(U-Th)/He thermochronology constraints on the Phanerozoic exhumation history of the eastern Pilbara Craton, Australia

By
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Abstract:

The Pilbara of Western Australia is an Archean craton that has provided key insights into the early Earth, including continental formation, continental emergence, and early evolution of life. However, its younger history of Phanerozoic burial, exhumation, and uplift is poorly understood due to its considerable age and scarcity of published regional low temperature thermochronology data. Here, we present new zircon and apatite, Uranium-Thorium/Helium ((U-Th)/He) data gathered from multiple Archean granitic intrusions across the Eastern Pilbara Craton. The samples cover an area of 12,000 km², and include intrusions emplaced between 3500 and 2900 Ma. They range in composition from true granites to granodiorites with one dolerite. Our preliminary findings indicate regional cooling between 425-370 Ma. An important additional geologic constraint is that the ~2940 Ma Chillerma granite is unconformably overlain by the Jurassic-Cretaceous Callawa Formation. Together the results imply the Chillerma was exhumed into the near-surface in the Silurian, and was exposed at the surface during the Mesozoic by the time of deposition of the Callawa formation. Previous apatite fission-track studies, from about 200 km south of the Chillerma, corroborate our interpretation, with Paleozoic cooling around 320 Ma (Weber et al. 2005). The Pilbara Craton had a dynamic and protracted Paleozoic exhumation history.
Introduction:

Global Archean craton thermochronology has been an arduous pursuit. This pursuit has been largely limited by complex sample histories. Ambiguous plate reconstructions and paleogeography further confound such efforts. In this thesis, I outline a study focused on constraining the low-temperature thermal history of the Archean Pilbara craton using zircon and apatite (U-Th)/He data obtained in the University of Colorado’s Thermochronology Research and Instrumentation Laboratory (TRaIL).

The uplift history from emplacement to exposure of the Achaean Pilbara Craton has been poorly constrained. While the Archean history of crustal growth and assembly is reasonably well constrained (Nijman et al., 2017; Kranendonk et al., 2002; Weber et al., 2005), there has been little study of the craton’s Phanerozoic history. Lithological, stratigraphic, and structural evidence of exhumation is not easily recognizable, due to the great age of the rock units and preexisting structures. In this study, I present new low temperature zircon and apatite (ZHe and AHe, respectively) (U-Th)/He thermochronometry data for samples from a 12,000km² area with compositions from true granites to granodiorites and one dolerite that help to better constrain the exhumation/uplift history of the Pilbara Craton.

Geologic and Tectonic Setting:

The geology of the Australian continent can be broken into four main geologic regions: Achaean Granite-Greenstone Terranes in the west, Proterozoic orogenic belts
scattered throughout western and central AU, Paleozoic-Mesozoic orogenic belts in the
east, and Proterozoic to Cenozoic sedimentary basin all throughout (Fig. 1). Australia is
fundamentally divided by the Tasman Line separating Precambrian blocks to the west
from Phanerozoic orogenic belts along the eastern margin (Gleadow et al., 2002). The
Pilbara Craton, located in Western Australia, is comprised of two fundamental
components: a Paleoarchean to Neoarchean (3.72-2.85 Ga) basement of granitoids
surrounded by greenstones in the northern region, which unconformably overlie a
volcanic-sedimentary package from the Neoarchean (2.77-2.40 Ga) to the south
(Kranendonk, 2002) (Fig. 2). The tectonic processes that formed the craton are still
debated (e.g., Smithies et al., 1999; Zegers, 1996). Hypotheses include: 1) an
amalgamation of Archaean terranes, which is the case for the Yilgarn Craton
immediately to the south, 2) solid-state diapirism (Weber et al., 2004), and 3) phases of
plutonism of the granitoids interjected with phases of microplate tectonics (Kranendonk,
2002) (Fig. 2). Regardless of the exact mechanism of formation, the granite-greenstone
Pilbara is one of the largest and best exposed Archean regions in the world. The age of
these rocks coupled with the low relief of this region has led to some researchers to
suggest that the craton has been exposed at approximately its current level for an
extended time interval, with little lowering by erosion since perhaps as early as
Mesoproterozoic (e.g., Fairbridge and Finkl, 1980). In addition, a valley-fill conglomerate
from the Northern Territory in Central Australia formed a depositional surface that has
been undisturbed and subaerial since the mid-Cambrian, implying little tectonism since
the Neoproterozoic (Weber et al., 2004).
Figure 1: Simplified geologic map of Australia (Gleadow et al., 2002) Showing the major geologic components of the continent along with the Tasman Line.

