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At the Dawn of Continents: Archean Tonalite-Trondhjemite-Granodiorite Suites

Laurent Oscar [1], Guitreau Martin [2], Bruand Emilie [2, 3], Moyen Jean-Francois [2]

[1] CNRS, Géosciences Environnement Toulouse, Toulouse, France
[2] Université Clermont Auvergne, Laboratoire Magmas et Volcans, Clermont-Ferrand, France
[3] CNRS, Geo-Ocean, Brest, France

Email addresses : oscar.laurent@get.omp.eu ; martin.guitreau@uca.f ; emilie.bruand@univ-brest.fr ; jean_francois.moyen@uca.fr

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Abstract :

Archean rocks of the tonalite-trondhjemite-granodiorite (TTG) suite are dominant constituents of Earth's earliest preserved silicic crust, while conversely rare in Phanerozoic continental crust. Their formation represents the first critical step towards the construction and preservation of continents. Formation of most TTG magmas involved partial melting of hydrous, probably silicified, mafic rocks at various depths (20-50 km, possibly up to 100 km). Many possible tectonic scenarios fit the petrological and geochemical constraints on TTG formation, whether compatible with a global plate tectoniclike regime or not. Refining such scenarios is a major challenge that requires systematically integrating the constraints on TTG formation-relying especially on accessory minerals as key petrogenetic tools-with the geological context on a regional scale.

Keywords : tonalite-trondhjemite-granodiorite suite, continental crust, grey gneisses, accessory minerals, Archean geodynamics

INTRODUCTION

The Earth is unique in the Solar System by its abundance of silica-rich continental crust and the crucial role this crust has played in the physical, chemical, and biological evolution of the planet. Present-day continents consist of a patchwork of individual domains that show a range of crust formation ages from the Hadean or Eoarchean (4.4–3.6 billion years ago [Ga]) to the present day. Archean cratons generally contain remnants of the oldest continental nuclei, around which younger lithosphere has progressively aggregated and been preserved over time. Exposed crustal parts of these oldest nuclei are dominated by a *suite* of igneous silicic rocks that is archetypal of Archean cratons: the tonalite-trondhjemite-granodiorite (TTG) suite. The construction of these TTG-dominated domains can therefore be regarded as the first critical step towards the preservation of significant volumes of continental lithosphere and, hence, the birth of cratons and continents.

The geological processes and tectonic settings in which TTG-dominated crust formed are fundamental to understanding continental crust evolution over time, the early Earth environment, and, therefore, how life arose on our planet. For these reasons, understanding the origin of TTGs has been an active research field over the past 50 years. In this contribution, we review the recent advances and persisting debates in TTG research, notably regarding their geological significance, magma-forming mechanisms, and general implications for crustal evolution and tectonic settings on the early Earth.

WHAT ARE TTGs?

Tonalite, trondhjemite, and granodiorite are quartz-rich igneous plutonic rocks in which plagioclase is more abundant than K-feldspar. The TTG suite hence includes rocks whose typical mineral assemblage consists of sodic plagioclase, quartz, and biotite, with minor to absent K-feldspar and amphibole, and accessory minerals (zircon, apatite, titanite, allanite/epidote, monazite, Fe-Ti oxides). However, Archean rocks fulfilling the mineralogical definition of TTGs do not all have the same geological significance. Some TTGs form intrusive igneous bodies ranging from small dykes to large zoned plutons, emplaced at shallow paleo-depths in the crust (within the first 10 km), some of which may be genetically linked with contemporaneous volcanic eruptions (e.g., Laurent et al. 2020; FIG. 1A). Other TTGs may represent mid-crustal (10 to 20 km depth) plutonic complexes (Kendrick et al. 2022; FIG. 1B) or magmas crystallized at or near their production site, comparable to “in-source” leucosomes in migmatites (Halla 2020; Pourteau et al. 2020; FIG. 1C).

