RESEARCH ARTICLE

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Key Points:

- Fennoscandian Shield zircon (U-Th)/He ages are negatively correlated with effective uranium (eU), which is proportional to radiation damage
- These negative zircon He age-eU correlations give long-term constraints on multiple cycles of heating and cooling from 1.8 Ga to the present
- Titanite (U-Th)/He ages are also negatively correlated with eU; we provide some of the first evidence for damage effects on titanite He ages

Supporting Information:

- Table S1
- Table S2
- Table S3

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Zircon, titanite, and apatite (U-Th)/He ages and age-eU correlations from the Fennoscandian Shield, southern Sweden

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Abstract Craton cores far from plate boundaries have traditionally been viewed as stable features that experience minimal vertical motion over 100–1000 Ma time scales. Here we show that the Fennoscandian Shield in southeastern Sweden experienced several episodes of burial and exhumation from ~1800 Ma to the present. Apatite, titanite, and zircon (U-Th)/He ages from surface samples and drill cores constrain the long-term, low-temperature history of the Laxemar region. Single grain titanite and zircon (U-Th)/He ages are negatively correlated (104–838 Ma for zircon and 160–945 Ma for titanite) with effective uranium ($eU = U + 0.235 \times Th$), a measurement proportional to radiation damage. Apatite ages are 102–258 Ma and are positively correlated with eU. These correlations are interpreted with damage-diffusivity models, and the modeled zircon He age-eU correlations constrain multiple episodes of heating and cooling from 1800 Ma to the present, which we interpret in the context of foreland basin systems related to the Neoproterozoic Sveconorwegian and Paleozoic Caledonian orogens. Inverse time-temperature models constrain an average burial temperature of ~217°C during the Sveconorwegian, achieved between 944 Ma and 851 Ma, and ~154°C during the Caledonian, achieved between 366 Ma and 224 Ma. Subsequent cooling to near-surface temperatures in both cases could be related to long-term exhumation caused by either postorogenic collapse or mantle dynamics related to the final assembly of Rodinia and Pangaea. Our titanite He age-eU correlations cannot currently be interpreted in the same fashion; however, this study represents one of the first examples of a damage-diffusivity relationship in this system, which deserves further research attention.

1. Introduction

Despite their long-term isolation from active plate margins, crystalline basement rocks in interior continental settings can possess complex thermal histories that encompass multiple phases of heating and cooling. Such thermal histories have been previously constrained by low-temperature thermochronology in diverse settings, primarily by the apatite (U-Th)/He (apatite He) and apatite fission track (AFT) chronometers [Crowley *et al.*, 1986; Gleadow *et al.*, 2002; Kohn *et al.*, 2005; Ault *et al.*, 2009; Flowers and Schoene, 2010; Ault *et al.*, 2013]. Collectively, these apatite He and AFT studies challenge or augment more traditional view that cratons represent regions of long-term erosional or geomorphic stability [e.g., Stewart *et al.*, 1986; Lenardic and Moresi, 1999; Hendricks and Redfield, 2005]. Due to the relatively low temperature sensitivity of the AFT and apatite He systems, the time-temperature (t - T) constraints from these studies are largely confined to the Phanerozoic and may represent only a portion of the potentially billion year thermal histories for these regions. A more complete picture of the long-term t - T paths for cratons could further improve our understanding of the dynamics of these supposedly quiescent continental interiors. Recent advances in the zircon (U-Th)/He system (zircon He) have resulted in t - T constraints for some geologic settings that extend over a billion years and include multiple episodes of heating and cooling [Guenthner *et al.*, 2014; Orme *et al.*, 2016]. This approach relies upon an improved understanding of the relationship between radiation damage and He diffusion in zircon, and here we use the damage-diffusivity relationship to constrain the ~1800 Ma thermal history for the Fennoscandian Shield in southeastern Sweden.

This region is an example of a basement terrane that has experienced a complex, but poorly understood, thermal history. In our study area (Figure 1), granitic crystalline rocks associated with the 1810–1670 Ma [Larson and Berglund, 1992] Transscandinavian Igneous Belt (TIB), at this particular site dated to 1800 Ma [Wahlgren *et al.*, 2008], crop out at the surface and represent the dominant rock unit in southeastern

Figure 1. Geologic map of the study area with sample locations. Map of (a) Sweden with (b) Laxemar and (c) Götemar regions and sample locations highlighted, as well as the position of the Caledonian and Sveconorwegian thrust fronts.

Sweden. Evidence for burial of this Proterozoic basement by Paleozoic-Mesozoic cover rocks, primarily associated with the Caledonian foreland basin, is provided by geomorphic analysis [Lidmar-Bergström, 1993; Lidmar-Bergström, 1996], discordant zircon U-Pb ages [Larson and Tullborg, 1998], Paleozoic sediments [Larson et al., 2006], apatite He and AFT thermochronology [Larson et al., 1999; Hendricks and Redfield, 2005; P. Söderlund et al., 2005; Green and Duddy, 2006], and by elevated fluid inclusion homogenization temperatures of Paleozoic fracture filling calcite [Drake and Tullborg, 2009]. These studies also provide evidence for Neoproterozoic exhumation that led to a widespread, sub-Cambrian peneplain throughout the region, and Mesozoic-Cenozoic exhumation following Caledonian foreland basin development. A Precambrian foreland basin associated with the ~1000 Ma Sveconorwegian orogeny also likely developed in our study region, but evidence for specific details of this basin burial event, such as maximum burial temperature and timing of subsequent exhumation to the sub-Cambrian peneplain is sparse and incomplete [Hansen et al., 1996; Larson et al., 1999]. In this study, we focus on the t - T characteristics of both the Caledonian and Sveconorwegian events in order to construct a more comprehensive and long-term thermal history for southeastern Sweden. We primarily rely upon the zircon He thermochronometer to constrain these thermal histories, with a particular focus on negative correlations between single grain zircon He ages and effective uranium (eU , $eU = U + 0.235 \times Th$) concentrations. These correlations can be used to reconstruct t - T paths from zircon He data sets when combined with forward and inverse thermal history models that utilize a parameterization of the radiation damage-He diffusivity relationship [Guenther et al., 2013]. Apatite and titanite He ages, as well as the previous thermochronologic results from this area, provide additional sets of t - T constraints that support our thermal history conclusions.

2. Geologic Setting and Previous Thermochronologic Results

The Fennoscandian Shield of southeastern Sweden exhibits a complex, ~1800 Ma geologic history that has been only partially characterized. The bedrock in our study area in the Laxemar region (Figure 1) is dominated by the 1860–1650 Ma granitic TIB [Patchett et al., 1987; Högdahl et al., 2004], which at this site dates to 1800 Ma [Wahlgren et al., 2008]. Amphibole and biotite $^{40}Ar/^{39}Ar$ ages from surface and drill core samples of TIB rocks that overlap with our samples locations are 1790–1770 Ma and 1620 Ma, respectively [Söderlund et al., 2008]. These ages indicate that TIB rocks cooled quickly through ~500°C and then more slowly through ~300°C post-formation. From this same study, several younger biotite $^{40}Ar/^{39}Ar$ ages were 1510–1470 Ma, which suggests a reheating event associated either with the widespread emplacement of anorogenic granites in the Baltic Shield at 1645–1470 Ma [Rämö and Haapala, 2005], magmatism at the beginning of the 1470–1440 Ma Danopolonian event [Bogdanova et al., 2001, 2008; Brander and Söderlund, 2009], or partial resetting in relation to intrusions of two adjacent granites at Götemar and Uthammar at about 1430 Ma. Both the Götemar and Uthammar granites crop out within several kilometers of our

sample locations, with some samples coming directly from Götemar surface locations (Figure 1). Biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 1420 Ma collected from these granites are indicative of cooling through $\sim 300^\circ\text{C}$ at this time [Söderlund *et al.*, 2008] and similar ages of muscovite (1423–1424 Ma) in greisen around the intrusion indicate cooling through $\sim 350^\circ\text{C}$ [Drake *et al.*, 2009]. These ages, as well as evidence for Götemar granite emplacement depths between 4.5 and 8 km [Kresten and Chyssler, 1976; Cruden, 2008], suggest that our samples were at temperatures below $\sim 300^\circ\text{C}$ post-1420 Ma. The absence of Proterozoic sediments in the region precludes more robust paleodepth estimates for our sample locations; however, north of our study area, outcrops of the Mesoproterozoic Dala sandstone sequence lying directly on TIB rocks are scattered over large areas of the east central Sweden [Aldahan and Morad, 1986]. These sedimentary units are intercalated with basaltic and doleritic units whose feeder dikes are ~ 1460 Ma [P. Söderlund *et al.*, 2005]. These lines of evidence further suggest that our sample locations resided at relatively shallow crustal depths after the emplacement of the Götemar granite.

