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Instability of the southern Canadian Shield during the late Proterozoic

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ABSTRACT

Cratons are generally considered to comprise lithosphere that has remained tectonically quiescent for billions of years. Direct evidence for stability is mainly founded in the Phanerozoic sedimentary record and low-temperature thermochronology, but for extensive parts of Canada, earlier stability has been inferred due to the lack of an extensive rock record in both time and space. We used ^{40}Ar/^{39}Ar multi-diffusion domain (MDD) analysis of K-feldspar to constrain cratonic thermal histories across an intermediate (∼150–350 °C) temperature range in an attempt to link published high-temperature geochronology that resolves the timing of orogenesis and metamorphism with lower-temperature data suited for upper-crustal burial and unroofing histories. This work is focused on understanding the transition from Archean–Paleoproterozoic crustal growth to later intervals of stability, and how uninterrupted that record is throughout Earth's Proterozoic "Middle Age." Intermediate-temperature thermal histories of cratonic rocks at well-constrained localities within the southern Canadian Shield of North America challenge the stability worldview because our data indicate that these rocks were at elevated temperatures in the Proterozoic. Feldspars from granitic rocks collected at the surface cooled at rates of $<0.5\,^{\circ}$C/Ma subsequent to orogenesis, seemingly characteristic of cratonic lithosphere, but modeled thermal histories suggest that at ca. 1.1–1.0 Ga these rocks were still near ∼200 °C – signaling either reheating, or prolonged residence at mid-crustal depths assuming a normal cratonic geothermal gradient. After 1.0 Ga, the regions we sampled then underwent further cooling such that they were at or near the surface ($\ll 60\,^{\circ}$C) in the early Paleozoic. Explaining mid-crustal residence at 1.0 Ga is challenging. A widespread, prolonged reheating history via burial is not supported by stratigraphic information, however assuming a purely monotonic cooling history requires at the very least 5 km of exhumation beginning at ca. 1.0 Ga. A possible explanation may be found in evidence of magmatic underplating that thickened the crust, driving uplift and erosion. The timing of this underplating coincides with Mid-Continent extension, Grenville orogenesis, and assembly of the supercontinent Rodinia. ^{40}Ar/^{39}Ar MDD data demonstrate that this technique can be successfully applied to older rocks and fill in a large observational gap. These data also raise questions about the evolution of cratons during the Proterozoic and the nature of cratonic stability across deep time.

1. Introduction

1.1. Cratons and stabilization

Cratons are made of ancient, tectonically quiescent continental lithosphere that has characteristically thick, chemically depleted mantle and low heat flow (e.g. Jaupart et al., 2014; Jordan, 1978; Rudnick and Nyblade, 1999). Cratons are intrinsically interesting because they record the secular evolution of the continents and a cyclic response to mantle dynamics. Moreover, cratonization and weathering of large, stable landmasses are considered integral to geo-biological evolution linked to fundamental environmental changes such as atmospheric and oceanic oxygenation and nitrification (e.g. Young, 2013 and references therein).

Here we define "stability" as resistance to internal deformation, limited magmatism, and maintenance of continental freeboard (Pollack, 1986). The established view is that most cratons underwent a period of long-term stability for most of the Proterozoic following early consolidation and exhumation at the end of the Archean. The lack of a record of significant tectonic events in the long interval between initial Archean cratonization and

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epeirogenic activity in the Phanerozoic is the basis for this assessment. This large time gap corresponds to the Great Unconformity, which in some places represents over 1–2 billion years of time (e.g. Karlstrom and Timmons, 2012). For the majority of the interval, time–temperature data are lacking, and there are few preserved extensive or temporally continuous sedimentary rocks in many cratonic terranes from this period, thus leaving the erosional record poorly constrained. Geochronologic study of cratons has usually been focused either on understanding cratonization and metamorphism during orogenic suturing using high-closure temperature ($>500\,^\circ$C) methods (e.g. Schneider et al., 2007) or alternatively, examination of more recent shallow exhumation and burial histories using methods with low closure temperatures ($<100\,^\circ$C) (e.g. Ault et al., 2009). From a thermochronological standpoint, the 1 to 2 billion-year gap in the Proterozoic record could simply reflect the lack of studies using methods that address the 500 °C to 100 °C temperature window.

This period of apparent cratonic lithosphere stability between 1.7 to 0.75 Ga contributes to the idea that it represents the "Boring Billion" or "Earth's Middle Age" (Cawood and Hawkesworth, 2014 and references therein), a time of geological, biologic, and environmental stability that is attributed in part to secular cooling of the mantle and the development of a strong continental lithosphere. The Columbia supercontinent cycle from ca. 2.1–1.3 Ga (Rogers and Santosh, 2002) began this period of pervasive stability and endured until protracted breakup of Rodinia between ca. 0.86–0.57 Ga (Li et al., 2008). The 1.1 Ga orogenic belts that occur on several modern continents (Hoffman, 1988; Li et al., 2008) are the basis for primary reconstructions of the late Mesoproterozoic supercontinent Rodinia. Rodinia formed through global contractional orogenesis from ca. 1.3–1.0 Ga. Reconstructed paleogeography demonstrates that the entire southeastern margin of Laurentia experienced several stages of accretion between ca. 1.75 and 1.0 Ga, whereas the Laurentian core underwent continental-scale northeast–southwest extension, causing rifting and numerous dike swarms (e.g. Whitmeyer and Karlstrom, 2007).

