# Delamination of Sub-Crustal Lithosphere

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**Introduction**: Lithospheric foundering from the base of continents is common beneath tectonically active areas. This is especially obvious beneath the western U.S., where tomographic images (Fig. 1) have relatively high resolution. While the style of foundering is debated in most instances, it is accepted that downwelling is driven by the negative buoyancy of the foundering lithosphere (e.g., Bird, 1979; Meissner and Mooney, 1998), and that the strength resisting sinking is low enough to allow sinking to occur faster than thermal conduction diffuses the thermal anomaly responsible for the observed seismic structure and negative buoyancy.

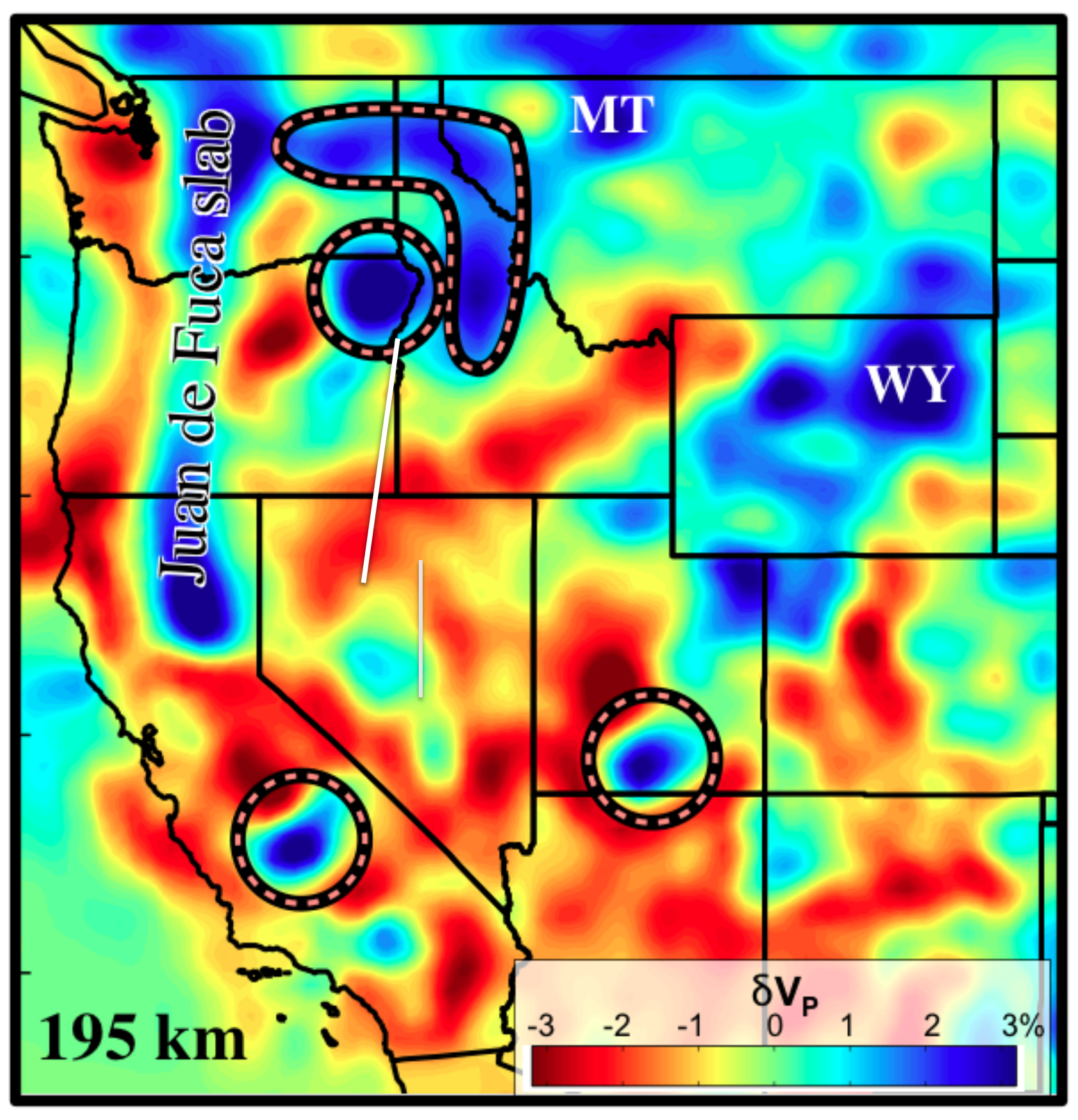


**Fig. 1.** P-wave velocity structure showing our four target structures we wish to model using Comsol. To be this seismically fast, these structures must be cool. Away from deep cratons in Wyoming and Montana, high-velocity structures represent young downwellings created after the Laramide orogeny. (Schmandt and Humphreys, 2010)

