TTG Rocks Geochemical Analysis: The New Constraints on The Thermal Condition of the Heat-Pipe Earth in Archean

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INTRODUCTION

TTGs (tonalite–trondhjemite–granodiorite) are intrusive rocks with typical granitic composition (quartz and feldspar) but containing only a small portion of potassium feldspar (Fig. 1). They are one of the archetypical lithologies of Archaean cratons, which is base rock of most of the present continental crust. Nowadays, the TTGs are thought to be generated by the fractional crystallization of the melting of the metamorphosized basalt in crust based on the chemical analysis of these rocks.

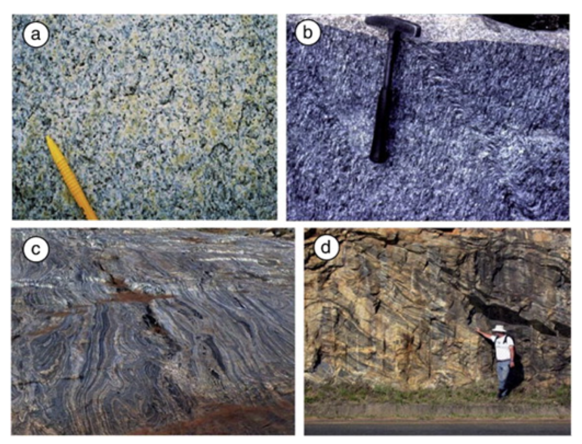

Figure. 1 The photos of the TTGs in the field.

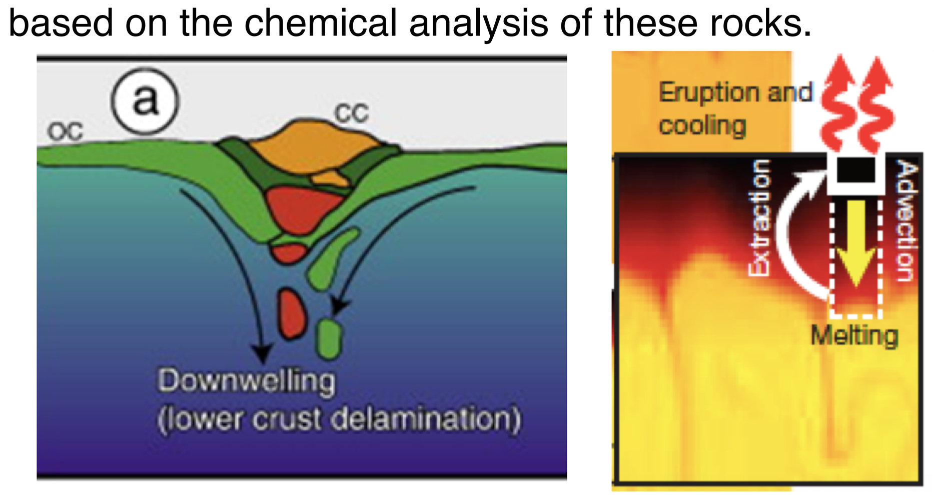

Figure. 2 a & b. The schematic graphs of the downward advection zone on the heat-pipe earth.

Heat-pipe earth (Fig. 2) is a geological setting that is able to form TTGs. In this setting, the magmas get erupted on some parts of the ancient ocean floor, which is called the downward advection zone, cool and interact with sea water to form the wet basalts. These basalts get buried by the new-erupted basalts and transported downward over time. These processes thicken the portions of the lower crust so they can delaminate and sink into the mantle. These basaltic rocks are therefore heated, metamorphized, and melting to form the parent's magma of TTGs. However, the thermal condition of the lithosphere, the rigid shell of the earth, under the heat-pipe earth setting in Archean (~3 billion years ago) is not well understood. The main parameters such as the downward advection rate and the lithosphere thickness need to be confined in order to better understand the lithosphere of the Archean earth.

RESEARCH OBJECTIVE

Confine ranges of the lithosphere thickness and the downward advection rate that allow the formation of the TTGs in the heat-pipe earth setting in order to better understand the thermal condition of the Archean lithosphere.