1.2. Stability: record or lack thereof?

The Phanerozoic sedimentary record within continental interiors primarily establishes the direct geologic evidence for more recent stability. Cratons in particular seem to have experienced no more than ∼1–3 km of vertical motion over many hundreds of millions of years during Paleozoic–Mesozoic time, based on a modest amount of stratigraphic data and low-temperature thermochronology (Ault et al., 2009; Flowers et al., 2012, 2006a). Suggested mechanisms for the observed epeirogenic motions in North America include far-field lithospheric responses to subduction (Mitrovica et al., 1989) and dynamic topography induced by mantle flow (Forte et al., 2010). In central Canada, the case for stability is based mostly on what is missing: a paucity of Proterozoic orogenic activity and preserved sediments, and a lack of disturbed (i.e. thermally reset) geochronological systems.

Extensive work in the western Superior Province suggests that orogenic activity over the Kenoran interval (Kenorland; ca. 2.75 to 2.65 Ga) ceased by 2.6 Ga and transitioned shortly thereafter to stable cratonic lithosphere by 2.5 Ga, with some immediate post-orogenic sedimentation (e.g. the Huronian Supergroup; Percival et al., 2012). Internal deformation occurred during mantle plume activity in the form of the Matatchewan large igneous province (LIP) and dike swarm at ca. 2.48–2.45 Ga during proto-continental breakup (Ernst and Bleeker, 2010) and 2.2 Ga emplacement of the Nipissing Sills fed by the Ungava plume. The Kapuskasing Uplift in the western Superior Province caused local deformation that exposed the middle-lower crust at ca. 1.9 Ga (Percival and West, 1994). The 1.86 Ga Penokean Orogeny resulted in the Himalayan-scale orogen that existed along the southern Superior margin, synchronous with the Trans-Hudson Orogeny (THO; ca. 1.9–1.8 Ga) to the north and northwest (Bickford et al., 2005) leading to Laurentian assembly. Yavapai orogenesis occurred to the south at ca. 1.75 Ga, leading to deposition of the Athabasca and Baraboo sequences, and other mature sandstones across Laurentia (Davidson, 2008 for review). Later, Rodinia assembly and Grenvillian orogenesis caused continental-scale extension, while concurrent hotspot magmatism produced the 1.27 Ga Mackenzie dike swarm, 1.24 Ga Sudbury dike swarm, and the 1.1 Ga Mid-Continental Rift (MCR) volcanism and Abitibi dike swarm (Ernst and Bleeker, 2010). Following these events, subtle epeirogenic motions of up to ±1–2 km characterized the Phanerozoic (Feinstein et al., 2009; Flowers et al., 2012).

The Trans-Hudson Orogen underwent an orogenic and stabilization sequence analogous to that of the earlier Kenoran Orogeny, where ca. 1.9 to 1.8 Ga granulite-facies metamorphic rocks (Alexandre et al., 2009; Flowers et al., 2008; Schneider et al., 2007; Williams and Hanmer, 2006) underlie Athabasca sediments deposited between ca. 1.7 to 1.6 Ga (Rainbird et al., 2007). This was seemingly followed by quiescence until modest Phanerozoic epeirogenesis (Ault et al., 2009; Flowers et al., 2012). Almost a billion years of thermal record is unaccounted for after initial stabilization. It is clear that certain locations on the North American craton such as Athabasca show that orogenic mid-crustal rocks were exhumed into the shallow crust soon after orogenesis (e.g. Williams and Hanmer, 2006). However, many other parts of the Canadian Shield are lacking conclusive information on post-orogenic activity in the late Archean through Proterozoic.

This paper addresses the apparent post-orogenic stability of the southern Canadian Shield during the Proterozoic using K-feldspar ^{40}Ar/^{39}Ar thermochronology and examines potential mechanisms to explain the thermal histories suggested by these data, including cratonic disruption near the end of the Proterozoic caused by crustal thickening and uplift due to magmatic underplating. Our conclusions suggest that parts of the Canadian Shield experienced significant exhumation beginning at ca. 1.0 Ga.

2. K-feldspar multi-diffusion domain ^{40}Ar/^{39}Ar thermochronology

2.1. Linking high and low-temperature thermochronometers

Potassium feldspar is a useful mineral for ^{40}Ar/^{39}Ar dating because of its high K content, ubiquity in felsic rocks, and stability during *in vacuo* heating (McDougall and Harrison, 1999). K-feldspar is moderately retentive of radiogenic ^{40}Ar, and low-temperature ordered K-feldspars usually exhibit complex microstructures that lead to what has been termed multi-diffusion-domain (MDD) behavior, which means that most grains of K-feldspar contain a distribution of diffusion domains that can record a range of temperatures (Lovera et al., 1989, 1991). ^{40}Ar/^{39}Ar K-feldspar MDD analysis is able to determine continuous temperature–time (T–t) paths over the range ∼150 °C to 350 °C and the shape of age spectra can distinguish between slow and rapid cooling. Continuous T–t paths can be established over this interval because the ^{39}Ar released during step-heating can be used to independently determine the sample's specific diffusion kinetics and domain-size distribution. These data can then be used to invert the observed ^{40}Ar/^{39}Ar age spectrum for the only remaining unknown, the thermal history. Modeling for thermal history is best done using an inverse approach to eliminate observer bias from forward modeling, and also speed up the recovery of a robust suite of thermal histories. K-feldspar ^{40}Ar/^{39}Ar thermochronology fills the middle-temperature range between higher temperature methods recording crystallization, such as U–Pb geochronology, and