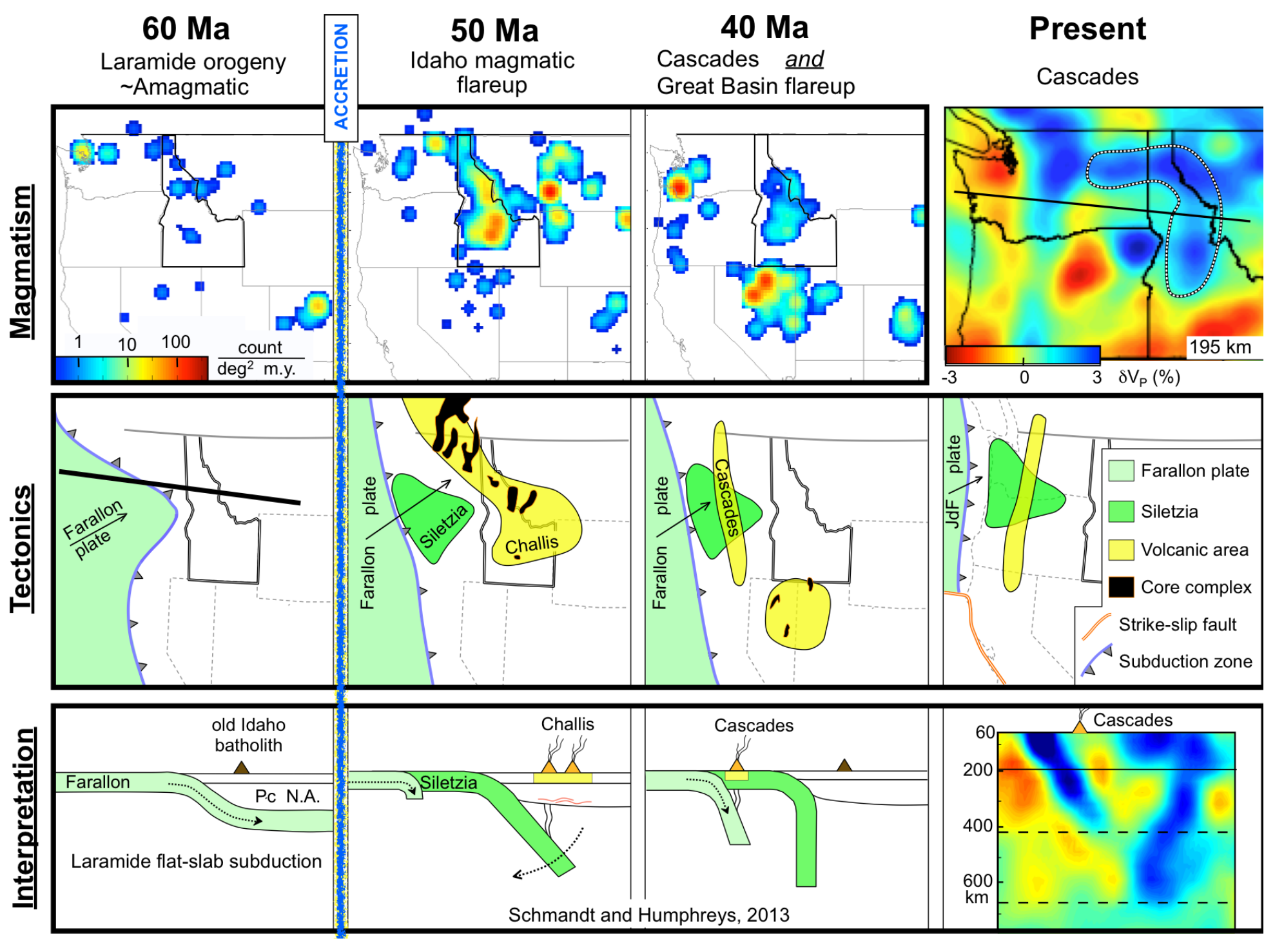


**Fig. 2**. **Main Point**: Subduction steps west with Siletzia accretion (dark green lithospehre) initiating Cascadia subduction; rapid initiation of Idaho magmatism requires the flat-subducting slab to loose contact with North America (delamination). (**Top Row**) Volcanic intensity with time via the inferred history of Slietzia accretion, which ended the Laramide orogeny (that uplifted the Rocky Mountains) and initiated the ignimbrite flareup and Cascadia subduction. (**Middle Row**) Sequence of events with accretions of Farallon plate (Siletzia) occurring at ~53 Ma. followed immediately by the ignimbrite flareup (yellow) and core-complex activity (black). (**Bottom Row**) Cross sections along the heavy dark line in the middle row. Laramide flat-slab subduction ended with accretion, initiating Cascadia subduciton. Magmatic flareup requires slab foundering, whtich we image today (far right). (From Schmandt and Humphreys, 2011).

**Computational Methods**: We solve the mass, momentum, and energy equations assuming infinite Prandtl number and using the Boussinesq approximation for bouyancy forces using the incompressible Navier-Stokes equations for fluid motion, and couple it to temperature using the energy conservation equation:

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right]-\nabla\cdot\eta\left(\nabla\mathbf{u}+\left(\nabla\mathbf{u}\right)^{T}\right)-\mathbf{g}\rho_{0}\alpha(T-T_{0})+\nabla P=0$$

$$\nabla\cdot\mathbf{u}=0 \qquad \frac{\partial T}{\partial t}=-\mathbf{u}\cdot\nabla T+\kappa\nabla^{2}T \qquad \rho=\rho_{0}\left[1-\alpha\left(T-273\right)\right]\left[1+\beta\left(P-1e^{5}\right)\right]$$

Here, vectors are bold with **g** being the acceleration due to gravity (vertical) and **u** being velocity. The pressure is P, t is the time, and rho is the material-dependent density with rho$_0$ being a reference density, alpha is the effective coefficient of thermal expansion for the material, and T is the temperature with T$_0$ being a reference temperature. Eta is the effective viscosity given by an Arrhenius viscosity law:

$$\eta=\eta_{0}\dot{\varepsilon}_{II}^{-(1-1/n)}\exp((E+PV)/nRT)$$

where eta$_0$ is a reference viscosity, epsilon(dot)$_{II}$ is the second invariant of the strain rate tensor, n is a power law exponent (one for Newtonian), E and V are the activation energy and volume, P the lithostatic pressure and R the gas constant. E, V, n and eta$_0$ depend on material (rock) type.