Two major post-1400 Ma orogenic events affected the Laxemar region. The earlier 1100–900 Ma Sveconorwegian orogeny imparted WNW-ESE directed shortening across much of western Sweden [Bingen *et al.*, 2006] and resulted in foreland basin development in eastern Sweden [Larson *et al.*, 1999]. Estimates of the amount and timing of burial associated with this foreland basin, including low-temperature thermochronologic results, are sparse and inconclusive. A handful of titanite and zircon fission track ages ranges from 929 to 666 Ma [Larson *et al.*, 1999], consistent with cooling through ~ 310 – 220°C at this time, but these data are mainly from single sample locations and lack a more comprehensive thermal history framework. Constraints from reset Rb-Sr isochrons suggest prehnite-pumpellyite facies metamorphism in southeastern Sweden that overlaps with the timing of Sveconorwegian orogenesis [Verschure *et al.*, 1980; Wickman *et al.*, 1983]. In Finland, AFT ages between ~ 1000 and 800 Ma are likely reset as a consequence of burial in the foreland basin of the Sveconorwegian event [Murrell and Andriessen, 2004; Kohn *et al.*, 2009]. Following the Sveconorwegian orogeny, our study area was exhumed to the surface by the end of the Proterozoic and composed part of a broad sub-Cambrian peneplain surface [Lidmar-Bergström, 1996]. A second orogenic episode, the Scandinavian Caledonides—comprising two tectonothermal phases from ~ 510 to 400 Ma, with the main Laurentia-Baltica collision event at about 430–400 Ma [e.g., Gee, 1975; Fossen and Dunlap, 1998; Roberts, 2003]—resulted in the creation of a foreland basin and Paleozoic sedimentation throughout the Laxemar region.

Because Paleozoic sediments are almost completely absent from the Fennoscandian Shield in southern Sweden, several studies have instead used apatite He and AFT data to constrain the timing and magnitude of burial associated with the Caledonian foreland basin. Most surface AFT ages in southern Sweden range from 313 to 150 Ma [Cederbom, 2001]. These surface ages have been combined with drill core samples to constrain Phanerozoic thermal histories that include reheating due to burial between ~ 350 and 300 Ma [Larson *et al.*, 1999; Cederbom, 2001] with maximum temperatures equivalent to ~ 2.5 – 4 km of total sediment thickness, followed by cooling during the Early Jurassic [Cederbom, 2002]. Apatite He ages corroborate this history and further suggest that the region has experienced minimal erosion since ~ 100 Ma [U. Söderlund, 2005]. The Mesozoic to recent thermal history for southern Sweden is disputed, however; with some authors arguing for a small amount ($\sim 15^\circ\text{C}$) of Late Cretaceous reheating [Green and Duddy, 2006]. We note that all of these thermal history constraints relied upon models that predate the advent of radiation damage and annealing models for interpreting apatite He results [Flowers *et al.*, 2009; Gautheron *et al.*, 2009]. Indeed, Green and Duddy [2006] raised concerns about the accuracy of the apatite He results and suggested that the canonical Durango kinetics [Farley, 2000] may not be appropriate for samples from the Fennoscandian Shield. In contrast, Hendricks and Redfield [2005] called into question the reliability of the AFT data in light of their apatite He results. The more recent advances in understanding the damage-He diffusivity relationship in apatite have largely resolved this issue and enabled both the apatite He and AFT ages to be properly interpreted in a congruent fashion. We will return to this discussion in later sections.

3. Methods

Samples were collected from surface outcrops and drill cores at several locations in southeastern Sweden (Figure 1). Sample vertical depths range from just below the surface to ~ 1700 m depth with samples spaced at ~ 250 m intervals. Apatite, titanite, and zircon grains were separated from these rocks by standard crushing,

sieving, and magnetic and density separation procedures. As is typically the case [e.g., *Reiners and Farley, 1999*], titanite grains recovered from the mineral separation process were blocky crystal fragments or irregular crystal shards. Three single-grain aliquots from each sample were selected for (U-Th)/He analysis performed at the University of Arizona. Analytical methods followed those described in *Guenther et al. [2016]* and consisted of diode, Nd:YAG, or CO₂ laser heating; cryogenic purification; and quadrupole mass-spectrometry for ⁴He analysis; and isotope-dilution high-resolution-inductively coupled plasma-mass spectrometry (HR-ICP-MS) for U and Th analysis.

In addition, masses of Zr in zircon grains and Ca in apatite and titanite grains were measured following the isotope-dilution protocols of *Guenther et al. [2016]*. We note that this previous study applied the Ca isotope dilution method only to apatite and that our current study represents the first application of this approach to titanites. With Zr and Ca measurement from each respective mineral, we can calculate U and Th concentrations (as opposed to just masses) by relating the total measured Zr or Ca in a given aliquot to grain mass through the zircon (ZrSiO₄), apatite (Ca₅(PO₄)₃F), and titanite (CaTiSiO₅) chemical formula. This chemistry-based method is of particular importance for titanite as traditional approaches to calculating whole-grain mass and therefore U and Th concentrations—morphologic dimension measurements converted to grain volume estimates—are difficult to perform on irregularly shaped crystal shards. We did obtain dimension measurements for our zircon and apatite grains, primarily for applying an alpha ejection correction, but these were also used to calculate eU concentrations for comparison purposes. The alpha ejection corrections for zircons followed *Hourigan et al. [2005]*, whereas for titanites, we assumed that crystal shards came from interior grain locations, and therefore, no alpha ejection correction was necessary, following *Reiners and Farley [1999]*.

4. Results

4.1. Zircon (U-Th)/He Ages

Our zircon He age results are listed in Table S1 in the supporting information. Both intrasample and intersample age variation exceed analytical precision. The remainder of this study will be mainly focused on explaining and exploiting the sources of this age variation. In order to inform this discussion, we examined if zircon He ages are correlated with several grain-specific characteristics that may explain this variation, including vertical depth below the Earth's surface and grain size (i.e., radius of a sphere with an equivalent surface-area-to-volume ratio and eU concentration). A broad negative relationship between age and grain size is evident if we ignore an outlier at ~79 μm, but no correlation is observed between age and depth. In contrast, a strong negative correlation is evident between He age and eU concentration (Figure 2), consistent with radiation damage being a fundamental control on the age variation.