The mineralogical assemblage of TTGs is stable over a wide range of crustal pressures and temperatures, such that the term also includes orthogneisses that have experienced metamorphism up to amphibolite-facies conditions. Therefore, due to their long geological history often characterized by several tectonic and thermal events, TTGs may crop out as components of heterogeneous, deformed, and metamorphosed “grey gneisses” (Moyen 2011). In this case, rocks that are not necessarily coeval or co-genetic may coexist on a small scale. For example, the outcrop in FIGURE 1D shows five distinctive igneous units, three of which are of TTG composition, emplaced over a time period exceeding 600 million years. Here, “TTG” should not be misused as a synonym for “grey gneiss” and, at best, represents a shortcut for “*part of a heterogeneous rock unit of TTG composition.*”

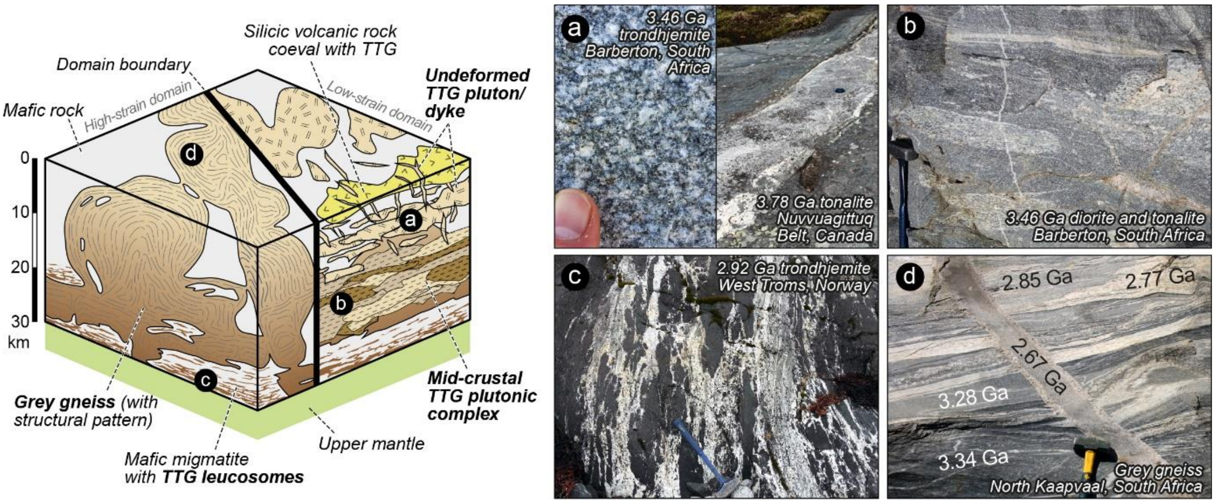

Figure 1: Sketch block diagram of Archean crust depicting the main structural settings in which TTG rocks can be found, with field examples.

The plagioclase-rich and K-feldspar-poor nature of TTGs (Fig. 2A) imparts a distinctive geochemical signature characterized by a sodic character (Na_2O > 4 wt.% and K_2O < 2 wt.%; hence, K/Na ratios < 0.6) at high silica concentrations (>64 wt.% SiO_2) (Moyen and Martin 2012). TTGs also show moderately to highly fractionated rare earth element (REE) patterns (La/Yb > 15) with weak to no Eu anomalies, and elevated Sr/Y ratios (>15). Importantly, some geochemical variability exists within TTGs (Fig. 2B, 2C), which allows definition of several sub-groups from low-HREE-Y, high-Sr to high-HREE-Y, low-Sr end-members (Moyen 2011). The geochemical characteristics of TTGs distinguish them from granitoids formed in most post-Archean geodynamic settings (Fig. 2A, 2B). Although sodic tonalites and trondhjemites do form on the modern Earth, mainly in intra-oceanic environments (mid-ocean ridges, oceanic arcs), they constitute a negligible fraction of the preserved Phanerozoic continental crust. In contrast, TTGs dominate the Archean felsic crust. These observations point to specific distinctions between continental crust formation and preservation on the early and the modern Earth.

