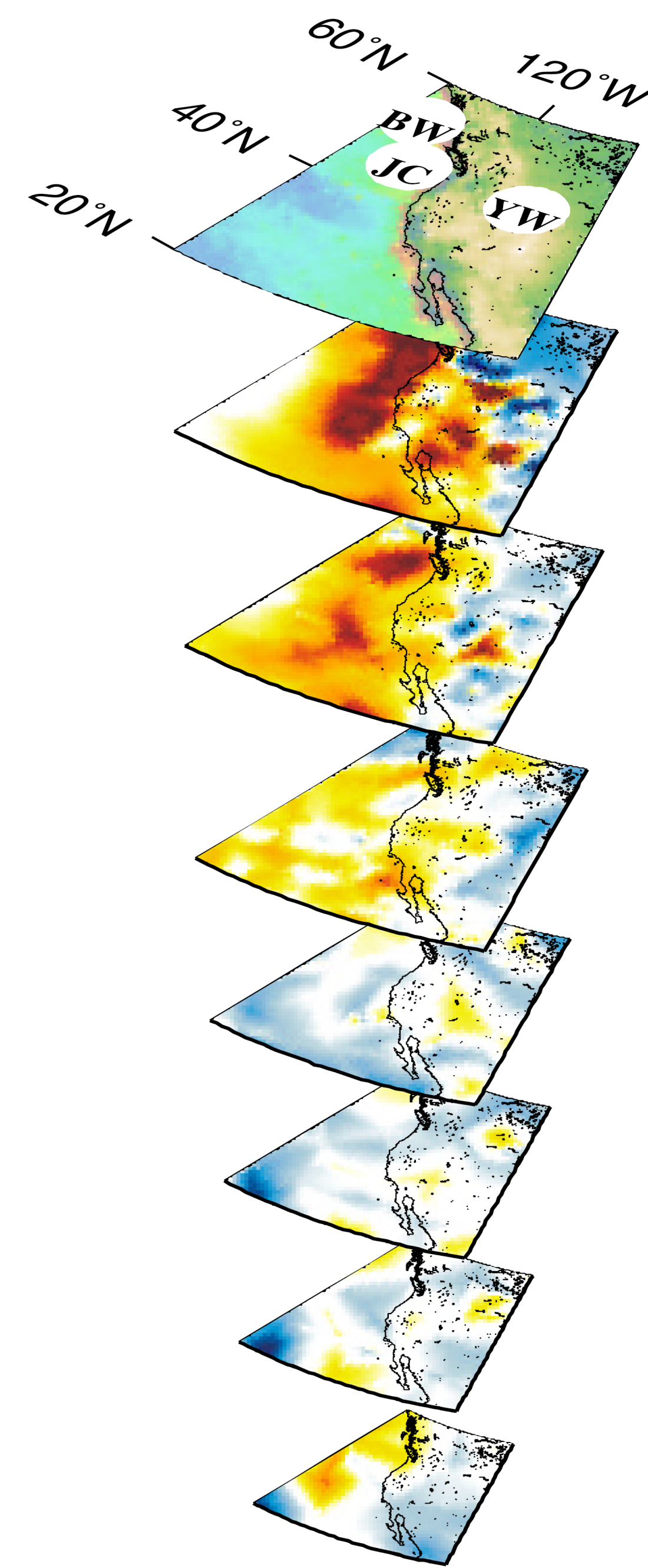


# Modelling Plume Evolution under Archean and Phanerozoic Mantle Conditions using ASPECT (Advanced Solver for Problems in Earth's Convection)

Quintin E. Muhlenkamp  
Department of Geology

## Introduction

The style of convection during the Archean is debated. The Archean is characterized by warmer temperatures of approximately 100 – 300°K relative to modern day (Herzberg et al., 2007) and is expected to have implications on convection, a phenomenon that occurs as hot, deep mantle material is brought near the surface, cools, and then sinks deeper back into the mantle. Mantle cooling through time has gradually changed convection and, therefore, tectonic processes.



Left: A three-dimensional tomographic image beneath Bowie, Juan De Fuca, and Yellowstone (image from Montelli et al., 2006). The plume appears to originate near the 660 km discontinuity. The authors attribute deeper velocity anomalies to leakage from the 600 km discontinuity. The bold values to the right of the images label the depth in km. These data give a general idea of plume geometry. One can see that the plume head expands significantly as it nears the surface. I can compare results from the ASPECT models to these tomographic images.