This age variation is useful for constraining *t-T* paths in thermal history modeling, as we describe in detail in subsequent sections. Differences in eU among grains from a given sample are proportional to differences in radiation damage. Because the He diffusivity and radiation damage degree of a zircon coevolves throughout a sample's thermal history [*Guenther et al., 2013; Ketcham et al., 2013*], eU variations among zircons that have experienced the same or similar thermal histories result in a range of grain-specific He diffusivities and closure temperatures (*T_c*). Each zircon therefore behaves as an independent thermochronometer that records a different He age from a shared thermal history. More specifically, increasing amounts of damage initially decrease He diffusivity in zircon, but after accumulated damage exceeds a critical threshold, He diffusivity increases with further damage. Negative age-eU correlations are indicative of grains that have experienced high damage amounts beyond this threshold and, as a consequence, have increasing diffusivity (or decreasing *T_c*) with increasing radiation damage (i.e., eU). For this modeling, we follow previous approaches that first consider the extent to which a single model age-eU correlation can explain all of the observed variation [*Guenther et al., 2014; Orme et al., 2016*]. That is, we hypothesize that all grains experienced the same *t-T* path and test this hypothesis by attempting to match the age-eU correlation from the full data set with model outputs from single sample *t-T* paths. We argue that such an approach is justified here because (1) no apparent correlation exists between depth and age alone (although some depth dependence is evident when eU is also considered), which would likely be the case if samples had differing thermal histories; (2) negative age-eU correlations typically manifest in data sets where all of the grains have experienced similar thermal histories [*Guenther et al., 2014*]; and (3) the range of eU concentrations in any one sample is too narrow

Figure 2. Comparison of zircon (U-Th)/He ages (each point represents a single grain aliquot) to (a) vertical depth, (b) grain size, and (c) eU concentration. KLX samples (circles and diamonds) are sourced from drill cores in the Laxemar region, whereas KKR and GOT samples (squares) are sourced from the Kråkemåla quarry in the Göttemar granite. A pronounced negative correlation exists between age and eU.

as a discussion of the possible thermal history significance of the titanite age-eU correlation, will be important points in later sections.

4.3. Apatite (U-Th)/He Ages

Apatite He ages are listed in Table S3 and, in a fashion similar to Figure 2, we plot apatite He ages from the KLX drill cores (Laxemar area TIB-rocks) against vertical depth, grain size, and eU in Figure 4. As with our zircon and titanite results, intrasample and intersample age variation exceeds analytical precision, and we use the plots in Figure 4 to explore some of the sources of this variation. We focus this summary on the samples collected from the series of KLX drill cores as these ages will be the most relevant for the thermal history

to effectively constrain model t - T paths. We stress though that this initial assessment represents a first pass and that further refined tests, described in greater detail below, will explore potential t - T differences among samples or groups of samples.

Intragranular zonation of U and Th in zircon can be an additional and problematic source of age variation because it is currently difficult to comprehensively measure and assess the influence of zonation on He ages. Typical zircons collected from our sample locations show predominantly oscillatory zonation with no evidence for inherited cores or metamorphic overgrowths [Wahlgren *et al.*, 2004], which can result in large, order-of-magnitude differences in U and Th concentration between cores and rims. This style of zonation is likely to cause the greatest amount of age variation in a given sample [Hourigan *et al.*, 2005; Guenthner *et al.*, 2013], and its absence provides confidence that the zonation effect is likely minimal for our data set.

4.2. Titanite (U-Th)/He Ages

Titanite He ages are listed in Table S2 and share similar characteristics to our zircon He results. Most strikingly, with the exception of a few outliers, the titanite He ages are negatively correlated with eU concentration, and this correlation overlaps in both age and eU space with the zircon data (Figure 3), though on average titanite ages are slightly older. Unlike with our zircon results, no quantitative model yet exists that allows for t - T constraints to be derived from titanite He age-eU correlations. As such, we do not include these data in our thermal history modeling. However, a comparison between both sets, as well

Figure 3. Titanite (U-Th)/He ages (each point represents a single grain aliquot) plotted against eU concentration. Greyed out symbols are the KLX zircon (U-Th)/He ages for comparison. All grains come from KLX samples, and the symbol scheme is the same as used in Figure 2. With the exception of a few outliers, a broad negative correlation is observed between age and eU.

modeling detailed in subsequent sections. Additional apatite He ages were collected from Götemar granite samples, but these grains are not shown in the plots or Table S3 as all of them contained inclusions and many were uncharacteristically old. Ages from the KLX samples are broadly correlated with depth, with minimum ages becoming younger with increasing depth. Depth alone cannot explain all of the observed variation, however; the deepest sample has an intrasample age range that encompasses nearly the total observed age range for all samples. Ages are both positively correlated with grain size and eU concentration, which suggests that these effects could account for the observed variation. In particular, the positive age-eU correlation can be

exploited to yield t - T information when an apatite radiation damage and annealing model (RDAAM) is used [Flowers *et al.*, 2009]. We model the age-eU correlations, combined with grain size and some additional depth control, using RDAAM in subsequent discussion sections, and these RDAAM outputs serve as a consistency check for our zircon age-eU model results. That is, we will focus our apatite discussion on the extent to which both the modeled apatite and zircon age-eU correlations agree with the observed data for a given t - T path.

5. Thermal History Modeling

A primary goal of thermal history modeling is to test the plausible range of thermal history scenarios that can reproduce an observed data set. Models can be generated in either a forward or inverse sense, and here we follow a strategy that first uses a forward model based approach, with a subsequent, refined search of t - T space using inverse modeling. Our forward model uses the algorithms of HeFTy [Ketcham, 2005] and the kinetic parameters used in ZRDAAM of Guenthner *et al.* [2013], but we implemented the model in MATLAB for ease of large data set input and creation of age-eU plots. Our results were cross-checked with HeFTy to assure consistency. The ZRDAAM uses a curvilinear fit to the zircon fission track (ZFT) annealing data of Yamada *et al.* [2007] to constrain the annealing of damage that affects He diffusivity (partial annealing zone of 310–223°C for 0.4–0.8 mean length reduction ratio, respectively, 10 Ma isothermal hold time). More work is required to improve our understanding of damage annealing in zircon. For example, high damage zircons may not fully anneal when subsequently exposed to high temperatures that nominally should result in complete annealing of ZFTs [Garver *et al.*, 2005; Marsellos and Garver, 2010]. Without a more comprehensive model that properly deals with this phenomenon, it is difficult to incorporate these errors into our model results presented here. However, we suggest that unannealed, high damage zircons would most likely allow for higher maximum burial temperatures in the model. We also stress that the ZFT annealing kinetics currently provide the most robust model for constraining the annealing process, despite these unresolved potential issues.

As inputs, the forward model takes in a particular t - T path, along with the grain size and eU concentration for a given grain, and generates an age-eU curve that can be directly compared to the observed data. Forward models provide a direct visual comparison between model outputs that result from specific t - T paths and data, which represents a distinct advantage over some inverse approaches. The ability to see how well a given t - T path captures an age-eU correlation is particularly relevant for zircon He results as certain effects on age variation are typically underconstrained. For example, although the first-order control on age variation in a data set may result from the damage-diffusivity relationship, additional sources of variation such as eU zonation can cause secondary variation that is difficult to model without additional in situ U and Th concentration profiles. Forward models also allow a visual comparison of extreme or end-member

Figure 4. Comparison of apatite (U-Th)/He ages (each point represents a single grain aliquot) to (a) vertical depth, (b) grain size, and (c) eU concentration. Panels show only the KLX samples, which are the primary focus of thermal history modeling. Ages generally become younger with depth, although large amounts of intrasample age variation are observed. For the KLX samples, positive correlations between both age and grain size and age and eU are observed.

these events are considered as constants throughout our model tests. Because our thermal history modeling focuses on zircons from TIB rocks (Figure 1), we use a zircon formation age of ~ 1800 Ma [Wahlgren *et al.*, 2008]. A second t - T constant relies upon evidence for near-surface temperatures at ~ 570 Ma due to the formation of a sub-Cambrian peneplain throughout southeastern Sweden [Lidmar-Bergström, 1993; Lidmar-Bergström, 1996]. Finally, we use a temperature of 20°C [Drake *et al.*, 2015] at the present day to reflect the mean sample depth for our zircon grains. We note that this temperature will be modified in subsequent model tests to reflect the variable depth of each sample, but as discussed above, our initial goal is to assess the extent of which a single age-eU correlation can explain the observed age variation.

Certain aspects of the two episodes of foreland basin formation are also considered constants or partially constrained based upon previous work. Specifically, for the Caledonian foreland basin we rely upon AFT

solutions that can be used to “bracket” the range of plausible thermal histories (see below). Current inverse models assume that all sources of age variation can be fully modeled from the available inputs and a given t - T path, and for these reasons, it can be difficult to explore in an inverse sense the extent to which a sample’s age variation is due to one particularly important source of variation, radiation damage. In contrast, the forward model approach is well suited to this task and therefore offers a greater degree of transparency in terms of how well (or not) a specific t - T path replicates the observed data’s first-order variation (i.e., negative age-eU trend).

