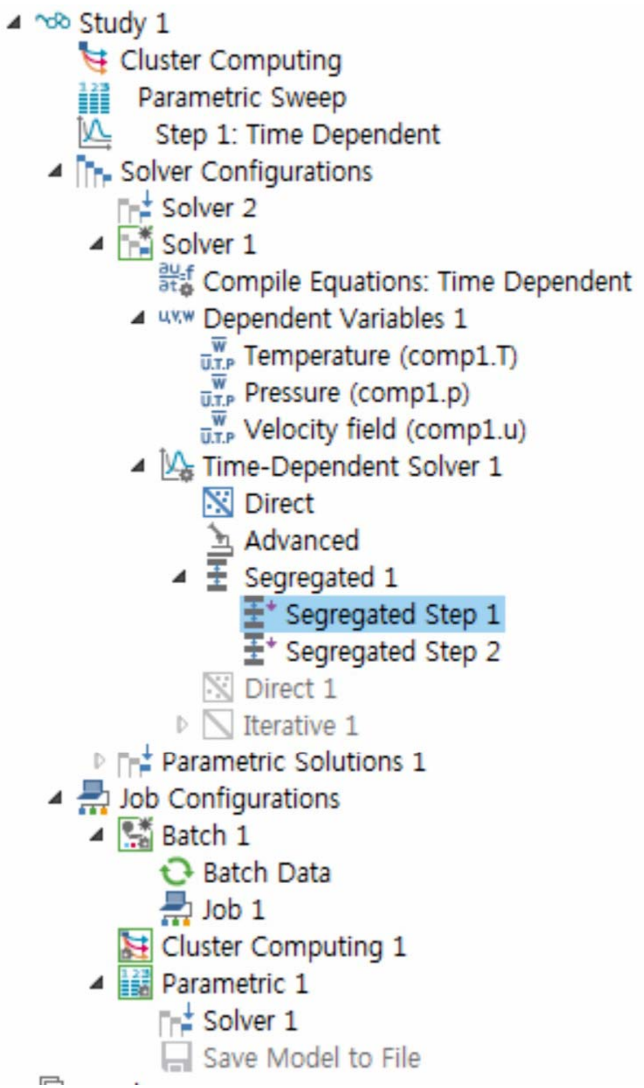




Lee and Lim (GR, accepted)

- Open and closed boundaries, and insulated and fixed T boundaries:
  Open for inflow/outflow of the mantle and slab, insulated for the sides, and fixed T for the surface, back-arc and trench sides.
- Time-evolving subducting slab:
  Convergence rate and slab age implemented to the slab domain have been evolved for the last 60 million years.

Solver and Parallel Computing



- Time Dependent step:

  Time-evolving subduction for the last 60 Millions years

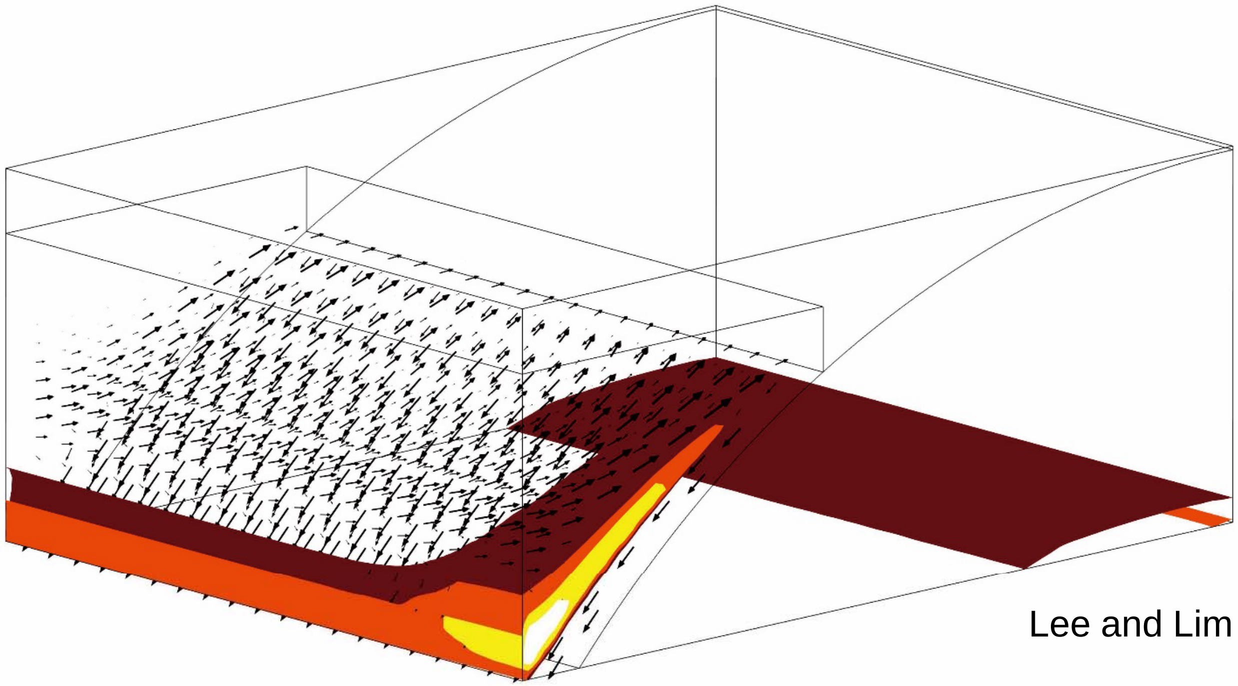
- Time-Dependent solver:

  1. non-dimensionalization of the variables
  2. direct with a time-stepping using the generalized alpha
  3. segregated step for P & V, and T.
  4. MUMPS with default setting in COMSOL

- Cluster Computing:

  Cluster type: general

Results

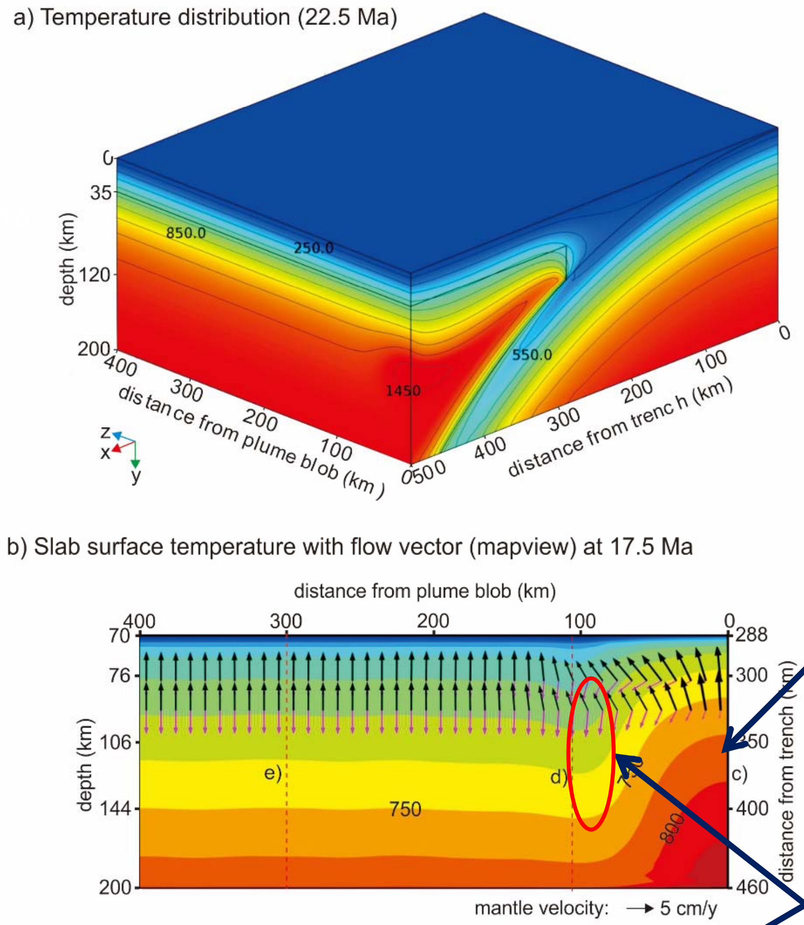


Lee and Lim (GR, accepted)