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Figure 2: Simplified geologic map of Pilbara Craton (Wacey, 2009) with sample locations.
Methods and Materials:

Samples:

Dr. Benjamin Johnson collected these samples in Western Australia during July of 2018 with the hopes of gathering geochronologic and thermochronologic data. There are a total of six granitic samples and one dolerite that were brought back with him to the University of Colorado. This is where I stepped in for further processing and data gathering for this research project.

Table 1: Sample list with date, location, rock type, and approx. age

<table>
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<tr>
<th>Sample name</th>
<th>Collection Date</th>
<th>Latitude (S, Decimal degrees)</th>
<th>Longitude (E, decimal degrees)</th>
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<td>118.11475</td>
<td>Granite</td>
<td>2946 Ma</td>
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</tbody>
</table>
BWJ18-001: Mt. Edgar Granite: Figure 3A and 3B
Granite to granodiorite showing high amounts of plagioclase feldspars and quartz, with potassium feldspar and biotite possibly amphiboles, with a crystallization age around 3420-3500 Ma.

BWJ18-002: Fig Tree Granite: Figure 4A and 4B
Granite displaying large potassium feldspar crystals, plagioclase feldspar, small but many quartz crystals, as well as biotite and accessory minerals, with a crystallization age of around the same time as the Mt. Edgar Granite 3420-3500 Ma.

BWJ18-031: Callina Granite Super Suite: Figure 5
Granodiorite showing lots of plagioclase feldspar, biotite, and quartz, medium-coarse grained with no obvious potassium feldspar, that was found underlying the Strelley Pool formation. This sample has a crystallization age of 3469 Ma.
BWJ18-078: Carlini Granite: Figure 6A and 6B
Granitoid exhibiting large amounts of quartz, plagioclase feldspar, light potassium feldspar and small amounts of scattered accessory minerals with a crystallization age of 2945 Ma.

BWJ18-081: Chillerma Granite: Figure 7A and 7B
This granite has large quartz, plagioclase feldspar crystals, with some small potassium feldspars and biotite. As seen in figure 5B, this granite is underlying the Callawa formation, a Jurassic to cretaceous sandstone. Same as the Carlini, this sample has a crystallization age of 2945 Ma.
BWJ18-082: Dolerite Dike: Figure 8A and 8B
Small tightly packed crystals of plagioclase feldspar and pyroxene with several accessory minerals. This Dolerite dike is cutting across the older Portree granite shown in figure 6B. The youngest of these samples, this rock has a crystallization age of about 2760 Ma.

BWJ18-083: Portree Granite: Figure 9A and 9B:
This sample has a similar age to the Carlindi and Chillerma Granites, with a crystallization age around 2946 Ma. A very pink granite showing lots of crystals of potassium feldspar, and some quartz, biotite and other accessory minerals.

Thermochronology Dating Methods:

(U-Th)/He Thermochronology is based on measuring the accumulation of alpha particles of Helium 4 (^4He) in mineral samples that are the result from decay of Uranium (U), Thorium (Th), and Samarium (Sm) in minerals. Helium diffuses out of the crystal at a higher temperature and is retained at lower temperatures. This generally means that
(U-Th)/He dates are cooling ages, and the more \(^4\)He a mineral retains, the longer it has been at near surface conditions (low temperature 80-100°C or less). This concept is straightforward, but cooling histories can be masked by reburial or reheating events. These events cause the mineral to go above its closure temperature with respect to He, and “reset” the He-clock. Potential reheating events are important to consider, especially in rocks that are as old as those in the Pilbara.