Alternatively (Gerya, 2010), the flow can be expressed in terms of the ordinary strain rate (where h=grain size, A$_D$=material constant, n=stress exponent (n=1 for diffusion creep and n>1 for dislocation creep), m=grain size exponent, Ea and Va are the activation energy and volumes, respectively):

$$\dot{\gamma}=A_{D}h^{m}(\sigma_{d})^{n}\exp\left(-\frac{E_{a}+V_{a}P}{RT}\right)$$

Brittle and plastic failure is implemented using an internal angle of friction (i.e., Mohr – Coulomb failure criterion) for brittle failure and a temperature, viscosity, and material-dependent yield stress.

$$\sigma_{yield}=C+\sin\left(\phi\right)P$$

$$\left\{\begin{array}{l}C=C_{0};\phi=\phi_{0};(case:strain\leq\gamma_{0})\\ C=C_{0}+(C_{1}-C_{0})/(\gamma_{1}-\gamma_{0})(strain-\gamma_{0});\phi=\phi_{0}+(\phi_{1}-\phi_{0})/(\gamma_{1}-\gamma_{0})(strain-\gamma_{0});(case:\gamma_{0}<strain<\gamma_{1})\\ C=C_{1};\phi=\phi_{1};(case:strain\geq\gamma_{1})\end{array}\right.$$

**Results**: Shown below are results using an open-source Matlab-based finite difference code by Teras Gerya (2010)—Figures 3 and 4, that we are working on implementing using Comsol—Figure 5. Figure 3 shows initial conditions. Figure 4 shows the simulation at time t = 1.9 My. The heavier lithospheric slab has begun to sink into the mantle after delaminating from the underside of the overriding plate which is less dense and hence more buoyant. Some of the crustal rocks remain attached to the underside of the overriding plate while some remain attached to the subducting slab. This ripping apart of lighter rock layers (delamination process) has important implications for magma composition heterogeneities observed in close proximity at the surface in continental volcanic arc settings like the Cascades (i.e., highly mafic lavas flows observed adjacent to highly silicous lava flows). Furthermore, the sudden (geologically-speaking) exposure of the lower crust to hot mantle asthenosphere can explain “sudden” onset of huge lava eruptive episodes like the Columbia River flood basalts, the Willowa and Steens Mountains, the Idaho batholith, etc. (see Fig. 2). We can learn a great deal about the time history of geologic events that form what is observed at the surface through modeling the tectonic processes using multiphysics simulations.