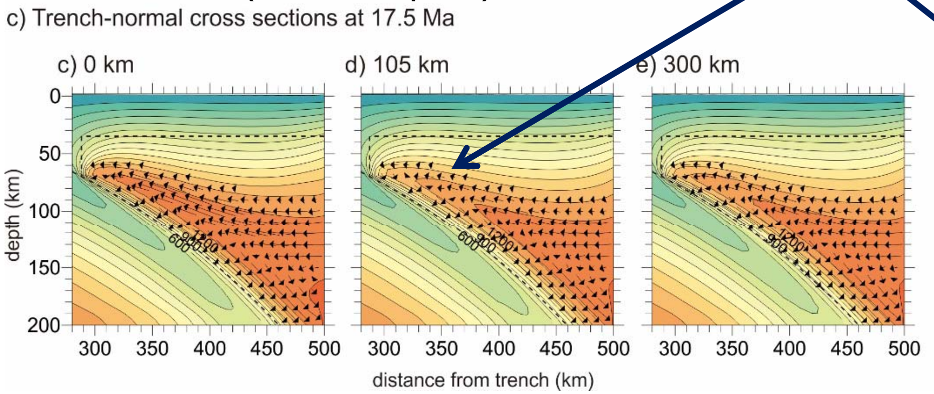
- 3-D plume-slab interaction:

  Injection of the pulse-like plume blob into the mantle wedge generates stronger corner flow along the plume blob. 3-dimensional Injection of the plume blob and mantle flow in the mantle wedge are depicted by using the ‘Isosurface’ and ‘Arrow Volume’ implemented in the COMSOL Multiphysics.

Results

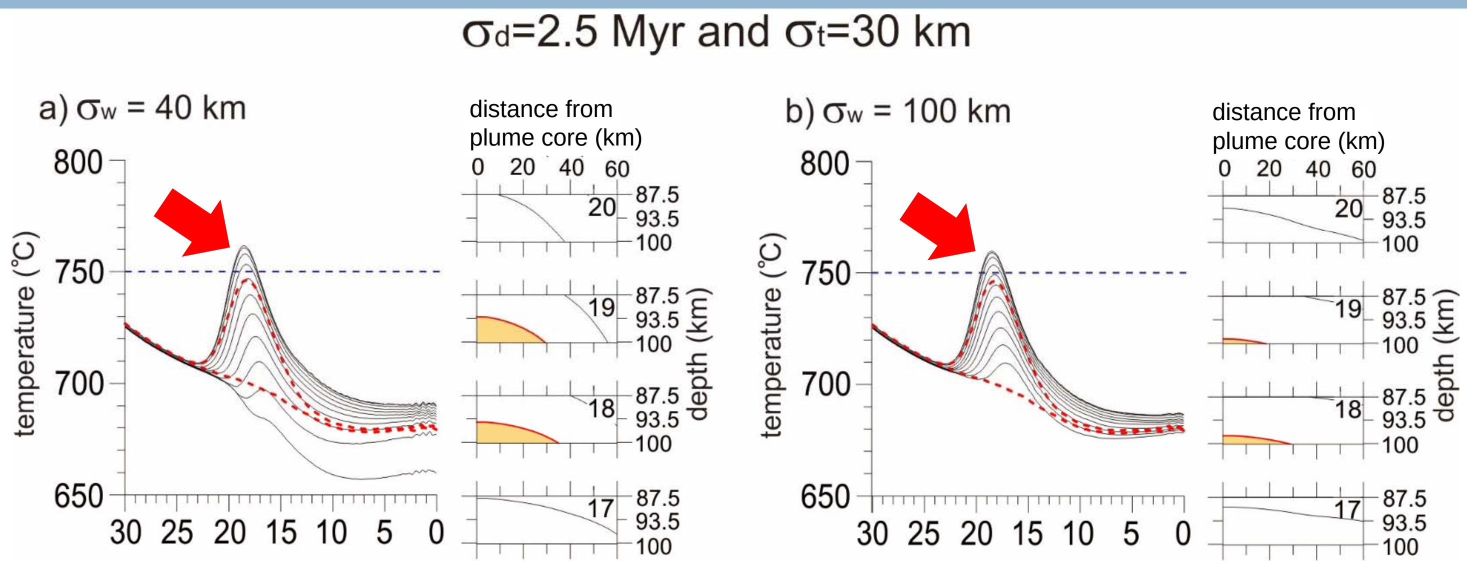


Lee and Lim (GR, accepted)



- Increased slab surface temperature:
  Injected hot plume blob locally increases slab surface temperature; localized slab melting for adakite
- Lateral returning mantle flow:
  Lateral mantle flow due to faster injection of the plume blob generated lateral mantle flow and weakens the corner flow by the plume-slab contact zone; trough of the lowered slab surface temperatures is established.