METHODS

The thermal structure of the lithosphere is constructed by the steady-state solutions of the energy equation with a term that accounts for the downward advection at a velocity v (Moore & Webb, 2013) :

$$\frac{k}{\rho C_p}\frac{d^2T}{dz^2} = v\frac{dT}{dz} - \frac{H}{\rho C_p}$$

k = thermal conductivity
ρ = density of basaltic rocks
C_p= thermal capacity
v = downward advection rate
H = heat production in the lithosphere

The boundary conditions of the solutions are fixed surface temperature ($T_s = 15\,°C$) and bottom temperature (given by the dry periodate solidus) of the lithosphere. ***It is assumed that the basalt will melt at the depth where the geotherm first cross the wet basalt solidus.***

P–T diagram (Fig. 3) showing the stability curve(band) for TTG's minerals (H: hornblende, G: garnet, R: rutile) as well as hydrous phases of the hydrated oceanic crust (A: anthophyllite; C: chlorite; Ta: Talc; Z: zoisite; Tr: tremolite); the "wet" and "dry" solidus for basalts; and the typical along-slab geotherms in both the modern and Archaean situation. The yellow field is the likely field for TTG genesis (Moyen & Martin, 2012) . According to it, ***the melting depth of the parent basalts are constrained to 50 - 85 km.***

The isotope Hf in the zircon can imply the age as well as the history of it. The previous isotope Hf study of the zircon bearing TTGs suggests that the metamorphized basalt, which melted to generate the parent's magma for TTGs, need to be preserved for ***250 – 500 Myrs*** (Reimink & etc., 2019). It can be used as the ***buried time constraint***..

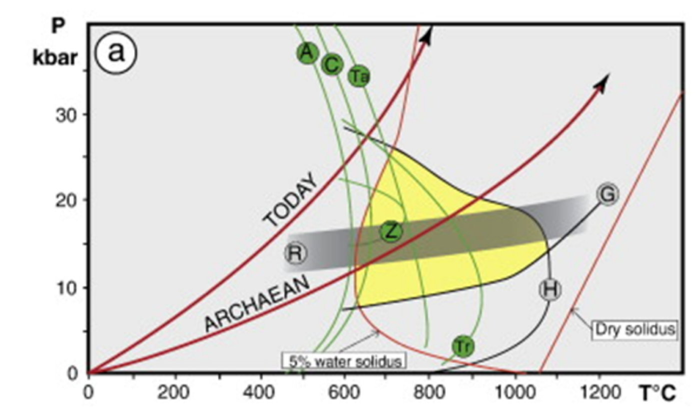

Figure. 3 P-T Diagram for TTGs formation.

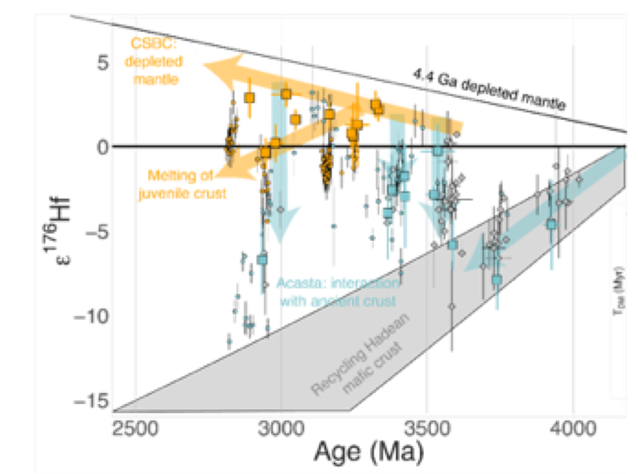

Figure. 4 Isotope Hf study of Archean TTGs. The time from the time when mafic crust started to form to the tine when the data points fall in the grey region is used as the buried time constraint.

