Chemical Geology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo

Helium trapping in apatite damage: Insights from (U-Th-Sm)/He dating of different granitoid lithologies

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ARTICLE INFO

Editor: Prof. K. Mezger

Keywords:
Apatite
Thermochronology (U-Th-Sm)/He
Damage
Trapping
Diffusion

ABSTRACT

Apatite (U-Th-Sm)/He (AHe) thermochronometry is widely used to constrain thermal histories and rates of tectonic, exhumation, and erosion processes. However, data interpretation is often challenging, especially when the thermal history includes extended residence time in the He partial retention zone (HePRZ), with highly dispersed dates revealing the complexity of diffusion processes in natural systems. This study investigates chemical and physical factors that may have impacted He diffusion in apatite over long timescales in a context of protracted residence in the HePRZ. Nine samples from the Ploumanac'h pluton and North Tregor (Armorican Massif, France) were collected in granitoids, differing in petrography and chemisty. This area was chosen because these samples underwent a similar thermal history since ~300 Ma. We report new (U-Th-Sm)/He dates, along with apatite fission-track (AFT) data, as well as lithological and chemical characterization. The results show dispersed (U-Th-Sm)/He dates, ranging from 87 ± 7 to 291 ± 23 Ma, whereas central AFT dates vary from 142 ± 6 to 199 ± 9 Ma. Current predictive models for He diffusion and fission-track annealing in apatite could not reproduce the two datasets together. However, this apparent discrepancy gives insight into the parameters influencing He diffusion at geological timescales. The data confirm that radiation damage enhances He trapping, as the AHe dates are positively correlated to effective uranium (eU) concentration. The He age dispersion for constant eU content cannot be explained just by variations in grain size or chemical composition. To explore the potential influence of recoil damage trapping behavior and annealing kinetics on AHe dates, we tested a new diffusion model from Gerin et al. (2017). Given the expected model of the thermal history provided by AFT inversion, we investigated the influence of the trapping energy on AHe dates. The AHe date variations can be explained only if the trapping energy evolves from one crystal to another, increasing with the amount of damage. For a given trapping energy, minor variations in the recoil-damage annealing rate can consistently explain most of the remaining dispersion of the AHe dates.

1. Introduction

Apatite (U-Th-Sm)/He (AHe) thermochronometry is widely used to determine the thermal histories of mountain ranges and sedimentary basins, as apatite crystals retain radiogenic helium at low temperature (< 150 °C) (e.g. House et al., 1998; Ehlers and Farley, 2003; Stock et al., 2006; Reiners and Brandon, 2005; Valla et al., 2011; Herman et al., 2013).

(U-Th-Sm)/He thermochronometry is based on the accumulation of radiogenic ^{4}He in apatite crystals, generated by ^{238}U, ^{235}U and ^{232}Th alpha decay chains, and to a lesser extent by ^{147}Sm alpha decay. Interpretation of a set of AHe dates is not straightforward though, especially when the cooling history is complex or long (e.g. Green et al., 2006; Green and Duddy, 2006; Shuster et al., 2006; Leprêtre et al., 2015) as this often produces high levels of intra and intersample dispersion. The extent to which such dispersion reflects complex He behavior during diffusion in apatite has yet to be fully explained.

Our knowledge of He diffusion in apatite has improved over the last

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http://dx.doi.org/10.1016/j.chemgeo.2017.09.002
Received 7 June 2017; Received in revised form 30 August 2017; Accepted 1 September 2017