In this study, we aim to test which t - T paths best reproduce the observed age-eU correlations, while remaining compatible with additional geochronologic and thermochronologic and geologic data. For our particular borehole locations, we will focus our model tests on two major episodes of foreland basin evolution: (1) the Neoproterozoic Sveconorwegian basin [Larson *et al.*, 1999] and (2) the Paleozoic Caledonian basin [Gee, 1975; Cederbom, 2001]. As discussed previously, the extent and timing of burial and subsequent exhumation in the Sveconorwegian foreland basin is not well constrained in our study area, and zircon negative age-eU correlations are expected to provide some constraints given their utility as records of long-term thermal histories that have experienced multiple heating and cooling episodes.

In order to simplify the modeling, we incorporate several key t - T observations from previous work. In some instances,

modeling which suggests that initial burial began at 400 Ma, with samples reaching maximum burial temperatures between 100 and 150°C sometime before 250 Ma [Larson *et al.*, 1999; Cederbom, 2001; Cederbom, 2002; Huigen and Andriessen, 2004]. Subsequent exhumation returned these samples to 50°C by 100 Ma [Cederbom, 2001]. Fewer *t-T* constraints are available for the Sveconorwegian foreland basin, but broad estimates of the timing of burial and amount range from 1050 to 850 Ma and possibly greater than 8 km [Tullborg *et al.*, 1996]. We include that full range in our modeling below.

With these constants and constraints in mind, our modeling strategy will first consider the default hypothesis that heating due to burial in the Sveconorwegian foreland is not required to explain the observed age-eU correlation. Such tests will consist of several *t-T* paths that bracket the full Proterozoic *t-T* space: one set with rapid cooling from high temperatures at 570 Ma (sub-Cambrian peneplain) and the other with rapid cooling from high temperatures at 1800 Ma (formation age) and subsequent residence at near-surface temperatures. If both model sets yield similar age-eU correlations, or if both can reproduce the observed correlation, then this suggests that our zircon data are relatively insensitive to the Precambrian thermal history in this region. A secondary variable in these tests will explore whether the full range of possible maximum burial temperatures achieved in the Caledonian foreland basin influences the model sensitivity (or insensitivity) to the Proterozoic *t-T* path. For example, Caledonian burial temperatures will reset the zircon He ages to varying degrees, and we want to explore which burial temperatures allow for some degree of age inheritance from the pre-Caledonian thermal history. As such, each of the model sets used in these initial tests includes Caledonian burial temperatures between 100 and 150°C.

Following these initial tests, we will then proceed to greater degrees of model refinement. If our first set of models reveals that the Proterozoic thermal history influenced the observed age-eU correlation, then we want to further define the specific set of Proterozoic *t-T* paths that are consistent with the geologic observations and explain our observed age variation. As discussed above, the timing of burial and exhumation, as well as the range of burial temperatures, associated with the Sveconorwegian foreland basin represents a key set of these Proterozoic constraints. However, other geologic events, such as the intrusion of the 1430 Ma Götemar Granite, and the relatively large amount of underconstrained *t-T* space between 1800 and 950 Ma could influence our observed age-eU correlations. In the subsequent sections—and following our tests of the default hypothesis—we therefore first model *t-T* paths with rapid cooling from high temperatures at 950 Ma, which will explore the extent to which only the Sveconorwegian foreland basin history influenced our zircon He ages. We will then model additional Proterozoic *t-T* paths that consider the pre-950 Ma thermal history of our samples, as further described in section 5.3. An important consideration in these more refined models will be the combined effects of depth and eU concentration. For example, Figure 2 shows that the four deepest samples (circles) are shifted toward slightly younger ages at a given eU concentration compared to the four shallowest samples (diamonds). Although our first-pass forward models do not explicitly attempt to constrain this additional depth dependence, the inverse modeling described in section 5.4 explores this age-eU-depth relationship more fully. For ease of comparison throughout this modeling discussion, we show all of the observed ages in two groups with two distinct symbols: the four deepest samples as red circles and the four shallowest samples as blue diamonds.

5.1. Initial Forward Tests: Necessity of Sveconorwegian Event

The results from our initial tests (Figure 5) demonstrate that some Precambrian *t-T* points must be included in our thermal histories to match the data. The model *t-T* path that begins with a rapid cooling event at 570 Ma with burial to low temperatures (100°C Figure 5a solid line) yields a flat age-eU curve, whereas a higher burial temperature (150°C, Figure 5a dashed line) gives a convex up age-eU correlation that is not observed in the data. Taken together, these results show that roughly 570 Ma of damage in growth is not enough time to allow all grains in our data set to exceed the damage threshold required for a negative age-eU correlation ($\sim 5 \times 10^{17}$ to 2×10^{18} *at/g*, see section 1). A more protracted, low-temperature Proterozoic thermal history is therefore necessary but must include more *t-T* complexity than simple cooling at 1800 Ma followed by prolonged residence at near-surface temperatures (Figure 5b). Indeed, when results from both sets of model scenarios shown in Figure 5 are compared, the model age-eU correlations approximately bracket the observed data, with the model age curves from simple 1800 Ma cooling showing a negative trend at too low eU concentrations. Because these model correlations bracket the observed results, a better *t-T* solution likely plots somewhere between these two sets

Figure 5. Forward model results for end-member t - T scenarios and KLX data set. For right-hand panels, blue diamonds represent the four shallowest KLX samples (in terms of vertical depth) and the red circles represent the four deepest samples. (a) Rapid cooling from high temperatures at 570 Ma with different amounts of Paleozoic reheating (100 and 150°C). Solid and dashed lines match the model age-eU curves shown in right-hand panel. Curves show the mean grain size, and grey envelopes show the 2 standard deviation grain size. (b) Similar to Figure 5a, except rapid cooling event is at 1800 Ma with long-term hold at 20°C until 570 Ma. No single curve captures the observed age-eU correlation, but combined, the model age-eU correlations in both Figures 5a and 5b bracket the full range of the observed age-eU correlation.

of thermal histories, with some amount of burial and exhumation in the Sveconorwegian foreland basin providing a geologically plausible scenario.

5.2. Refined Forward Tests: Specific t - T Paths for Sveconorwegian and Caledonian Events

Despite the need for Precambrian portions of our thermal histories, including only t - T constraints related to the Sveconorwegian foreland system is insufficient to explain our data. In Figure 6a, we show model results from t - T paths that include the full range of burial temperatures for both the Sveconorwegian and Caledonian basins as described above, but with no low-temperature history prior to 950 Ma. Regardless of the specific combination of modeled burial temperatures, all of these thermal history yield age-eU correlations with a negative trend that occurs at eU concentrations that are too high compared to the observed data set. As previously discussed, the placement of these correlations in eU space suggests that not enough damage accumulation has occurred in our model grains when the t - T path effectively begins at 950 Ma.

We also consider thermal histories that model both foreland basins but simulate low (near-surface) temperatures between ~1800 and 950 Ma (Figure 6b). At the lower modeled burial temperatures, these t - T constraints give model age-eU correlations that show negative trends at too high eU concentrations. However, at the highest modeled burial temperatures (Figure 6b, 240–250°C for the Sveconorwegian, 140–150°C for the Caledonian), model age-eU correlations capture some aspects of the observed negative trend. Specifically, the negative correlation between ~100 and ~750 ppm eU is similar to the observed correlation and a distinctive change in the model age-eU correlation to a flatter slope is also observed in the data set. Most importantly, model results bracket the observed data if we consider both sets of models in Figure 6. As such, these combined model results suggest that we must also consider pre-Sveconorwegian geology in order to constrain thermal histories for our samples.

