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New geophysical insight into the origin of the Denali volcanic gap

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1- Finite Element Models

The numerical models of mantle flow field and temperature structure were developed using the commercial numerical software Comsol Multiphysics™. Comsol is a generic Finite Element package, whose strength is to easily enable the user to couple different physical applications. It also features flexible meshing capacities. We simultaneously use two predefined applications: the Navier-Stokes application, with P2-P1 mixed mode elements, and the Convection and Conduction application with second-order elements for the heat equation. In fact, we use two instances of the Navier-Stokes application as the backarc domain is solved separately from the forearc domain.

The parameters entering the models are gathered in Table A1 and described below.

The full computation domain is a rectangle of length L and height H, in which we define a priori the outline of the subduction interface (Figure A1). Near the trench, the slab is a circular arc so that the slope of the interface increases from δ_T at the trench to the slab dip δ_S. Further down, the slab interface is a straight line dipping at δ_S until a depth of z_S. An additional geometrical boundary links the tip of the predefined slab to the bottom right corner of the model to fully separate the backarc from the forearc domains. A two-layer crust is defined in the backarc only. Each crustal layer is 20 km thick.

The entire domain is meshed with quadrilateral elements using a Delaunay method. Thus, the mesh conforms to the complex geometry of the model and has a variable resolution. A finer mesh is imposed in the wedge near the trench. We tested that the basic features of the model are mesh independent as long as the maximum element size in the refined region is less than 5 km (Figure 12A). Numerical results are presented with a maximum element size of 2 km in the refined region. Example meshes for the Western Alaska and Denali Volcanic Gap models are presented in Figure A1.

We impose the subduction velocity V_S on the forearc domain along the entire downgoing plate, including the slab, to a depth of z_S. Circulation in the mantle wedge is driven by the backarc velocity V_B at the base of the crust and coupling with the forearc domain along the slab interface: $V = C\ V_S$. Coupling increases linearly from $C = 0$ at the base of the crust to $C = 1$ at 100 km depth. To capture slab advance (or rollback) in the reference frame of the subduction point, where the slab is no longer in contact with the overlying crust, we reduce the velocity of the downgoing plate by a trench advance rate V_T and increase the backarc velocity correspondingly so that $V_B + V_S = V_C$, the convergence velocity. The velocities of the backarc and forearc domains are matched across the boundary that links the tip of the predefined slab and the model corner, and along the slab interface below z_S, allowing free flow across this boundary. The bottom and side edges of the model are open free-flow boundaries. Following van Keken et al. (2002), the crust is immobile and rigid.

The viscosity can be temperature-dependent, according to

$$\eta = \eta_0 \exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right], \qquad \text{(A1)}$$

where T is the absolute temperature, R=8.314 J/mol/K is the gas constant, Q is the activation energy, and η_0 and T_0 are reference viscosity and temperature. The value of η_0 does not affect model results as there is no other stress scale (we neglect buoyancy), but the activation energy changes significantly model behaviour (Figure 11). To avoid numerical issues, we implement an upper viscosity cut-off of $10^7\ \eta_0$.

The temperature field is determined by solving the time-dependent heat advection and diffusion equations with the thermal parameters reported in Table A1 throughout. On the forearc side, 100 km before the trench, we impose the conductive temperature profile of an oceanic plate of predefined age. On the backarc side, we impose a steady-state geotherm carrying a surface heat flow of 90 mW.m^{-2}, corresponding to the regional heat flow in most of Alaska (Blackman and Richards, 2004). Following Kneller et al. (2005), radiogenic heating is included only in the crust (see Table A1). Both temperature profiles saturate to an isotherm mantle at 1450 °C. That same temperature is imposed at the bottom of the model while the surface remains at 0 °C.

The temperature profiles from each edge are imposed initially throughout the forearc and backarc domains. The model is then run forward in time. A cold region corresponding to the slab is advected downward. If the viscosity is sufficiently temperature-dependent, the cold region is also rigid. It continues downward at approximately the imposed slab slope δ_S until it is artificially heated and absorbed by the fixed temperature boundaries of the model domain (Figure A1). Steady state is typically achieved ~50 Myr into the simulation. The results of Figure 11 and A1 show the state of the model after 100 Myr, and serve as the initial conditions for modelling the transient behaviour displayed in Figure 12.