## The Model

In this study, the computation takes place in a two-dimensional box heated from the bottom. The temperature at the bottom of the box is equal to the temperature of the ambient mantle, while the top and sides are set to an approximated surface temperature of 273°K.

The density is assumed to have a linear dependence on temperature. This study uses the Boussinesq approximation, assuming that density variations are negligible everywhere except at the driving force of the flow, and also assumes that the system is incompressible.

This model uses an inclusion shape perturbation. This function sets the initial temperature of the ambient mantle and initiates the convection currents with a perturbation of a defined radius and inclusion temperature.

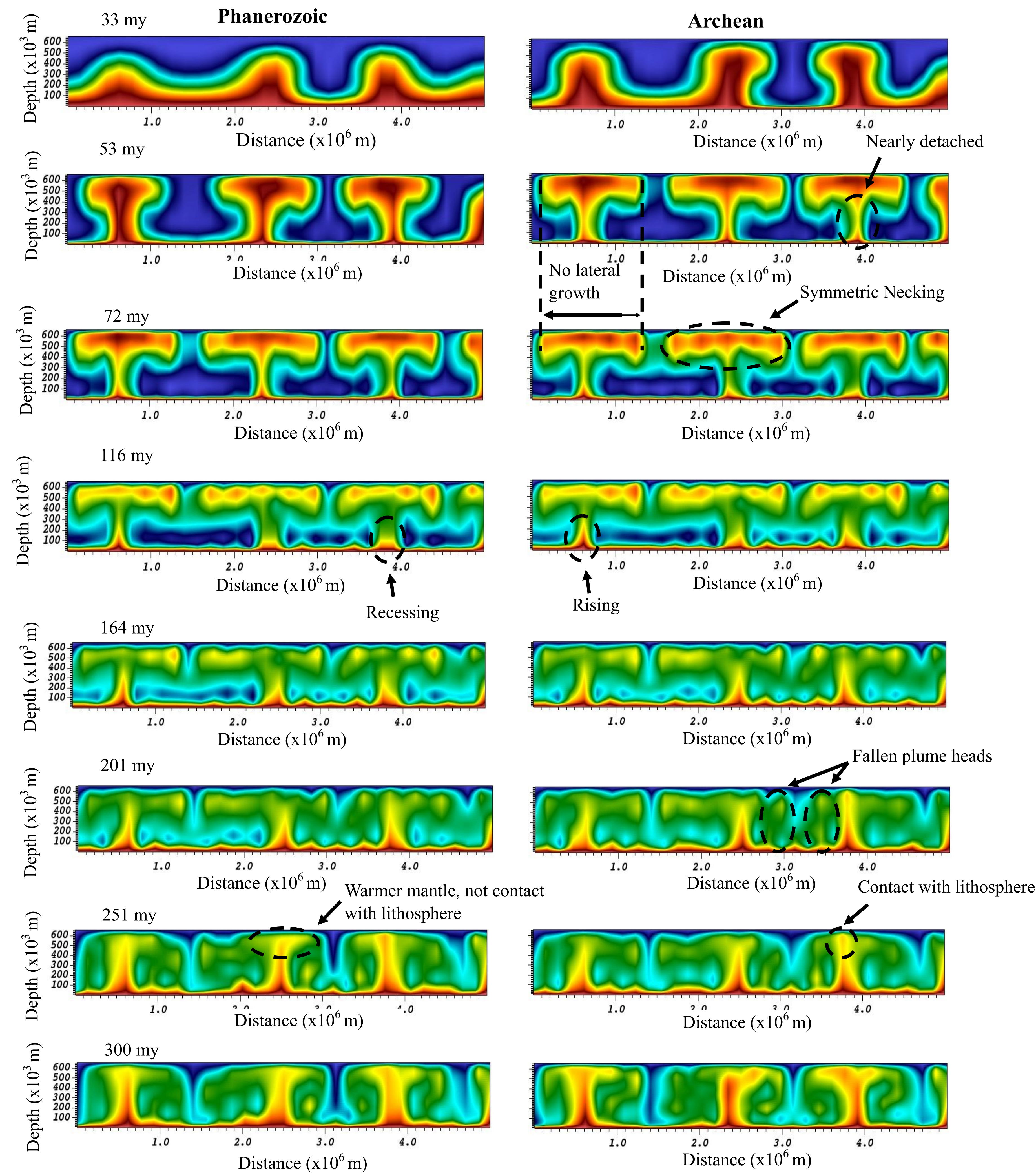
The only difference between Archean and Proterozoic setups is the magnitude of the inclusion and ambient temperatures, as the ratio between these temperatures must remain constant (Herzberg et al., 2007).