Figure 6. Forward model results for t - T scenarios and KLX data set with two phases of reheating and cooling that correspond to the Sveconorwegian (reheating to either 150 or 250°C from 950 to 850 Ma) and Caledonian (reheating to either 100 or 150°C from 570 to 400 Ma) orogens. Symbols and curves are similar to Figure 5. (a) Rapid cooling from high temperatures just prior to 950 Ma. (b) Rapid cooling at 1800 Ma and long-term holding at 20°C. The highest modeled burial temperatures in Figure 6b (250°C for the Sveconorwegian, 150°C for the Caledonian) best capture aspects of the observed age-eU trend of the outputs shown here. The combined model results from both Figures 6a and 6b again bracket the observed data, which suggests that pre-Sveconorwegian geology is required to constrain our sample's t - T paths.

5.3. Refined Forward Tests: Additional Proterozoic t - T Constraints

For the final set of forward model tests, we explore how pre-Sveconorwegian thermal events may have influenced our sample age-eU correlations. These tests primarily focus on a possible short-lived heating and cooling pulse associated with emplacement of the ~1430 Ma Göttemar granite. As such, we first model a simple t - T path with residence at surficial temperatures between ~1800 Ma and 1430 Ma, followed by heating to some maximum temperature at 1425 Ma and cooling back to low temperatures by 1420 Ma. Both the duration of this heating pulse and the maximum temperatures achieved by this heating are underconstrained, but regional Ar-Ar data suggest heating above 300–350°C [Söderlund *et al.*, 2008]. Our primary objective in this section is therefore to simply explore if a short-lived heating event gives a plausible model age-eU correlation. We initially model this event with a duration of only 10 Ma and a maximum reheating temperature of 350°C. We also model the pre-1430 Ma with a parsimonious set of inputs that include two bounding t - T paths: one with residence at surficial temperatures between 1800 and 1430 Ma and the other with rapid cooling from high temperatures at 1430 Ma. In subsequent inverse modeling sections, we expand on this investigation by testing a wider region of t - T space, both at ~1430 Ma and between 1800 and 1430 Ma. All other model inputs are similar to those used in previous sections.

Representative results from both sets of models—high temperatures or low temperatures before 1430 Ma—are shown in Figure 7. Both model trends are identical and overlap in the right-hand panels (hence, only one set of model age-eU curves can be observed), which suggests that at least as currently modeled, this heating event was sufficiently hot enough to reset the He age and damage level in our zircon grains. That is, a t - T path that begins at 1800 and has a high-temperature (350°C), short-lived (10 Ma) pulse at 1430 Ma yields the exact same model age-eU correlation as a forward model that starts at 1430 Ma. This similarity in model outputs further suggests that our data are relatively insensitive to differences between thermal histories that begin at 1800 or 1430 Ma, at least from a forward model perspective and in the absence of additional t - T

Figure 7. Forward model results for two t - T scenarios and KLX data set that consider a short-lived (10 Ma) reheating pulse (to 350°C) at 1445 Ma (dashed line), and a t - T path that begins at high temperatures at 1445 Ma (solid line). Symbols and curves are similar to Figures 5 and 6. Only a single curve and envelope is shown in the right-hand panel because both model t - T paths yield the same output, which suggests that at least for our forward models, a short-lived reheating pulse at 1445 Ma is effectively the same as starting the model at 1445 Ma.

information. Inverse models that rely on heftier approaches to statistical comparison among model outputs can better distinguish between these two scenarios (see next section). Of the various forward models we tested, a t - T path with 150°C maximum burial temperatures for both the Sveconorwegian and Caledonian foreland basins captures the highest number of observed ages (10 out of 24). Although this percentage appears low, we note that this particular model correlation still captures the first-order trend of the data set (i.e., negative age-eU correlation), and similar scenarios are therefore worth investigating with our inverse models.

As an initial test, the combined results from these forward models (Figures 5–7) show that the age-eU correlation in our data set reflects the timing and maximum temperatures of various Proterozoic and Paleozoic geologic events in southeastern Sweden. These models further suggest that the Götemar granite emplacement, the Sveconorwegian foreland basin, and the Caledonian foreland basin must all be considered in order to find plausible thermal history solutions. However, forward modeling is limited in both the number of t - T paths that can be reasonably tested and the slightly subjective nature of what constitutes the “best” t - T path. For these reasons, we further refine our thermal history modeling of these data with inverse models in the next section.

5.4. Inverse Models

Here we describe the results of inverse modeling used to test a wider region of t - T space and constrain a more complete range of t - T solutions. In particular, we investigated the timing and maximum temperatures of the two major episodes of foreland basin deposition in our study area, as well as whether our samples experienced reheating associated with emplacement of the 1430 Ma Götemar granite. A limitation of this modeling approach, as previously discussed, is that some averaging of grain-specific information is needed to construct zircon He age-eU inverse models. This averaging is necessary for both practical reasons (i.e., limited number of grain inputs) and, more importantly, because all sources of possible age variation such as U and Th zonation or He trapped in fluid inclusions [Danisik et al., 2017] are not known for this data set, which is typical for most zircon (U-Th)/He studies. As such, a careful consideration of grain inputs is required. We adopted an approach similar to one used in inverse modeling of age-eU correlations in the apatite He system that relies upon average or “synthetic” grains [Ault et al., 2009; Flowers and Kelley, 2011; Murray et al., 2016]. First, we divided eU space into discrete bins in order to best reproduce the range of age, size, and eU of the measured grains in our synthetic inputs. We then averaged the grain size and He age of all grains that fell within each bin and used the standard deviation on the mean age as the age uncertainty.

Inverse models were run in HeFTy (version 1.9.1) [Ketcham, 2005] using the zircon radiation damage and annealing model of Guenthner et al. [2013]. This most recent version of HeFTy allows for the modeling of multiple samples separated by a vertical distance, like our borehole samples, and can be used to restrict the region of t - T space that produces viable paths thereby improving the veracity of t - T hypothesis testing [Ketcham et al., 2016]. In our data set, separating samples by depth, while also interrogating the observed

age-eU correlation, is difficult for reasons previously discussed in section 4. In summary, age variation among individual samples does not display a strong correlation with depth. The average difference in depth between individual samples is ~250 m. Even with a moderate geothermal gradient of 25°C/km, this difference in sample depth only yields an ~6°C difference. However, the data set as a whole shows a distinct negative age-eU correlation, which strongly suggests that radiation damage is the dominant control on age variation in our data set. Still, the deepest sample appears to have mostly younger ages than the shallowest sample, consistent with the deepest sample experiencing higher temperatures throughout its thermal history. Moreover, if we consider the four deepest samples as a distinct group, then they are shifted toward younger ages at a given eU concentration compared to the four shallowest samples (Figure 2). We therefore separated our samples into these two groups by vertical depth and used the median depth between the shallowest and deepest sample in each group as the depth inputs in HeFTy (391 m and 1312 m). The noticeable offset between the two groups in age-eU space, combined with the need to maintain the dominant age-eU trends in the modeling (i.e., not overly subdivide the samples so as to obscure this trend), justifies this grouping.

The HeFTy inversion mode uses a Monte Carlo approach to test tens of thousands of t - T paths that pass through certain, user-prescribed t - T constraint boxes. These boxes are imposed on the basis of the available geologic observations and used to test specific t - T hypotheses. In part, we relied upon such geologic constraints here, but we also used the information gleaned from our forward models and used the main conclusions from that exercise to guide our inverse hypothesis testing. As such, we placed the following fixed constraint boxes: 1800–1700 Ma, 450–500°C to start the model at high temperatures; 1050–950 Ma, 0–250°C and 950–850 Ma, 50–300°C to simulate burial (and subsequent exhumation) in the Sveconorwegian foreland basin; 600–500 Ma, 0–50°C to simulate surficial temperatures associated with the sub-Cambrian peneplain; and finally, a box at 400–250 Ma and 100–200°C to model burial and exhumation in the Caledonian foreland. We note that two boxes, offset in temperature space, are required between 1050 and 850 Ma in order to induce reheating in the inverse model (otherwise, Monte Carlo simulations are only monotonic cooling for this time period). A simpler approach to the Precambrian portion of our inverse model might be considered by underconstraining the period between 1800 and 600 Ma and allowing for HeFTy to only consider monotonic cooling. We note that tests that include only monotonic cooling for this time period failed to yield “good” solutions (see discussion below for further details on inverse output) after 100,000 attempted paths. Moreover, although monotonic cooling did yield a limited number of “acceptable” t - T paths (6 out of 1000,000 attempted), for these inverse models, we are not interested in the simplest possible explanation, but rather whether burial in the Sveconorwegian foreland basin provides viable solutions and over what range of maximum burial temperatures.