Apatite and zircon are the most commonly used minerals for (U-Th)/He thermochronology, since they are common minerals, have abundant parents (U, Th, Sm), and can retain measurable quantities of He. The production of these alpha particles, \(^4\)He, is a function of the decay of 238U -235U -232Th and can be shown in this age equation:

\[
\frac{^4D}{P} = 0
\]

\[
T_c
\]

\[
\frac{^4D}{P} > 0
\]

Figures 10 and 11: (Metcalf and Flowers, In Press) Fig. 10 showing parent daughter ratio relationship in relation to closure temperature \((T_c)\) and in Fig. 11 a graph depicting the approx. closure temperatures for a suite of minerals. Notice zircon He and apatite He in blue boxes to the right, used in this study.
\[ ^{4}\text{He} = 8 \times ^{238}\text{U}(e^{\lambda_{238}t} - 1) + 7 \times ^{235}\text{U}(e^{\lambda_{235}t} - 1) + 6 \times ^{232}\text{Th}(e^{\lambda_{232}t} - 1) + 147\text{Sm}(e^{\lambda_{147}t} - 1) \]

where \( t \) is the age or accumulation time, \( \lambda \) is the respective decay constant and the

He, U, Th, and Sm is the amount of atoms in the mineral (Metcalf and Flowers, In Press).

Levels of U, Th, and Sm along with daughter product He were measured in
apatites and zircons from the collected samples. These data were used to calculate (U-
Th)/He dates, with the goal of constraining the cooling history of the Pilbara craton. This
cooling history can then be related to a
variety of geologic processes like
erosional exhumation, formation of
features, deformation of features and
emplacement.

To obtain robust dates from (U-
Th)/He data, we needed to have a
selection of quality individual apatite
and zircon minerals. To do this we
begin with the hand samples and break
them down into individual minerals.

This is accomplished by running the
samples through the Jaw Crusher and
Vertical Disk Grinder-Pulverizer (Fig.
12) in CU Boulder’s rock shop, turning
the previous whole rock into a mixture
of fine powder to a small gravel. This sample is then sieved through wire mesh to a level
of less than or equal to 500 \( \mu m \) and following this it is separated hydrodynamically via
Wilfley Table (Fig. 13) to isolate higher density minerals. Next the sample undergoes a magnetic separation process with first a hand magnet and then through the Frantz Magnetic Separator set to 1.0 Amp and at an angle of 20°. Lastly, with the denser, mostly non-magnetic minerals, the sample is partitioned via heavy liquid separation using Lithium Metatungstate at a specific density around 2.95 g/cm³.

This final selection of minerals, usually just a tiny pinch, is placed under a Leica binocular microscope for each apatite or zircon mineral (Fig. 14) to be carefully selected and packaged in niobium (Nb) tubes. Selection of minerals are based on size (> 60 μm), the euhedral shape of the crystal, and free of inclusions for apatites especially.

These mineral packages are then loaded into an ASI Alphachron He extraction line (UHV ~3x10⁻⁸torr) and subjected to 25W diode laser for five to ten minutes, heating the packaged mineral to about 800 to 1100°C to extract the radiogenic ⁴He. Next, the minerals are spiked with a ²³⁵U -²³⁰Th -¹⁴⁵Nd tracer and either the apatite is dissolved in a HNO₃ solution or the zircons are dissolved in a multiple acid-vapor dissolution using HF placed in a Parr...
dissolution vessel. After baking (80°C at 2 hours for apatites or 220°C for 72 hours for zircons) the samples are dried, then placed under another acid-vapor dissolution HCl and baked again (200°C at 24 hours). After the mineral samples are fully dissolved, measurements of U, Th and Sm are analyzed using an Agilent ICP-MS and compared against standards of Durango fluorapatite and Fish Canyon Tuff zircons. From this He raw dates are calculated from the methods based on Ketcham et al. (2011).

Raw dates are corrected for alpha ejection. When the decay of U, Th, and Sm takes place the alpha daughter particles shoot out about 20 μm from the parent nuclides. This alpha ejection has the probability to release the 4He atom, or alpha particle, out of the crystal. To account for this loss an alpha ejection correction must be made to the raw calculated dates, determined by the size and shape of the crystal and an assumption that levels of U and Th are uniformly distributed about the crystal (Flowers et al. 2009). Uncertainties are reported with the corrected date based on total U, Th, Sm, and He levels within 2σ standard deviation.