Variable	Proterozoic	Archean
X-extent	5000 km	5000 km
Y-extent	660 km	660 km
Ambient temperature	1593 °K	1893 °K
Inclusion temperature	1843 °K	2148 °K
Shape radius	1 km	1 km
Bottom temperature	1593 °K	1593 °K
Left/right/top temperatures	293 °K	293 °K
Reference density	3300 kg/m <sup>3</sup>	3300 kg/m <sup>3</sup>
Reference specific heat	1250 J/kg <sup>o</sup> K	1250 J/kg <sup>o</sup> K
Reference temperature	293 °K	293 °K
Thermal conductivity	4.7 W/m <sup>o</sup> K	4.7 W/m <sup>o</sup> K
Thermal expansion coefficient	2x10 <sup>-5</sup> 1/ <sup>o</sup> K	2x10 <sup>-5</sup> 1/ <sup>o</sup> K
Viscosity	5x10 <sup>24</sup> kg/m/s	5x10 <sup>24</sup> kg/m/s

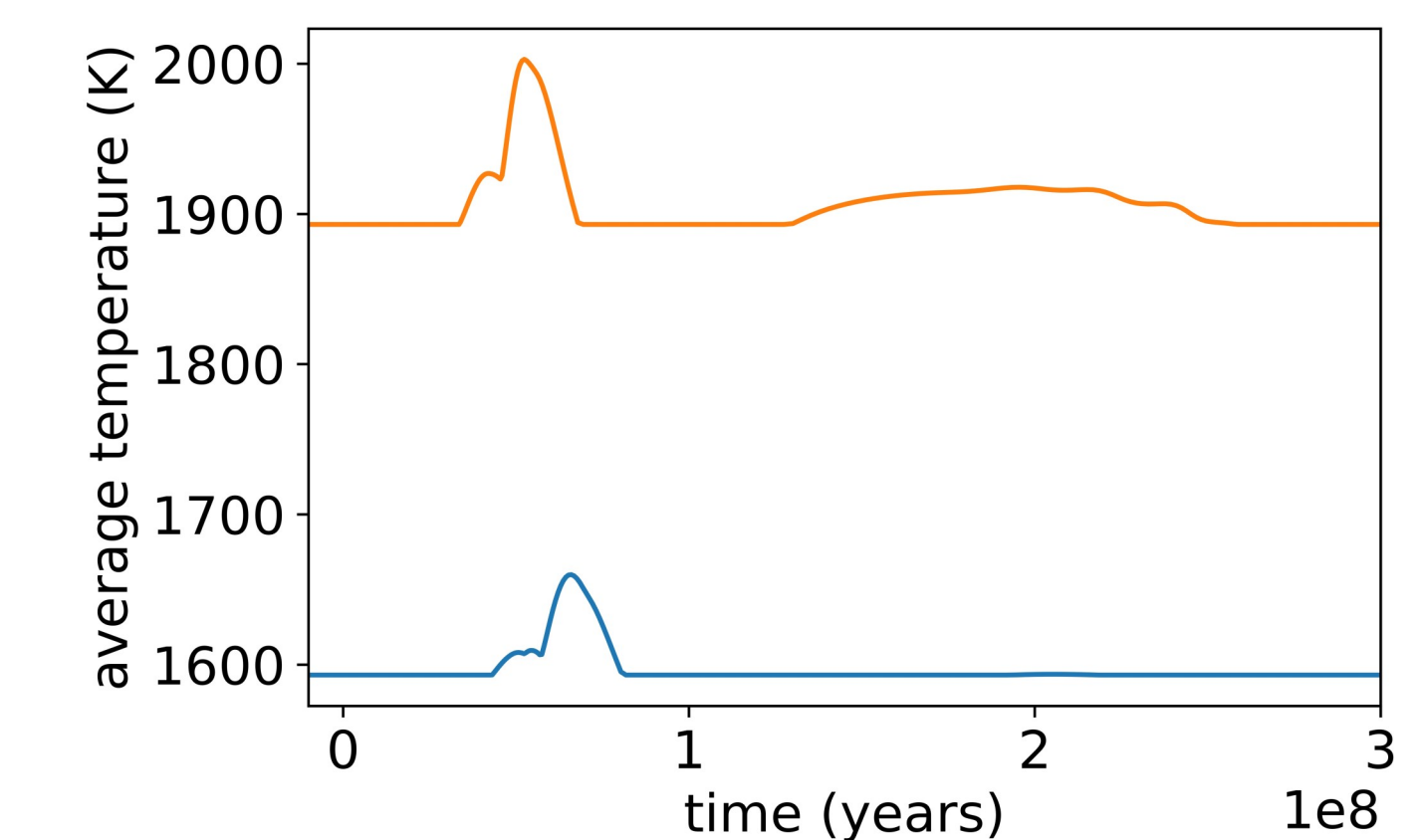
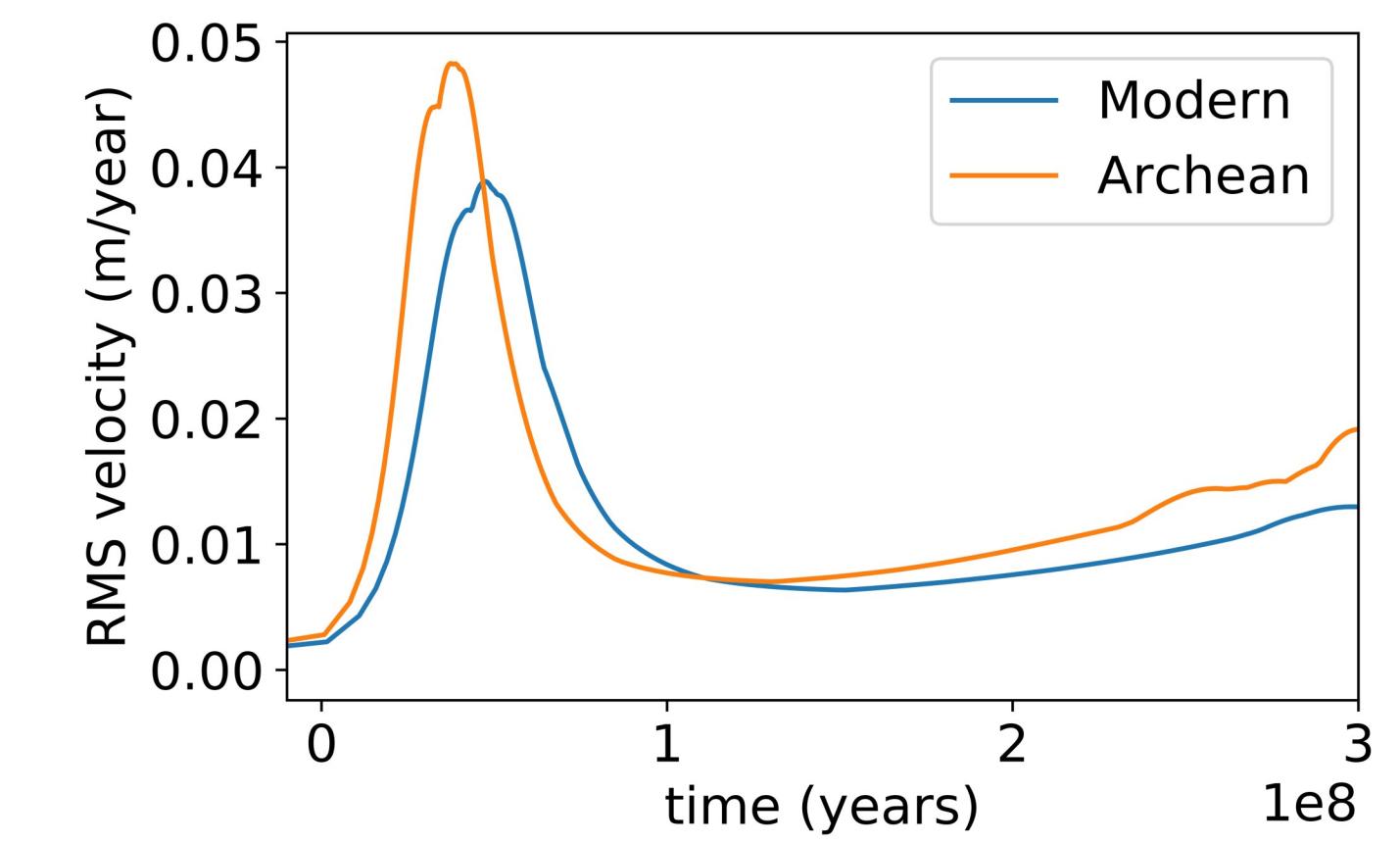
## Abstract