In addition to an exploration of maximum burial temperatures in both foreland basin systems, we also tested the influence of a heating event at 1430 Ma (Götemar granite) on our sample age-eU correlations. Because the temperature and duration of this possible heating event are not well defined, we tried a simple test to examine if our data were fully reset for both He age and damage amount by granite emplacement. More subtle reheating involving only partial resetting of our samples could be modeled as well, but the lack of any supporting thermal history information makes this test more speculative. As such, this binary test is instructive as to whether our data can rule out a high-temperature event for this area associated with the Götemar granite. This test is also informed by our forward model approach, where we found that a short-lived (10 Ma) pulse at high temperature (350°C) at 1430 Ma was effectively the same as starting our model t - T paths at that time. Our inverse tests can therefore be divided into two basic groups, those with an initial constraint box at 1450–1425 Ma, 450–500°C, and those with an initial constraint box at 1800–1700 Ma, 450–500°C.

Results from the 1800–1700 Ma group of models are shown in Figure 8. Paths are color coded based on goodness of fit (GOF), with light grey paths classified as acceptable (GOF > 0.05) and dark grey paths classified as good (GOF > 0.5). Here we focus on the results from the good-fit paths and the sample group at greater vertical depth. Maximum burial temperatures for the Sveconorwegian foreland are ~262–185°C (mean of ~217°C) achieved as early as 944 Ma or as late as 851 Ma (mean at 891 Ma). For the Caledonian foreland, maximum burial temperatures are ~173–120°C (mean of 154°C) achieved as early as 366 Ma or as late as 224 Ma (mean at 303 Ma). In both cases, the paths plot well within the bounds of the constraint boxes, which suggests that this result is well constrained. In contrast, our models with an initial constraint box at 1450–1440 Ma, 450–500°C (i.e., no thermal history modeled prior to 1450 Ma) give no good paths and a limited number of acceptable paths (2 out of 100,000 tested, not shown in Figure 8).

Figure 8. Inverse model results for the KLX data set. (top) Green boxes represent the t - T constraints as defined in the text. Lighter grey paths represent acceptable fits, whereas the solid black paths represent good fits. The solid yellow line represents the mean path (this path is not the best fit solution). Note that these paths correspond to the lower depth sample group (upper sample group paths have the same trajectory but are adjusted to $\sim 15^\circ\text{C}$ cooler temperatures). (bottom) The data set has been divided by depth into a lower (red circles) and upper (blue diamonds) group as described in the text. The bold symbols shown represent the synthetic grains with the full KLX data set shown in grey. Red and blue curves represent the model age-eU correlations that result from the good fit paths for the lower and upper sample group, respectively.

(Figure 5), but only paths that take into account a more complex Precambrian thermal history (Figures 6 and 7) begin to match the data. The degree of permissible complexity that should be allowed in inverse models is debatable, with some authors advocating a framework that seeks to maximize the simplicity of the thermal history necessary to fit the data [Gallagher, 2012]. This approach is appropriate and preferred in some situations, but for our data set, additional geologic and thermochronologic constraints suggest that our samples have experienced burial in at least two foreland basin systems. In this sense, zircon He age-eU correlations can be an effective tool for augmenting and refining previous observations. In particular, our thermal history models constrain details for older geologic events that are not well known, such as maximum burial temperatures and timing of exhumation for the Sveconorwegian foreland basin, and not previously available from AFT ages alone. Our forward model results also provide confidence that our data retain information about the Precambrian thermal history of the region by showing the limits of model t - T scenarios that only consider the Phanerozoic. Taken together, the forward and inverse models presented here illustrate an effective approach for interpreting and utilizing zircon He age-eU correlations.

A comparison between our model results and previously published AFT ages lends further credence to our thermal history interpretations. This comparison is admittedly slightly circular as the inverse model

This result differs from our forward model outputs (Figure 7) where no difference was observed between a model t - T path that began at 1430 Ma versus a model t - T path that had a short-lived (10 Ma), high-temperature (350°C) reheating pulse at 1430 Ma. In particular, these inverse models suggest that a pre-1430 Ma set of t - T points must be included in our models in order to produce good-fit paths. Because the inverse approach uses a more rigorous statistical comparison between output and data, this discrepancy is not surprising. The inverse results further imply that our samples were likely not fully reset by the emplacement of the Göttemar granite. We focus the remainder of our discussion on the post-1430 Ma portions of our model results.

6. Discussion

6.1. Comparison to Other Thermochronometers

Our inverse results demonstrate that complex paths consisting of multiple episodes of heating and cooling can be constrained using zircon He age-eU correlations. The ability to constrain more than one cycle of heating and cooling is in turn bolstered by the series of forward model results (Figures 5–7) that demonstrate how simple, end-member thermal histories with only one Phanerozoic cycle of heating and cooling (following some initial rapid cooling event) might bracket the observed data

constraint boxes for the Phanerozoic were partially constructed based on the AFT ages, but the internal consistency of our results is still important to assess. We focus here on data presented by *Larson et al.* [1999] as this study has samples that overlap with (and in some cases are derived from) our Laxemar sample locations (KLX) and drill-core depths. *P. Söderlund et al.* [2005] presented apatite He ages that were also collected from the Laxemar drill cores, but these ages are problematic for several reasons. Most of the aliquots used in the *P. Söderlund et al.* [2005] study are composed of multiple (two to six) grains and individual samples show a large amount of age variation among aliquots. One potential way to evaluate this dispersion would be to examine apatite age-eU correlations, but the multigrain nature of these aliquots makes such an analysis difficult and somewhat meaningless. As such, we discuss only the AFT ages from previous publications but include a discussion of our own apatite He data below. These ages are (all errors 2 sigma): 264 ± 16 Ma with mean track length of 12.17 ± 0.20 μm for a sample at 994 m depth, and 206 ± 12 Ma with mean track length of 11.30 ± 0.30 μm for a sample at 1696 m depth. We highlight the fact that no Dpar or Cl-content data are available for these results. These data have been modeled by various authors [*Cederbom*, 2002; *Green and Duddy*, 2006], but many of these previously constrained thermal histories begin between 400 and 200 Ma and include no pre-Phanerozoic *t-T* segments. In contrast, our model constraints extend back to 1800 Ma, and we are therefore more interested in whether our modeled *t-T* paths can reproduce the observed AFT ages, rather than a direct comparison between the different model outputs.

These age and length data are compared to models, in a forward sense, that used the range of good-fit *t-T* paths shown in Figure 8. These paths correspond to the sample group at greater vertical depth (1312 m) so we compare the model output to both sample AFT ages. The variable sample depths make a direct comparison difficult and are the primary reason that all thermochronometric results were not combined into a single inverse model. We again used HeFTy for this comparison with the annealing model of *Ketchum et al.* [2007]. Our model AFT age outputs range from 170 to 269 Ma, which encompasses the observed AFT ages of 206 and 264 Ma. The track length data are less of a good match as the model range is 12.45 to 13.50 μm compared to 11.30 and 12.17 μm in the observed. In summary, we find that our models derived from zircon He age-eU correlations are in general agreement with previously published AFT results, but that some discrepancies are apparent. We again stress that this comparison is nonideal given both the absence of Dpar and *c* axis projections in the *Larson et al.* [1999] data and the variable apatite sample depths that differ from our zircon sample depths. To first order, however, our constraints on burial and exhumation during the Caledonian orogeny match those obtained from previous studies.