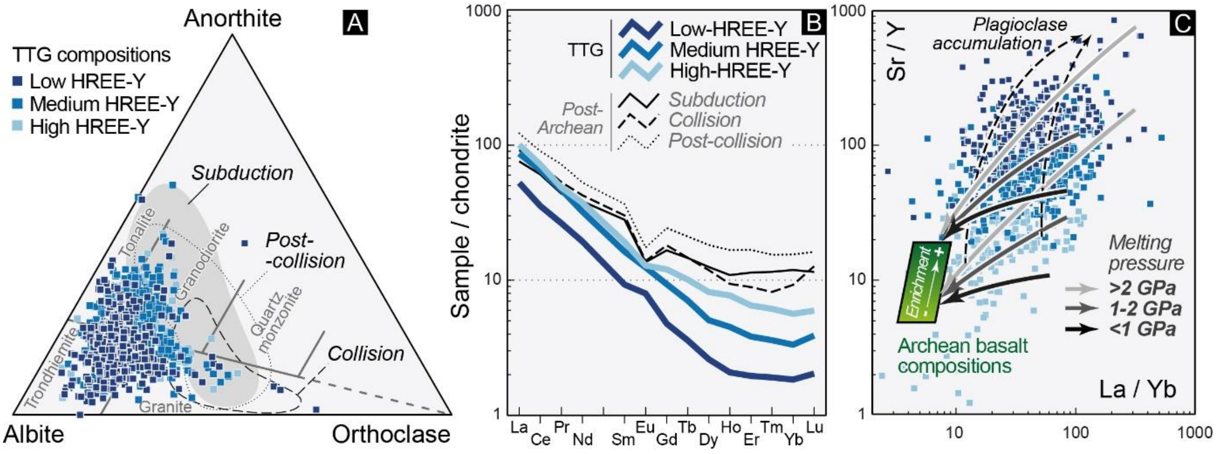

Figure 2: Mineralogical and geochemical characteristics of Archean TTGs, subdivided in three groups based on their HREE-Y (± Na, Sr, Eu) contents (Moyen 2011), compared to post-Archean granitoids. Data from Bonin et al. (2020). (**A**) Normative ternary feldspar diagram; (**B**) chondrite-normalized REE diagram; and (**C**) Sr/Y versus La/Yb plot (values not normalized to chondrite). As depicted in (**C**), this geochemical diversity results from a combination of variables: source compositions (green box), different melting depths (arrows show the evolution of melts produced at different pressures from low to high melt fractions, after Moyen 2011), and plagioclase accumulation and/or amphibole fractionation (Kendrick et al. 2022).

RECIPES FOR TTG MAGMAS

The Ingredients—Mafic Rocks from Undepleted Mantle

Experimental petrologists have long demonstrated that sodic silicate liquids of TTG affinity can be produced by 20%–30% (volume) melting of basaltic rocks, leaving an amphibolite or eclogite residue depending on pressure (review in Moyen and Martin 2012). Other studies have argued that fractional crystallization of basaltic melts would also produce TTG liquids (e.g., Smithies et al. 2019). Although this hypothesis is difficult to reconcile with the requirement that the source of TTG suites has undergone surficial alteration (see below), it is an alternative to generating at least some TTGs.

Regardless, the alkali (Na, K) and other lithophile and highly incompatible element (Rb, Ba, Th, U) contents of TTGs indicate that their mafic parental material must have been richer in these elements than the most common basalts on the modern Earth, i.e., mid-ocean ridge basalts (MORB) (e.g., Martin et al. 2014). This could indicate that the mantle source of Archean basalts was less depleted in these elements than the modern asthenosphere from which MORB are generated (Bédard 2018; Moyen and Laurent 2018), and/or slightly enriched in lithophile and incompatible elements by recycling pre-existing crustal material into depleted mantle (Smithies et al. 2019, 2021).

The Seasoning—Water and Ocean-derived Silica

Water plays an essential role in the production of most silicic magmas. The high abundance of TTGs in Archean cratons, therefore, requires partial melting of hydrous, likely amphibole-rich, mafic source rocks. The actual origin(s) of the water is still debated, but Archean mafic rocks commonly show evidence of eruption under water, implying that seafloor-related alteration could account for the hydration of TTG sources. In support of this hypothesis, TTGs exhibit Si isotopic compositions compatible with silicification of their mafic source by seawater-derived silica during seafloor alteration (Deng et al. 2019; André et al. 2019). Some authors have further proposed that the mantle-like oxygen isotopic compositions of TTG-hosted zircon (δ^{18}O of +5‰ to +6.5‰) reflect reworking of a mafic parent that did not interact with the surface and already contained enough water to melt, due to its derivation from a non-depleted, volatile-rich mantle (Smithies et al. 2021). However, this interpretation overlooks isotope fractionation between zircon and its parental melt, which can vary significantly and may imply a higher δ^{18}O in TTG magmas (above +7‰; Lei et al. 2023) for the same δ^{18}O measured in zircon. This, in turn, would be consistent with surface hydration of the TTG mafic source before melting.