Because plate tectonics and mantle convection are interrelated, studying convection will aid in understanding tectonic properties that are observed on Earth's surface. This study presents a numerical model for mantle plume evolution over a 300-million-year period to identify major differences between Archean and Phanerozoic plume characteristics. Results suggest that Archean plumes generally have higher temperatures and velocities than Phanerozoic plumes, but have similar geometric characteristics. The rate at which Phanerozoic plumes penetrate the mantle is slightly faster than expected, passing through in only 50 my, a phenomenon that could be the subject of further studies.

## Results



Above: Temperature plots showing plume evolution for Phanerozoic (left column) and Archean (right column) mantle conditions. The plots have been normalized to the start of the perturbation. Exact temperature scales are relative to each time slice, dark red being the hottest, dark blue the coolest. The Archean plumes develop faster than the Phanerozoic for a significant portion of the model. Significant developmental stages and comparisons between the two models are shown as markings on the contour plots.



Above: Plots showing the RMS velocity (top) and the average temperature (bottom) for the Archean (orange) and Phanerozoic (blue) models. Time is scaled to the eighth order of magnitude, so 1 on the horizontal axis corresponds to 100 my. The plot of RMS velocity confirms that the Archean convection runs faster than the Phanerozoic for most of the time. However, the Archean rms velocity peaks and begins to decline earlier, resulting in a short period where Phanerozoic events happen faster than Archean events. Both systems start to gain velocity again, and the Archean surpasses the Phanerozoic. The average temperature plots shows the lag in Phanerozoic mantle by means of a delayed spike in the temperature profile, caused by the development of large, hot, plume heads around 50 my.

## Conclusions

Understanding the dynamics of mantle processes aids in understanding the tectonic processes observed on Earth's surface. An outstanding question in this field is the behavior of Archean-age plumes, and the manner in which they evolved into the systems observed today. This study investigated the properties of Archean and Phanerozoic mantle plume models to better understand their major differences. Simple numerical models yielding graphical and statistical output show that plume geometries differ little between the Archean and Phanerozoic. However, the rate at which the processes occur varies throughout the models, and the Archean mantle, in general, exhibits higher velocity plumes. The rate at which the plumes penetrate the mantle is problematic, as the values obtained for penetration of the upper mantle in this study are significantly slower than the penetration times for the entire mantle given by Condie (2001). This discrepancy could be the result of a simplifying assumption in the model, such as the linear dependence of density on temperature, and would need to be investigated further. The basic geometries of the plumes matches that of observed plumes originating from around the 660 km discontinuity in the sense that the plume head is larger than the plume stem.

## References

- Condie, K., 2001, Mantle Plumes and Their Record in Earth History: Cambridge University Press.
- Herzberg, C., Asimow, P.D., Arndt, N., Niu, Y., Leshner, C.M., Fitton, J.G., Cheadle, M.J., Saunders, A.D., 2007, Temperatures in ambient mantle and plumes: Constraints from basalts, picrites, and komatiites: Geochemistry, Geophysics, Geosystems, v. 8, no. 2.
- Kronbichler M., Heister, T., Bangerth, W., 2012, High Accuracy Mantle Convection Simulation through Modern Numerical Methods: Geophysical Journal International, v. 191, no. 1, p. 12–29.
- Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., 2006, A catalogue of deep mantle plumes: New results from finite-frequency tomography: Geochemistry, Geophysics, Geosystems, v. 7, no. 11.

## Acknowledgements

The Computational Infrastructure for Geodynamics (Kronbichler et al., 2012; geodynamics.org) which developed ASPECT is funded by the National Science Foundation, award EAR-0949446 and EAR-1550901. I would also like to thank Wittenberg University for the use of their computing cluster.