We also use comparisons between modeled and observed apatite He age-eU correlations as a second check on the validity of the thermal histories derived from zircon model results. As a starting point for this comparison, we took the good fit *t-T* paths shown in Figure 8 and used them as forward model inputs in HeFTy. The other inputs consisted of four or five model grains that were spaced at regular eU intervals in order to span the full range of observed eU in Figure 4 and average grain sizes appropriate for each eU interval. We used the *Flowers et al.* [2009] kinetics to generate ages for these model grains from a given *t-T* path. Finally, we separated the KLX drill core data set into two sample groups, an upper (surface to 789 m, blue diamonds) and lower (964 to 1699 m, red circles) group, in a fashion similar to our zircon He age-eU modeling. Results from these forward models are compared to the observed data in Figure 9a. For both the upper and lower sample groups, the model age-eU correlations that result from each of the good fit *t-T* paths shown in Figure 8 encompass almost the entire range of observed ages. No single age-eU correlation passes through all of the observed ages, but this is rarely the case in the apatite He system and most authors rely upon an average or synthetic grain approach to fit all of the data [*Ault et al.*, 2009; *Flowers and Kelley*, 2011; *Murray et al.*, 2016]. We also used this synthetic grain approach to construct inverse models that combine apatite and zircon He ages in order to further investigate congruence between the zircon He and apatite He data sets. The inverse model uses the same constraint boxes and zircon He inputs as shown in Figure 8, with additional apatite He ages for both the upper and lower sample group (see figure caption for inputs). Results from this inverse exercise (Figure 9b) are indistinguishable from the inverse models that use only zircon He data (Figure 8).

Finally, we note that the observed zircon age-eU correlation has an interesting “pediment” of relatively consistent ages over a certain span of eU concentration (~500 to ~1000 ppm). This pediment is captured in both the forward and inverse models (e.g., Figures 7 and 8) and the observed and model ages are ~200 to 350 Ma, which broadly overlaps with our apatite He ages. This observation, and the ability of the good

Figure 9. Model apatite age-eU correlations compared to the observed data for KLX samples. Sample grouping is the same as shown in Figures 5–8 for our zircon age-eU models. (a) Forward model results with t - T inputs that consist of the good fit paths shown in Figure 8. Each model age-eU curve corresponds to one of these individual good fit paths, with the red model curves representing the deeper t - T paths and the blue curves representing the shallower paths. As with Figure 8, the shallower and deeper t - T paths are nearly identical with the only difference being an $\sim 15^\circ\text{C}$ offset at each t - T point. (b) Inverse model paths that result from the combined inputs of zircon He and apatite He data. The apatite He inputs rely upon synthetic grains, in a fashion similar to Figure 8: 217 ± 32 Ma (48 ppm eU, $50 \mu\text{m}$ grain size), 242 ± 28 Ma (64 ppm eU, $46 \mu\text{m}$ grain size), and 252 ± 44 Ma (89 ppm eU, $45 \mu\text{m}$ grain size) for the upper group; 147 ± 35 Ma (27 ppm eU, $36 \mu\text{m}$ grain size), 186 ± 37 Ma (51 ppm eU, $40 \mu\text{m}$ grain size), and 202 ± 42 Ma (68 ppm eU, $42 \mu\text{m}$ grain size) for the lower group. These paths are nearly indistinguishable from those shown in Figure 8. (c) Inverse model age-eU output. The bold symbols shown represent the synthetic grains with the full KLX data set shown in grey. Red and blue curves represent the model age-eU correlations that result from the good fit paths for the lower and upper sample group, respectively. In both Figures 9a and 9c, the model curves encompass the full range of age-eU correlations for both the lower and upper sample group, which provides supporting evidence for the validity of our zircon age-eU results.

fit thermal histories from Figure 8 to reproduce the spread in apatite He ages, provides further confidence in the validity of the t - T constraints from our zircon He age-eU correlations.

6.2. Radiation Damage Controls on Titanite (U-Th)/He Ages

Although our titanite He ages were not used in constructing thermal histories for the Laxemar region, the observed negative correlation between age and eU concentration warrants further discussion (Figure 3). We interpret this correlation in a similar fashion as our zircon He results and, as such, these data represent some of the first examples of a possible relationship between damage and He diffusivity in the titanite system. The lack of a detailed damage-diffusivity relationship for the titanite system prevents comprehensive thermal history modeling of these data. Still, we can draw a number of conclusions from the observed negative titanite He age-eU correlation and how it relates to the zircon He age-eU correlation.

Despite some titanite He age variation that does not correlate with eU, the dominant negative correlations in both systems follow a similar trend and occur over the same range of eU concentrations (modeled titanite He ages are between 574–705 Ma for the lower sample group and 735–825 Ma for the upper sample group using our good t - T paths). This correspondence suggests that the processes of damage accumulation and annealing, and the influence of damage on the kinetics of He diffusion in titanite, could be comparable to those in zircon. We can use the kinetics of fission track annealing as a proxy for the annealing of damage that influences He diffusion [e.g., *Flowers et al.*, 2009; *Guenthner et al.*, 2013; *Ketcham et al.*, 2013]. The most recent estimates of the titanite fission track partial annealing zone (PAZ) are 265–310°C [*Coyle and Wagner*, 1998]. This PAZ overlaps with the zircon fission track PAZ of *Yamada et al.* [2007] used to constrain damage annealing in our zircon age-eU modeling: 223–310°C. These annealing kinetics suggest that, for certain types of t - T paths, the levels of accumulated damage should be similar for both a titanite and zircon that have experienced the same thermal history. However, given the slightly higher temperature PAZ for the titanite system, we expect that only thermal histories with rapid cooling through ~350 to 250°C will yield overlapping age-eU correlations in both the titanite and zircon systems, as we observe in our Laxemar data set. That is, in order to lock in the same amount of damage accumulation for both systems, samples must cool rapidly across the entire span of both PAZs. For our samples, this additional constraint might modify the results in Figure 7 by dictating a more rapid cooling event sometime in the Proterozoic. We also note that titanite fission track data northwest of our study area yield ages of ~670–690 Ma [*Zeck et al.*, 1988], which also hints at potentially higher burial temperatures for our samples in the Neoproterozoic than those modeled here. However, an improved damage-diffusivity model and new He diffusion data for titanite are required in order to further explore these possibilities.

The currently available He diffusion kinetics for titanite do not show strong evidence for a radiation damage effect [*Reiners and Farley*, 1999; *Cherniak and Watson*, 2011], although early studies suggested a possible correlation between titanite He age and radiation damage [*Hurley*, 1952; *Hurley and Fairburn*, 1953; *Hurley*, 1954]. In order to further compare diffusion data from these titanites to our data set, we examine the alpha dose (α/g), which gives an estimate of the degree of radiation damage for a given grain. To calculate dose requires an estimate of U and Th concentration, as well as an estimate of the duration of time over which the damage accumulation that results from alpha decay has occurred. This time component can be difficult to assess due to uncertainties in the damage annealing process. Here we use the average titanite fission track age from *Larson et al.* [1999] for our data set (766 Ma), the titanite He age for samples quickly cooled from high temperatures, such as Mount Dromedary and Fish Canyon Tuff (FCT) from the *Reiners and Farley* [1999] study, and a t - T point equivalent to a titanite fission track age (but constrained by K-spar $^{40}\text{Ar}/^{39}\text{Ar}$ data) for samples from the Chain of Ponds pluton from the same study. Only the masses (not concentrations) of U and Th were measured for the *Reiners and Farley* [1999] titanites, and we use the average U and Th masses for all grains from a given sample. The lack of grain volume estimates makes a calculation of concentration difficult and limits this discussion to only those grains that have some estimate of crystal size. The Chain of Ponds, FCT, and Mount Dromedary grains were all between 300 and 800 μm in their long axes, and we use spherical radii of both 300 and 800 μm for each sample type to estimate volume. Alpha doses for these three samples overlap and are 5×10^{14} to 9×10^{15} α/g for the Mount Dromedary titanite, 6×10^{13} to 1×10^{15} α/g for the FCT titanite, and 4×10^{14} to 8×10^{15} α/g for the Chain of Ponds titanites. In contrast, our titanites have, in some cases, 5 orders of magnitude greater alpha dose and range from 3×10^{16} to 3×10^{18} α/g . Many of the titanite grains from this study overlap with the damage threshold for

negative correlations in zircon ($\sim 5 \times 10^{17}$ to 2×10^{18} a/g). Our data suggest that early titanite diffusion studies were conducted on grains with relatively low amounts of radiation damage and the possible relationship between damage and He diffusivity in titanite should be further investigated.