The Cooking Conditions—Pressure and Temperature of Partial Melting

Results from experimental petrology have shown that melts of TTG composition can be produced by melting mafic rocks at temperatures of 750 to 950 °C and pressures from 0.5 to 4 gigapascals (GPa) (review in Moyen and Martin 2012), corresponding to a wide depth range of about 20 to 150 km. Refining this depth range relies on the identification of trace element characteristics of natural TTG rocks that reflect the stability of pressure-sensitive minerals in the melting residue. Martin (1986) was among the first to demonstrate that the low HREE-Y and high Sr-Eu contents in TTGs (FIG. 2B, 2C) were diagnostic of an amphibole- and/or garnet-bearing, plagioclase-poor melting residue, as garnet and amphibole scavenge Y and HREE, whereas plagioclase preferentially incorporates Sr and Eu. In fact, the continuous compositional spectrum of TTGs in terms of HREE-Y and Sr-Eu contents (FIG. 2B, 2C) could be explained by variable proportions of garnet and plagioclase in the residue, indicating melting at a range of possible pressures (e.g., Moyen 2011) from 2.0–2.5 GPa for the lowest Y-HREE, highest Sr-Eu TTGs down to 0.5–1.0 GPa for the highest Y-HREE, lowest Sr-Eu TTGs (FIG. 2C).

However, the melting pressure required to produce a given TTG composition also depends on the source composition, which influences the trace element signature of the resulting melt. A TTG magma with a given set of Sr/Y and La/Yb ratios, for instance, could result from melting either an enriched mafic source (high Sr/Y and La/Yb) at pressures <1.5 GPa or a less-enriched (lower Sr/Y and La/Yb) source at higher pressures (>2.0 GPa) (FIG. 2C). In fact, phase equilibria calculations using undepleted to enriched Archean basalts as the source of TTG magmas, instead of modern basalts (e.g., MORB) as has commonly been considered, show that the TTG compositional spectrum could form through melting within a more restricted pressure range than previously thought, i.e., 0.7 to 1.8 GPa (Palin et al. 2016; Johnson et al. 2017). Additionally, water-fluxed melting would generate apparent "high-pressure" signatures at 1 GPa or even less (Pourteau et al. 2020), as high H_2O activity has effects comparable to those of pressure on melting residues (i.e., promoting amphibole and garnet stability and suppressing plagioclase crystallization).

Lastly, the observed range of TTG trace element compositions does not necessarily reflect only source compositions and the nature of residual mineral assemblages, but also derives to some extent from differentiation processes during magma transfer and crystallization. This includes fractional crystallization (Liou and Guo 2019; Smithies et al. 2019) and its consequences, such as crystal accumulation and concomitant loss of interstitial melt (Laurent et al. 2020; Kendrick et al. 2022). Amphibole fractionation and/or plagioclase accumulation hence could account for the composition of TTGs with the highest Sr/Y and La/Yb ratios (FIG. 2C). In such a case, primary melts would be represented by TTGs with intermediate to low Sr/Y and La/Yb ratios (FIG. 2C), entailing again a more restricted melting pressure range (0.5–1.5 GPa) than previously thought (Laurent et al. 2020). Alternatively, TTG parental melts could be represented by mafic magmas derived from melting of enriched mantle, i.e., already showing high Sr/Y and La/Yb ratios (Smithies et al. 2019).

In summary, most TTG magmas were formed through partial melting of hydrous, probably silicified, mafic rocks at temperatures between 750 and 950 °C and a range of possible melting depths spanning from 20 to >100 km. However, recent studies have emphasized that source composition, presence of water during melting, and magma differentiation processes all critically influence element abundances and ratios that were previously interpreted as melting pressure indicators. Based on these recent findings, a more restricted melting depth range of 20–50 km would also account for the geochemical diversity of TTGs.

ACCESSORY MINERALS IN TTGs: TINY CRYSTALS WITH LARGE IMPLICATIONS

Zircon Age and Hf Isotopic Records of TTG Crust Evolution

Zircon is a popular "time capsule" used to understand the evolution of Archean crust because it is highly robust and can preserve geochemical information about its parental magma through multiple metamorphic events and/or sedimentary cycles. In detail, zircon can provide reliable U-Pb crystallization ages for TTGs and information about their source(s) through Hf isotopes expressed as εHf(t) (see *Toolkit*). Because most TTG magmas cannot be directly extracted from the mantle, their εHf(t) signatures are generally interpreted in terms of crustal residence time of their mafic source and/or mixing between crustal and mantle sources. A compilation of Hf isotopic compositions of TTGs worldwide (i.e., excluding more granitic and mafic compositions) and their zircons shows that about 80% of the data are roughly centered on the chondritic value (εHf(t) between −2 and +4; FIG. 3A). This indicates that the mafic precursor of TTGs was extracted from chondritic to mildly depleted mantle sources and re-melted to produce TTG magmas <100 My thereafter (Guitreau et al. 2012; Kemp et al. 2023).