**Results:**

Out of the seven total samples that were processed and separated, only four of these samples produced quality apatites and zircons. Two samples, the Fig Tree granite (BWJ18-002) and the Chillerma granite (BWJ18-081) yielded apatite and zircon that gave reproducible dates. Five apatites and three zircons from the Fig Tree granite were analyzed along with eight apaties and three zircons from the Chillerma granite. In addition, three zircons were analyzed from the Callina Super Suite granite (BWJ18-031) and three apatites were analyzed from the Carlinidi granite (BWJ18-078).
In the Fig Tree Granite, the Apatite (AHe) dates range from about 350 to 435 Ma and Zircons (ZHe) range from about 310 to 350 Ma. And in the Chillerma Granites AHe dates range from about 345 to 410 Ma and ZHe range from about 420 to 440 Ma. In the Callina Super Suite, zircon (ZHe) dates range from about 230 to 340 Ma. and in the Carlindi granite results were inconclusive with apatite (AHe) dates ranging from 415 to 1070 Ma with no clear average. Of all of these samples, two apatite minerals from the Carlindi, one apatite from the Chillerma, and one zircon are disregarded. There appear to be micro-inclusions not seen during hand picking that potentially influenced the levels of U, Th, and Sm to produce unusually high data levels thus skewing the calculated date.

Radiation damage of crystals affects the retention of He and because of this, it affects the temperature sensitivity of the apatites and zircons. To account for this, effective uranium (eU= [U] + 0.235[Th]) concentration is used as an intermediary tracker to radiation damage, it is a parameter that weighs the decay of the two parent atoms against their alpha productivity (Flowers et al., 2007). Common practice in the (U-Th)/He thermochronology community is to compare these levels of eU to the corrected dates as seen in the plots below (Fig. 15 & 16). Radiation damage in apatites increases the closure temperature which affects both eU and analyzed date positively for samples that have experienced long histories (Shuster et al., 2006; Flowers et al., 2009).

Damage to the zircon is a bit different, as it accumulates damage, the He closure temperature increases until it reaches an alpha dose threshold of about \(150 \times 10^{16} \alpha/g\), after this the retention of He is lost and closure temperature decreases (Guenthner et al., 2013; Ketcham et al., 2013). Another concern is that at higher temperatures, the
radiation damage can be annealed thus reversing the effects of He diffusivity in accumulation (Baughman, 2017). Factoring in the damage, annealing, and alpha ejection correction, we use a conservative 20% uncertainty for reporting eU values. Reasoning for this uncertainty is grounded in the maximum eU difference that is calculated from the volumes of the grains (Baughman et al., 2017).
Table 2. (U-Th)/He analysis results of apatite (aHe) and zircon (zHe) samples

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<th>length 2 (mm)</th>
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<th>rs (mm)</th>
<th>radius (mm)</th>
<th>4He (nmol/g)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>(He/Ar)</th>
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Note: The table contains analysis results of (U-Th)/He for apatite (aHe) and zircon (zHe) samples. The columns include sample names, full samples, length and width dimensions, results of radiogenic and initial helium, and other relevant parameters for the analysis.
Figure 15: Plot of apatite aHe (A) and zircon zHe (B) displaying corrected date (Ma) vs. eU levels in parts per million.
Figure 16: Plot of apatite aHe and zircon zHe from Fig Tree (A) and Chillerma (B) samples displaying corrected date (Ma) vs. eU levels in parts per million
Discussion:

It is not uncommon with rock samples of this age to measure AHe and ZHe data points with widespread scatter, due to the long geologic history and potential for reburial, reheating, or other tectonic events. This is not the case for the Pilbara samples in this study. The AHe and ZHe dates produced after (U-Th)/He Thermochronology analysis have good agreement and estimate very similar cooling ages seen on the plots. (Figs. 15 & 16).

The reproducibility of these samples and the overlap of the AHe and ZHe dates provide evidence for a regional cooling event that occurred ~340-440 Ma. Such an event would have caused both minerals to drop below their closure temperatures and begin retaining $^4$He at that time.