6.3. Geologic Significance of Thermal Histories

Our data and thermal history models suggest that this portion of the Fennoscandian Shield was subjected to at least two main phases of heating and cooling over an ~ 1000 Ma time span. We interpret both episodes in the context of foreland basin burial and subsequent exhumation. Basin subsidence in both the Neoproterozoic and Paleozoic can be tied to the Sveconorwegian and Caledonian orogenic events, respectively. These data therefore represent the first estimates of burial due to both orogenic events to be obtained from a single thermochronometer. For estimates of total burial depth during each orogeny, we rely upon the inverse model results shown in Figure 7. Converting these temperatures into burial depths requires an assumption of geothermal gradients; here we use an average range of gradients, between 20 and 25°C/km. With these gradients, a mean burial temperature of 224°C (range of 262–185°C), and an average surface temperature of 20°C, our deepest sample group was buried to a mean depth of 8.1 km (range of 9.7–6.6 km) or 10.2 km (range of 12.1–8.3 km maximum) during the Sveconorwegian event. An additional ~ 1300 m of vertical depth in the drill core can be subtracted from these estimates to yield maximum sedimentary burial depths (i.e., assuming that the present-day surface corresponds with the top of the basement in the Neoproterozoic). The lowest of these estimates, ~ 6.6 km, is within the range of typical foredeep depozone sedimentary thicknesses (2–8 km) [DeCelles and Giles, 1996], albeit on the higher side of that range, but this depth could be further reduced if the overlying sediments had low conductivity. These estimates are more comprehensive than previous estimates from zircon and titanite fission track ages that suggest only approximate burial depths sometime between ~ 930 and 670 Ma [Larson *et al.*, 1999]. We note that several kilometers of crystalline basement, in addition to foredeep sediments, could have been exhumed post-Sveconorwegian, which would reduce this sedimentary thickness estimate.

The depth of burial during the Caledonian orogeny is substantially less than what we calculate for the Sveconorwegian. With a mean burial temperature of 147°C (range of ~ 173 –120°C) and our range of geothermal gradients, we estimate mean burial depths of 5.1 km (range of 6.1–4 km) to 6.4 km (range of 7.7–5 km). Because our sample locations were closer to the load of the Sveconorwegian orogenic wedge than the Caledonian [Larson *et al.*, 1999], a lower burial depth during the Caledonian orogeny is not surprising given that our area likely underwent less flexural subsidence at that time. Our data support previous results that subsidence related to the Caledonian foreland occurred over a broad region, including locations far from the front of the thrust belt [Larson *et al.*, 1999; P. Söderlund *et al.*, 2005], which suggests that the Fennoscandian Shield possesses sufficient effective elastic thickness to transmit a flexural response far into the foreland.

Although flexural subsidence and sedimentary burial provides a relatively straightforward explanation for sample reheating, the mechanisms responsible for exhumation and cooling of our samples following this phase of burial are less apparent. As such, we consider a number of possibilities. Extensional collapse of the orogen has been demonstrated for the Caledonian event following the cessation of collision [Andersen, 1998; Roberts, 2003; P. Söderlund *et al.*, 2005]. Although similar evidence from the Sveconorewegian orogeny is lacking, it is reasonable to assume that orogenic collapse also occurred post-Sveconorwegian. In both cases, extension along normal faults likely resulted in some amount of tectonic exhumation within the orogenic wedge proper [Roberts, 2003]. However, despite pervasive lineaments throughout southern Sweden, significant footwall exhumation along documented faults does not seem likely for the foreland area in Laxemar [Cederbom, 2001; Cederbom, 2002]. Instead, removal or dismemberment of the wedge as a consequence of orogenic collapse could lead to rebound of the flexed foreland basin and subsequent exhumation.

An alternative explanation for postorogenic foreland exhumation consists of surface uplift and erosion in response to mantle dynamics. The two major cooling portions of the *t*-*T* paths shown in Figure 7 (~ 850 –600 Ma and ~ 300 –200 Ma) overlap broadly with the timing for final assembly of the Rodinia and Pangaea supercontinents, respectively [Scotese, 2009; Zhang *et al.*, 2010]. In the case of Pangaea, global mantle convection models retrodict a dynamic uplift response to Pangaea formation as the mantle warms and becomes more buoyant beneath Laurussia following the cessation of subduction [Zhang *et al.*, 2012]. These models produce as much as ~ 1 km of surface uplift between 330 Ma and 250 Ma in portions of Laurussia. Given this timing, we suggest that the Fennoscandian Shield could have been subjected to

dynamic processes due to Pangaea formation, as evidenced by our thermal history results. Although the magnitude of dynamic topography seems incongruent with our modeled Paleozoic exhumation for Fennoscandia, dynamic topography can be effectively eroded by surficial processes, which enhances the exhumation effect of relatively low amplitude dynamic uplift, particularly if the mantle source of this topography is not transient [Braun *et al.*, 2013]. Similar models of possible dynamic topography related to Rodinian assembly have not been produced. However, plate reconstructions suggest that the Pacific superplume was created following final assembly of Rodina between ~750 and 600 Ma [Maruyama *et al.*, 2007]. This warm, buoyant feature could produce a surface uplift response akin to modeled dynamic topography post-Pangaea formation.

In this sense, our zircon He results may provide constraints on the timing and magnitude of exhumation events related to Wilson Cycle and global processes. Further analysis of Proterozoic-Cenozoic zircon He age-eU data sets from other craton cores may shed further light on this possibility. We note that Ault *et al.* [2013] suggested that post-Pangaea formation dynamic topography could explain some of their modeled thermal histories for the Slave craton derived from apatite He age-eU correlations. For the time period between ~400 and 200 Ma, models presented by Ault *et al.* [2013, Figure 7] are strikingly similar to model *t-T* paths shown here (our Figure 7). Regardless of the exact geodynamic mechanisms, our results provide strong evidence that seemingly quiescent craton interiors can experience multiple episodes of burial and exhumation over long time scales (>1000 Ma).

7. Conclusions

Zircon, titanite, and apatite (U-Th)/He ages from the Fennoscandian Shield yield constraints on multiple cycles of heating and cooling, primarily related to two distinct orogenic events: the Neoproterozoic Sveconorwegian and the Paleozoic Caledonian orogens. Negative correlations between zircon He age and eU allow for detailed thermal history modeling (using a radiation damage-He diffusivity model) from ~1.8 Ga to the present of drill core samples from the Laxemar region. These negative correlations constrain an average reheating temperature of ~224°C (range of 262–185°C) between 944 Ma and 851 Ma, followed by cooling to near-surface temperatures at the beginning of the Cambrian, and then reheating to an average temperature of ~147°C (range of ~173–120°C) between 366 Ma and 224 Ma. We interpret these cycles of reheating and cooling in the context of sedimentary burial caused by foreland basin development during both orogens and subsequent exhumation. For the Sveconorwegian orogen, our new constraints on timing and temperature of burial and exhumation represent a more detailed and robust *t-T* path than was previously available. Exhumation related to both orogens may have been caused by long-term orogenic collapse and rebounding of the foreland basin, but because the major cooling episodes (~850–600 Ma and ~300–200 Ma) overlap with the timing for final assembly of the Rodinia and Pangaea supercontinents, a dynamic topographic response could provide an alternative driving mechanism for this exhumation. The timing and magnitude of burial and exhumation related to the Caledonian orogeny is further supported by positive age-eU correlations in the apatite system. Titanite He results also show a negative correlation between age and eU, and an important observation from our study is that the negative age-eU correlations in both the zircon and titanite systems overlap in age and eU space. We therefore provide one of the first examples (along with Baughman *et al.* [2017]) of the possible importance of radiation damage effects on titanite He ages.

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