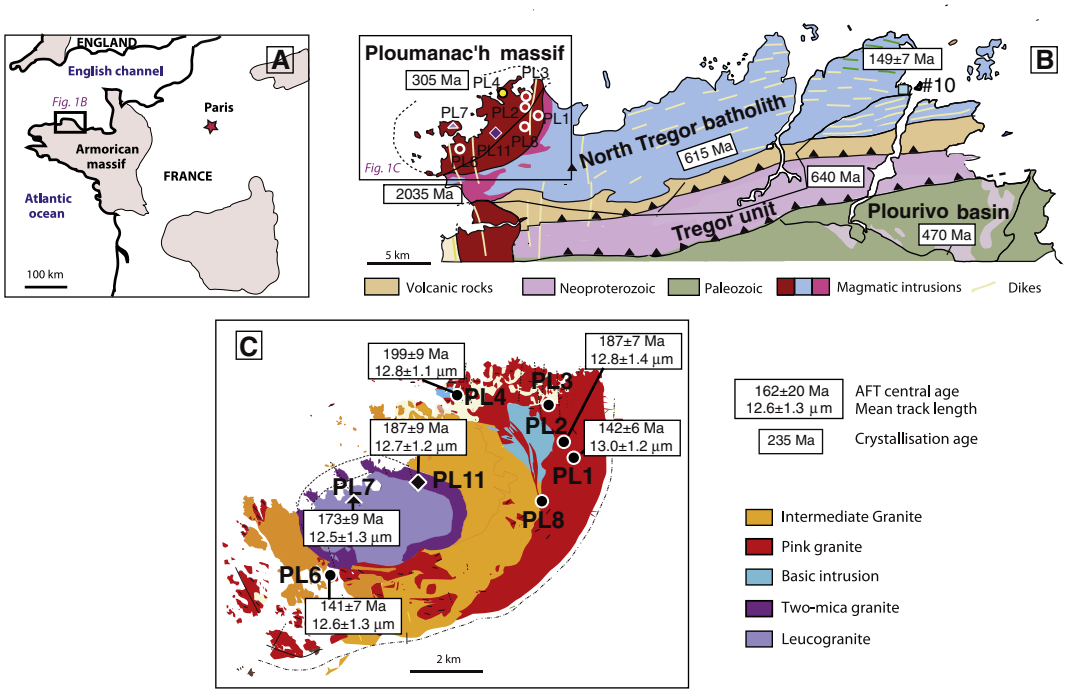

Fig. 1. Geological setting and sample location. (A) Regional map of northwestern France, and location of the Armorican massif. Pink areas are outcropping Paleozoic basement massifs. (B) Geological map of the "pink granite coast" (Brittany, France), and location of the Ploumanac'h pluton. (C) Lithological map of the Ploumanac'h intrusion, and fission track analysis results (this study). Sample locations, crystallization ages, central AFT ages, and mean fission track lengths are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

decade due to numerous experiments and atomistic models (e.g. Farley, 2000; Shuster et al., 2006; Cherniak et al., 2009; Bengtson et al., 2012; Djimbi et al., 2015). In natural apatite, damage is produced during U-Th-Sm decay (alpha and recoil damage) and natural fission of ^{238}U and may undergo annealing (self repair) at elevated temperatures (Chaumont et al., 2002; Shuster and Farley, 2009). The level of preserved damage produced by alpha decay in an apatite can influence helium retention (reduced diffusion) due to the trapping of He atoms in the damaged areas which act as holes within the crystal structure (Shuster et al., 2006; Shuster and Farley, 2009; Gautheron et al., 2009; Gerin et al., 2017). Damage density depends on U-Th-Sm contents and on the damage-annealing rate, which varies with crystal chemistry and thermal history (Chaumont et al., 2002, Shuster and Farley, 2009; Gautheron et al., 2013, Fox and Shuster, 2014).

Currently, two main models take into account the effect of damage trapping and annealing on He retention in apatite (Flowers et al., 2009; Gautheron et al., 2009). Both models imply that the diffusion coefficient decreases with increasing damage fraction (or effective track density). Damage annealing is known to make the apatite lattice more diffusive for He atoms (Shuster and Farley, 2009), and has been suggested to be sensitive to apatite chemical composition as is fission track annealing (Gautheron et al., 2013). In the absence of specific damage annealing studies, alpha recoil damage and fission tracks are generally assumed to behave similarly. However, recent simulations from Fox and Shuster (2014) indicate that alpha damage may anneal slower than fission tracks.

Recently, a new radiation damage diffusion model was published by Gerin et al. (2017), and was implemented in QTQt for the purpose of our study. In this model, the closure temperature in undamaged apatite is assumed to be 30–40 °C (Djimbi et al., 2015), and diffusion processes kinetics decrease with the alpha damage content as a function of damage retentivity. This last parameter is controlled by the trapping energy that adds to the activation energy, with a linear He trapping behavior.

Further work is required to better understand the long-term controls on helium retentivity in apatite, such as He damage trapping efficiency, the damage annealing rates, and the influence of microvoids in apatite (Zeitler et al., 2017). To this end, it is desirable to study the natural variability in helium dates (as in Green et al., 2006; Gautheron et al., 2009, 2013). Careful selection of apatite crystals is paramount for such work, as implantation, broken grains with mineral inclusions can also lead to significant scatter in AHe dates distribution (Vermeesch et al., 2007; Spiegel et al., 2009; Gautheron et al., 2012; Beucher et al., 2013; Brown et al., 2013; Murray et al., 2014; Janowski et al., 2017).

This study focuses on data from samples in the North Armorican Massif (western France), and particularly within the Ploumanac'h pluton and North Tregor massif. This region represents a single geological and tectonic domain and the samples experienced a common thermal history since Carboniferous time. As the massif includes a variety of lithologies, the samples were selected specifically to assess whether petrography and apatite chemistry can account for the dispersion in the AHe datasets. The present work combines low temperature thermochronology, including apatite (U-Th-Sm)/He and fission-track analysis, and sample petrography/chemistry from the hand specimen to the mineral scale.

The aim of this study is to better understand the behavior of helium in apatite, as well as to test the current models for alpha damage accumulation and annealing. We first investigate the AHe date dispersion as a function of different physical and chemical parameters. Then, we try to model our dataset using the Flowers et al. (2009) and the Gautheron et al. (2009) models. We investigated the role of the damage retentivity and damage annealing kinetics to reproduce our dataset. To this aim, we used the new Gerin et al. (2017) model, as it is based on the most recent physical representation from Djimbi et al. (2015) and has a linear trapping behavior. We tweaked the trapping energy and damage annealing characteristics in order to predict our dataset. This approach give new insights into radiation damage and into the role of apatite chemistry on helium retentivity.