The link between closure temperature of the mineral sample and a cooling event taken place can be explained with geothermal gradient (Fig. 17). This is a rate of increasing temperature with respect to an increase in depth into the Earth’s crust and interior. Typically, at the near surface this gradient is ~25-30°C/km on average. So for a mineral in our sample to reach ~80-100°C this means it would likely be within ~3-4 km of the Earth’s surface. A possible explanation for such a cooling episode is an uplift event followed by

Figure 17: Schematic of the geothermal gradient of Earth’s interior (Adapted from Boehler, R., 1996)
an erosional event that removed rock layers that were on top of the formed minerals bringing the Earth’s surface down.

Additionally, Mid to Late Mesozoic riverine deposits that overlie the Chillerma Granite sample, indicate that this sample was exhumed to the surface by this time (Fig. 7B). Moreover, the consistency of the AHe and ZHe data suggests that they were not reset by reheating after 440 Ma. This implies that if reburial did occur that it was not deep enough to reset sampled minerals.

It is possible that regional events such as rifting, extension, uplift and erosion, could explain the cooling indications we found in the apatite and zircon minerals. During this age window, Australia was being amalgamated into Gondwana and Pangaea. Events happening around this time include: The Larapinta Seaway rifting (490-460 Ma), Harts Range orogen inversion (450-410 Ma), Strangways Range

Figure 18: From Blewett’s 2012 Shaping a Nation: A Geology of Australia, depicting the extension, rifting, and uplift events from 490-340 Ma.
thrusting (400-380 Ma), and the Alice Springs Orogeny (360-340 Ma) (Fig. 18) (Blewett, 2012).

Previous low temperature thermochronology using apatite fission-track (AFT) technique suggests that cooling of a region ~200 km south of the Chillerina Granite sample, occurred around 320 Ma (Weber et al., 2005). Interestingly, other AFT studies of Australia have similar recorded ages mostly grouped in a range from about 200-400 Ma. (Fig. 19) (Gleadow et al., 2002).

After looking at these data and the work done here in my study, I hypothesis the Alice Springs Orogeny to be the best possible explanation for the cooling event signature seen in the results. The ~ 360-340 Ma uplift event falls right in line with the (U-Th)/He dates of both aHe and zHe samples found my analysis. The majority of cooling ages are just under 400 Ma, suggesting close correlation in time with the Alice Springs event.

The Alice Springs orogeny is a reactivation of previously established normal faults (Blewett, 2012). Fairly distant convergence may have provided necessary tectonic stress to cause uplift and erosion, perpendicular to the direction of convergence in an analogous way to the Uintah Mountains of North America. Thus, while the Alice Springs orogeny is relatively far from a plate boundary, the coincidence of cooling ages

Figure 19: From Gleadow et al., 2002, showing apatite fission track data from around Australia.
with this mechanism for uplift suggest it to be a possible geologic cause of Paleozoic cooling. In addition, close age ranges found in the Weber et al. and Gleadow et al. studies from AFT methods. The comparison of these studies implies that the Pilbara Craton had a dynamic and protracted Paleozoic exhumation history.

**Conclusion:**

The Pilbara Craton is one of the best preserved and pristine fragments of Archean crust on the planet. The Pilbara has proved to have many key observations into the Archean geologic setting of early Earth, however its more recent Phanerozoic history is not as well known. This is in part due to the lack of published work on the area, as well as the region’s substantial age and complexity. The samples I analyzed using (U-Th)/He thermochronology methods imply a regional cooling event around ~340-440 Ma. In addition, observations from the Callwa Formation, a Jurassic-Cretaceous sediment layer that unconformably overlies my Chillerma Granite sample (Fig. 7B), indicate that the Pilbara craton basement in this region was exhumed to the surface by Jurassic-Cretaceous time. We also know that reburial to temperatures greater than 80-100°C could not have taken place as radiogenic He would have been lost from the crystals, causing the dates to be younger than observed. It would be intriguing to examine more low temperature data or other dating techniques of the Phanerozoic history of the Pilbara and Western Australia. Continuing work into the three remaining un-analyzed samples would prove valuable to a larger picture of the region.
**Reference list**