RESULTS

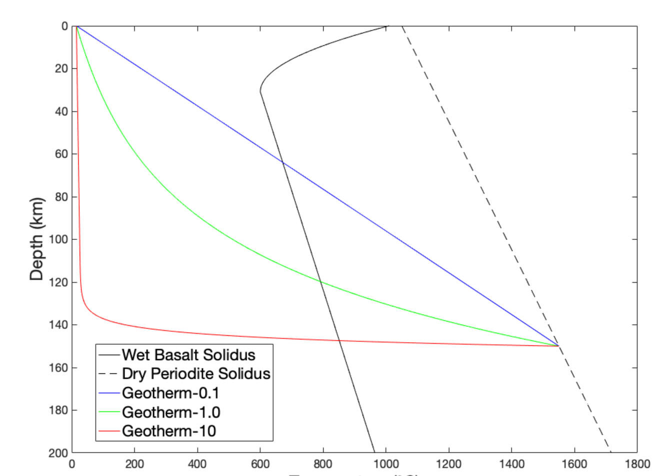

Figure. 5 Geotherms are calculated by the solutions of the energy equation. They are the geotherms of the region where the basalts are advected down. Therefore, they are also the temperature of the basalts. The basalts will melt once their geotherm cross the wet basalt solidus. For example, the green line represents that the basalt will melt at about 115 km depth when the downward advection rate is 1.0 mm/yr.