Short-term and Localized Abukuma Adakite



Lee and Lim (GR, accepted)

- Short-term slab melting:

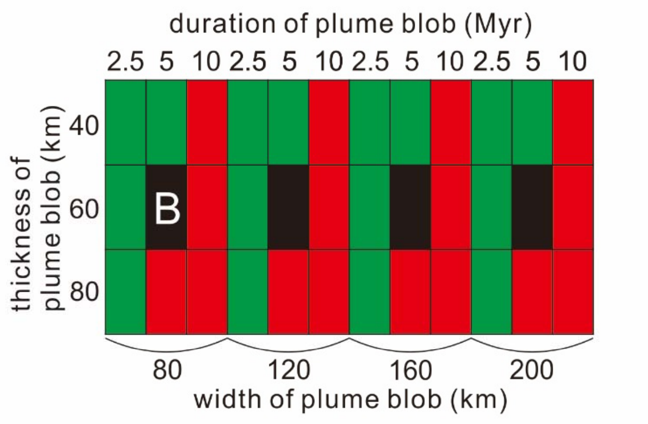
  Short-term slab melting by the temporally increased slab temperature for ~2 Myr, consistent with the short-term eruption of the Abukuma adakite.

- Localized slab melting:

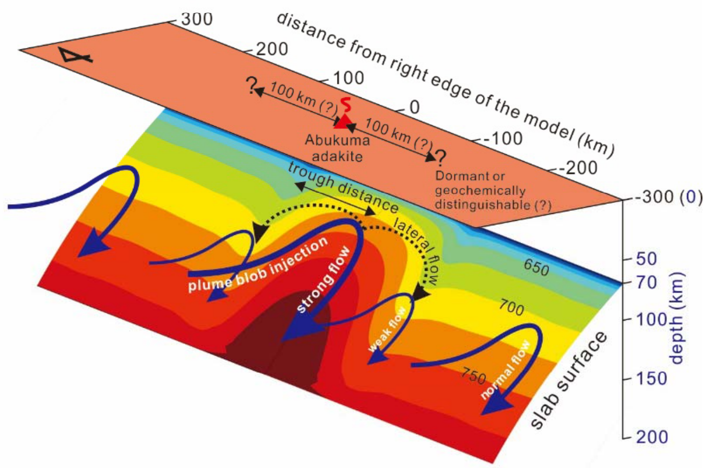
  3-dimensional model shows localized slab melting, consistent with the localized distribution of the Abukuma adakite.

Abukuma Adakite: Implications

a) Plume parameters relevant to Abukuma adakite



b) Model for Abukuma adakite at ~17 Ma



Lee and Lim (GR, accepted)

- Slab tear or neck?:

  Due to paucity of seismic evidence, it is not clear yet. However, the localized Abukuma adakite may result from slab neck, 'hole' in the subducted Pacific plate. Localized slab neck would be plausible.

- Along arc variations in volcanism?:

  Injected plume blob strengthened the corner flow and resulted in the Abukuma adakite. Weak corner flows by the lateral mantle flow may result in dormant volcanism and/or distinguishable geochemistry, to be studied in the future.

Summary

- Injection of 3-D hot plume blob develops localized and short-term increases in slab surface temperatures, consistent with the Abukuma adakite, Northeast Japan. 3-D mantle flow develops trough of the lowered slab surface temperatures, implying along-arc variations in volcanism.

- COMSOL Multiphysics using the CFD module allows easier modeling of the 3-D subduction experiments and visualization. However, export of the vector graphics (e.g., PDF or PS formats) is required for a better visualization for high-quality figures.

Thank you!