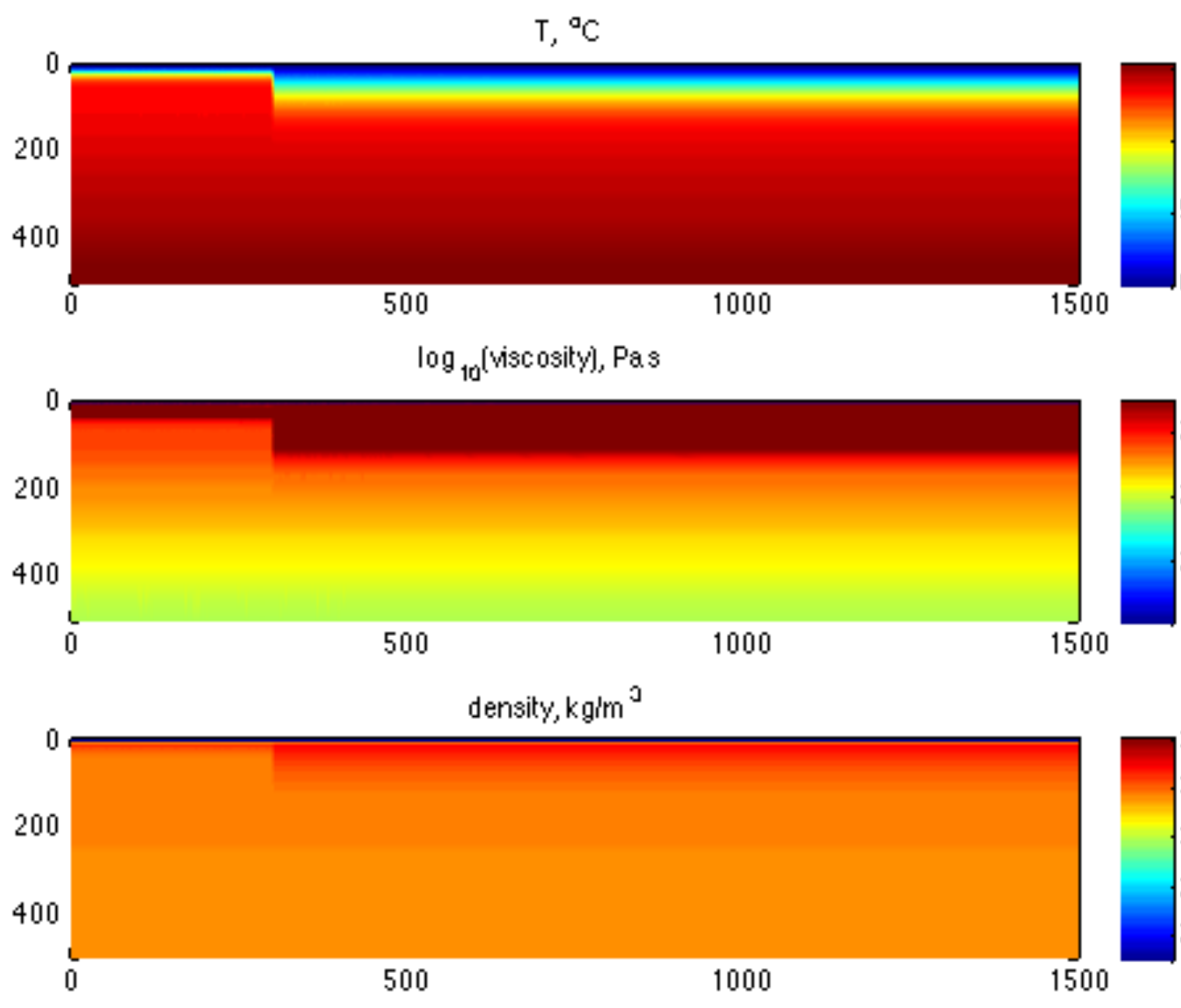


**Fig. 3**. Initial Conditions.

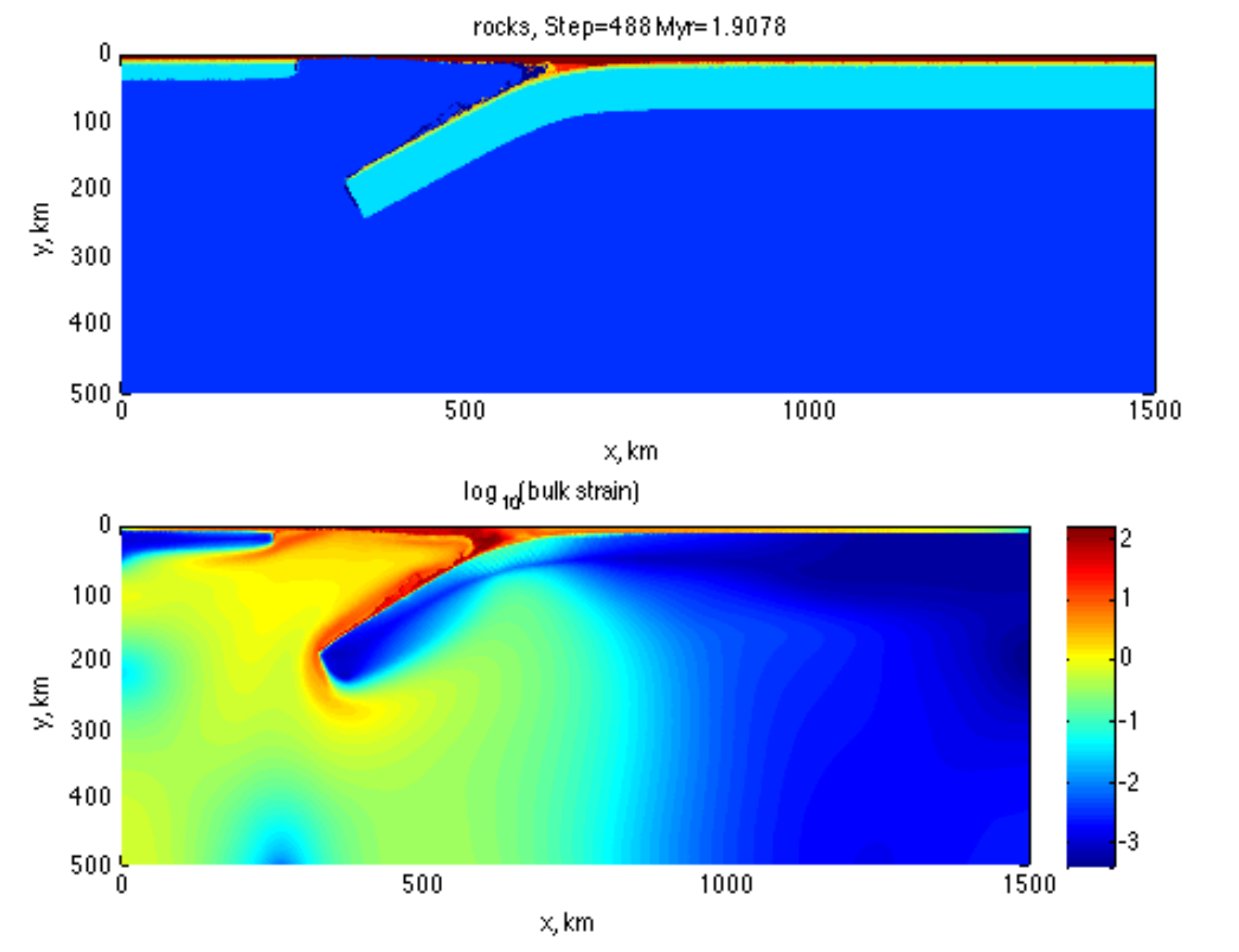
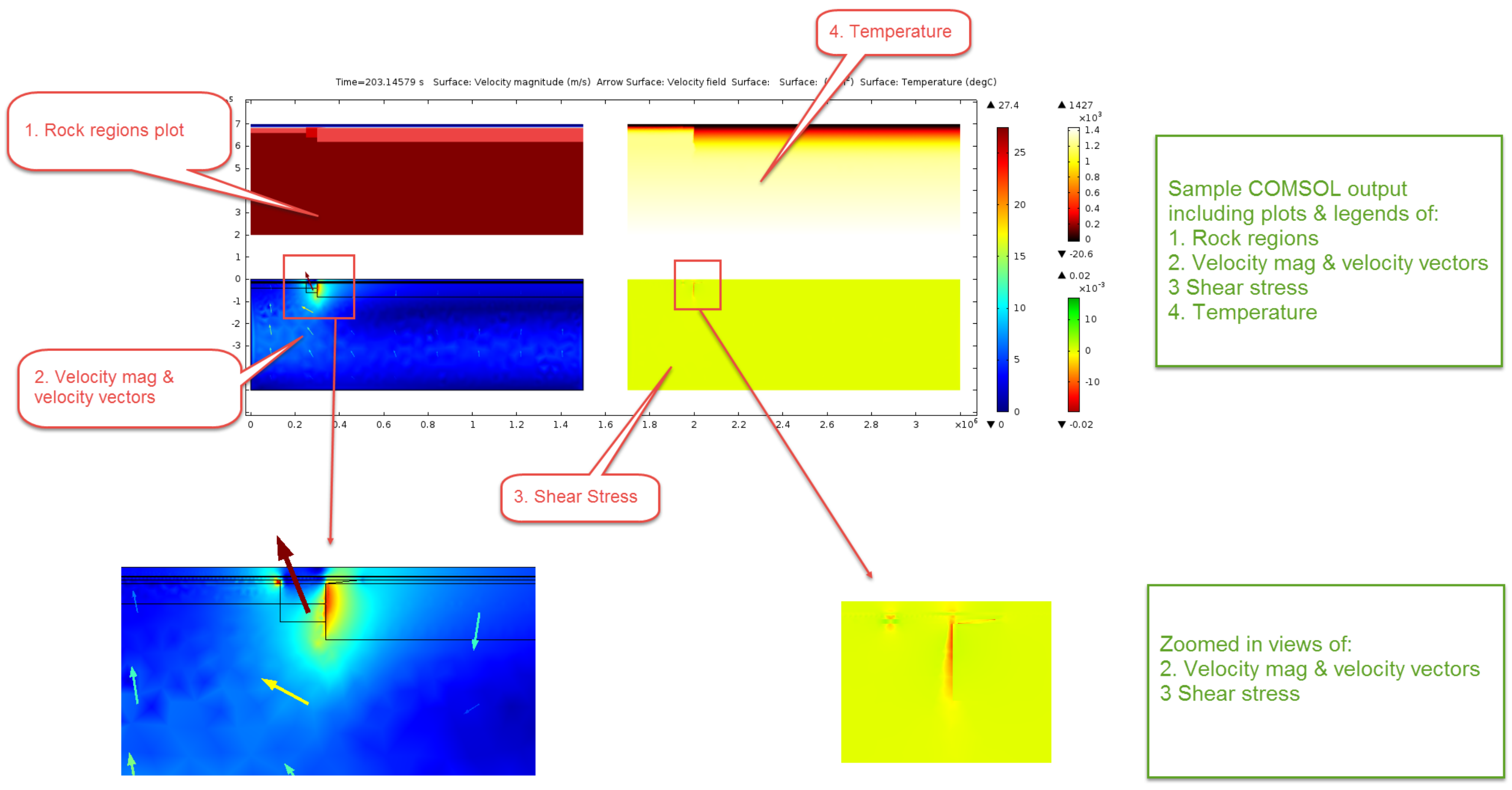


**Figure 4**. Delamination and initiation of subduction.

**Figure 5**. Preliminary Comsol results. (Right) Initial geometry. (Below) Preliminary results showing high shear stresses at zone of weakness where subduction initiation takes place.



Sample COMSOL output including plots & legends of:
1. Rock regions
2. Velocity mag & velocity vectors
3 Shear stress
4. Temperature

Zoomed in views of:
2. Velocity mag & velocity vectors
3 Shear stress

**Conclusions**: Using the Matlab-based finite difference (FD) code by Gerya (2010) as a numerical benchmark, we are implementing a similar simulation using Comsol. An important challenge has been mimicking the “marker-in-cell” technique within a FD framework that the example above uses for advection of different rock materials (e.g., basaltic upper crust, gabbroic lower crust, mantle lithosphere, mantle asthenosphere). In addition, the Matlab-based implementation of plastic yield and brittle fracture coupled to fluid flow has not been implemented yet in our Comsol model. These challenges have made for a longer development time than anticipated and this is a work in progress. We plan to continue this work to improve our Comsol model to resolve some of these challenges.

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**References**:

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