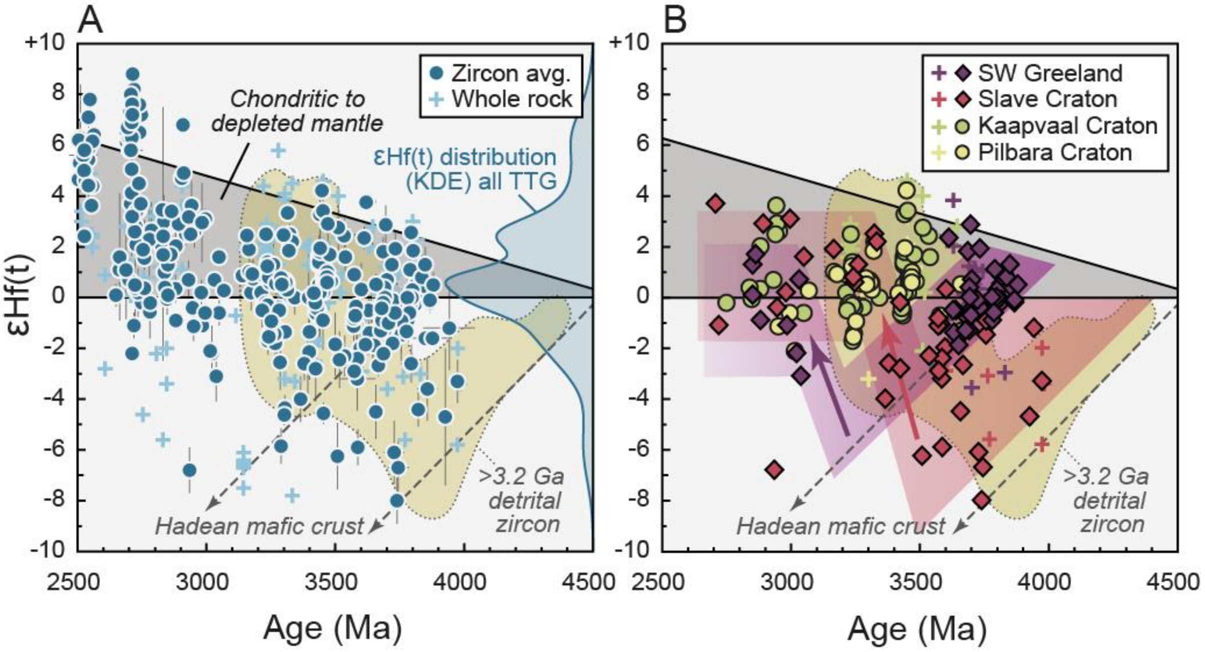

Figure 3: (**A**) Compilation of εHf(t) versus age data for Archean TTGs worldwide (data and references are available as online supplementary material); circles correspond to averages (± 1 standard deviation) of zircon analyses from single samples (average Hf isotopic composition of cogenetic zircon crystals, analyzed mainly by laser ablation, or solution MC-ICP-MS), crosses are bulk-rock values (Guitreau et al. 2012), all calculated at the respective rock crystallization age given by zircon U-Pb dating. The blue curve is the kernel density estimate (KDE) of the whole εHf(t) dataset; >3.2 Ga detrital zircon field is after Drabon et al. (2022). (**B**) Same plot containing data from selected cratons; colored fields and bold arrows correspond to the εHf(t)–time evolutions proposed for the Slave craton and SW Greenland by Bauer et al. (2020) and Kirkland et al. (2021), respectively.

However, a non-negligible amount of >3.2-Gy-old TTGs shows negative εHf(t), pointing to the contribution of a relatively old crustal source (FIG. 3A). This is also true for detrital zircons of that age (FIG. 3), many of which probably derived from erosion of TTG-like crust (e.g., Laurent et al. 2022). When Hf isotopic data are examined on a local, as opposed to global, scale it appears that such >3.2-Gy-old TTG-hosted and detrital zircons from various cratons (e.g., Frost et al. 2017; Guitreau et al. 2019; Bauer et al. 2020; Kirkland et al. 2021; Mulder et al. 2021; Drabon et al. 2022) define an evolutionary trend characterized by a steady decrease of εHf(t) to negative values, followed by an abrupt εHf(t) increase to near-zero or positive values (FIG. 3B). This observation has been tied to a transition in crust-forming mechanisms from closed-system reworking of mafic crust over hundreds of millions of years followed by rapid reworking of recently emplaced mafic material (Bauer et al. 2020; Kirkland et al. 2021) and formation of a complementary thick, buoyant depleted mantle, enabling craton stabilization (Guitreau et al. 2012; Mulder et al. 2021).