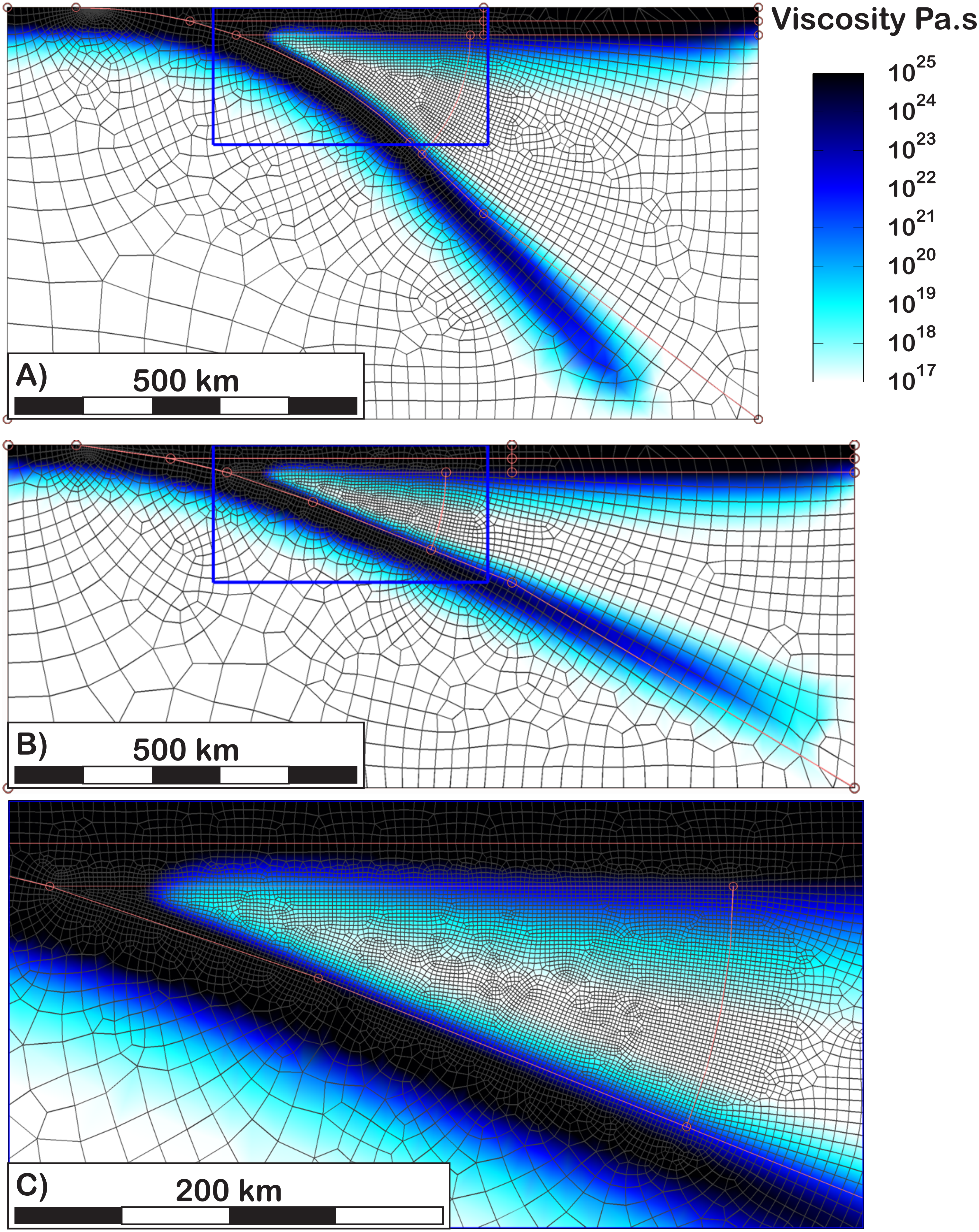
ADDITIONAL REFERENCES

Kneller, E.A., van Keken, P.E., Karato, S., Park, J., 2005. B-type olivine fabric in the mantle wedge: insights from high-resolution non-Newtonian subduction zone models. Earth Planet. Sci. Lett. 237, 781–797.

SUPPLEMENTARY TABLE 1: Model parameters

Parameter	Western Alaska	Denali Volcanic Gap	Description
L	1034 km	1235 km	Model length
H	600 km	500 km	Model width
δ_T	0°	5°	Dip at the trench
δ_S	44°	22°	Slab dip
R_S	700 km	1200 km	Slab radius of curvature
z_C	196 km	83 km	Depth of the circular slab tip
x_C	486 km	345 km	Distance from the trench to the circular slab tip
z_S	300 km	200 km	Depth of the predefined slab tip
x_S	593 km	635 km	Distance from the trench to the predefined slab tip
H_U	20 km	20 km	Thickness of the upper crust
H_L	20 km	20 km	Thickness of the lower crust
V_C	48 km/Myr	55 km/Myr	Convergence velocity
η_0	10^{18} Pa s	10^{18} Pa s	Reference viscosity
T_0	1200 °C	1200 °C	Reference temperature
ρ	3300 kg/m^3	3300 kg/m^3	Density
C_p	1250 J/kg/K	1250 J/kg/K	Heat capacity
K	3.3 W/m/K	3.3 W/m/K	Heat conductivity
A_{U}	1.3 μW/m^3	1.3 μW/m^3	Heat generation (upper crust)
A_{L}	0.27 μW/m^3	0.27 μW/m^3	Heat generation (lower crust)
A	46 My	38 My	Plate age 100 km from the trench
Q_C	90 mW/m^2	90 mW/m^2	Continental heat flow

SUPPLEMENTARY FIGURE 1: Example meshes for the Western Alaska model (A) and the Denali Volcanic Gap model (B, C). Geometry edges are highlighted in red and with nodes indicated by circles. The blue box in A and B delineates the wedge focus region shown in Figures 11 and 12 and in panel C. The coloured field represents the viscosity of the steady state subduction models using temperature-dependent viscosity with Q=300 kJ/mol (as in Figure 11). The maximum element size in the wedge region is 5 km in panels A and B and 2 km in panel C, as for the models of Figure 11 and 12.



Viscosity Pa.s
10^{25}
10^{24}
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
A)
500 km
B)
500 km
C)
200 km