Figure. 6

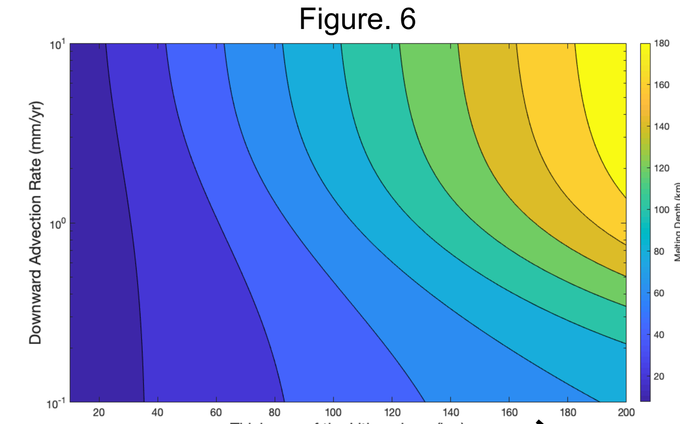

Figure. 7

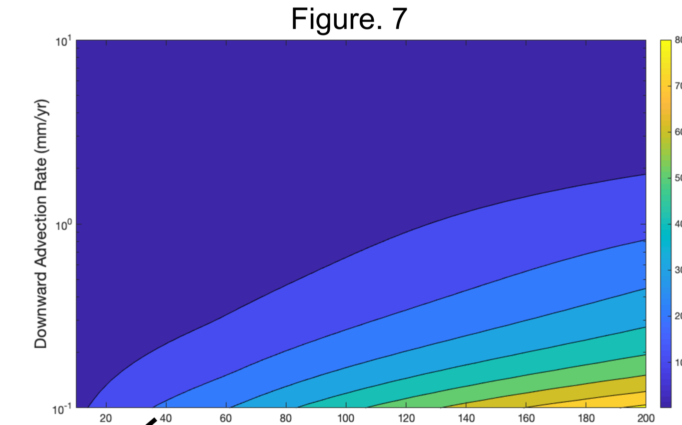

Figure. 8

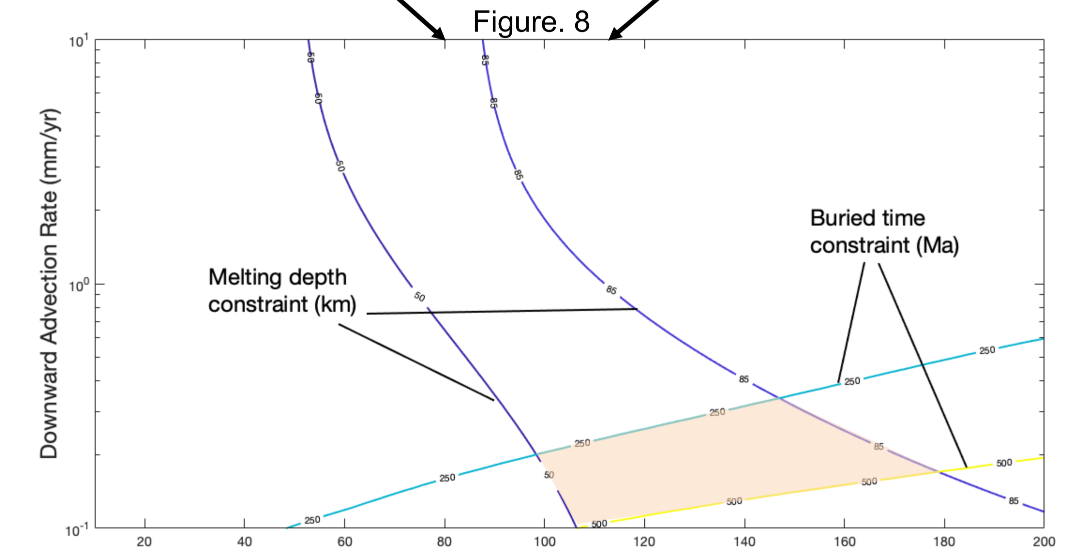

Figure. 5 is the geotherms of the lithosphere with a thickness of 150 km at different downward advection rates (v = 0.1 mm/yr, 1.0 mm/yr, 10 mm/yr). It is referred to the thermal structure of the lithosphere in the discussion.

Figure. 6 is the contour map of the melting depth. It shows the melting depth of the wet basalt in different lithosphere thickness and downward advection rate condition.

Figure. 7 is the contour map of the buried time. It shows the time that the wet basalts get buried in the lithosphere before they melt in different lithosphere thickness and downward advection rate condition.

The orange region in Figure. 8 indicates the downward advection rate and lithosphere thickness which is possible for Archean TTGs formation. It suggests that Archean TTGs was formed under the condition where the downward advection rate is between 0.1mm/yr and 0.2 mm/yr and the thickness of the lithosphere is between 100 km and 120 km.

DISCUSSIONS

The thermal condition of the lithosphere in the downward advection zone

The thickness of the lithosphere is artificially chosen for the convenience of calculation in this study so the results of this study does not imply any relationship between the downward advection rate and the thickness of the lithosphere.

The geotherms of the lithosphere change gradually when v is small (0.1 mm/yr) and are much steeper when v is large (10 mm/yr) (Fig. 5). The larger the downward advection rate v is, the colder the basalts as they are transported to the bottom of the lithosphere. Thus, the melting depth is greater (Fig. 6) because the temperature of the basalt does not have enough time to increase if it gets advected downward quickly. At the same time, the larger the v is, the shorter the buried time is since the buried time is given by (melting depth)/v (Fig. 7). Figure. 6 also shows that the thicker the lithosphere, the greater the melting depth is, especially when the downward advection rate is high. However, this relationship may be partially caused by artificially fixing the thickness of the lithosphere.

The melting depth constraint suggests a thick lithosphere and the buried time constraint suggests a low downward advection rate (Fig. 8). The ranges of v and the lithosphere thickness constrained by the melting depth is similar to the previous studies. However, ***the range of v constrained by the buried time given by the Hf isotope study is much lower than the v proposed by the previous study.*** The Hf isotope study of TTGs requires the buried time to be long. The v has to be low, or else the lithosphere has to be extremely thick, which is unlikely to be the case.

Implication of the dynamics of the Archean lithosphere

The downward advection rate is positively correlated to the intensity of the volcanic activity. The more intense the magma eruption on the surface is, the faster the old basalts are buried and transported downward. The low downward advection rate implies that the volcanic activities in the heat-pipe earth during Archean were not very intense which means less heat can escape from the earth surface. It contradicts with the high heat production of the Archean earth because a higher heat production requires more heat diffusions to prevent the earth surface from melting. One explanation to this paradox is that although the heat diffusion from the volcanic activities in the downward advection zone was low, the other parts of the surface, which are similar to the modern ocean lithosphere, diffused more heat. It implies that the thickness of the lithosphere in the non-volcanic regions might be thinner back in Archean.

FUTURE WORKS

The stimulation of the geotherm of the lithosphere by the steady-state solutions to the energy equation is simplistic. It does not account for heat input in the lithosphere due to the magma intrusion. However, the heat input from the intrusion substantially affects the thickness of the lithosphere, which determines whether the magma can rise up to the surface, erupt and form basalt or not. If the lithosphere becomes so thick that the magma is no longer able to erupt on the surface, the heat-pipe earth setting will not hold. In order to better understanding the thermal condition of the lithosphere in a heat-pipe earth, a more complex model is needed to be built.

Study on the heat diffusion in the non-volcanic regions is also needed in order to solve the paradox between the less heat diffusion from volcanic activities and the higher heat production of the Archean Earth.

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