The transition visible in the εHf(t)–age trends has been attributed to global changes from so-called stagnant-lid to mobile-lid tectonics (Bauer et al. 2020; Kirkland et al. 2021; Mulder et al. 2021). However, the variable transition timing (e.g., 3.8–3.6 Ga in the Slave craton and 3.2–3.0 Ga in SW Greenland; FIG. 3B) most likely points to craton-specific evolution histories rather than synchronous events at a planetary scale. In support of this, note that the zircon εHf(t)–age trends observed in some cratons are missing from others (e.g., Pilbara and Kaapvaal; Kemp et al. 2023) (FIG. 3B). It is therefore emphasized that the global εHf(t) range can be explained by local variations in the composition, crustal residence time, and reworking histories of the mafic precursors of TTGs.

Unravelling the Complex History of TTGs using Multiple Accessory Minerals

Depending on the timing of their crystallization, different accessory minerals may provide “snapshots” of distinct magma and/or metamorphic evolution stages. For instance, TTG-hosted zircon can show homogeneous trace element compositions regardless of the geochemical diversity of the host rocks (from high-HREE-Y- to low-HREE-Y TTGs) and very low Ti contents, interpreted to record crystallization mainly from compositionally uniform (near-eutectic) melts formed within the last 100 °C of the TTG crystallization history (Laurent et al. 2022). In contrast, apatite compositions of some TTGs mirror those of the bulk rocks: apatite from high-HREE-Y, low-Sr TTGs exhibit higher Y and lower Sr contents than those from low-HREE-Y, high-Sr TTGs (Bruand et al. 2020). This suggests that apatite crystallized early enough in these TTG suites to record compositional differences related to distinct melt production mechanisms in the source.

Several studies of metamorphosed Eoarchean TTG gneisses have further shown that micro-analysis of accessory minerals has the potential to identify whether metamorphic events resulted in changes of whole-rock chemical and isotopic signatures. For example, apatite, titanite, and monazite from Eoarchean TTG gneisses document metamorphic re-equilibration of the Sm-Nd isotopic system at the sample scale, such that whole-rock Nd isotopic compositions no longer reflect those of the initial magma sources (Hammerli et al. 2019). In other cases, accessory minerals preserve information about the magma sources and their compositions, even in highly metamorphosed TTGs. For example, apatite inclusions encapsulated in zircon have been shown to partially or completely preserve U-Pb ages and chemical compositions of the parent magma, whereas matrix apatite was re-equilibrated at the age of the metamorphic event (Antoine et al. 2020; FIG. 4).

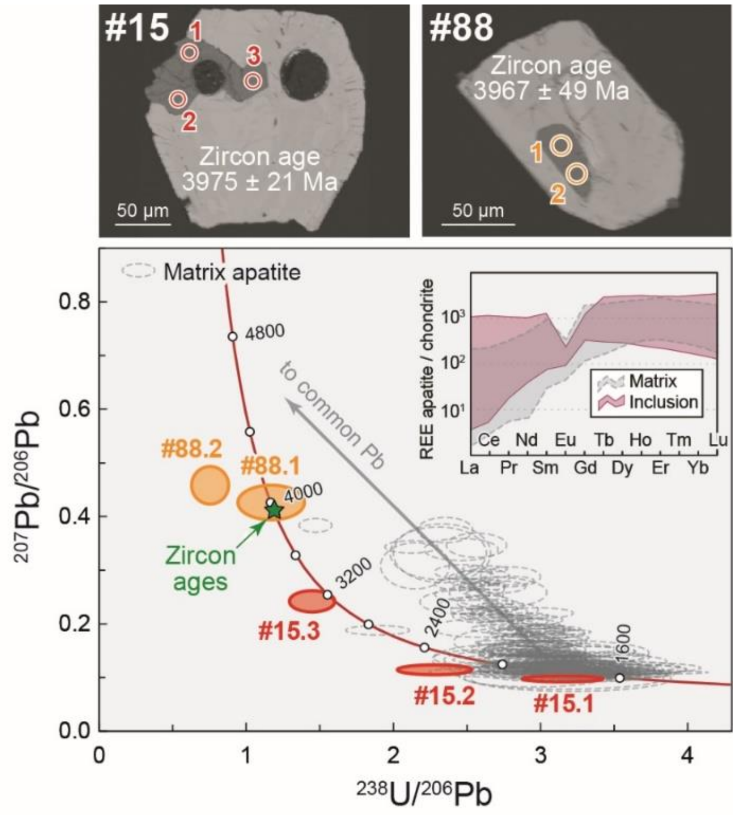

Figure 4: Zircon-hosted apatite inclusions as tools to distinguish primary from secondary information in metamorphosed TTGs. MODIFIED FROM ANTOINE ET AL. (2020). The back-scattered electron images show apatite (dark gray) inclusions in ca. 3.97 Ga zircons (light gray) from a TTG sample of the Acasta Gneiss complex in Canada. Circles represent micro-analytical (laser ablation ICP-MS) spots, with corresponding U-Pb data reported in a Tera-Wasserburg plot (see *Toolkit*). While fully included apatite (#88) has recorded U-Pb dates comparable to those of the host zircon, apatite partly connected to the matrix (#15) does not. Instead, it records dates near those of matrix apatite, which reflect regional metamorphism at ca. 1.72 Ga. Despite U-Pb resetting, the latter largely preserved magmatic REE compositions, as they overlap with those of apatite inclusions (inset plot).

One important potential future outcome of studies on multiple accessory minerals will be a better understanding of the geochemical signatures of TTGs. In particular, this will allow focusing exclusively on observations pertaining to magma sources and petrogenesis, in contrast to using only whole-rock compositions, which represent the integrated, end-product of a complex array of magmatic and potentially metamorphic processes.

POSSIBLE GEODYNAMIC IMPLICATIONS OF TTG FORMATION

For the purpose of this discussion, it is important to distinguish (1) the *conditions* (temperature, depth) *of TTG magma generation*; (2) the *local tectonic site* through which the hydrated mafic source was transported to these conditions; and (3) the *global-scale geodynamic setting* that comprises this tectonic site, among others (e.g., in the case of modern plate tectonics, convergent margins coexist with mid-ocean ridges, hotspots, etc.). Critically, petrological and geochemical data on TTGs and their accessory minerals constrain the *conditions of magma generation* only, namely, temperatures of 750–950 °C and a range of possible melting depths. This range may either span from ca. 20 to >100 km or, as mentioned above, be more restricted (20–50 km), depending on the composition of the source, the presence or absence of water during melting, and the role played by magma differentiation processes.

FIGURE 5 shows a variety of *tectonic sites* that may satisfy these two end-members in terms of melting depth ranges, classified based on their likelihood to be found in a *global geodynamic setting* resembling modern plate tectonics. Melting of mafic crust along anomalously hot subduction zones (e.g., Martin 1986), characterized by continuous steep to flat-lying slabs (FIG. 5A, 5B), could take place in a plate tectonic environment. However, the relevant melting depth ranges can also be reached in situations still resembling convergent plate margins, yet characterized by processes unlike modern subduction, such as intermittent dripping of the lower plate ("dripduction"; e.g., Moyen and Laurent 2018; FIG. 5C) and under-thrusting of mafic slices at the leading edge of a drifting lithospheric block ("subcretion"; e.g., Bédard 2018; FIG. 5D). Finally, melting in an essentially "intraplate" environment is also possible, notably at the base of mafic plateaus and/or from rafts of lower crust "dripping" into the underlying mantle (e.g., Johnson et al. 2017; Smithies et al. 2019; FIG. 5E, 5F). These scenarios are unlikely to be found in a global plate tectonic environment, as shown by the paucity of silicic magmas produced in modern intraplate settings like oceanic plateaus.

It is stressed that all sketches presented in FIGURE 5 are only possible snapshots of transient and/or local tectonic processes that occurred within broader-scale geodynamic environments. Therefore, these scenarios are not mutually exclusive and could have either happened simultaneously, or successively in time, on both local and global scales. This is well illustrated by zircon Hf isotopes versus time systematics in TTGs, pointing to diachronous crust formation and evolution from one craton to another (see FIG. 3). For these reasons, to address the problem of early Earth geodynamics, it appears necessary to investigate the evolution of crust-forming processes on a local or regional scale (i.e., craton, or terrane within a craton) and draw comparisons between them. In general, a more robust understanding of Archean geodynamics would certainly arise from a more systematic integration of information about TTG petrogenesis (field observations; petrological and geochemical data, including geochronology and trace element/isotopic data on accessory minerals; thermodynamic modeling) with the regional geological context and independent constraints (e.g., data from other granitoid types, structural and metamorphic records of greenstone belts, thermo-mechanical modeling, study of cratonic mantle xenoliths, etc.).

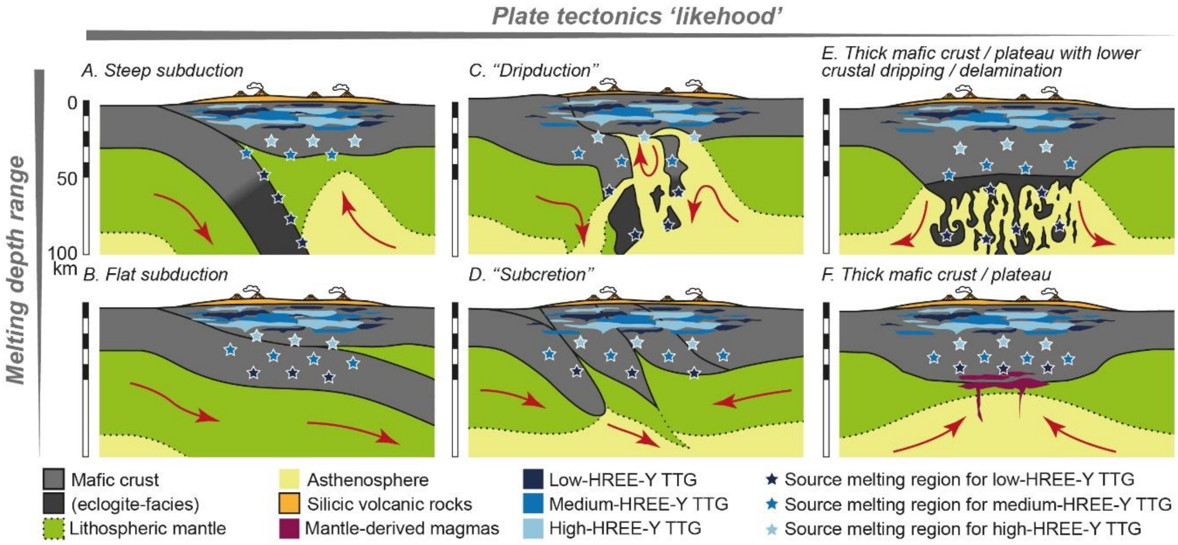

Figure 5: Possible tectonic sites for forming TTG magmas. The two rows of images correspond to the two end-member ranges of melting depths, from large (20–100 km; **TOP**) to restricted (20–50 km; **BOTTOM**), as constrained by the petrological and geochemical data on TTGs and their minerals. The three columns of images depict the likelihood to find these sites in a global geodynamic environment similar to modern plate tectonics, from high (**LEFT**) to intermediate (**MIDDLE**) and low (**RIGHT**).

CONCLUSIONS AND OUTLOOK

Rocks of the TTG suite represent the dominant, oldest preserved crustal lithology of Archean cratons. The term "TTG" applies to rocks that do not all have the same significance, including shallow intrusions, heterogeneous plutonic to migmatitic complexes, and deformed and metamorphosed "grey gneisses." Considering these contextual differences and filtering out the effects of syn- to post-magmatic processes specific to each rock assemblage are critical tasks to retrieve the geochemical signals corresponding to magma-forming conditions and address the geodynamic significance of TTGs. Data from TTG accessory minerals hold promise of being highly relevant to address this issue (FIG. 4).

The formation of TTG magmas requires two essential steps: (1) formation of a hydrous basaltic source and (2) transport of the source to depth to reach the pressure and temperature conditions required for partial melting: ca. 750–950 °C and a range of possible melting depths (from 20–50 km to 20–100 km) depending on source composition (enriched or primitive Archean basalt, respectively). However, the mechanisms by which water was brought to the melting site (burial of mafic rocks hydrated at the surface or primordial water contained in mafic magmas extracted from undepleted mantle) are still debated. Likewise, a variety of tectonic configurations may account for the melting conditions in which TTG magmas formed, involving or not a global plate tectonic regime.

Individual blocks of Archean crust, including distinct terranes from a given craton, have their own particular history of mafic and TTG crust formation, amalgamation, and reworking, that may last tens to hundreds of millions of years. These crustal evolution histories should be investigated through a systematic linkage between petrological and geochemical constraints on TTG magma formation, data from accessory minerals (e.g., zircon Hf-O isotopes; monazite/titanite/apatite Nd isotopes; and newly developed tools such as Si isotopes in zircon, S speciation in apatite, etc.), and local geological contexts.

Closing the knowledge gaps summarized above is an exciting challenge for future research, as this will enlighten our understanding of how Archean cratons and continents in general formed and became preserved. This understanding is fundamental to solve the enduring mystery of the emergence of life on Earth.

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